ASSESSING AND MITIGATING RISK IN A DESIGN FOR SUPPLY CHAIN PROBLEM

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Industry leaders in today's global market strive for continuous improvement in order to remain competitive. One method used by firms for cutting costs and improving efficiency is Design for Supply Chain (DFSC). The objective of this methodology is to design the supply chain in parallel to designing or redesigning a new product. Risk is an inherent element of this DFSC process. Although supply chain risk models and new product development risk models are available, there are few models that consider the combined effect of risk to product development and the supply chain. A gap in the body of knowledge could be filled by a DFSC and risk model that looks at design, supply chain and risk concurrently. This research develops such a model and tests it on two data sets. The most critical risks to incorporate in the model were found through a review of the literature and a survey of industry experts. The model consists of two components. The first component is a Mixed Integer Programming (MIP) model which makes the DFSC decisions while simultaneously considering time-to-market risk, supplier reliability risk and strategic exposure risk. The results from the MIP are then used in the second model component which is a discrete event simulation. The simulation tests the robustness of the MIP solution for supplier capacity risk and demand risk. When a decision maker is potentially facing either of these risks the simulation shows whether it is best to use an alternative solution or proceed with the MIP solution. The model provides analytical results to be used by decision makers, but also allows decision makers to use their own judgment to select the best option for overall profitability. It is shown that the DFSC model with risk is a powerful decision making tool.

Keywords: Design for Supply Chain, Supplier Selection, New Product Development, Risk, MIP, Simulation

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PREFACE

It is a pleasure to thank those who made this dissertation possible. My dissertation advisors Dr. Bryan Norman and Dr. Kim LaScola Needy were truly a pleasure to work with. They offered me guidance, support, encouragement and most importantly patience. I would also like to thank the committee members, Dr. Mary Besterfield-Sacre, Dr. Jeffrey Kharoufeh, and Dr. Scott Mason for their time and valuable suggestions. I am grateful to Mehmet Nuri Gokhan for sparking my interest in this area and for his guidance and support through my own research. I would also like to thank Sheng-I Chen for answering all of my questions about the Arena simulation software package and Visual Basic coding and Sam Dedola for his insight and advice from an industry perspective.

This dissertation would not have been possible without the support of my family. I am grateful for my parents, Glenn and Lynne, my siblings, Sarah, Kate and Grant and my in-laws, Rick, Barb, Matt and Becky. They all provided encouragement and countless hours of babysitting through all of my *many* years of schooling. My children, Kaylee, Carter and Owen, were the best little helpers that any mother could ask for. And finally, I would like to thank my wonderful husband, Rick, for his support and encouragement throughout the entire process. It would have been next to impossible to write this dissertation without everyone's help and guidance.

LIST OF ACRONYMS

3D-CE – Three-Dimensional Concurrent Engineering

ABC – Activity Based Costing

AHP – Analytic Hierarchy Process

ANOVA – Analysis of Variance

BOM – Bill of Materials

DEA – Data Envelopment Analysis

DFSC – Design for Supply Chain

FST – Fuzzy Set Theory

HP – Hewlett-Packard

MIP – Mixed Integer Programming

NPD – New Product Development

SC – Supply Chain

SMART – Simple Multiattribute Rating Technique

TTM – Time-to-Market

VIG – Visual Interactive Goal Programming

1.0 INTRODUCTION

1.1 MOTIVATION

In today's highly competitive and globalized market, manufacturing firms are placing an emphasis on efficiency and cost effectiveness. Banerji et al. (2009) states that, "In the aftermath of the global economic crisis of 2008-09, the pressure to cut costs – whether driven by cash flow, shareholders, uncertainty, or investment needs – has been extraordinary." Cost-cutting initiatives are present throughout the business process – in design, manufacturing and even in the disposal of products. Outsourcing to foreign countries, focusing on sustainability, and recycling of materials are some popular methods currently used for achieving these goals.

Another method for cutting costs and improving efficiency that is gaining popularity is a concept known as Design for Supply Chain (DFSC). The objective of this methodology is to design the supply chain in parallel to designing a new product. Traditionally, the supply chain is designed after the product design phase has been completed, which often results in a longer design cycle time and sub-optimal overall product profitability. It has been shown that huge productivity improvements and cost reductions can be achieved by collaborating with the supply chain engineers early in the design process. For example, in the first four years after implementing Design for Supply Chain Management at Digital Equipment Corporation, they have realized a cost savings of approximately $1 billion. These savings can be broken down into many different areas, including simpler, streamlined supply chain and product designs, more efficient and effective planning techniques, and improved cooperation and planning between their twelve plants (Arntzen et al., 1995).

Regardless of the method used to cut costs and improve efficiencies, all companies face risk. Risk has been defined by Lowrance (1976) as a “measure of the probability and severity of adverse effects.” In this research, risks are referred to as events, which if occur, will have detrimental impacts to the product or supply chain. For example, outsourcing to a foreign country might drastically reduce labor-related costs, but this approach also imposes intellectual property risks. In the event that a breach of intellectual property occurs, this will have detrimental effects to the company and their product. This event is defined as intellectual property risk. Similarly, companies that design, manufacture and distribute all of their products domestically face the risks of natural disasters, design failures, quality or supply issues. A survey by Accenture, found that 110 of 151 U.S. supply chain executives said that their companies faced supply chain disruptions in the past five years (Singhal, 2008). Similarly, most new products never reach the market, and those that do suffer failure rates around 25-45% (Cooper, 2001). Therefore, for a company to actively compete in today’s global economy it is very important to manage cost, quality, efficiency, and also risk.

This research is specifically focused on the incorporation of risk management into the DFSC methodology. Risk management is a technique that has been used for centuries. Many analytical models have been developed, and are available, to analyze supply chain risks, and models have also been created to evaluate risk in the New Product Development (NPD) process. Haimes (2004) and Modarres (2006) focus on risk management in engineering, but their risk analysis and modeling tools can be applied to many different fields. Commercial tools are even available to help companies identify, quantify and mitigate risks related to either supply chain or product design. These include commercial risk management software packages such as PRAM (Procurement Risk Assessment and Mitigation) developed by Dow and i2, which is a what-if simulation tool (Teague, 2007). However, there is room for improvement with these models and tools. Marsh, Inc. surveyed 110 risk managers, who all stated that their current supply chain risk management practices are not highly effective (Singhal, 2008). Risk needs to be taken into consideration when using a DFSC methodology. Supply chain risk models and NPD risk models are available, but there are few models that cover both aspects simultaneously.

1.2 PROBLEM STATEMENT

When a company is designing a new product and its corresponding supply chain, it is difficult to select the optimal product design and supply chain combination while simultaneously evaluating risks associated with different design and supply chain alternatives. It is even difficult to determine whether the best approach is to consider risks while simultaneously evaluating designs and supply chains, or if it is best to evaluate risks after the design and supply chain have been selected. Further, it is complicated to determine how to incorporate risk into mathematical models used for DFSC decisions. Some risks are easily modeled in a mathematical manner, while others are more qualitative in nature and are more difficult to model mathematically.

Designing a new product and its corresponding supply chain consists of many aspects and decisions. Product design is a multiple phase process, and supply chain design consists of many different components, all of which cannot be adequately addressed in this research. The scope of the research is, therefore, limited to a set of decisions, which is illustrated in Figure 1. Components in Figure 1 shaded in gray were not included in the scope of this research.

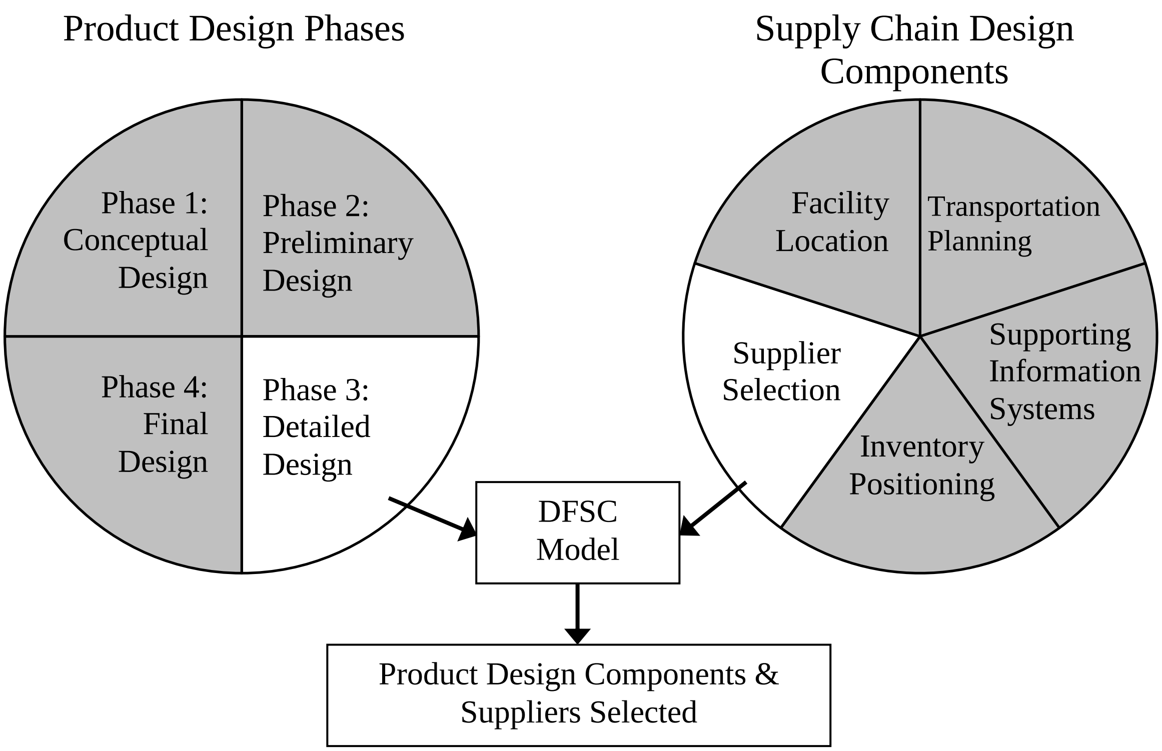


Figure 1. Research Scope Definition

The product design process begins with an idea, an identification of a need, or a requirement from a customer. Then, as shown in Figure 1, the design process consists of the following phases: conceptual design, preliminary design, detailed design and final design. This process is described by Dym and Little (1999, p.28).

In Phase 1, the conceptual design phase, design concepts are generated. Some design details are worked out so that cost and dimensional estimates can be made. Those details are then enhanced in the preliminary design phase, Phase 2. This phase is more technical in nature than the conceptual phase, but estimates and rules of thumb are still generally used. Specific part types and dimensions are not determined until the detailed design phase, which is Phase 3. This phase is within the scope of the research because DFSC models can be used to select the optimal design alternative for each design component. Data that is generated in the detailed design phase, such as supplier alternatives, component cost, and customer needs and preferences are used as inputs in the proposed DFSC model. Outputs from the model can then be used in the final design phase, Phase 4, where fabrication specifications and documentation are completed. Therefore, only a portion of the detailed design phase is within the scope of this research. The scope is also limited to the design of one product, as opposed to a product family.

Supply chain design also consists of many different decisions. A supply chain is defined as, "the global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash" (Ayers, 2006). To design a supply chain, an organization must select suppliers, determine where to locate production facilities, warehouses, distribution centers and physical inventory, determine modes of transportation and design the supporting information systems, as shown in Figure 1. The scope of this research is limited to the selection of suppliers and the allocation of total order quantities to each supplier. Optimal ordering policies will not be determined, only the total order quantities from each supplier.

While companies are making these NPD and supply chain decisions, they should also be assessing risk. Many tools exist for risk management. However, FM Global conducted a study of over 600 financial executives from around the world and found that supply chain risks pose the most significant threat to profitability of companies (Singhal, 2008). Therefore, companies could benefit from a combination system, namely a DFSC and risk tool or a methodology that considers DFSC *and* risk analysis.

This research is a significant extension of Mehmet Nuri Gokhan's dissertation titled "Development of a Simultaneous Design for Supply Chain Process for the Optimization of the Product Design and Supply Chain Configuration Problem" (Gokhan, 2007). The objective of Gokhan's research was to build a DFSC model which effectively synchronizes product design and supply chain design for new and existing products, in a Mixed Integer Programming (MIP) framework. The desired result from the model was a good product design and a cost effective supply chain that minimizes lead time, ensures quality, and maximizes profitability over the product lifetime. To extend that work and solve the research problem stated, risk is incorporated into Gokhan's DFSC framework. This extension is anything but trivial, due to the number of risks under consideration, the uncertainty associated with the risks and the complexity of modeling risk. The primary contributions of this research are to determine which risk factors are most critical for organizations to consider and the development of a DFSC and risk model.

1.3 RESEARCH QUESTIONS

It is difficult to consider all of the risks that a product design or supply chain faces. This is especially true when using a mathematical model to analyze risks because models quickly become too complex to solve efficiently. However, the more risks that an organization is able to take into consideration and plan for, the more realistic the model will be, which will minimize disruptions to the supply chain. A major contribution of this research is to determine which risks are most critical to include in the model. Therefore, the goal of this research is to answer the following research questions:

1. *Which risks to the supply chain and NPD are the most critical for companies to consider?*
    a. *Which events have the highest likelihood of occurrence and the most impact to the organization if they are to occur?*
    b. *Which risks should be included in models used to analyze NPD and supply chain design decisions?*
2. *What is the best approach for incorporating the critical risks in a DFSC Mixed Integer Programming (MIP) framework?*
    a. Is it possible to model all of the critical risk factors in the existing Gokhan MIP framework or are risks better modeled using some other tool?
    b. If another tool is necessary, what is the best way to use the MIP and the new tool together?

Gokhan's DFSC MIP model is extended in this research to include risk. However, the best method for accomplishing that and modeling risks is not straightforward. Several modeling methods are considered, including modeling all risks in the MIP versus developing a separate model that includes risks that are difficult to incorporate into the MIP. In the event that a separate model needs to be developed, then the two models also need to be integrated.

1.4 CONTRIBUTIONS

There are numerous contributions from this research. First is the determination of the most critical risk factors related to NPD and supply chain design decisions. This analysis was not limited to one industry; it was broad enough to give a general set of risk factors which are important to several industry types. Observations from the literature were used to identify potential risk factors and then a survey of industry experts was used to identify candidate risk factors. Then a statistical analysis of survey results was completed to select a set of critical risk factors related to NPD and supply chain design.

The second major contribution is the extension of the DFSC knowledge base to include a comprehensive model for simultaneous DFSC decision making and risk analysis. Currently there are no DFSC models which also include risk modeling. A few of the DFSC models include a handful of risk factors, such as Lee and Sasser (1995), Arntzen (1995) and Graves and Willems (2005), but none include a comprehensive risk analysis. To close that gap, first several improvements were made to the Gokhan (2007) DFSC formulation. Then, the critical risk factors were incorporated into to the formulation and a process was developed for risk analysis. The DFSC and risk model was used to analyze two different sets of data.

Finally, this research includes validation work that was done by working closely with a medical device manufacturing company during preliminary model development. They provided a small set of data from a recent project that was used to validate the model.

1.5 DISSERTATION OVERVIEW

Chapter 2 of this dissertation contains a review of the related literature. The chapter is divided into five subsections, each one focused on a separate body of literature, including risk theory, DFSC theory, supply chain risk management, NPD risk management and DFSC risk management. Chapter 3 reviews the analysis done to determine which factors to include in the model. This process includes a review of the relevant literature and an industry survey. Then, in Chapter 4, the selection process for an appropriate DFSC risk modeling methodology is explained and the final model is presented. Chapter 5 includes computational results from the final DFSC risk model and Chapter 6 concludes the dissertation and provides recommendations for future research in this subject area.

2.0 LITERATURE REVIEW

Examination of the scholarly literature encompassed several bodies of knowledge. These include risk, DFSC, supply chain risk management and NPD risk management. Some literature spans more than one category, but mostly each body of knowledge was examined separately, as it appears in the following sections.

2.1 RISK THEORY

The risk theory body of knowledge is large and extensive. The first studies of risk are dated several decades back, with work continuing until today (Knight, 1921) (Keynes, 1921) (Morgenstern & von Neumann, 1944). The applications of risk management are also vast. It has been applied to the financial, manufacturing, insurance and project management sectors, among several others.

Peter Bernstein's book *Against the Gods: The Remarkable Story of Risk*, published in 1996, gives an in depth examination of the history of risk and risk management. Bernstein explains that gambling prompted the development of risk management, as gamblers realized they could estimate their odds through probability theory. The first evidence of this is in Girolamo Cardano's book, *Liber de ludo aleae*, which was a book on games of chance, written in the 1560's and published in 1663. This was the first effort to develop statistical principles of probability – a significant step in allowing risk management to evolve. By the end of the 17th century, major problems in probability analysis had been resolved. Bernstein (1996) goes on to explain that the insurance and investment industries revolutionized the way that people viewed and managed risk.

Now, there is a wealth of scholarly literature written on risk management. Likewise, there are numerous ways to classify the vast number of models and methods contained in that literature. One way is to distinguish between qualitative and quantitative risk management methods. Alternatively, methods can be classified by their application area. Models have been developed specifically for financial risks to an organization, which is commonly known as enterprise risk management. Other models have been established for the risk management of projects, supply chains, etc. Frosdick (1997) argued that they can be categorized as intuitive tools (brainstorming), inductive tools (FMEA – Failure Modes and Effects Analysis), and deductive tools (accident investigation and analysis).

Since there are many different methods, models and classification methods, there are many differing opinions in the literature as to which theories and models are best. In practice, however, Hood and Rothstein (2000) have found that business executives prefer to combine subjective and objective methods. This gives them the flexibility to make a decision based not just on numerical analysis but also subjective opinions.

White (1995) made the case that most approaches can be generalized into a framework consisting of three stages: risk identification, risk analysis and risk evaluation. This framework can clearly be seen in the work presented by Slywotzky and Drzik (2005). Their risk management process is to identify, assess and quantify risks, and then develop risk mitigation action plans. This approach is also the foundation for this research, as risks are identified and then quantified in the DFSC model. Finally, after a company receives quantitative model results, they can use those results to develop risk mitigation plans. Haimes (2004, p. 57) presented a similar framework. His risk assessment and management process has five steps – (1) risk identification, (2) risk modeling, quantification and measurement, (3) risk evaluation, (4) risk acceptance and avoidance, and (5) risk management.

This research is primarily focused on quantitative risk management methods, as the objective of the research is to develop a quantitative mathematical model for DFSC and risk. However, we can gain valuable insight from some of the qualitative work. Swaminthan and Tomlin (2007) provided qualitative advice for managing risk by discussing different ways to avoid big pitfalls. For example, they do not assume that disruptions will only occur when operating under normal conditions. They argued that disruptions can occur on top of disruptions. This is one mistake that companies have a tendency to make when assessing the impact of risks. It is also something to keep in mind when creating the DFSC and risk model. Riswadker and Jewell (2007) discussed the management of import risks. Their paper gave information about risks faced when outsourcing the product design and/or manufacturing process to a foreign manufacturer. One of these risks is that the importer is normally held liable for manufacturing defects caused by the foreign manufacturer. This can lead to high litigation costs and also the importer's reputation is at stake if product recalls occur.

Valuable insights can also be gained from literature that discusses quantitative risk management models. For instance, Grabowski et al. (2000) discussed the challenges associated with modeling risk in large systems. They warn of risk migration, which occurs when risk mitigation is used against one risk, but actually induces others. Other challenges include poor information flow in large systems and human error. These challenges are kept in mind when developing the DFSC and risk model.

The remainder of the literature pertaining to quantitative risk management has been analyzed in the Supply Chain Risk Management and the NPD Risk Management sections of this literature review.

2.2 DESIGN FOR SUPPLY CHAIN THEORY

"Design for X" is a term used to categorize design methodologies that encourage comprehensive design work. If these methodologies are not used, design teams often include only design engineers, not manufacturing, marketing or supply chain personnel. Their objective is to design products to meet design requirements only. This practice often results in a product that is difficult to manufacture, does not meet cost thresholds, or does not have a feasible supply chain to support it. The product is sent back to the design engineers for redesign, and the cycle continues. Design for X tools promote diverse design teams and offer guidelines for considering the manufacturability or serviceability of the product while it is being designed. Other Design for X tools include Design for Cost, Reliability, Safety, Quality, Logistics and one of the most recent additions is DFSC.

Researchers and practitioners began to recognize the benefits of an integrated DFSC approach in the early nineties. In 1990, Keys made one of the first attempts to document this type of methodology, as he discussed the Design for Life Cycle concept. This methodology was described as the combination of all design efforts including but not limited to manufacturability, assembly, cost, quality, customer support logistics, and supply chain. He suggested that it is very important to keep the focus on the product life cycle since “the planning of new products includes second, third, etc., generation product follow-ons. Product support must be a part of an integrated life-cycle strategy.” Although, he did not use the DFSC term, the concepts are similar.

The term Design for Supply Chain Management was first used in 1992, in an article by Lee and Billington (1992). Fourteen pitfalls of supply chain management were discussed, and corresponding opportunities for improvement were presented. It is here that they introduced the concept of Design for Supply Chain Management as an opportunity to improve the product design process,

> A lot has been written on design for manufacturability, for assembly, for quality, for producibility, and for serviceability. To this list we would add “design for supply chain management.” Thus product designs should be evaluated not only on functionality and performance but also on the resulting costs and service implications that they would have throughout the product’s supply chain. The same applied to process designs (Lee & Billington, 1992, p. 11).

Several years later, Lee and Sasser (1995) gave an actual case study of a DFSC implementation. In their study, Hewlett-Packard (HP) used a DFSC model on a new product line, to determine the optimal product differentiation point. The model included stochastic demand, lead time decisions, service level targets, and inventory, stockout, and shipment costs. Analytical solutions for different product life cycle phases, as well as for different design alternatives, were given. This study is especially interesting, because real data was used and the results were validated after the product was launched. Another important contribution was that the modeling and analysis was done during the product design phase. This differs from the majority of supply chain related studies that try to optimize the supply chain for products after the design phase. Although Lee and Sasser studied a supply chain configuration problem, the limitation is that they did not incorporate supplier selection and the associated uncertain quality, lead time, and capacity problems.

Around the same time as the HP case study, Lee and Billington (1995) also reported on the evolution of Supply Chain Management models and practices at HP. These new practices were driven by high inventories and high customer dissatisfaction rates. Through this evolution HP developed a successful approach for modeling and optimizing the supply chain, which added distribution, market, and product specifications into their previous inventory modeling efforts. Four key company requirements were given as the basis for their model: (1) benchmarking inventory and service tradeoffs; (2) assessing the impact of uncertainties on operational performance; (3) analyzing what-if questions for different scenarios and operating characteristics; (4) evaluating product design impacts on the supply chain, that is, predicting how the supply chain would perform under different product and process design alternatives (Lee & Billington, 1995). Risk is an inherent element in these four requirements. The reported benefits of their new models and practices include incorporating all related divisions of the company, key suppliers, and key customers into the SC design decisions and developing product-based supply chains.

Arntzen et al. (1995) conducted a DFSC analysis at Digital Equipment Corporation. Changes in the computer industry drove change in Digital Equipment Corporation's business, which led to this study and the development of their Global Supply Chain Model. The model included supply chain, manufacturing and logistics elements. The objective was to minimize cost and time. A Mixed Integer Linear Programming framework was used to model the problem and then a branch and bound algorithm was used to solve it. This model was used in the design of 20 new products and helped achieve a reported savings of $1 billion in four years with approximate unit production improvements around 500 percent. Limitations of the model include an assumption of fixed demand and an objective function limited to time and cost.

Fandel and Stammen (2004) presented a strategic supply chain management model that incorporates the entire product life cycle from selecting a development program through recycling. It enabled designers to compare product life cycles, development and recycling strategies for different product alternatives. However, due to the size of this model, it could not be solved efficiently and thus no results were given in the article.

Graves and Willems (2005) did not explicitly create a DFSC model, but rather a supply chain decision model that took into consideration a product design which has already been selected. A genuine DFSC model determines the supply chain and product design in conjunction with one another. Even though this model did not do that, it is still important to study, because it provides valuable insight. The model is solved with dynamic programming, modeling the supply chains as spanning trees. Validation of the model was achieved by performing a four-week case study at a Fortune 100 computer manufacturer. This resulted in several observations about general supply chain behavior which are useful to understand. For example, they found that the benefits of supply chain configuration increase as relative demand variability increases.

Lamothe et al. (2006) proposed a model that was closer to the DFSC concept. This model was used for a product family selection and supply chain network design problem. In this model each product family variant was associated with a different market segment. The demand in these market segments had to be satisfied by the associated product family or one that was better. The objective of the model was to minimize total supply chain cost. The main limitation of the model was its inability to directly relate product design with demand generation. In other words, demand levels were not affected by the product design.

Sharifi et al. (2006) presented a theoretical framework for operating in a DFSC environment. They also provided a case study, which simply proves that it is more effective to operate in a DFSC manner as opposed to designing the new product and supply chain separately. No analytical models or results are presented. Finally, Zhang et al. (2008) simultaneously optimized over variants of a product platform and the corresponding supply chain, using a MIP.

Although there have been some DFSC models created, they each have some limitations. The DFSC model presented in Gokhan (2007) attempted to create a model without the limitations of the previous research. It included manufacturing costs, customer satisfaction, demand generation, in-bound supply chain operation, and maximized profitability over the entire lifecycle of the product. However, Gokhan's model did not consider risk. This research is a significant contribution to the body of knowledge, because DFSC and risk are considered in a simultaneous manner.

2.3 SUPPLY CHAIN RISK MANAGEMENT

Risk in the supply chain refers to uncertain or unpredictable events that can occur at any point in the supply chain which can negatively affect supply chain functionality or profitability. Waters (2007) defined risk in the supply chain as follows,

> There are risks in the supply chain when unexpected events might disrupt the flow of materials on their journey from initial suppliers through to final customers. (Waters, 2007, p.7.)

The purpose of supply chain risk management is to reduce the impact of these risks by developing methods and models to identify, assess and mitigate supply chain risks. There is a vast amount of literature in this body of knowledge for several reasons. First, the terrorist attacks on the United States on September 11, 2001, the Asian Tsunami of 2004 and Hurricane Katrina in 2005 demonstrated the vulnerability within many supply chains. Prior to these events, supply chain risk management research was an active field, but the devastating impacts of these events to supply chains worldwide spawned even more interest and research activity.

Another reason for the large amount of literature is that supply chain design and supply chain management are very broad fields encompassing many different decisions. Figure 2 shows the five major supply chain design components which were previously defined, in Section 1.2. The major supply chain design decisions will now be discussed in more detail, to provide an overview of the types of literature contained within this body of knowledge.

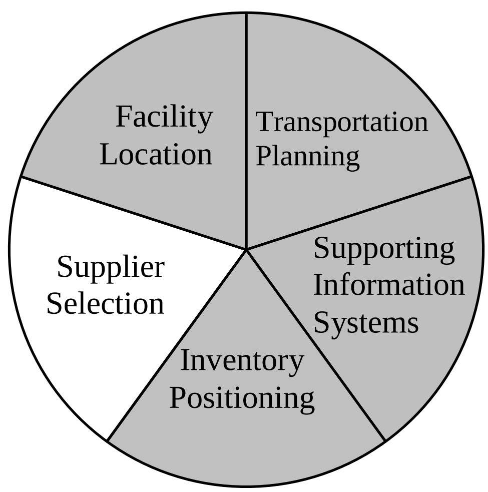


Figure 2. Supply Chain Design Components

The facility location component of supply chain design involves the design and location of production, distribution and storage facilities (Govil & Proth, 2002). In some cases, when the supply chain is very small, one facility might be sufficient for all production, distribution and storage activities. In other cases the supply chain network is large enough that multiple facilities for each function are required and locations are dispersed worldwide. Factors evaluated when locating facilities include proximity to suppliers, customers, airports, ports of entry, major highways, rail lines and other facilities within the supply chain. Factors specific to each potential location such as space surrounding the location for future expansion, labor rates, tax rates and incentives, low-interest economic development loans, political stability of the country, tariffs and duties, and environmental factors are also of concern. Capacity levels for each of these facilities must also be determined (Chopra & Meindl, 2004).

Transportation of product within the supply chain network also requires design and planning. This is referred to as transportation planning, in Figure 2. This includes the coordination of shipments between locations, the allocation of resources (trucks, planes, ships and containers) to shipping needs, routing, scheduling and tracking of shipments (Govil & Proth, 2002). Factors to consider when making these decisions include transportation costs, inventory costs, facility costs, processing costs, and service level costs (costs of not being able to meet delivery commitments). Different strategies for the transportation network include direct shipping, milk runs, shipping through a central distribution center or a combination of these strategies (Chopra & Meindl, 2004).

An information system is needed for the supply chain. Depending on the size of the supply chain network, this could either be a small database or a very large Enterprise Resource Planning (ERP) system. This information system is normally used for tracking inventory, production and sales information. However, some supply chain networks also use it for production planning, transportation planning, facility planning, raw materials replenishment, financial and management accounting, human resources functions, customer relationship management, supplier relationship management, etc. Considerations when selecting an information system include software functional performance, integration with other software packages, cost, regulatory requirements and ease of use (Chopra & Meindl, 2004).

The inventory positioning component of supply chain design involves all activities related to the storage of raw materials, work-in-process and finished goods inventories. The primary decisions pertain to where inventory should be physically located, the quantity of inventory to hold and optimal ordering policies. Other considerations involve inventory tracking, replenishment policies (continuous or periodic review), determination of safety stock levels, prevention of loss caused from damage, obsolescence or mishandling and the determination of supply contract type (revenue-sharing contracts, quantity flexible contracts, buy-back contracts or vendor-managed inventory) (Govil & Proth, 2002); (Chopra & Meindl, 2004).

Finally, supplier selection entails choosing suppliers for raw materials sourcing. There are many factors to consider in this decision including cost, quality, reputation, location, lead time, capacity, financial health, design and development capabilities, etc. Strategically, if long-term relationships are desired with each supplier, the nature of those relationships needs to be decided upon. Further, decisions pertaining to sourcing strategy (single vs. dual) also need to be evaluated (Govil & Proth, 2002).

Each of these five design components is subject to numerous risks and many methods exist for managing those risks. Therefore, the supply chain risk management body of knowledge is vast. Much of the literature is not relevant to this research, because the scope of this research is limited to the supplier selection design component. Further, we are only focused on the selection of suppliers and the determination of appropriate order quantities from each, not long term sourcing strategies or optimal ordering policies. The following is an examination of the literature pertaining to risk in the supplier selection problem.

The supplier selection problem has been analyzed in many qualitative and quantitative studies. Qualitative literature mostly consists of prescriptions for strategic risk management strategies and survey studies to determine which risk factors should be analyzed when selecting suppliers. The quantitative research consists of mathematical approaches and models for the supplier selection problem. For the purposes of this research, the quantitative literature is more relevant. However, the qualitative literature is briefly examined, to provide an overview of this field of research. An example of qualitative supply chain risk management research is Lonsdale (1999). He developed a tree diagram model that a company can step through to determine if outsourcing is the best decision for their company for a particular product, process or service. This model specifically addresses the risks associated with outsourcing production. It does not provide a cost analysis, as quantitative models do, but it is useful for considering risk factors associated with it.

Zsidisin (2003) discussed different characteristics of supply risk and the ways in which management perceives those risks. It was found that supply risk is perceived by the effect that purchased items and services have on corporate profitability, market factors, and supplier characteristics. In other words, risk perceptions can be classified into three levels – those associated with the purchased item, the individual supply sources and the entire supply market. The point was also made that managers who have a good understanding of risk will be able to manage the risks.

Martha and Subbakrishna (2002) gave general ideas for managing risks. The article focused on risks caused by major disasters or disruptions. Some risk management ideas include dual sourcing, dual transportation methods and proper inventory management. Similarly, Lee and Wolfe (2003) presented a conceptual model for simultaneous design and evaluation of supply chain efficiency improvements and security risk mitigation. Kleindorfer & Saad (2005) also developed a conceptual model for disruption type risks, including natural disasters, terrorism, political instability, strikes, etc. The authors also analyzed some empirical data from the chemical industry related to these risks.

Another emerging field of research is that which involves environmental concerns, recycling and "greening" efforts, such as green construction. Cousins et al. (2004) presented a conceptual model for risks faced when companies consider green issues in their supply chain.

Wu et al. (2006) did not consider the supplier selection problem, but rather developed a general supply risk management software tool. They developed a list of 19 inbound supply risk factors through a literature review and industry interviews. This list of risk factors was used in their risk management software tool. Users selected the risk factors that are most relevant to their company or industry and then the Analytic Hierarchy Process (AHP) is used to evaluate the risks.

Juttner et al. (2003) presented an agenda for future research related to supply chain risk management. One of their agenda items was closely related to this dissertation research. The objective of this dissertation research is to develop a model which will help companies mitigate supply chain and NPD risks while they are in the product development and supply chain design phases. Juttner et al. stated that processes need to be developed for supply chain tradeoff decision making. This will be accomplished with the DFSC risk model. Different alternatives will be assessed based on their various tradeoffs.

There are numerous other articles which offer conceptual risk management models or give recommendations for managing supply chain risk. However, since the goal of this research is to develop a quantitative model, the majority of the literature reviewed was research on mathematical modeling of supply chain risks.

Many mathematical risk models built for the supplier selection decision have been identified and reviewed. First, there are models that optimize several supply chain design components and decisions from Figure 2, including the supplier selection decision. These models are often called supply chain network optimization models, because they optimize the entire network. Only a few of these models were reviewed, because they are beyond the scope of this research. The first of these models is by Huchzermeier & Cohen (1996), who incorporated supply chain decisions and risk factors together in one mathematical model. One of the main risk factors focused on in this study was exchange rate risk. They developed a stochastic dynamic program to model exchange rate risk and also flexible global manufacturing strategies. Their work showed that flexibility can be used to mitigate against exchange rate risk. They also provided an extensive literature review of other analyses that include supply chain decision models with considerations for exchange rate risks.

Vidal and Goetschalckx (2000) gave a simple MIP model for global logistics planning including supplier selection. They also performed sensitivity analysis on the model results to test the effects of demand changes, exchange rate changes, supplier reliability, and lead time variation. Valuable conclusions were drawn from this analysis. First, the authors show that the original configuration of a global supply chain might not be the most profitable when events occur to induce risk, such as a change in demand. This was seen with sensitivity analysis. Second, MIP models provide an efficient way to test stochastic elements, through the use of sensitivity analysis. In their opinion, it is more beneficial to use sensitivity analysis on one comprehensive MIP model, rather than having separate deterministic and stochastic models.

Goetschalckx et al. (2002) presented two models for supply chain network design. The scope of their models includes the design of a logistics system in which the model chooses between various manufacturing facilities, distribution centers and suppliers and also selects the optimal transfer prices between different facilities. The first model was used to determine optimal transfer prices in the global supply chain. The second model was used to determine optimal production and distribution allocation in a single country.

Nembhard et al. (2005) incorporated exchange rate risk into a stochastic dynamic programming model for supplier selection, plant location and market region selection. Another method for modeling a supply chain selection problem with risk is to use multi-objective stochastic mixed integer non-linear programming. This was done by Azaron et al. (2008). They modeled the risks of supplier reliability, variance of total cost and financial risk, which they defined as the risk of not meeting certain cost levels or budgets. The model was solved using the goal attainment technique and their results showed that taking risk into consideration has an effect on results and thus should be considered.

The remainder of this section focuses on mathematical models for the supplier selection problem only. Most of these models were not developed specifically for risk management of the supplier selection decision. Rather, they were developed for the supplier selection problem and some of the factors incorporated into the model can be considered risk factors. Most of the models include the risks of poor delivery performance and poor supplier quality.

Several modeling techniques have been used to solve the supplier selection problem. AHP has been widely used, because of its capability to simultaneously analyze qualitative and quantitative factors in a structured mathematical manner. Supplier selection involves many different factors, some of which are qualitative in nature such as the reputation of suppliers and some of which are quantitative such as unit cost.

Tam and Tummala (2001) showed that AHP is an effective tool for solving the supplier selection problem. Their research was specific to a telecommunications system. A case study was given, for the evaluation of suppliers on 26 different criteria including the following risk factors: system reliability, system security, system performance, future technology development, quality of support services and delivery lead time. The AHP model developed in the case study led the company to select the same supplier that was previously selected and found to be the best choice. With the AHP model this decision can be reached more quickly and systematically.

Liu and Hai (2005) used the voting AHP, which is the same as the traditional AHP, except the paired comparisons are replaced with a weighting procedure. This technique was proposed by Yahya et al. (1999). Their model incorporated six criteria for evaluating suppliers. Four of these criteria – quality, delivery, responsiveness and financials – can be viewed as risk factors. The article gave a case study and analyzed the differences between using voting AHP and traditional AHP to solve this problem. The major advantage of the voting AHP is that it is simpler for users to understand.

An integration of AHP and Goal Programming was used by Kull and Talluri (2008) for a supplier selection model with the objective of minimizing various types of supplier risks. More recently, Lee (2009) also used AHP to create a supplier selection model which incorporates risks. He also used fuzzy set theory to model the uncertainty and ambiguity in the human decision making process. These two models were used together to create a Fuzzy Analytic Hierarchy Process model. This model was applied, in a case study, at an LCD manufacturer in Taiwan. It was shown that the model helped the manufacturer evaluate various factors and then determine an overall ranking of potential suppliers.

Also, in the decision models category, the Simple Multiattribute Rating Technique (SMART) and Fuzzy Set Theory (FST) have been utilized. Chou and Chang (2008) used a combination of FST and SMART to create a model for supplier selection. The model was designed to include risk factors, but the authors made no relevant risk findings. The main benefit of this system is that qualitative and quantitative factors can be incorporated in one model. Amid et al. (2006) claimed they were the first to develop a fuzzy multiobjective model for supplier selection. The model was general so that different criteria can be included for which the exact value is unknown.

Li and Kouvelis (1999) focused on demand risks by developing valuation methodologies for awarding supply contracts. The objective was to select the best suppliers such that fluctuating demand risks are mitigated in an environment of uncertain prices.

Gurmani and Shi (2006) used a Nash bargaining game to evaluate the delivery reliability of a new supplier. The model balanced the supplier's estimate of their own delivery performance versus the customer's perception of their reliability. The game computed the optimal contract price and quantity of trade.

Simulation was used by Wu and Olson (2008) to incorporate risks into a simple supplier selection model. In addition to simulation, they also solved the supplier selection problem by using Data Envelopment Analysis (DEA), multi-objective programming and chance constrained programming. Each model solved the same problem, but it was shown that it was easier to incorporate certain risk factors into some model formulations than others. The results were consistent among all models in selecting the preferred suppliers.

Karpak et al. (1999) utilized Visual Interactive Goal Programming (VIG) to solve the supplier selection problem. VIG is a menu-based modeling program for personal computers that enables the user to develop it, solve and analyze the results. In this article, VIG was used to select suppliers for an original equipment manufacturer. The model selected optimal suppliers and determined order quantities while simultaneously considering cost, quality and delivery reliability.

DEA is a linear programming methodology. Weber and Desai (1996) used DEA to measure supplier performance and efficiency across multiple dimensions. A case study was presented in which a company's suppliers are evaluated on price, quality and delivery performance. It was determined that the model could be easily extended to include more criteria in future research. Liu et al. (2000) also used DEA. Their model included delivery performance which can be considered a risk factor. The objective of the model was to limit the total number of suppliers, rather than maximize the overall profitability of the supply chain.

Feng et al. (2001) developed a stochastic integer programming model for the concurrent selection of suppliers and tolerance design of components. The model considered quality, cost and production capabilities. By considering tolerance design, the model was designing the supply chain while mitigating quality problems with the product components.

Finally, the methodology that appears to be used most often is MIP. Kasilingam and Lee (1996) developed a MIP model for the selection of suppliers and the determination of order quantities. The model included stochastic demand through the use of a chance constraint, and also considers supplier quality.

Activity Based Costing (ABC) was incorporated into a supplier selection process by Degraeve and Roodhoft (2000). They developed a mixed integer linear programming model to optimize the supplier selection decision and ABC was used to determine accurate estimations of the cost parameters used in the model. This technique resulted in the minimization of total purchasing costs for the system that is more accurate than in other models. Risks were not explicitly considered in this model.

Ghodsypour and O'Brien (2001) presented a mixed integer non-linear programming model. The model was focused on incorporating logistical costs of sourcing components from suppliers, but also took into consideration the risk of poor quality from the supplier and capacity risks.

Two different, simple supply chain models were given by Gaonkar and Viswanadham (2004). Each model was a supplier selection model which minimized supply chain cost and risk. One model included risks, such as variations in supply or demand, while the other model included more infrequent yet substantial disruptions such as natural disasters. One was an integer quadratic programming model and the other was a MIP model. The risks were modeled by constraints which calculated the shortfall of each possible supply scenario.

Kumar et al. (2004, 2006) developed a fuzzy MIP for a supplier selection problem. The model had three objectives: minimizing cost, maximizing on-time delivery and maximizing quality. The last two objectives can be considered risk minimization objectives. Wu et al. (2010) developed a fuzzy multi-objective programming model for supplier selection, while considering the following risk factors – cost, quality, logistics, economic environmental factors and vendor ratings.

The desirability of splitting demand among multiple suppliers as a risk mitigation technique was investigated by ElMaraghy and Majety (2008). A MIP model was used for this analysis that included on-time delivery risks and quality risks associated with new suppliers.

Results indicated that it is desirable to split demand. The model also determined how to make the split.

Wang et al. (2010) used a single product newsvendor problem to study the problem of supplier reliability. The model was used to determine whether it is best to use dual sourcing or to exert efforts to improve the reliability of their supplier. This was not a traditional supplier selection model. It was a risk mitigation model, but valuable insights are gained from the research. They decided whether improvement or dual sourcing is favored in the cases where the underlying supplier reliability issue is a matter of random capacity risk or random yield risk. The answer is dependent on whether the supplier's cost heterogeneity and supplier reliability heterogeneity is high or low in each case.

This review of the supply chain risk management literature focusing on supplier selection research shows that much research has been done in this field. Ho et al. (2010) provided a comprehensive review of literature on the supplier selection problem from the past decade. They reviewed 78 articles to determine which modeling approaches and evaluation criteria were used most often. They found that DEA models were developed most often and the most popular supplier evaluation criteria was quality.

A complete summary of supply chain risks identified in the literature is provided in Appendix A. This summary indicates that lead time variation risk, supplier reliability, and quality issues are the most frequently appearing risks in the literature. However, this does not necessarily indicate that these risks are the most important to analyze. Before deciding which risks to incorporate into the DFSC model, a sample of professionals working in supply chain and NPD roles was surveyed to gather more data. This process is discussed in Chapter 3.

2.4 NPD RISK MANAGEMENT

Risk in NPD has been defined as "the probability that the product will not satisfy all of its requirements" (Deyst, 2002). Just as supply chains have risks, the process of developing a new product is also faced with a multitude of risks. If a NPD team can identify and manage those risks, the product is more likely to be successful.

Halman and Keizer (1994) used three questions to assess whether a NPD activity can be considered risky or not. These include (1) if the likelihood of a bad result is considerable, (2) the impact of the success of the NPD project is great, and (3) the ability of the team to influence it within the time and resources limits of the project is small. They termed these three dimensions as occurrence, impact and control. These questions essentially cover the identification, assessment and management of risks, which was also found in the supply chain risk management literature. In fact, several connections between the two bodies of literature were found. Some of the same methodologies are used for modeling risks and some risks are even overlapping, such as the risk of outsourcing and data integrity risks. Just as with the supply chain risk management literature review, first a brief examination of the qualitative NPD literature is given.

One of the first research studies conducted to determine success factors in NPD was Project SAPPHO, which was published in 1974 (Rothwell et al., 1974). It was a comparative analysis of successful and unsuccessful technological innovations. The results indicated that the five main factors which influence success or failure are related to the innovators understanding of user's needs, efficiency of development, characteristics of managers, efficiency of communications and finally marketing and sales efforts. This was one study of NPD risk factors. Although the results may be outdated, due to a changing global economy, it is worthwhile to note that the methodology used to identify these risks has since been replicated several times. Thus, there is a vast amount of literature that can be used to identify risks related to the NPD process.

Robert G. Cooper has done extensive research in the areas of NPD and product innovation management. Like Project SAPPHO, many of his early studies served as the foundation for work in this area by other researchers (Cooper & Edgett, 2009). Cooper's early work on identifying factors critical to new product success and failure is largely summarized in Montoya-Weiss and Calantone (1994). This article was a meta analysis of 52 articles which analyzed NPD success factors. The results showed that the literature, research methodologies and data pertaining to NPD success factors is highly diverse. Consistency was not found amongst the factors studied and statistics reported. However, from the data gathered, the factors which seemed to have the most influence over product performance were strategic factors, such as product advantage, technological synergy and marketing synergy, and also development process factors such as proficiency of technological activities, proficiency of marketing activities, protocol, top management support, and proficiency of predevelopment activities. These factors were also the ones which appeared in the literature the most.

Another article which summarizes much of the early work in this area is Souder and Jenssen (1999). The literature review in this article summarized the factors studied in 27 previous articles. A total of 50 factors were listed. There was no indication as to which factors were the most influential. They were simply listed and indicated which articles studied which factors.

Cooper and Kleinshmidt (1993) surveyed 21 major chemical firms from four different countries. The survey evaluated 298 factors related to NPD success at each firm. They received complete data on 103 projects. The results indicated that NPD success is easy to predict in the chemical industry. The number one success factor found in the study was termed "product differential advantage," which is when the new product gains it advantage in the market due to product differentiation.

All of the previous studies were focused on identifying risk factors associated with NPD success. Halman and Keizer (1994) provided a more comprehensive methodology for overall risk management. Their approach was similar to Potential Problem Analysis or FMEA. It is called the Risk Diagnosis and Management approach. In summary, the approach entails identification of project risks, valuation of project risks, decision making about the diagnosed risks, and then development and execution of a risk management plan.

Intel Corporation also developed an overall risk management approach within the company. It began in 2001 with the development of a database called "High Speed Database – Risk" which provided a standardized way to identify, assess, prioritize, plan, prevent and deal with risks. However, managers were not using it to its fullest potential. In 2005, the tool was revised to include relationships between different risks, and not just individual risks. Also, managers were encouraged to take a more active risk management approach, which involved using the tool on a weekly basis. In conclusion, they argued that qualitative risk management is appropriate because "… many managers still struggle to see the bottom line value that risk management can bring to their project. Keeping the process quick, easy, and intuitive is a critical success factor in active risk management adoption in these project teams. Quantitative approaches tend not to have those qualities" (Goodman et al., 2007, p. 111).

Keizer et al. (2005) presented a review of relevant literature on risks associated with NPD. Through this literature review, they showed that some methods used to measure and manage risk include: Potential Problem Analysis, Failure Tree Analysis and FMEA. They also argued that prior research on NPD risk is limited in that it mostly occurred after projects were completed. The limitation with this approach is that risks occurring in the latter phases of NPD are given more emphasis than those in the earlier phases. They also compiled a list of NPD risks that were identified in the literature and supplemented this list with factors identified by 117 employees from a consumer goods company. The employees were interviewed to determine which risks are most frequently faced. This study was very insightful, but the authors do recognize that the results are specific to the consumer goods industry and that the individuals interviewed were involved with NPD projects that were in the feasibility phase. They noted that different results might be obtained in different industries and with projects that are in different phases.

Finally, a collection of general results is obtained from additional studies. Gidel et al. (2005) argued that the use of formal models to identify risks sometimes impedes creativity and puts constraints on decision making. They also revealed unknown risks and note that there are usually insufficient resources to deal with them all. Jerrard et al. (2008) stated, “It became clear from a search of risk literature that design and NPD risk is an emergent field and that linkages between formal views of design processes and risks within them are largely under researched.” In de Lemos et al. (2004), the authors argued that complete risk management must include not only the technical factors but also a realistic assessment of environmental and social risks. Khan et al. (2008) examined the role that product design plays in risk management, through a review of the literature and then a case study in the clothing and textile industry. They found that product design is crucial to risk management when the design is directly related to market competitiveness. In other words, close communication between clothing designers and suppliers is essential to produce clothing that will meet specifications and consumers needs.

Mathematical and quantitative studies that include models to analyze NPD risk vary greatly in their techniques. Crossland et al. (2003) used object-oriented modeling to create a framework for modeling various different design risks. This framework was based on the commercial risk management software package called RiTo. Ahmadi & Wang (1999) also used object-oriented modeling to develop a model which manages NPD risks. The authors felt that to manage NPD risk, managerial reviews should be used. However, if too many or too few reviews are used, it could lengthen the development process unnecessarily. The model monitors management involvement to determine the appropriate amount of involvement they should have in design reviews.

A different technique used for modeling risk is estimation theory, which involves estimating parameter values from measured or empirical data. Deyst (2002) used this approach to model some NPD risks. This theory works, because he was able to form an analogy between design uncertainty and measurement noise. The model included performance risk and is tested on an aerodynamic design task for the design of a long range transport aircraft.

Wang & Lin (2008) used two techniques to model scheduling or lead-time risks in a NPD process. They used simulation and also a basic process model. The process model was populated with the development activities, showing which activities can be completed simultaneously to reduce overall Time-to-Market (TTM). Then, the simulation was run to show the complex interactions between these development activities and to provide a more accurate estimate of total development time.

Kumar et al. (2009) simultaneously considered market risks and manufacturing and product development decisions when designing an entire product family. While recognizing the cost and lead time benefits of designing a product family versus several different products, it is also noted that the disadvantage or risk of this, is not capturing the entire profit or market share. To model and solve this problem a four-step, iterative approach was taken. First, an enhanced market segmentation grid was created for the problem, which gives visualization into product differentiation and platform leveraging strategies. The second and third steps involved the creation of two models, one for demand and another for product performance and cost. Finally, the fourth step was optimization, which was done using MATLAB's optimization toolbox. The objective of this analysis was to introduce this comprehensive design approach rather than developing a robust optimization tool. However, a small case study with hypothetical data was completed and revealed that it is important to take into consideration market risk factors when designing a product family.

Wouters et al. (2009) incorporated monetary factors into a structural equation NPD model so that more factors than just purchase price of supplier components are taken into consideration. They incorporated monetary quantification of points of difference to create a more representative model. It was shown through a case study that uncertainty is reduced by including these monetary factors. In other words, they were able to model the risk of supplier's price changes.

It can be seen from this review of the literature that some work has been done with mathematical modeling of NPD risks but more work seems to have been focused on qualitative models and the identification of NPD success factors. In the future, more research needs to be focused on integrating those factors which have been found to be critical into mathematical models. This research made a valuable contribution to filling this gap in the body of knowledge.

2.5 DESIGN FOR SUPPLY CHAIN RISK MANAGEMENT

Through an examination of the literature, no studies were found that comprehensively considered new product design, supply chain design and risk factors associated with each. However, some of the DFSC models examined earlier do take into consideration a few risk factors.

For example, Lee and Sasser (1995) created a DFSC model, which HP used during the development of a new product. It was particularly important for the success of this product to determine the optimal product differentiation point, to avoid high inventory, inventory stockout and long lead times. These factors were included in the model, so that the risk of the selected product experiencing those issues was minimized. Although these are not the only risks that the product faced, they were considered to be of high importance and critical to the product's success, which prompted their inclusion in the model. To be a complete DFSC and risk model, HP should have considered all potential risks and then determined which key risks should be included in the model.

The Global Supply Chain Model presented in Arntzen et al. (1995) includes duty considerations for international suppliers. By including this factor the risk of working with an international supplier is being modeled. Although the constraints in the model are not inclusive of all international business risks, it does at least account for some of these risks.

Graves and Willems (2005) created a supply chain design model for a product that has already been designed. This model was not exactly a DFSC model; however, it is interesting to note that they created a large designed experiment to test for several different factors that can be considered as risks. The experiment included 810 different supply chain configurations with varying cost-accrual profiles, time-accrual profiles, demand values, standard deviations of demand and holding cost rates. This is one method for testing the risk of variation on all of these factors.

Other studies that incorporated some design, supply chain selection and risk management factors together include that of Fine et al. (2005). This analysis falls in the category of three-dimensional Concurrent Engineering (3D-CE), which incorporates not only product and supply chain decisions, but also process design decisions. Some work has been done in this field in the past several years. Fine et al. (2005) presented the first quantitative 3D-CE model. It included supplier selection decisions, supplier fixed costs, manufacturing costs, lead times and also considers supplier risks and the risk that the design meets its intended function. The model was solved using a goal programming approach. It is limited, however, in the level of detail used to make product design and supply chain selection decisions.

In conclusion, this review of the literature showed that risk theory is a very diverse and very large body of knowledge. It has been applied to supply chain management and NPD, as researchers have recognized the need for risk analysis and risk planning in these areas. When risk mitigation is not undertaken it can lead to reduced profitability, customer dissatisfaction, etc. Researchers have also realized the need to integrate supply chain planning and NPD decisions. This has resulted in a methodology called DFSC. The next step, and the objective of this research, is to combine risk theory and DFSC. As shown in this review of the literature, there are a few instances of DFSC models that incorporate some risks; however there is a gap in the literature for comprehensive DFSC *and* risk models and theories. The purpose of this research is to close that gap.

3.0 DATA COLLECTION AND SELECTION OF CRITICAL RISK FACTORS

Modeling is used to create a representation of a system for the purpose of testing changes to the system and predicting behavior. Therefore, most decision makers prefer the model to be as realistic as possible. The challenge in creating a realistic model is maintaining the ability to run or solve it efficiently. To achieve this balance in realism and solution time, factors included in the model need to be selected carefully. Factors must be representative of the system and also make a significant contribution. This is a challenge faced in the research, because the model quickly becomes quite complex. For example, the model from Gokhan (2007) had a processing time of over 48 hours when solving a data set of 8 components and 10 suppliers. This is simply too long for practical use in industry. When adding risk factors to Gokhan's model, these modeling concepts were kept in mind. To determine the appropriate risk factors to include in the model, a review of the literature and a survey of industry experts were used.

3.1 OBSERVATIONS FROM THE LITERATURE

First, the scholarly literature was examined to determine which risk factors have been studied, analyzed and modeled in the past. From this analysis, many risk factors were identified in the supply chain and NPD areas and were aggregated into 50 categories. The frequency with which each risk appeared in a quantitative model in the literature was tallied. This tally revealed that for supply chain related risks, lead time variation risk, the risk of poor supplier reliability, and the risk of quality problems are modeled most frequently in the literature. In the NPD area, product technology risks and supply chain / sourcing risks were found most often. Product technology risks are defined as the risk that the new product will not fulfill its intended function or meet safety and technical requirements. A detailed summary of these results appears in Appendix A.

3.2 INDUSTRY SURVEY DESIGN

To confirm or refute whether this analysis from the literature review was successful in identifying the most critical risk factors, data was obtained from industry. The 50 risk categories identified through the literature were used to create a risk survey. This survey was distributed to sixteen companies, from several different industries to obtain a broad range of industry views. The survey participants from each company had either a NPD or a supply chain related role in their company. Table 1 provides a brief description of each company targeted for the survey.

The survey was created in an electronic format to facilitate efficient collection and analysis. It was also believed to improve the response rate. An online survey creation tool called Survey Monkey was used, because it was low cost, fit the data collection and analysis needs, and enabled easy distribution and collection of the survey via the internet. A copy of the survey is included in Appendix B.

Table 1. Companies Targeted in Industry Survey

Company	Description
1	Manufacturer of laser-optic materials, optics, components, electro-optical products and radiation detection devices
2	Manufacturer of materials testing equipment and process heating equipment
3	Design and manufacturer of complete transportation systems
4	Design and manufacturer of pumps, motors, generators, control rod drive mechanisms and power conditioning electronics
5	Power management company
6	Custom manufacturer of rotating equipment / turbo machinery (steam turbines, generators, etc.)
7	Design and manufacturer of underground mining machinery
8	Engraving products and services
9	Medical imaging device manufacturer
10	Manufacturer of safety products designed to protect people
11	Manufacturer of sleep and respiratory products
12	Complete range of high-end analytical instruments as well as laboratory equipment, software and services
13	Manufacturer of replacement windows and doors
14	Integrated steel producer
15	Voice systems to guide workers through tasks
16	Provides fuel, services, technology, plant design, and equipment to utility and industrial customers in nuclear electric power industry

Risk factors were evaluated in the survey on two different criteria – the Likelihood of Occurrence and the Impact of Occurrence. The reason for this is that some risk factors are very important to consider, but not very likely to occur. An example of this is the risk of natural disasters. In the same regard, some risk factors are very likely to occur, but their effects are less significant. Risk factors that score highly in both categories are regarded as those that are most important to industry and therefore critical to consider. The Impact of Occurrence and Likelihood of Occurrence criteria were each evaluated on a four point scale – low, medium, high and very high. "Unable to answer" was also an option for each question.

Evaluating the "availability of data" for each risk factor was also considered. The intention of this is to identify risk factors that typically have data available for modeling.

However, it was decided that this is difficult for survey participants to assess accurately, because they are not aware of all data that is collected throughout their company. Further, data availability is not a limiting factor in long term risk planning. If a risk factor is deemed very important or crucial to model, then a company begins collecting any necessary data related to that risk factor. For these reasons, the data availability assessment was not included.

The survey was divided into two sections. Section One included 29 supply chain risk factors and Section Two included 21 NPD risk factors. Before respondents evaluated the risk factors they were asked to provide their number of years experience with supply chain and NPD and also rate their knowledge in each field as either poor, fair, good or excellent. If a respondent rated himself/herself as either poor or fair, the survey tool automatically skipped the corresponding risk evaluation section. The respondent's opinions were assumed to be of limited value and so they were not permitted to evaluate those risks. At the beginning of the survey, respondents were also asked to indicate their company name, so response rates could be tracked by company.

3.3 SURVEY RESULTS

Survey responses were received from 46 participants. The breakdown of responses by company is shown in the table below.

Table 2. Survey Response Rate

Company	Number of Responses
1	0
2	5
3	0
4	2
5	0
6	0
7	10
8	4
9	3
10	0
11	3
12	13
13	0
14	0
15	0
16	5
17	1
TOTAL	46

Company 17 was not originally targeted. However, one response was received from them. It is assumed that another company forwarded the survey to them. The survey questions were answered legitimately, so their response was kept as a valid result. Company 17 designs and manufactures industrial mobile robots for material handling purposes.

It should also be noted that 3 of the 46 surveys returned were not filled out completely. In these cases, the respondent only completed the first page of the survey, so the responses had to be discarded. This resulted in 43 completed surveys. Within these 43 responses, 35 respondents rated their supply chain knowledge as either excellent or good and thus assessed the supply chain risk factors. 24 of the 43 respondents completed the NPD section, because their knowledge self assessment was either excellent or good. Figure 3 shows a breakdown of the 43 respondents with regard to their NPD and supply chain knowledge level ratings. It can be seen that very few respondents rated themselves as being fair or poor in both categories. Most rated themselves as good or excellent in at least one category. This was expected, because companies with knowledgeable supply chain or NPD employees were targeted. Five individuals had adequate knowledge in NPD, but not in supply chain. Sixteen were knowledgeable in supply chain but not in NPD. Nineteen had sufficient knowledge in both the NPD and supply chain areas.

NPD v. SC Knowledge Levels

NPD Knowledge Level	Poor	Fair	Good	Excellent
Excellent	0	0	2	1
Good	2	3	10	6
Fair	1	1	3	3
Poor	0	0	3	3
No Response	1	0	3	1

SC Knowledge Level

Figure 3. NPD vs. Supply Chain Knowledge Levels

The breakdown of respondents by years of experience was also useful to analyze. This is shown in Figure 4 and Figure 5 for supply chain and NPD, respectively. It is interesting to note that in the supply chain area, the breakdown of respondents is quite varied. For example, 12 individuals indicated that their experience level was 20 or more years, while the other groups had a much smaller sample size. Before any analysis of the risk factors was completed, the correlation of responses between these different age groups was tested.

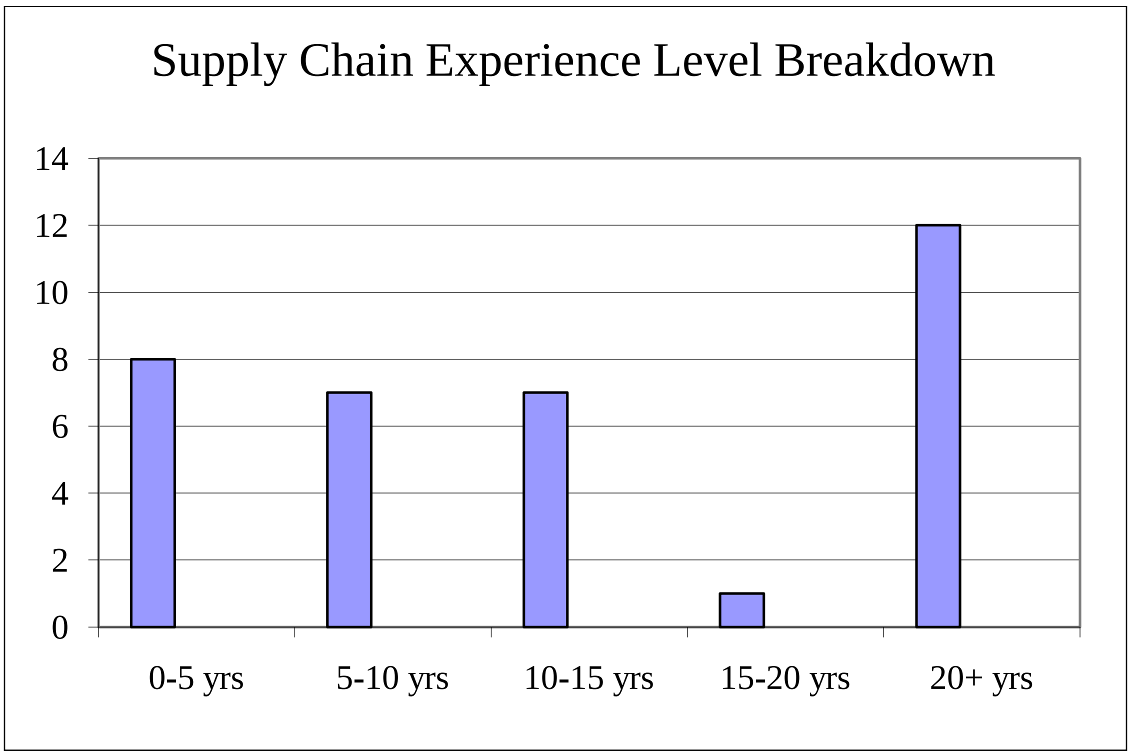


Figure 4. Supply Chain Experience Level Breakdown

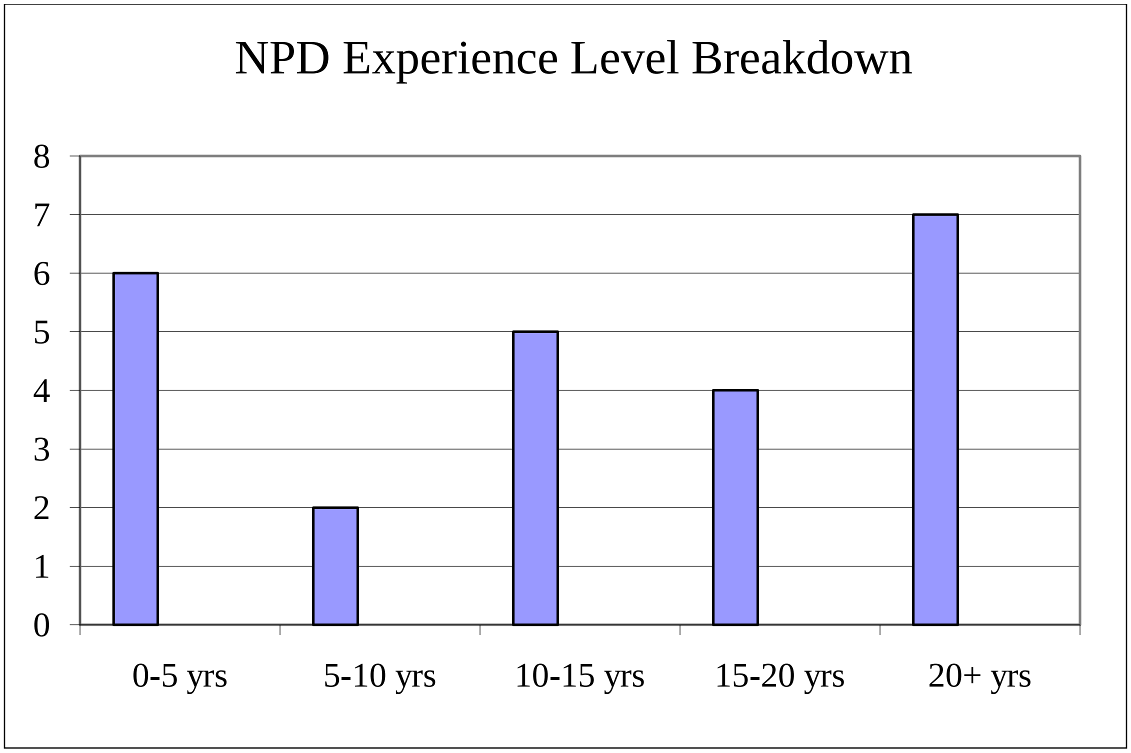


Figure 5. NPD Experience Level Breakdown

To test the correlations between groups of respondents, several different population groups were considered. First, the correlation between respondents with 0 – 15 years of experience and those with more than 15 years experience was tested. However, the supply chain groups had fairly unequal sample sizes, with 22 respondents in the first group and only thirteen in the other group. In an attempt to analyze equal sized groups, the data was then divided into the following groups: 0 – 10 years, 10 – 20 years and 20+ years. Sample sizes were still not exactly equal, but more balanced with groups of 15, 8 and 12 respectively. Correlations between pairs of these groups were then tested.

To calculate the correlation, the following process was used. 29 supply chain risk factors were evaluated by each respondent. The participants were asked to rate each risk factor low, medium, high or very high in the categories of Likelihood of Occurrence and Impact of Risk. It was assumed that this rating scale was linear. Therefore, numerical weights of one through four were given to each rating. In other words, a low rating carried a weight of one and a very high rating carried a weight of four. A weighted average was then calculated for each risk factor with the following formula:

$$Weighted\ Avg = \frac{\sum_{i=1}^{4} i \times (no.\ participants\ who\ selected\ i)}{(no.\ participants) - (no.\ participants\ who\ selected\ \text{unable to answer})}$$

For example, in the supply chain category, the first risk factor – the risk of manufacturing or production problems – was assessed by 35 people, with the following breakdown of responses:

	Low	Medium	High	Very High	Unable to Answer	Total
Likelihood of Occurrence	14	16	3	1	1	35
Impact of Risk	2	9	15	8	1	35

For Likelihood of Occurrence, the weighted average of responses was,

$$\text{Weighted Avg} = \frac{(1 \times 14) + (2 \times 16) + (3 \times 3) + (4 \times 4)}{35 - 1} = 1.735$$

This was done for each risk factor, for the Likelihood of Occurrence and Impact of Risk ratings. Then, the correlation of averages between age groups was calculated, using the following formula,

$$\text{Correl}(X, Y) = \frac{\sum[(x - \bar{x})(y - \bar{y})]}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}$$

where *x* is one population group of respondents and *y* is another. The weighted averages for each risk factor are listed in Appendix C.

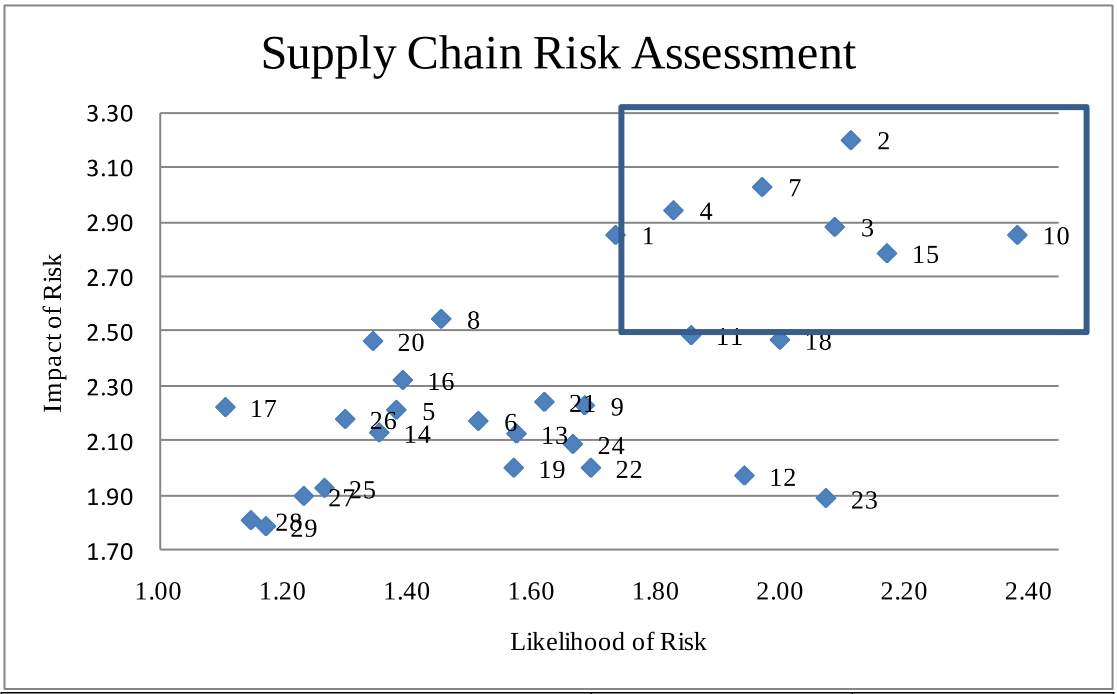
The correlation values between the smaller groups, 0-10 years, 10-20 years and 20+ years were very poor. This was partly due to the fact that sample sizes were so small. Therefore, we decided it was better to split the respondents into two groups, a younger group with 0-15 years experience and an older group with greater than 15 years experience. The results of these correlation tests are in Table 3. The Likelihood of Occurrence correlation values were fairly high, at 0.869 for supply chain and 0.812 for NPD. However, the Impact of Risk correlation values were not as high. It was decided that these separate Impact of Risk populations should be analyzed in addition to the entire population.

Table 3. Correlation Analysis Results

SUPPLY CHAIN			
Impact of Risk		Likelihood of Occurrence	
0-15 yrs	15+ yrs	0-15 yrs	15+ yrs
N = 22	N = 13	N = 22	N = 13
Correlation = 0.636		Correlation = 0.869	
NEW PRODUCT DEVELOPMENT			
Impact of Risk		Likelihood of Occurrence	
0-15 yrs	15+ yrs	0-15 yrs	15+ yrs
N = 13	N = 11	N = 13	N = 11
Correlation = 0.656		Correlation = 0.812	

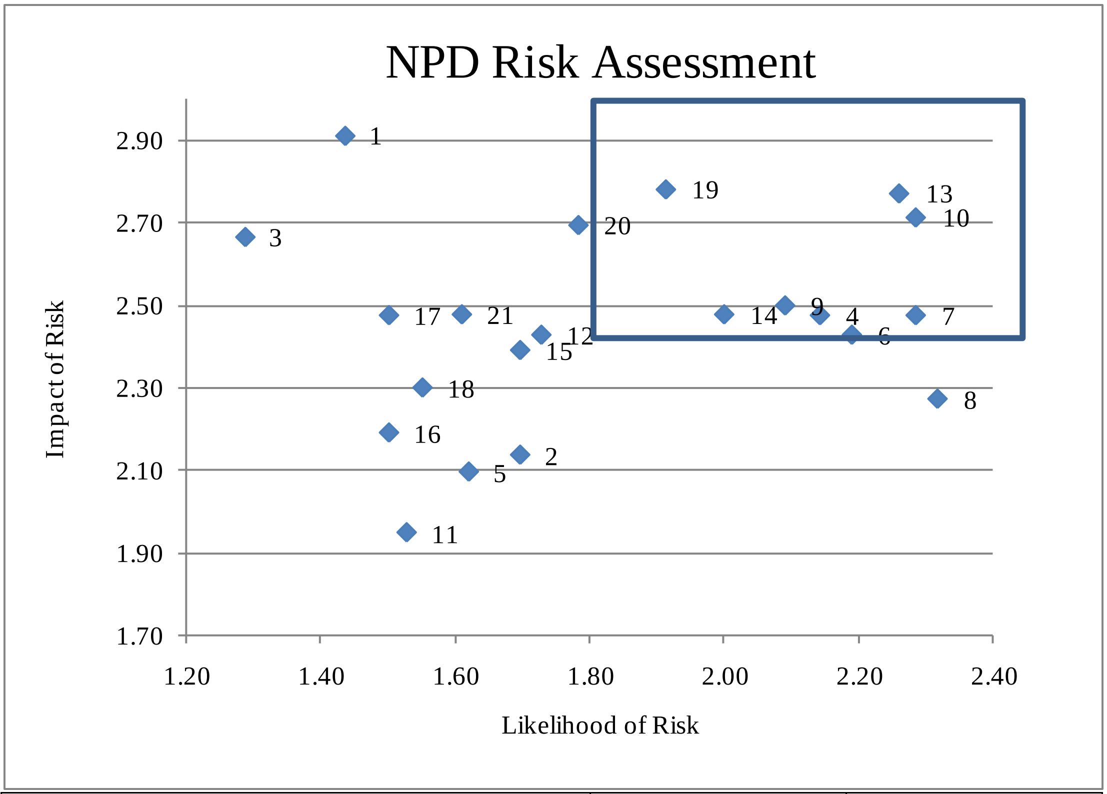
The next step was to analyze the risk factors and determine which were considered most important from an industry perspective. The weighted averages were used to assemble scatter plots. The Likelihood of Occurrence weighted average was plotted against the Impact of Risk weighted average. Separate plots were constructed for supply chain and NPD risks. The scatter plots quickly revealed which risk factors appeared to rate highly in both categories. These are shown in Figure 6 and Figure 7.

To visually show highly ranking risks, a box was drawn around data points in the upper right quadrant of the plots. This quadrant was found by calculating the midpoint of the range in average values for Impact and Likelihood. Then, the box was drawn around all points that were above the midpoint on both axes. Each data point is labeled with a number to identify the risk factors. A complete list of numbered risk factors and weighted averages is in Appendix C, and a list of the highly ranking risk factors is also contained with the scatter plots.



Risk		Impact		Likelihood	
		Avg	Sdev	Avg	Sdev
1	Manufacturing/Production Problems	2.85	0.86	1.74	0.75
2	Inventory Management / Stock Out Risk	3.20	0.63	2.11	0.90
3	Capacity Risk	2.88	0.77	2.09	0.87
4	Quality Problems	2.94	0.84	1.83	0.71
7	Supplier Reliability	3.03	0.71	1.97	0.79
10	Strategic Exposure Risk	2.85	1.05	2.38	1.04
11	Outsourcing Risk	2.49	0.95	1.86	0.77
15	Market/Demand Risks	2.79	0.83	2.17	0.89
18	Demand Forecast Risk	2.47	0.92	2.00	0.76

Figure 6. Supply Chain Risk Scatter Plot

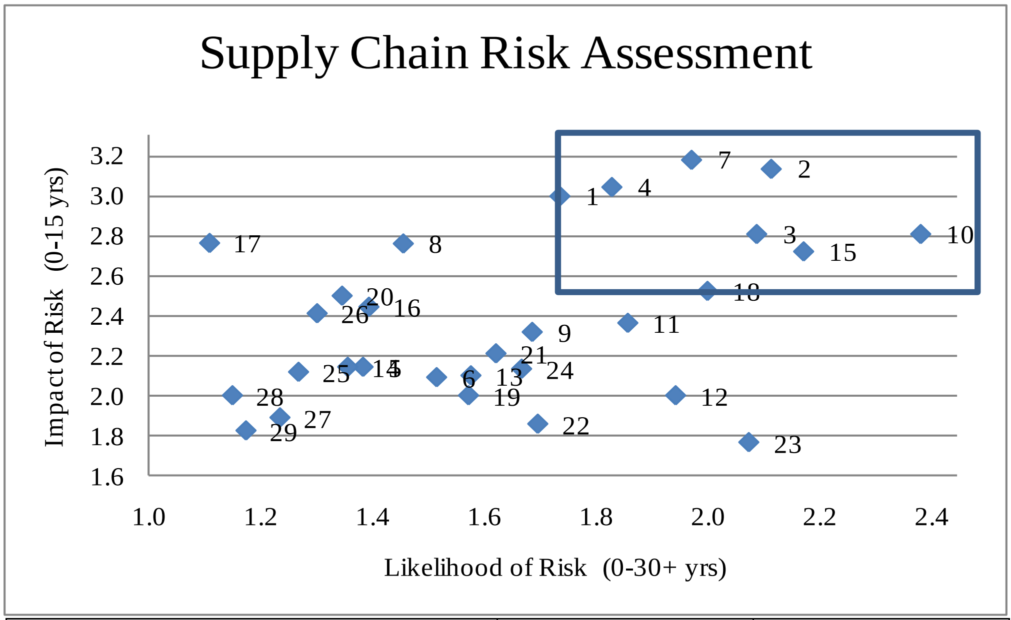


Risk		Impact		Likelihood	
		Avg	Sdev	Avg	Sdev
4	Financial Risk	2.48	1.03	2.14	0.73
6	Market Research Risk	2.43	1.03	2.19	1.12
7	Marketing Proficiency	2.48	0.81	2.29	0.96
9	Market Competitiveness	2.50	0.67	2.09	0.75
10	Commercial Viability	2.71	0.85	2.29	0.72
13	Organizational and Project Mgmt Risks	2.77	0.75	2.26	0.81
14	Company Resources	2.48	0.85	2.00	0.85
19	Supply Chain and Sourcing	2.78	0.80	1.91	0.60

Figure 7. NPD Risk Scatter Plot

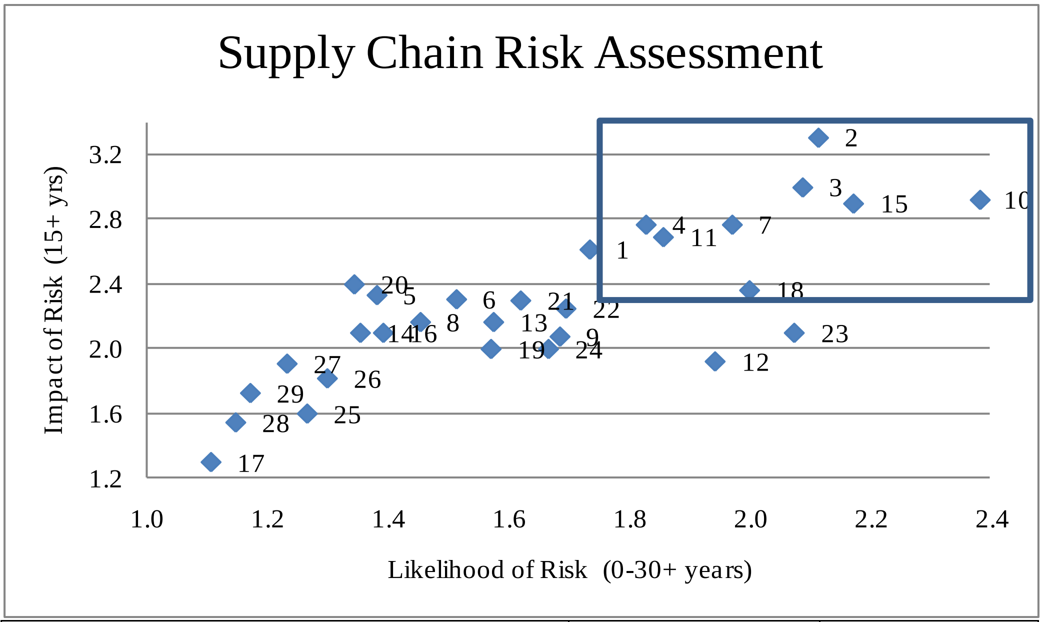
It is interesting to note that of the supply chain risk factors in Figure 6, the risk of poor supplier reliability and the risk of quality problems appear to be highly ranked. These risk factors also ranked highly in the analysis of the literature. Of the NPD risk factors, in the upper right quadrant of Figure 7, supply chain and sourcing risks was ranked highly in the literature analysis.

As noted previously, the Impact of Risk ratings from the survey participants with less than 15 years experience were not correlated well with the ratings from survey participants who had more than 15 years experience. Therefore, scatter plots were also assembled for each of these smaller populations, which are shown in Figure 8 through Figure 11.



	Risk	Impact (0-15 yrs)		Likelihood (0-30+ yrs)	
		Avg	Sdev	Avg	Sdev
1	Mfg/Production Problems	3.00	0.84	1.74	0.75
2	Inventory Mgmt/Stock out Risks	3.14	0.64	2.11	0.90
3	Capacity Risk	2.81	0.81	2.09	0.87
4	Quality Problems	3.05	0.79	1.83	0.71
7	Supplier Reliability	3.18	0.59	1.97	0.79
10	Strategic Exposure Risk	2.81	1.03	2.38	1.04
15	Market/Demand Risks	2.72	0.89	2.17	0.89
18	Demand Forecast Risk	2.52	0.93	2.00	0.76

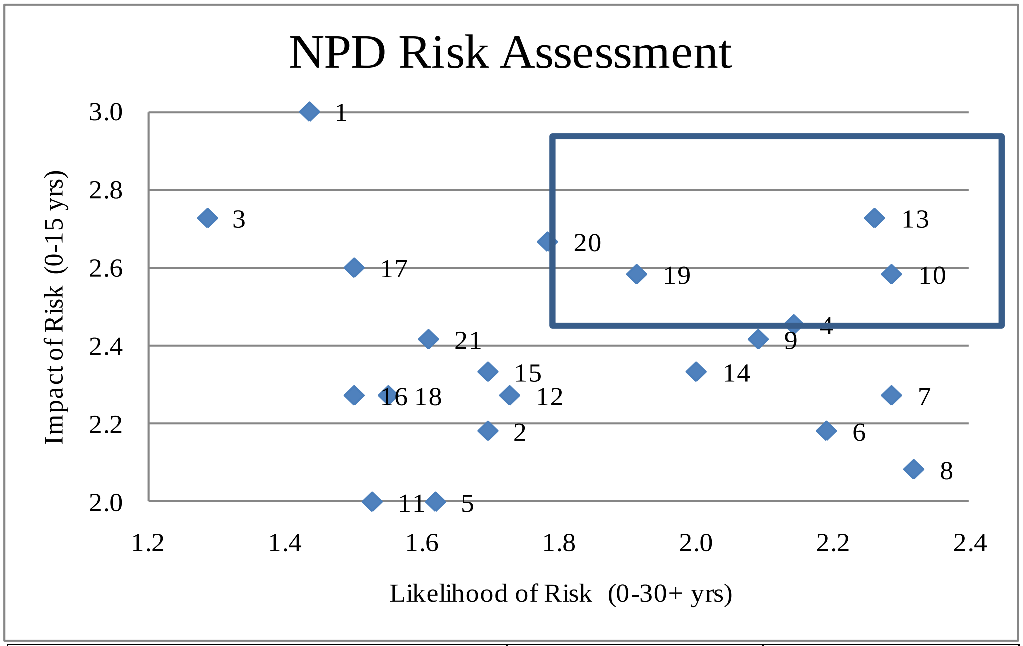
Figure 8. Supply Chain 0-15 yrs Experience Scatter Plot



Risk		Impact (15+ yrs)		Likelihood (0-30+ yrs)	
		Avg	Sdev	Avg	Sdev
1	Mfg/Production Problems	2.62	0.87	1.74	0.75
2	Inventory Mgmt/Stock out Risks	3.31	0.63	2.11	0.90
3	Capacity Risk	3.00	0.71	2.09	0.87
4	Quality Problems	2.77	0.93	1.83	0.71
7	Supplier Reliability	2.77	0.83	1.97	0.79
10	Strategic Exposure Risk	2.92	1.12	2.38	1.04
11	Outsourcing Risk	2.69	1.03	1.86	0.77
15	Market/Demand Risks	2.90	0.74	2.17	0.89
18	Demand Forecast Risk	2.36	0.92	2.00	0.76

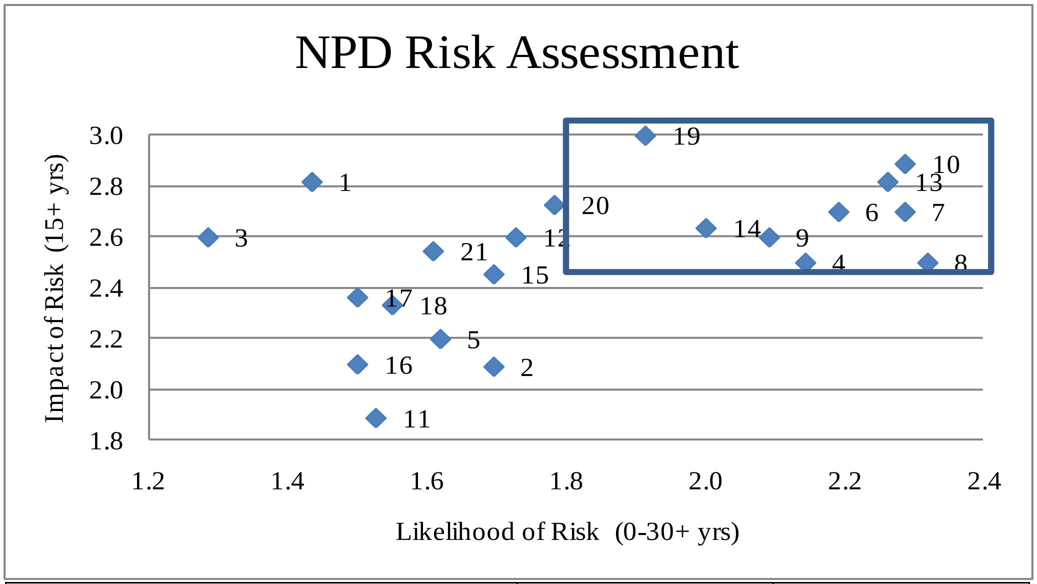
Figure 9. Supply Chain 15+ yrs Experience Scatter Plot

The scatter plots of the smaller populations reveal almost identical "top supply chain risks" as those identified in the entire population. Each plot includes risks 1, 2, 3, 4, 7, 10, 15, and 18 in the upper right quadrant box.



Risk		Impact (0-15 yrs)		Likelihood (0-30+ yrs)	
		Avg	Sdev	Avg	Sdev
4	Financial Risk	2.45	1.04	2.14	0.73
10	Commercial Viability Risks	2.58	0.90	2.29	0.72
13	Org. and Project Mgmt Risks	2.73	0.90	2.26	0.81
19	Supply Chain and Sourcing Risks	2.58	0.90	1.91	0.60
20	Manufacturing Technology Risks	2.67	0.89	1.78	0.80

Figure 10. NPD 0-15 yrs Experience Scatter Plot



Risk		Impact (15+ yrs)		Likelihood (0-30+ yrs)	
		Avg	Sdev	Avg	Sdev
4	Financial Risk	2.50	1.08	2.14	0.73
6	Market Research Risk	2.70	0.95	2.19	1.12
7	Marketing Proficiency	2.70	0.67	2.29	0.96
8	Time-to-Market Risk	2.50	0.71	2.32	0.72
9	Market Competitiveness	2.60	0.70	2.09	0.75
10	Commercial Viability Risks	2.89	0.78	2.29	0.72
13	Org. and Project Mgmt Risks	2.82	0.60	2.26	0.81
14	Company Resources	2.64	0.81	2.00	0.85
19	Supply Chain and Sourcing Risks	3.00	0.63	1.91	0.60
20	Manufacturing Technology Risks	2.73	1.00	1.78	0.80

Figure 11. NPD 15+ yrs Experience Scatter Plot

The NPD results were not as consistent between different populations. However, every group identified risk factors 4, 10, 13, and 19 as important. Other risk factors that were identified as top risks by at least one group were 6, 7, 8, 9, 14 and 20.

3.4 SELECTION OF RISK FACTORS

The scatter plots were useful in identifying a group of candidate risk factors for modeling. However, to make a final selection a quantitative analysis was used. A limitation with the scatter plots was that Impact and Likelihood were assumed to have equal weights of importance. However, it is not clear how these two different measures should be weighted. Therefore, several different weighting schemes were considered. Risk factors that ranked highly in the majority of these were considered important risks.

The following combination measures were evaluated, where I = Impact Weighted Average and L = Likelihood Weighted Average: I, L, I + L, 2I + L, I + 2L, I × L, $I^2 \times L$, $I \times L^2$. Individual I and L measures were considered to see if the individual measures gave different results than the combined measures. For the combined measures, additive and multiplicative measures were considered. I + L is a simple combination measure. 2I + L and I + 2L give more weight to impact and likelihood respectively. Similarly, I × L is a simple combination that looks at the expected value of I and L. $I^2 \times L$ and $I \times L^2$ also give more weight to impact and likelihood respectively.

3.4.1 Supply Chain Risk Factor Analysis

Table 4 shows which supply chain risks were ranked in the top ten positions with each of the different combination measures. The numbers listed in the table correspond to risk factors. Table 39 in Appendix C contains a complete list of supply chain risk factors and their corresponding numbers. A visual examination of the table shows that risks consistently scoring highly among all combination measures were (2) inventory management / stock out risks, (3) capacity risk, (7) supplier reliability, (10) strategic exposure risk and (15) market / demand risks.

Table 4. Supply Chain Combination Measure Analysis

Rank	**I**	**L**	**I + L**	**2I + L**	**I + 2L**	**I × L**	**I^2 × L**	**I × L^2**
1	2	10	2	2	10	10	2	10
2	7	24	10	10	2	2	10	2
3	4	2	7	7	15	15	7	15
4	3	9	3	3	3	3	3	3
5	1	15	15	15	7	7	15	7
6	10	23	4	4	4	4	4	18
7	15	3	1	1	18	1	1	4
8	8	21	18	18	1	18	18	1
9	11	7	11	11	11	11	11	11
10	18	6	8	8	23	23	8	23

The combination measures that were the most inconsistent among all results were I and L. A closer examination of the raw Impact and raw Likelihood values showed that the survey participants almost always gave a higher Impact rating than a Likelihood rating for each risk factor. To normalize the data to account for this, the Likelihood values were multiplied by a factor of 1.42. This normalization factor was obtained by dividing the overall Impact average of 2.33 by the overall Likelihood average of 1.64. Then, all of the combination measures in Table 4 were recalculated using the normalized data set. These results are shown in Table 5. Although slightly different results were obtained when the Likelihood values were normalized, the same risks appeared consistently in the top positions.

Table 5. Normalized Supply Chain Combination Measure Analysis

Rank	I	L	I + L	2I + L	I + 2L	I × L	I^2 × L	I × L^2
1	2	10	10	2	10	10	2	10
2	7	15	2	10	2	2	10	2
3	4	2	15	7	15	15	7	15
4	3	3	3	3	3	3	3	3
5	1	23	7	15	7	7	15	7
6	10	18	4	4	18	4	4	18
7	15	7	1	1	4	1	1	4
8	8	12	18	18	1	18	18	1
9	11	11	11	11	23	11	11	11
10	18	4	23	8	11	23	8	23

Visual analysis shows that risk factors 2, 3, 7, 10 and 15 are all ranked highly, but their order was not clear. To determine this, a simple metric was used. The sum of the rank positions for each combination measure was calculated. In other words, risk #10 had a score of 15, by the following calculation: 6 + 1 + 1 + 2 + 1 + 1 + 2 + 1 = 15, where 6 was the rank position for the first combination measure, 1 was the rank position for the second combination measure, etc. If a risk factor was not in one of the top ten positions for a certain combination measure, then a score of 11 was assumed for that column. The risk with the lowest overall score was the top risk. This analysis was done for the normalized and non-normalized data. Also, this calculation was done by including all combination measures/columns and then columns I and L were excluded, since those combination measures were thought to be inconsistent. Table 6 shows the results of this analysis for the supply chain risk factors.

Table 6. Supply Chain Top Risks

Overall Rank	Non-Normalized Data		Normalized Data	
	Including all Columns	Excluding Columns I & L	Including all Columns	Excluding Columns I & L
1	2	2 & 10 tied	2	10
2	10		10	2
3	3 & 7 tied	3, 7 & 15 tied	15	15
4			3	3
5	15		7	7

These results confirmed that risks 2, 3, 7, 10 and 15 were ranked highest and it showed that risks 2 and 10 are consistently ranked higher than 3, 7 and 15.

3.4.2 New Product Development Risk Factor Analysis

The same analysis was completed for NPD risk factors. Those results are shown in Table 7. Table 38 in Appendix C contains a complete list of NPD risk factors and their corresponding numbers. Risk factors that appeared to score highly across all combination measures were (6) market research risk, (7) marketing proficiency, (8) TTM risk, (10) commercial viability risks, (13) organizational & project management risks and (19) supply chain & sourcing risks.

Table 7. NPD Combination Measure Analysis

Rank	I	L	I + L	2I + L	I + 2L	I × L	I^2 × L	I × L^2
1	1	8	13	13	13	13	13	10
2	19	7	10	10	10	10	10	13
3	13	10	7	19	7	7	19	7
4	10	13	19	1	8	19	7	8
5	20	6	4	7	6	6	4	6
6	3	4	6	20	4	4	9	4
7	9	9	8	4	9	8	20	9
8	14	14	9	9	19	9	6	19
9	21	19	14	6	14	14	14	14
10	4	20	20	14	20	20	1	20

The NPD risks also had higher Impact ratings than Likelihood ratings, as was seen with the supply chain risks. To account for this, the Likelihood ratings were normalized. The likelihood values were multiplied by a factor of 1.34, because this was the overall Impact average of 2.46 divided by the overall Likelihood average of 1.83. The result of the normalized data on the different combination measures is shown in Table 8. Top risks identified were consistent with those identified in Table 7.

Table 8. Normalized NPD Combination Measure Analysis

Rank	I	L	I + L	2I + L	I + 2L	I × L	I^2 × L	I × L^2
1	1	8	13	13	10	13	13	10
2	19	7	10	10	13	10	10	13
3	13	10	7	19	7	7	19	7
4	10	13	8	7	8	19	7	8
5	20	6	6	4	6	6	4	6
6	3	4	4	9	4	4	9	4
7	9	9	19	6	9	8	20	9
8	14	14	9	20	19	9	6	19
9	21	19	14	1	14	14	14	14
10	4	20	20	8	20	20	1	20

Although risk factors 6, 7, 8, 10, 13 and 19 scored highly in both tables it was not clear which of these six risk factors ranked highest. Therefore, the same metric that was developed for ranking the supply chain risk factors was used with these risk factors. The result of this analysis is shown in Table 9.

Table 9. NPD Top Risks

Top Risks	Non-Normalized Data		Normalized Data	
	Including all Columns	Excluding Columns I & L	Including all Columns	Excluding Columns I & L
1	13	13	13	13
2	10	10	10	10
3	7	7	7	7
4	19	4	19	19
5	4	6	4	4

This analysis showed that risks 4, 7, 10, 13 and 19 ranked highest in the industry survey, with risk 13, organizational & project management risks, clearly in the top position. Risk factor 6 only showed up in the top five list once, and therefore was not considered for inclusion in the model.

3.4.3 Final Selection of Critical Risk Factors

Five supply chain and five NPD risk factors were identified as scoring highly in the industry survey. A complete list of these risks and their definitions are shown in Table 10. They are listed in the table in order of their rankings with the highest ranking risks first.

Table 10. Top Risk Factors

Type	No	Name	Description
SC	2	Inventory Management / Stock Out Risk	Risk of inventory stock-out due to poor management of materials, supplier deficiency, etc.
SC	10	Strategic Exposure Risk	Risk of being over-reliant on a single or limited number of suppliers.
SC	15	Market / Demand Risks	Risk that a change in the market will affect demand. (Ex - customers lose interest in product, seasonality, volatility of fads, customers change orders, one-of-a-kind competitor will appear and seize market share, etc.)
SC	3	Capacity Risk	Risk that system is unable to produce a particular quantity of product(s) in a particular time period.
SC	7	Supplier Reliability	Risk that supplier is unable to provide quality product in a timely manner, has poor customer service, does not have ample capacity, etc.
NPD	13	Organizational and Project Management Risks	Risk that top management will not actively support project, project goals and objectives are not feasible, decision making process is not effective, and/or collaboration within project team is not effective.
NPD	10	Commercial Viability Risks	Risk that the market target will not be clearly defined and agreed upon, estimated ROI will not meet company standards, and/or long term market potential is not realized.
NPD	7	Marketing Proficiency	Risk that proficiency of market development, market launch, market research, market startup, and/or market testing will not be adequate.
NPD	19	Supply Chain and Sourcing Risks	Risk that supplier(s) will not meet required quality standards, not have required capacity, their financial position will not be sound, etc.
NPD	4	Financial Risk	Risk of incorrect pricing, and/or inability to build adequate sales (with respect to the new product).

To determine if the survey participants were consistent with their rankings of these top risk factors, correlation values between the risk factors were calculated. These results are shown in Table 11 and Table 12. In general, the correlation values between the risk factors are low. However, supply chain risk factors 3 (capacity risk) and 7 (supplier reliability) have moderately high correlation values. The NPD risk factors have slightly higher correlation values than the supply chain risk factors. Risk factors 4 (financial risk), 10 (commercial viability risk) and 13 (organizational and project management risks) appear to be correlated. Similarly, risk factors 7 (marketing proficiency) and 10 (commercial viability risk) are also correlated.

Table 11. Correlation Values Between Top Ranking Supply Chain Risk Factors

Supply Chain Risk Factors		Likelihood of Occurrence Correlation	Impact of Risk Correlation
2	3	0.240	0.296
2	7	0.338	0.448
2	10	0.295	0.182
2	15	0.170	0.441
3	7	0.414	0.501
3	10	0.152	-0.051
3	15	0.285	0.195
7	10	0.075	0.221
7	15	0.425	0.192
10	15	-0.170	0.299

Table 12. Correlation Values Between Top Ranking NPD Risk Factors

NPD Risk Factors		Likelihood of Occurrence Correlation	Impact of Risk Correlation
4	7	0.371	0.253
4	10	0.492	0.506
4	13	0.519	0.444
4	19	0.031	0.026
7	10	0.525	0.494
7	13	0.399	0.142
7	19	0.116	0.111
10	13	0.648	0.628
10	19	0.175	0.352
13	19	0.425	0.457

All of these risks were found to be critical to consider. However, a few are interrelated and overlapping, which would make modeling efforts redundant if they were all added to the model. Supply chain risk factor 2, inventory management and stock out risks, and risk factor 3, capacity risks, are related to one another. Capacity risk can be incorporated into the model, by modeling the risk that individual suppliers are unable to meet demand. Inventory management and stock out risks can be modeled in a similar manner. The reason for this is that the DFSC model is a high level, strategic model. As explained in the scope definition, detailed decisions about the ordering policies with suppliers or inventory position decisions are not made. Therefore, inventory management and stock out risks can only be modeled at the supplier capacity level. Modeling of more detailed stock out risks is a valuable contribution to this research, but this is recommended for future work.

Strategic exposure risk, which is supply chain risk factor 10, and the risk of poor supplier reliability, which is supply chain risk factor 7, are both good candidates for inclusion in the model. They are both related to the performance of the suppliers. If these risks are not considered then a cost-effective, yet poorly performing, supply chain design could be selected by the model. Therefore, they are both selected for inclusion in the model.

Supply chain risk factor number 15, market/demand risks, specifically deals with changes to the market which affect demand. If this risk is not considered, the demand calculated in the MIP which drives product and supplier selection decisions could unintentionally cause an incorrect design decision to be made. This risk is also related to NPD risk factors 7, marketing proficiency, and 10, commercial viability risks and 4, financial risks. Marketing proficiency deals with the adequacy of marketing activities such as market development and market research. Commercial viability is dealing with ROI and long term market potential. Financial risks are related to incorrect pricing decisions. These three risks relate to different aspects of market and demand. However, at the strategic level of this DFSC model, they were all included by using the risk model to test the impacts of inadequate market research on demand. Market research inputs to the MIP include demand coefficient parameters, design values of components, price estimates and period lengths. The MIP uses these inputs to calculate an expected demand value for each time period. Analysis of this overall demand level calculation will be used to test for inaccurate market research in the DFSC and risk model.

NPD risk factor 13 is organizational and project management risks. Qualitative aspects of this risk include lack of top management support, effectiveness of the project team and the availability of resources. Quantitative considerations include time-to-market (TTM) and the project budget. The TTM component of this risk will be incorporated into the MIP model. In fact, at the strategic level, many of the qualitative aspects of this risk can be modeled through the TTM element. In other words, if top management support is not available or the project team is not working together well, it will ultimately slow down the project. The TTM risk can be used to model many aspects of the organizational and project management risk. When soliciting this piece of information from a decision maker, they will be asked to take these aspects into consideration when generating TTM estimates.

The final NPD risk, number 19, is supply chain and sourcing risks. By simply using a DFSC model to make design decisions, supply chain and sourcing risks are being taken into consideration during the NPD decision. No further modeling efforts are needed to account for this risk. The model already considers supply chain risks while selecting the best product design.

Therefore, the DFSC model will be converted to a DFSC and risk model by adding the risk of poor supplier reliability, strategic exposure risk, capacity risks, TTM risks and market/demand related risks. These modeling efforts are described in Chapter 4.

4.0 SOLUTION METHODOLOGY AND IMPLEMENTATION

The objective of the research is to develop a DFSC risk model. The previous three chapters showed the work done to determine which risk factors should be included in the model. The remaining chapters explain how those risk factors are added to the DFSC model (Chapter 4) and the quantitative results obtained from the completed model (Chapter 5).

Once risk factors were selected for inclusion in the DFSC model, the next decision was how to incorporate them. In other words, what type of model should be built? This decision depends on the types of risk factors being modeled and the expectations of the final model.

Vidal and Geotschalckx (2000) give some insight on how model factors influence modeling methodologies, for global logistics systems. They argue that model factors fall into three different categories. The first category is factors that can be realistically modeled with mathematical formulations. This includes simple BOM constraints, supplier capacities and fixed supplier costs. This type of factors is already in Gokhan's model, which is a deterministic MIP model.

The second category contains factors that can be modeled with mathematical formulations by making assumptions. Examples include assuming deterministic demand or assuming transportation and production costs are linear. Again, several of these assumptions are already made in Gokhan's model.

The last category includes factors that are very difficult to model realistically using mathematical formulations, such as stochastic lead times and demands, stochastic inventory policies, currency exchange rate fluctuations, reliability of vendors and transportation modes and random variations of tax rates due to political and economic instabilities. These types of factors are not included in Gokhan's model.

The risk factors to be added to the DFSC model are the risk of poor supplier reliability, TTM risk, strategic exposure risk, capacity risk and demand risks. Supplier reliability, TTM risk and strategic exposure risk can be modeled directly in the MIP by creating additional constraints. Capacity and demand risks fall into Vidal and Geotschalckx's third category. They are difficult to model realistically in a MIP. Therefore, different techniques such as simulation, stochastic programming, and Fuzzy Set Theory (FST) are considered for modeling these risk factors. This creates the additional challenge of integrating two separate models for the purposes of finding the optimal solution. The following sections provide further details on the development of the final models.

4.1 SELECTION OF A SOLUTION METHODOLOGY

Simulation, stochastic programming, Markov Decision Processes (MDP) and FST could all be used as modeling methodologies for risk factors that are stochastic in nature. Stochastic programming and MDP produce very rigorous and elegant models, but these analytical methods generally require more restrictive assumptions on sources of variation such as demand. FST is a good methodology for modeling uncertain parameters, but the major disadvantage of FST is that it would increase the size of the MIP once risk factors are added and then fuzzified.

Discrete-event simulation is not as rigorous a modeling methodology, but it does offer a few advantages. First, it enables the user to analyze several different scenarios simultaneously. The user can study the effects of stochastic supplier lead time, stochastic demand and fluctuating values for price all at the same time, as opposed to sensitivity analysis in an MIP which requires each of these effects to be studied individually. Second, simulation is flexible enough that the decision maker can later add additional risk factors as necessary to the model, or even other unrelated factors that might be of interest to the decision maker. Finally, simulation is a great way to present different scenarios or options to a management team. The challenge with using any of these stochastic modeling techniques is determining the appropriate mechanism for linking it with the original MIP model.

It was determined that the best modeling approach is to develop an integrated MIP and simulation model. The MIP optimizes the product and supply chain designs while simultaneously considering supplier reliability risk, TTM risk and strategic exposure risk. That information is then used in the simulation model to simulate the production and supply chain system while testing various demand and capacity risk scenarios.

4.2 MIXED INTEGER PROGRAM

Gokhan's DFSC model formulation can be found in (Gokhan, 2007) and in Appendix D. However, the following provides a brief overview of the MIP model. All of the factors in the model are evaluated over the lifetime of the product.

Objective:	Maximize	Profitability = Revenue – Product Cost – Network Cost – Transportation Cost – Inventory Cost
Subject To:	Product Bill of Material (BOM) Manufacturing Requirements	
	Demand Satisfaction Requirements	
	Customer Satisfaction Requirements	
	Supplier Capacity Limitations	
	Lead Time Limitations	
	Supply Chain Network	
	Transportation Limitations	

It should be noted that Gokhan created three different model formulations. The first had extremely long run times for data sets on the order of 8 components and 10 suppliers or larger. To overcome this limitation, two additional models were created by making a few simplifying assumptions in each. The run times of these models decreased significantly. Gokhan presented all three models to several companies and they all felt that the simplified models were acceptable. Therefore, for this research one of the simplified models is used since it had shorter run times. This model formulation is shown in Appendix D.

Gokhan also developed a hybrid solution methodology that was a combination Genetic Algorithm and MIP. This hybrid approach was an efficient solution methodology, with respect to run time, in instances when the MIP had long solution times. In this research, however, the MIP is used, because it gives exact, as opposed to approximate, optimal solutions.

4.2.1 Changes to Gokhan's DFSC MIP Framework

Before the critical risk factors were incorporated into the MIP, a few changes to Gokhan's formulation were made. These changes made the model assumptions more realistic. The first change was to add in costs for switching between designs or suppliers in different time periods. The original formulation permitted the freedom to switch between different designs or suppliers with no penalty. For example, Table 13 shows part of a solution obtained by the original MIP.

Table 13. Sample MIP Output

Time Period	Component	Design Alternative	Supplier
1	3	1	2
2	3	1	2
3	3	2	3
4	3	2	3

Notice that in time period 3, the design selection switches from alternative 1 to alternative 2 and the supplier is switched from supplier 2 to supplier 3. This scenario might occur when a product design has a high design value in time period 1, but then after some market change the value of that design decreases. To maintain market position, the company changes their design and also decides to switch to a new supplier. In the original formulation, no costs are incurred with these changes, which is an unrealistic simplifying assumption. When a company makes a design or supplier change there are normally substantial costs incurred for engineering time, documentation changes, product validations, supplier validations and production process changes.

To account for this, a "change of design or supplier cost" was added to the objective function. Now the model maximizes profitability over the lifetime of the product, where

Profit = Revenue – Manufacturing Cost – Transportation Cost – Supply Chain Network Cost – Inventory Cost – Design Change Cost – *Supplier Change Cost*

It is assumed that the design change cost is only incurred once per time period, even if design changes are made on multiple components. The reason for this is that most of the costs incurred with these design changes are not incremental to the number of components changed, such as the costs for documentation changes and product validations. If one or three components are being changed, the entire product can be re-validated, at one time. Also, counting each individual design change would require a more extensive formulation and extend the solution times. The constraints added to model these switch costs are shown in Section 4.2.3.

The second change made to the original MIP formulation was to the lead time calculations and constraints. In the original formulation a production time parameter is provided for each component at each supplier. This value is assumed to be the production time while operating at full capacity utilization. The parameter is then adjusted in the MIP according to how much supplier capacity is actually used. In other words, if only 50% capacity is required to fulfill the demand of a component, then the lead time is reduced by half. This is a poor assumption because a linear relationship between capacity utilization and lead time does not always exist. Further, this production time parameter is a combination of manufacturing time and transportation/shipping time. Manufacturing capacity utilization does not affect shipping time, but with this assumption partial capacity utilization was causing transportation times to also be reduced accordingly. To make these calculations more realistic, lead time was split into two different parameters, one for manufacturing time and one for transportation time. The manufacturing time parameter is assumed to be an average production lead time for one batch of material and the capacity utilization adjustment was removed.

Another lead time assumption in the original MIP was that the bill of materials (BOM) affected the lead time of components. For example, consider the case where the production time of component 1 is five days and the production time for component 2 is seven days. If component 1 consumed component 2 with a 1:3 BOM relationship, then the original model assumes that the lead time of component 1 is calculated as follows:

$$\text{Lead Time of Component 1} = 3(7 \text{ days}) + 5 \text{ days} = 26 \text{ days}$$

A more realistic calculation of lead time is to ignore the BOM ratios and assume that the lead time of component 1 is the sum of subcomponents, which is 7 days + 5 days. This calculation assumes that the three subcomponents are built as a batch and completed within seven days. The model formulation was changed accordingly and the new complete model with these changes and risk factors is shown in Appendix E.

4.2.2 Addition of Risk Factors to Gokhan's DFSC MIP Framework

Once those changes were made to the original MIP formulation, the next step was to add in the risk of poor supplier reliability, TTM risk and strategic exposure risk in the MIP.

Supplier reliability can be interpreted several different ways. It can be the risk that a shipment will not meet the customer's quality standards. Or it can be the risk that a shipment will be late, or the quantity will be inaccurate. For the purposes of this research, supplier reliability risk is defined as the supplier's ability to provide quality product on time. In other words, a probability is given for each supplier indicating their reliability in supplying product. This risk is incorporated into the model by requiring the overall weighted average probability of all suppliers selected to be at a certain level.

TTM risk is modeled by assigning each component alternative a TTM value, which is the time it takes to reach the market in time period one. Since these values are given at the component level, the overall TTM for the product is the maximum TTM for any one component. It is not a cumulative statistic, because it is assumed that design and development work for components will be done in parallel to one another. A loss in demand is assumed to occur the longer the product takes to get to the market; i.e., more customers will become dissatisfied and search for a different product. This loss is assumed to be a function of the TTM. The overall TTM value is divided by the length of time period one. This percentage is then used to determine how much demand is lost, based on a degradation of loss schedule, shown in Table 14. This degradation schedule is used for this research, but it could be modified to reflect market behavior for another scenario.

Table 14. TTM Demand Degradation Schedule

TTM / Period Length	% of Time Period 1 Demand Lost
< 0.5	0
0.5 – 0.8	0.5
≥ 0.8	0.8

Strategic exposure risk is the risk of a company being too reliant on one or a few suppliers. A common mitigation strategy for this risk is to source key components from multiple suppliers. This strategy is effectively modeled in the MIP through the use of a constraint. The constraints added for these risks are shown in Section 4.2.3.

4.2.3 DFSC and Risk MIP Formulation

The following parameters and variables are used to create the switch costs and risk constraints.

Parameters:

F: Total number of components used in the product

$\mathcal{I}$: Set of components, $\mathcal{I} = \{1, 2,\ldots, F\}$

A_i: Number of design alternatives for component i

$\mathcal{A}_i$: Set of design alternatives for component i, $i \in \mathcal{I}$

S: Total number of available suppliers

$\mathcal{J}$: Set of suppliers, $\mathcal{J} = \{1, 2,\ldots, S\}$

T: Number of time periods (each representing a product life cycle phase)

$\mathcal{T}$: Set of time periods, $\mathcal{T} = \{1, 2, 3, 4\}$

l_t: Length of time period t (in the same units as lead time)

$\sigma_{p1,i}$: BOM relationship of component i to component 1 (final product)

$c_{ij\alpha_i t}$: Unit manufacturing costs of design α_i of component i at supplier j in time period t

W_{jl}: Fixed supply chain network costs between suppliers j and l

$S_{jkl\alpha_k t}$: Unit transportation cost of design α_k of component k from supplier l to j in period t

h_t: Unit inventory holding cost of the final product in time period t

θ: Fixed cost of switching between different product designs

θ': Fixed cost of switching between different suppliers

$C_{ij\alpha_i t}$: Total production capacity of supplier j for design α_i of component i in time period t

z: z-value from the normal distribution corresponding to the given safety stock ratio

M: Maximum potential demand over all periods

Φ_t: A parameter value used to adjust demand value according to the time period t

β_1, β_2: Demand function coefficients

ρ_2: Constant coefficient of variation for lead time

ω_{1t}, ω_{2t}, ω_{3t}: Allowed values that price can take in time period t

$\mu_{ij\alpha_i t}$: Probability that supplier j will deliver a quality product (design α_i of component i) in time period t to satisfy demand requirements

Γ_t: Overall desired probability of timely delivery of all components in the final product

$m_{i\alpha_i 1}$: Time-to-market for design α_i of component i in time period 1

η_{it}: Maximum percentage of total demand that any supplier can supply of component i in time period t

Decision Variables:

$x_{ij\alpha_i t}$: Total production quantity of design α_i of component i built at supplier j in time period t

$x'_{ij\alpha_i t}$: 1, if $x_{ij\alpha_i t}$ is positive; 0, otherwise

$\pi_{i\alpha_i t}$: 1, if design α_i of component i is selected for time period t; 0, otherwise

y_{jl}: 1, if suppliers j and l provide components to one another; 0, otherwise

$u_{jkl\alpha_k t}$: Total amount of design α_k of component k manufactured at supplier l and transported to supplier j in time period t

υ_t: Total value of the final product design for time period t (between 0 and 1)

λ_{1t}, λ_{2t}: Variables that reflect pricing decision onto demand generation via ϕ_{1t}, ϕ_{2t}, and υ in time period t

ψ_{1t}, ψ_{2t}, ψ_{3t}, ψ_{4t}: Control variables that link pricing decisions and demand or total production values for revenue calculation in time period t

δ_{nt}: A variable to reflect lead time-demand multiplication via binary factorization in time period t

k_t^+: Equal to *demand*, if *total production* > *demand*; 0, otherwise

k_t^-: Equal to *total production*, if *demand* > *total production*; 0, otherwise

$D_{1,1}$: Total demand for component 1 in time period 1

$B_{t,t+1}$: 1, if a design change occurred between time period t and t+1; 0, otherwise

$G_{t,t+1}$: 1, if a supplier change occurred between time period t and t+1; 0, otherwise

m_{max}: Maximum time-to-market for the final product

m_{b1}: 1, if $\frac{m_{max}}{l_1} < 0.5$; 0, otherwise

m_{b2}: 1, if $0.5 \leq \frac{m_{max}}{l_1} < 0.8$; 0, otherwise

m_{b3}: 1, if $\frac{m_{max}}{l_1} \geq 0.8$; 0, otherwise

d'_1 ,d'_2: Variables to indicate the amount of demand lost (dependent on TTM value)

Objective Function:

$$max\left(\sum_{t=1}^{T} \omega_{1t}(k_t^+ + k_t^-) + (\omega_{2t} - \omega_{1t})(\psi_{1t} + \psi_{3t}) + (\omega_{3t} - \omega_{1t})(\psi_{2t} + \psi_{4t}) - \right.$$

$$\sum_{t=1}^{T}\sum_{i=1}^{F}\sum_{j=1}^{S}\sum_{\alpha_i=1}^{A_i}(c_{ij\alpha_i t}x_{ij\alpha_i t}) - \sum_{j=1}^{S}\sum_{l=1}^{S} y_{jl}W_{jl} - \sum_{t=1}^{T}\sum_{j=1}^{S}\sum_{k=1}^{F}\sum_{l=1}^{S}\sum_{\alpha_k=1}^{A_k} u_{jkl\alpha_k t}S_{jkl\alpha_k t} -$$

$$\left.\sum_{t=1}^{T}\frac{1}{2}h_t(1 + (z \times \rho_2))\sum_{n=0}^{N} 2^n\delta_{nt} \underbrace{- \theta\sum_{t=1}^{T} B_{t,t+1} - \theta'\sum_{t=1}^{T} G_{t,t+1}}_{\text{new switch costs}}\right) \tag{4.1}$$

Such that:

Design Switch Costs

$$B_{t,t+1} \geq \pi_{i\alpha_i t} - \pi_{i\alpha_i t+1} \qquad \forall\, i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \qquad (4.2)$$

$$B_{t,t+1} \geq \pi_{i\alpha_i t+1} - \pi_{i\alpha_i t} \qquad \forall\, i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \qquad (4.3)$$

Supplier Switch Costs

$$x_{ij\alpha_i t} \leq x'_{ij\alpha_i t} \times C_{ij\alpha_i t} \qquad \forall\, i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \quad (4.4)$$

$$G_{t,t+1} \geq x'_{ij\alpha_i t} - x'_{ij\alpha_i t+1} \qquad \forall\, i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \quad (4.5)$$

$$G_{t,t+1} \geq x'_{ij\alpha_i t+1} - x'_{ij\alpha_i t} \qquad \forall\, i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \quad (4.6)$$

Supplier Reliability

$$\sum_{i=1}^{F}\sum_{j=1}^{S}\sum_{\alpha_i \in Q}\left(\frac{x_{ij\alpha_i t}}{\sigma_{1,i}} \times \left|\log \mu_{ij\alpha_i t}\right|\right) \leq |\log \Gamma_t| \times \sum_{\alpha_i \in Q}\sum_{j=1}^{S} x_{1j\alpha_i t} \qquad \forall t \in \mathcal{T} \qquad (4.7)$$

where, $Q = \{\alpha_i | \mu_{ij\alpha_i t} > 0, i \in \mathcal{I}, j \in \mathcal{J}, t \in \mathcal{T}\}$

Time to Market Risk

$$m_{max} \geq m_{i\alpha_i 1} \times \pi_{i\alpha_i 1} \qquad \forall i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i \qquad (4.8)$$

$$0.8 \geq \frac{m_{max}}{l_1} - m_{b3} \qquad (4.9)$$

$$0.5 \geq \frac{m_{max}}{l_1} - m_{b3} - m_{b2} \qquad (4.10)$$

$$m_{b1} + m_{b2} + m_{b3} = 1 \qquad (4.11)$$

$$d'_1 \geq 0.5 \times D_{1,1} - (1 - m_{b2}) \times M \qquad (4.12)$$

$$d'_2 \geq 0.8 \times D_{1,1} - (1 - m_{b3}) \times M \qquad (4.13)$$

$$D_{1,1} = \left(\left(\beta_1 \omega_{1,1}^2 + \beta_2\right)\upsilon_1 + \beta_1 \lambda_{1,1}\left(\omega_{2,1}^2 - \omega_{1,1}^2\right) + \beta_1 \lambda_{2,1}\left(\omega_{3,1}^2 - \omega_{1,1}^2\right)\right)\Phi_1 - d'_1 - d'_2 \qquad (4.14)$$

Strategic Exposure Risk

$$x_{ij\alpha_i t} \leq \eta_{it} \times \sum_{\alpha_i=1}^{A_i}\sum_{j=1}^{S} x_{ij\alpha_i t} \qquad \forall\, i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \quad (4.15)$$

Equations (4.2) and (4.3) determine if a design change occurs between consecutive time periods. Equation (4.4) is used for the assignment of binary variables, to indicate which suppliers are selected by the MIP. Equations (4.5) and (4.6) determine if a supplier change occurs for any components in consecutive time periods. The new objective function (4.1) includes the penalty costs for changing designs or suppliers.

Constraint (4.7) requires the overall weighted average probability of all suppliers selected to be at a certain level, Γ_t. The formulation of (4.7) was derived as follows. The overall reliability of the system is the product of each supplier's reliability (assuming independence). However, in this model multiple suppliers can supply one component, so a weighted average needs to be considered. This is done by multiplying each supplier's percent produced by each supplier's reliability, in inequality (4.16).

$$\prod_{i}\left(\sum_{j=1}^{S}\left(\left(\frac{x_{ij\alpha_i t}}{\sigma_{1,i} \times \sum_{\alpha_i=1}^{A_i}\sum_{j=1}^{S} x_{1j\alpha_i t}}\right) \times \mu_{ij\alpha_i t}\right)\right) \geq \Gamma_t \qquad \forall t \in \mathcal{T} \tag{4.16}$$

The other challenge with this constraint is that it is nonlinear. To linearize it, the traditional approach is to use a log function. Through experimentation it was determined that this gives accurate results when the μ values are relatively close to one. Appendix F shows examples of the linear behavior of the log function as the μ values approach one. It is assumed that the supplier reliabilities will be close to one, as a supplier with a very low reliability would not be considered in practice. When the log function is applied to equation (4.16), the result is constraint (4.7).

Equation (4.8) calculates the m_{max} variable to be the maximum TTM value of all selected components. Selected components are indicated through the binary variables ($\pi_{i\alpha_i t}$). Calculations for these variables are shown in Appendix E, equations (E.6) through (E.8). Equations (4.9) through (4.11) govern the assignment of the TTM binary variables, which indicate the percentage of demand lost, as shown in Table 14. Equations (4.12) and (4.13) are used to determine the amount of demand that will be lost due to the TTM delay. The longer the delay, the more demand will be lost. Equation (4.14) is the demand calculation which includes the TTM demand loss penalty.

Equation (4.15) requires the amount of product supplied by each individual supplier to be less than a specified percentage, η_{it}. This percentage, η_{it}, is specified for each component i in each time period t. This allows the decision maker to develop specific sourcing strategies for different components. This is important, because components that are inexpensive to purchase and store, such as hardware, are typically single sourced. In most cases, it is less expensive to carry a higher inventory of these parts, as a risk mitigation strategy, rather than the costs of maintaining a relationship with a second supplier. In this case, the η_{it} parameter is equal to 1.0, to indicate that a single supplier can supply 100% of the demand. For other components that are more expensive or critical, the η_{it} parameter is typically lower.

4.3 SIMULATION MODEL

The simulation model was built with ARENA 12 by Rockwell Automation Technologies, Inc. The model consists of three major components – (1) reading and writing data, (2) the customer arrival and order fulfillment process, and (3) the production processes at supplier/manufacturing sites.

The function of the first simulation component is to read data from a Microsoft Excel input file and store it in the ARENA simulation at the start of the simulation. At the completion of the simulation, summary data is also written to a Microsoft Excel output file. The Excel input file includes the BOM, demand levels for each component, time period lengths, selling price of the final product, production quantities, manufacturing and transportation lead times, unit production and transportation costs and inventory costs of the final product. This data is a combination of inputs and outputs from the MIP. For example, manufacturing and transportation lead times are MIP inputs. Demand levels for each component are MIP outputs. Visual Basic code was written in ARENA to access and open the Excel file, read the data and store it in ARENA. All of the data is stored in ARENA variables when the simulation begins and then accessed at various points in the simulation.

The second major component of the simulation is the customer arrival and order fulfillment process. Customer arrivals are based on the total expected demand in each time period, which is an output from the MIP. One entity is created each simulation day and is assigned an attribute to represent the demand level for that day. This is one of the stochastic elements of the simulation. The daily demand values are generated based on a Poisson distribution, where the mean is equal to average daily demand. This entity is held in a queue until finished product inventory is available. When product becomes available, waiting customers are served. Inventory is reduced by the number of units that the customers purchase and the revenue variable is updated accordingly. If inventory is not available, then the customers wait until it is and a shortage cost is incurred each day the customers are waiting.

Several assumptions were made while creating the customer arrival process. The first assumption is related to the actual arrival rate of customers. The MIP determines an expected demand level for each time period, but since it is a strategic planning model it only determines the overall demand value. It does not give any information about daily demand patterns. Therefore, a Poisson distribution is used to generate the daily demand values, since it is commonly used for arrival processes in queuing theory (Ross, 1996). The average daily arrival rate is assumed to be the total demand for the time period divided by the time period length, rounded up to the nearest integer. For example, if total demand in time period 1 is 52,350 and the time period length is 1,000 days, then the average daily demand is 53 units.

The reason for using a single entity to represent daily demand is to facilitate efficient run times. Initially each unit of demand was represented by an individual entity. This was done to create a visually straightforward simulation. However, due to ARENA limits on the number of entities that can be created (59,170), the simulation reached this limit in less than 100 simulation days. To solve this problem and improve run times, the simulation was changed so that a single entity is created each day, which represents daily demand.

The other assumption is related to the shortage costs. Stock out costs consist of direct and indirect costs. Direct costs are fairly easy to estimate. These are extra administration costs, material and transportation costs for expediting the product, loss of profit from discounted prices, etc. Indirect costs are related to the loss of customer goodwill and decline in future demand.

These are more difficult to estimate, but a lot of research has been done on developing accurate estimates.

Liberopoulos et al. (2010) is one of the most recent studies in this area. They provide a thorough review of the literature and also derive an estimate for the backorder penalty cost coefficient in the classical Economic Order Quantity model with planned penalized backorders. This estimate is based on the fill rate of demand. It is assumed that the optimal fill rate is either 0 (make-to-order), 1.0 (make-to-stock) or somewhere between 0 and 1.0, which is a mixed make-to-order and make-to-stock operation. In the make-to-order operation, the backorder penalty is 0, because all orders are backordered. In the make-to-stock operation, the backorder penalty is ∞, because backordering is not permitted. In the mixed operation, the backorder penalty is $h\frac{F'}{1-F'}$, where h = inventory holding costs and F' = the fill rate of demand. In our model, preliminary runs yielded an average fill rate of approximately 92.5%. Using this estimate, the value of the shortage cost was assumed to be twelve times the unit inventory holding cost.

The third component of the simulation is the supply chain and it is the most complex. In this part of the simulation, components are produced at supplier sites and shipped to the next step in the process. For each component in the BOM, the MIP selects one or more suppliers for sourcing. These selections are also made specific to each time period. Therefore, there are many component, supplier, time period combinations and each of these are represented in individual sub-models within the simulation. The reason for this is that it allows the simulation to be easily customized to different data sets. At the beginning of the simulation the Excel input file is read, and then the required number of supplier sub-models are created and customized.

Within these sub-models, one entity is created per day. Just as in the customer arrival process, this entity is used to represent the total amount of daily production. An attribute is assigned to the entity to represent this production quantity. The entity moves through the following steps within the production sub-module:

Step 1: Create entity.

Step 2: Assign attribute to specify daily build quantity.

Step 3: Assess inventory levels of subcomponents that are required for production (per the BOM). If specified build quantity cannot be met due to a subcomponent shortage then deficit is moved to backlog.

Step 4: Consume subcomponents.

Step 5: Determine if production capacity is available.

Step 6: If capacity is available, then build components. If not, then wait until capacity is available.

Step 7: Transport components to next step in supply chain.

Step 8: Update inventory levels and incur manufacturing and transportation costs.

Step 9: Dispose of entity.

In step 2, an attribute is assigned to each entity to specify the daily build quantity. This quantity is calculated by the following formula.

$$\text{Daily Build} = \frac{\text{Total Production Quantity}}{\text{Time Period Length} - \text{Lead Time of Comp and Higher Level Comps}}$$

It is shown in the formula that the MIP specified production quantity for the entire time period is divided by the time period length, which is reduced by the lead time of the component and all higher level components. The reason for this is that all production must be given enough time to complete processing. In other words, a batch of product cannot be started on the last day of the time period if the lead time is greater than one day. Also components need to be available for consumption by higher level components before the end of their adjusted time periods. This is illustrated in Figure 12. In this example, the last batch of component 1 must be started 18 days before the end of the time period. The last batch of component 4 must be started 72 days before the end of the time period, (18 days + 26 days + 28 days). This will ensure that all components are completed on time.

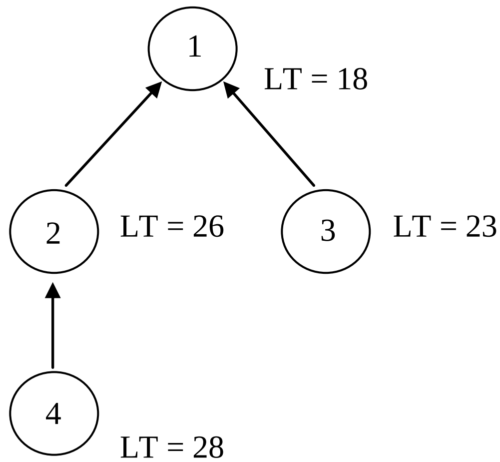


Figure 12. Lead Time Example

Another assumption made is that inventory is available to sell to customers on simulation day one. All of the design, validation and production start-up activities are assumed to be complete. For this to be possible there must be some inventory of each component in the system when the simulation begins. These starting inventory positions are calculated by multiplying daily demand by component lead time. For example, if the top level component has a daily demand of 50 units and a lead time of five days, then the starting inventory is 250 units. Then the BOM is exploded to calculate lower level inventory. This assumption also affects the daily build quantity of each component because this starting inventory needs to be subtracted from the total production quantity. Therefore, the formula for calculating the daily build quantity in each supplier sub-model becomes:

$$\text{Daily Build} = \frac{\text{Total Production Quantity} - \text{Starting Inventory}}{\text{Time Period Length} - \text{Lead Time of Comp and Higher Level Comps}}$$

The final consideration for this calculation is rounding. The daily production quantities need to be rounded up to the next highest integer to ensure everything is built by the end of the time period.

In steps 3 and 4, before the entity moves into production, the required subcomponents are consumed. If subcomponents are not available for consumption, then the daily build quantity is adjusted and the balance is backlogged. Then the entity moves into production if capacity is available. This is done in step 5. Capacity is an input to the MIP, but just like demand and production quantities, it is an aggregate value for the entire time period. In the simulation, the assumption is made that daily capacity is total capacity divided by the number of days in the time period minus the lead time of the component and any higher level components.

Steps 6 and 7 are the manufacturing and transportation steps. In the MIP, the simplifying assumption must be made that manufacturing lead time is deterministic. In the simulation this is changed to a stochastic parameter using a truncated Normal distribution (not allowing negative values). The mean of the distribution is the average lead time, which is used in the MIP. The standard deviation is estimated to be ¼ of the mean. Similarly, in step 7, the transportation step is also made stochastic using a truncated Normal distribution. The mean is the average transportation lead time used in the MIP and standard deviation is also estimated to be ¼ of the mean.

In step 8, the inventory variable is updated to reflect the production quantity of the component that was built and shipped in steps 6 and 7. This step is a simplification from the MIP. The MIP specifies exact quantities to be transported between different suppliers. For example, consider the case where component 3 is sourced by suppliers 2 and 5. Component 3 is a subcomponent to component 2, per the BOM. Component 2 is built at suppliers 1 and 4. The MIP determines how much of component 3, sourced by supplier 2 should be transported to suppliers 1 and 4 for the next step in the production process and also specifies unit costs for this transportation. This network is shown in Figure 13.

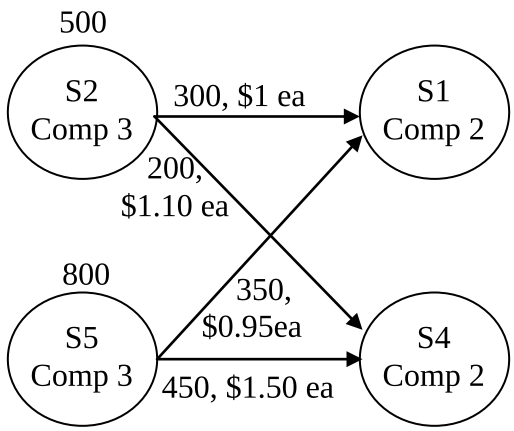


Figure 13. Example MIP Transportation Network

This level of detail is not required in the simulation, because transportation risks are not analyzed. Therefore, this detailed transportation network is simplified in the simulation. Rather than tracking which components flowed to which suppliers and inventory levels of components at each supplier, it is assumed that at the completion of production, the product was transported to the appropriate destination and an average transportation cost is incurred. Then, the finished goods inventory level of that component is increased by the amount that was produced. In other words, components are built at their designated supplier sites and then placed in an aggregate inventory pool. Upstream in the process, when a higher level component consumes the component that was just built, the inventory of that component is reduced accordingly. This is shown with the supply chain network diagram in Figure 14.

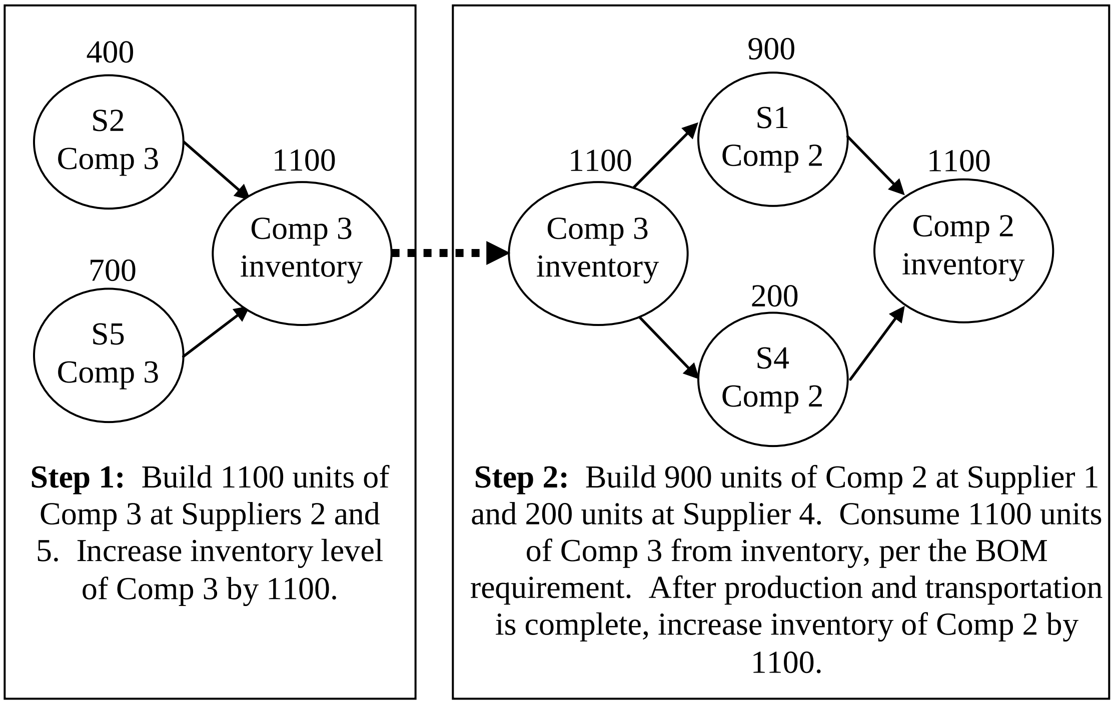


Figure 14. Example Simulation Transportation Network

After the production and transportation steps are complete, appropriate costs are incurred for manufacturing and transportation and then the entity is disposed of.

A few other changes were made between the MIP and the simulation. The first change was in the treatment of unmet demand. In the MIP, excess demand is permitted when capacity is 100% utilized. This occurs because the MIP determines optimal production and demand values and there is no penalty for shortages. In the simulation, however, shortage costs are incurred to make the model more realistic. In some cases, unmet demand is so high that it creates an overall negative profitability scenario due to the high shortage costs. Therefore, the assumption is made that in the simulation, orders that cannot be filled are not even taken. This normally happens in industry if possible, because otherwise it puts unnecessary stress on the production facilities, goodwill of the customers is lost and unnecessary shortage costs are incurred.

In a similar manner, the original MIP permits production to exceed demand. This occurs in cases where extra production is necessary to make the supplier reliability and strategic exposure constraints feasible. For example, consider the case where demand for the top level component in time period 1 is 10,000 units and suppliers 1 and 2 can be used for production. Supplier 1 has a reliability rating of 0.90 and supplier 2 has a reliability rating of 0.96. The strategic exposure constraint requires a dual sourcing scenario with at least 20% of production from the back-up supplier. The supplier reliability constraint requires an overall reliability level of 0.95 for the product. Therefore, the optimal scenario from a reliability criterion is for supplier 1 to produce 2,000 units and supplier 2 to produce 8,000. However, this only gives an overall supplier reliability rating of 0.948, according to equation (4.3). The constraint becomes feasible when 8,021 units are sourced from supplier 2. The problem with this is that supplier 1 still needs to source 2,000 units to maintain feasibility of the strategic exposure risk constraint. But then in the simulation extra inventory costs are incurred. Therefore, the production constraint was changed in the MIP so that this overproduction scenario does not occur. This is shown in equation (E.5) of Appendix E. With this change, the problem becomes infeasible for this example case. The decision maker can then determine whether they should mitigate this supplier reliability risk with extra inventory, by lowering their overall supplier reliability threshold, lowering their strategic exposure risk threshold or by finding an alternate supplier with a higher reliability rating. These changes were made to make the simulation model more realistic than simply allowing overproduction.

4.4 MIXED INTEGER PROGRAM / SIMULATION INTEGRATION

Shanthikumar and Sargent (1983) define a hybrid simulation/analytic model as “a mathematical model which combines identifiable simulation and analytic models.” They sort these models into four different classes. Class I contains models whose behavior over time is obtained by alternating between using independent simulation and analytic models. Gnoni et al. (2003) and Rabelo et al. (2007) are examples of Class I models. The next class contains models in which a simulation and an analytic model operate in parallel over time with interactions through their solution procedure. Representative Class II models found in the literature include – Nolan and Sovereign (1972), Byrne and Bakir (1999), Lee and Kim (2000), Kim and Kim (2001), Byrne and Hossain (2005), and Bazargan (2007). Models in Class III are those in which a simulation model is used in a subordinate way for an analytic model of the total system. An example of this type of model was not found. Class IV contains models in which a simulation is used as an overall model for the total system and requires values from the solution procedure of an analytic model representing a portion of the system for some or all of its input parameters. The DFSC risk model developed in this research falls into Class IV, along with Pereira (1992), Mendes et al. (2005) and Lim et al. (2006).

In this research, the MIP and the Simulation were integrated to create a hybrid simulation/analytic model. Outputs from the MIP are used as inputs in the simulation, as described in the definition of a Class IV hybrid model. Once the simulation is completed, the decision maker uses those outputs and their subjective judgments to determine the best plan for risk mitigation. This integration process is shown in Figure 15 and explained in further detail below.

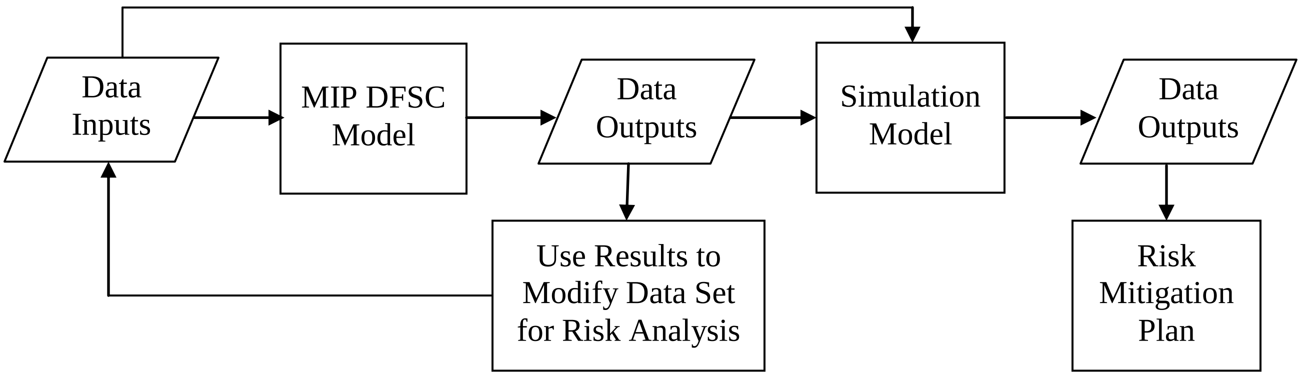


Figure 15. Risk Model Integration Schematic

The simulation serves two purposes. The first is to model the MIP results in a stochastic environment. In the MIP, demand and lead time are assumed to be deterministic, but these assumptions are removed in the simulation. These were the only parameters that were converted to be stochastic because they were the only ones that are truly stochastic in nature. In addition the impacts of shortages are captured through the use of shortage costs.

The second objective of the simulation is to analyze capacity and market/demand risks. Capacity risk is modeled from the perspective that one supplier might have some issue(s) that prevents it from operating at full capacity. This supplier is called the "risky supplier." Three different risk mitigation options are analyzed as methods to make up the lost capacity from this supplier.

Option A is to not use the risky supplier at all. This option is normally undesirable because the risky supplier was selected by the MIP because overall it was the optimal choice for the supply chain. A back-up supplier will either have higher costs, longer lead times, or lower reliability. Therefore, two more options are considered where the risky supplier is still used, but to a lesser extent. In Option B, it is assumed that the risky supplier will definitely suffer a loss of capacity. A backup plan is found and put in place initially for any components that the risky supplier will not be able to provide, due to their capacity issues. If the supplier does not actually experience any issues, then this option will put a less optimal supply chain in place unnecessarily. The last option, Option C, is to wait to see if there actually is a capacity issue and then find and implement a backup plan. The limitation with this option is that there will be fewer options for backup plans once production has already begun through the initial supply chain. The additional capacity needs can only be met by increasing production at a current supplier or finding an additional supplier. In Option B, the backup plan is put in place initially, so the entire supply chain can be re-optimized for these new conditions. In Options B and C, three different levels of reduced capacity are tested – 90%, 80% and 70% of the risky supplier's total capacity.

The second risk factor analyzed in the simulation is market/demand risk. This is the risk that a change in the market will affect demand. Theoretically, market changes could cause demand to fluctuate up or down. Analysis is not interesting when demand is reduced, because within the scope of this model, nothing can be changed to counteract the demand loss. It is assumed that the decision maker established binding contracts with their suppliers, so if demand goes down the decision maker suffers reduced profitability. However, in the cases where demand increases, there are several different scenarios and decisions to consider.

If the decision maker anticipates a demand increase, there are three different scenarios that could be used to increase production and mitigate the risk. Option A is to put a plan in place initially for increased production, assuming that the demand increase will definitely occur. The risk with this approach is that if demand never increases, then the decision maker will carry extra inventory. Option B is to use a wait and see approach. After a definite demand increase occurs, then a plan is put into place for increased production. The risk with this approach is that shortage costs will be incurred until the backup plan is put into place. Finally, Option C is also a wait and see approach, but when demand does increase, additional production can only be obtained from the original set of suppliers in the supply chain. The difference between Options B and C is that in Option B the production increase can come from any supplier but in Option C the production increase can only come from the original suppliers. For all three of these options, demand increases of 10%, 20% and 30% are analyzed.

For each of the three scenarios in the capacity and demand analysis, the MIP is used to find the backup plans and the simulation is used to analyze the results of implementing the backup plan. In the "wait and see" options the simulation tests the effects of switching to a different supply chain in the middle of a time period, which the MIP is not designed for. In these cases, it is assumed that on Day 100 the backup plan will be put into place. This value was chosen because it gives the user slightly more than three months to determine if a capacity decrease or demand increase will actually occur.

To complete the demand analysis, another assumption had to be made. In all cases, the price and product design selections should remain the same as those originally selected by the math program. It is assumed that due to market changes, the original product design at the original price experienced a demand increase. In the math program, demand is a function of price and product design selection. If these values are not forced to remain at their original values, and demand increases then in some cases the product design or price structure changes. This is also true for Option C in the capacity analysis. To give the most realistic scenario, the product design and price structure should remain the same.

In the capacity analysis, theoretically Option B should perform better than Option C and both should perform better than Option A. In the demand analysis Option A should perform better than Option B and Option B should perform better than Option C. The integrated MIP and simulation structure enables a decision maker to analyze all of these cases. The simulation results should be weighed against the likelihood of an actual demand increase, an actual capacity issue and the decision maker's own risk threshold. In this way, a decision maker is able to make a decision based on both quantitative results and their subjective judgments. A detailed list of the steps followed to complete the integrated MIP/Simulation procedure is found in Appendix H.

4.5 VALIDATION AND VERIFICATION

4.5.1 MIP Model

A critical step in the model development process is validation. The DFSC and risk MIP model was validated with data from industry. The research objectives and model were presented to key individuals at a local, highly regulated manufacturing company. They were interested in the model and thought that it might be useful to their organization. However, they were not willing to dedicate many resources or a large amount of time to the project. As a compromise, we were able to work with one supply chain analyst to obtain data from a recent, completed design project.

The data set was limited in several ways. First, it was small. The product BOM consisted of only five components. The other major limitation was that the company's product design approach did not match the DFSC concept at all. Their approach was more sequential in nature. An initial, conceptual design was developed by engineers at the company. This design was then sent to three potential suppliers, because the remainder of the development work and the actual production was planned to be outsourced. Each supplier quoted the initial design in terms of further product development costs and unit production costs. A supplier was selected from those quotes and then the company worked with the supplier to finalize a product design. Therefore, it was essentially a supplier selection problem.

The only data the company was able to provide were the quotes on the initial design from two of the three suppliers. The third supplier's quote was missing. Additionally, the company provided estimates on design values, supplier reliability, price and TTM. This was not enough data to run the DFSC model. There was no data for the design and supplier alternatives for each individual component. Data was only available for the initial, final product design. Therefore, to expand the data set to fit the DFSC model, several assumptions were made.

The first and most significant assumption was that the initial product design and the final product design were two feasible design alternatives that were analyzed in parallel to one another rather than developed in a sequential process. It was also assumed that each of the two suppliers could source either of these two products and the suppliers would not do any design work. Instead the company would complete the design work, and select one of these two designs and one of these two suppliers, which makes the problem more similar to a DFSC problem.

Supplier data was only available for the initial design. To create data for the final design, the manufacturing costs were extrapolated in the following way. The final design consisted of five components and the initial design only had three. It was assumed that product costs for the two extra parts were $0.10 total and additional labor costs for assembly were $0.05 total, which was similar to the other costs. The total increase in manufacturing costs was $0.15 for the final design. Transportation costs were assumed to be equal to the initial design because the package sizes were identical. Supplier capacity and lead time values were also assumed to be equal, because the additional assembly time for the two extra components was very small.

The design values were estimated by the company at 1.0 for both the initial and final designs, which is the highest possible rating. These values were estimated by the company's marketing department. They felt that the customer would be completely satisfied with either design alternative. This assumption was later found to be poor.

The last assumption made was about the model time periods. The model was designed to include four time periods covering the entire life cycle of the product. However, the data was not broken down into these segments. It was broken into annual time periods. Therefore, the four time periods in the model were simply assumed to be years one through four of the product life cycle. These assumptions enabled the creation of a complete data set, which is contained in Appendix G.

Obtaining this data from the company was very difficult and time consuming. The lesson learned was that it is best to be extremely detailed in regards to the specific pieces of information that are needed. Also, a data collection form greatly facilitates the process.

The industry data set was used to run Gokhan's model and the DFSC and risk model that included supplier reliability and TTM risk factors. Run times for both models were very short because the data set was so small. A summary of the results is shown in Table 15.

Table 15. Industry Validation Results

	Gokhan Model	Preliminary Risk Model
Design Selected	Initial	Initial
Supplier Selected	1	0 (78%)* 1 (22%)
Profit	$ 2,496,879	$ 2,189,359
Demand – YR 1	100,000	100,000
Demand – YR 2	200,000	200,000
Demand – YR 3	300,000	300,000
Demand – YR 4	100,000	100,000

*dual sourcing strategy

Both models selected the initial product design. However, the company actually selected the final product design. The reason this occurred is because the design values were assumed to be equal for both designs. Several other factors were also equal, with the exception of manufacturing costs. The initial design had lower costs, which is the reason it was selected. This behavior is discussed in further detail below. Another interesting result is the change in supplier selections between Gokhan's model and the preliminary risk model. Supplier 1 was only given a reliability rating of 75%, so to mitigate this risk, the preliminary risk model selected a dual sourcing scenario with supplier 2 who had a reliability rating of 100%. The company actually selected supplier 1 to completely design and source the product. When this result was discussed with the company, they indicated that there have been no issues with supplier 1 and that their initial 75% rating was probably too low.

After the model was run and results were obtained, a meeting with the company was held. They provided valuable feedback and made suggestions for model improvements. The most important idea they had, was to incorporate technical risk into the model, which they defined as the reliability of functionality of the product. The only factor currently in the model that is somewhat similar to this is component design value. This factor captures the percent contribution that the component makes towards demand generation. In other words, if a product consists of 4 components, each of those components has an impact on the amount of demand that is generated, some more than others. Component 1 could be an internal wire that the customer does not see and does not care about. Therefore, it might only contribute 5% towards total demand generation. Alternatively, component three might be the external housing which the customer sees and uses directly. This would have a much higher impact on demand generation, because it directly impacts how the customer perceives the product. Further, each of the design alternatives for these components may have slightly different design values based on how well the customer perceives each design. This concept is illustrated in Table 16, with dummy data.

Table 16. Design Value Example

		Component Alternative Design Values				
Component	Maximum Component Design Value	A	B	C	D	E
1	0.05	0.04	0.05	0.01	0.04	-
2	0.10	0.10	0.10	-	-	0.08
3	0.75	-	-	0.70	0.75	0.71
4	0.10	0.06	-	0.01	-	0.09

In the data set from the company, both product alternatives were deemed equal from the customer's perspective. They both completely satisfy customer needs and requirements, so they were given equal design values of 1.0. Also transportation costs, lead times and supplier capacities were assumed to be equal for both alternatives. Therefore, the major differentiator between the two designs was manufacturing cost. This resulted in the selection of the less expensive, initial design alternative because there was no benefit to selecting the more expensive, final design alternative. However, this is an incorrect selection, because the initial design was not adequate in terms of functionality and safety. The incorporation of functionality and safety into the model would have prevented this incorrect selection. This could be done by simply redefining the design value factor or by incorporating these risk factors into the model.

The company also felt that this type of model would not be very useful to them, because their design decisions are very limited by functionality, safety and cost considerations. This is due to stringent regulations in their industry. In other words, after an initial design concept is developed, the design process consists of mostly refining that design until it meets all functional and safety requirements. Often times this limits the design to only one option. If there are multiple options, the least expensive alternative is always selected. The company did agree, however, that the model would be helpful with the supplier selection decisions. Even though design decisions are usually limited, this is not the case for supplier alternatives.

Another model limitation identified by the company is its limited supply chain design capabilities. As noted previously, the scope of the research limited the supply chain design problem to only the supplier selection problem. While the company appreciated the value in this, they strongly expressed interest in a model that would also include the design of the distribution network.

This work showed that the model may be more applicable to companies in less regulated industries. Also, it showed that all factors currently included in the model are useful and the addition of a factor related to technical risk could be included to give more realistic results.

4.5.2 Simulation Model

Validation and verification of the simulation was completed by ensuring that the simulation results matched the MIP results, since the simulation is intended to be a representation of the MIP. This was straightforward, since both models calculated revenue, manufacturing costs, transportation costs, inventory holding costs and profit. A deterministic simulation was built first and this was debugged until the values obtained for these parameters matched those in the MIP.

The inventory holding costs do not match exactly between the two models. There are two reasons for this. First, the inventory cost calculation in the original MIP was based on demand levels rather than production levels. The calculation was,

$$\text{Inventory Cost} = \tfrac{1}{2} \times \text{Lead Time} \times \text{Demand} \times \text{Unit Holding Cost} \times \text{Safety Stock Inflation}$$

A complete derivation of this calculation can be found in Appendix A.3 of Gokhan (2007). The reason for this formulation in Gokhan's model was to incur a penalty for generating high demand and not satisfying it with a good supply chain. However, this created a problem during the demand risk sensitivity analysis. During this analysis, demand is increased by 10%, 20% and 30%. Scenarios are tested to determine the best demand risk mitigation strategy, as described in Section 4.4. In some cases when demand was increased by 30%, the overall profitability of the solution was worse than the case when demand was increased by 20%. The reason this happened was because capacity was 100% utilized, all demand could not be satisfied in the 30% case, and thus the inventory penalty was incurred which caused profitability to suffer. An example of this is shown in Table 17.

Table 17. Inventory Calculation Inconsistency

	Percent Demand Increase				
	10%	20%	25%	27%	30%
Revenue	$ 92,856,000	$ 94,752,000	$ 95,700,000	$ 96,000,000	$ 96,000,000
Manufacturing Cost	$ 23,017,580	$ 23,477,360	$ 23,707,250	$ 23,780,000	$ 23,780,000
Transportation Cost	$ 8,477,740	$ 8,672,080	$ 8,769,250	$ 8,800,000	$ 8,800,000
Inventory Cost	$ 11,436,021	$ 12,475,659	$ 12,995,478	$ 13,203,405	$ 13,515,297
Shortage Cost	-	-	-	-	-
Network Cost	$ 15,070,000	$ 15,070,000	$ 15,070,000	$ 15,070,000	$ 15,070,000
Switch Cost	-	-	-	-	-
Profit	$ 34,854,659	$ 35,056,901	$ 35,158,022	$ 35,146,594	$ 34,834,703

It is seen in this table that the point of maximum revenue is reached somewhere between a 25% and 27% increase in demand. At that point manufacturing costs plateau at $23,780,000 which indicates that capacity is 100% utilized. However, it can also be seen that the inventory costs continue to rise. This is because inventory costs are based on demand rather than the amount of product that is actually being held. This causes the 30% demand increase case to perform worse than the 20% demand increase case, because demand is higher. Theoretically 30% should always perform at least as good as the 20% case. Therefore, the inventory cost calculation in the MIP was changed so that it is based on production values. This was felt to be a more realistic modeling method. This is shown in equations (E.17) through (E.19) of Appendix E.

The second reason that inventory costs differ between the MIP and simulation is also due to the inventory cost calculation. The calculation assumes that the inventory levels follow the pattern shown in Figure 16 in the MIP. This is a common approximation used in inventory models. However, in the simulation the inventory levels follow a more discrete pattern, as happens in industry when customers buy whole units of product. This is shown in Figure 17. For this reason, the simulation inventory holding costs are typically higher than those in the MIP.

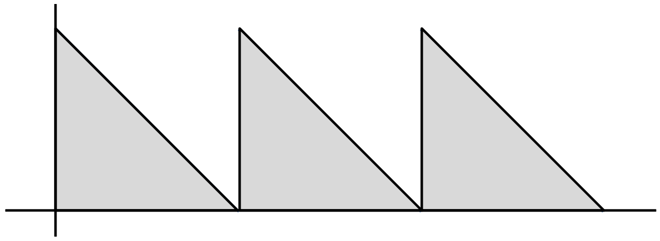


Figure 16. MIP Inventory Calculation

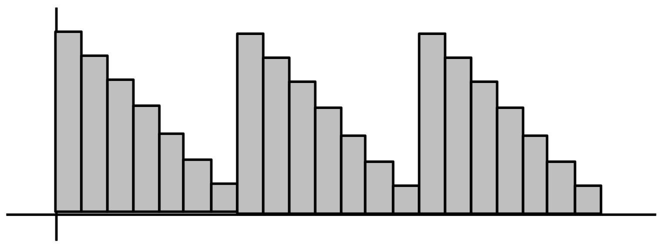


Figure 17. Simulation Inventory Calculation

Once the validation of the deterministic simulation model was complete, the demand and lead time parameters were changed to stochastic parameters. Through the validation of the stochastic simulation model, it was determined that a separate random number generation seed should be used for the random number generator that was used to generate daily demand values. This ensured that the same daily demand values were obtained in each simulation replication.

5.0 COMPUTATIONAL RESULTS

To run the complete DFSC and risk model, three simulated data sets were created, because real data from industry was not accessible. These data sets were used to debug the models, perform sensitivity analysis and draw conclusions about risk mitigation strategies.

5.1 DATA SET DEVELOPMENT

The first data set contained 4 components and 6 suppliers and is referred to as the 4_6 data set henceforth. The other data sets are called 5_5 and 6_7 as they contained 5 components, 5 suppliers and 6 components, 7 suppliers, respectively. The complete data sets are contained in Appendix I.

In data set 4_6, component 1 has three design alternatives from which to choose, components 2 and 3 have two alternatives and component 4 has one alternative. The BOM is shown in Figure 18, with the build relationships marked in the figure. In data sets 5_5 and 6_7, each of the components has two different design alternatives to choose from and there is a 1:1 build relationship between all components. The data set 5_5 BOM is shown in Figure 19 and the data set 6_7 BOM is shown in Figure 20.

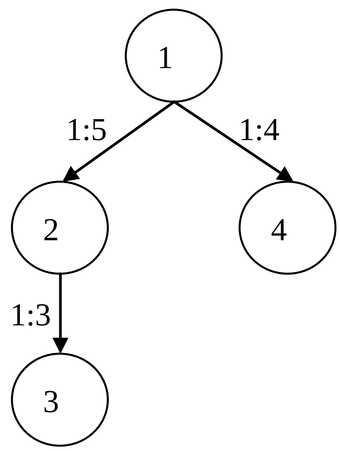


Figure 18. Data Set 4_6 BOM

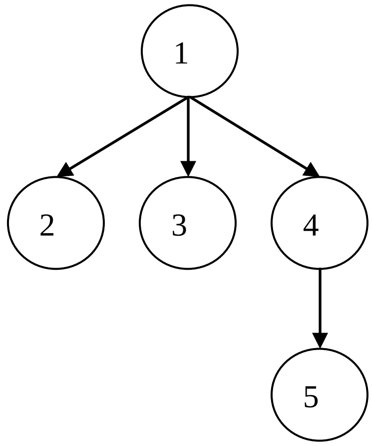


Figure 19. Data Set 5_5 BOM

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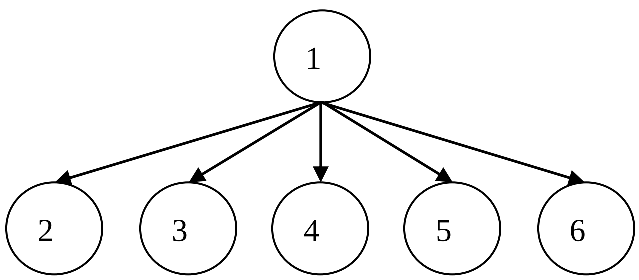

Figure 20. Data Set 6_7 BOM

All three of the data sets were used to run the MIP model and perform sensitivity analysis. Data sets 5_5 and 6_7 were used to run the hybrid MIP/simulation model and complete a designed experiment. These experiments and results are discussed in the following sections.

5.2 MIP ANALYSIS

The DFSC and risk MIP model included the risk of poor supplier reliability, TTM risk, and strategic exposure risk. This model and Gokhan's original model were run with each of the three data sets in CPLEX 12.2. Additionally, three separate models were created and run, each with only one of the risk factors included. The purpose of this was to test the impact of each individual risk factor. Table 18 provides a summary of objective values (profit) and run times from these runs. The results show that the addition of risk factors to the DFSC model caused the objective values to be reduced. In other words, profitability decreased. This behavior is expected, as the addition of risk factors into the models restricts options for product and supplier selections.

Table 18. DFSC and Risk MIP Model Results ($ in 000's)

Data Set		Gokhan	Supplier Reliability	TTM	Strategic Exposure	Complete DFSC Risk MIP Model
4_6	Objective	$ 157,805	$ 144,593	$ 148,688	$ 150,827	$120,906
	Run Time	3 sec	14 sec	7 sec	35 sec	33 sec
5_5	Objective	$ 52,829	$ 47,680	$ 49,792	$ 49,792	$45,428
	Run Time	2 sec	5 sec	41 sec	40 sec	5 sec
6_7	Objective	$ 4,766,144	$ 4,459,248	$ 4,706,241	$ 4,706,241	$4,424,559
	Run Time	53 sec	11 sec	4 sec	4 sec	19 sec

Table 19 provides a detailed sample of the results from data set 4_6. This table shows which suppliers and product alternatives were selected in time period 1 for the Gokhan, supplier reliability, TTM and strategic exposure risk models. Columns one through four list all of the component and supplier alternatives available for selection and each supplier's available capacity. These are model inputs. The other columns show results. The columns titled "Build Amt", lists the optimal order quantities found by the models. A value of zero in this column indicates that the supplier and component pair were not selected. Columns titled "Demand" show demand, at the component level. Demand is a function of product selling price, design value (customer's perspective of each component's design value) and time period. Therefore, depending on which components are selected, demand can change, which is shown in the table. Additionally, in the TTM model, the TTM value also affects demand. Component demand levels are also a function of the BOM. For example, if demand for component 1 is 57,600 and component 2 is 288,000, this indicates that the BOM ratio between components 1 and 2 is 1:5.

Table 19. Detailed Results for 4_6 Data Set - Time Period 1

				Gokhan Model		Supplier Reliability Model (Γ = 0.9)			TTM Model			Strategic Exposure Model	
Comp	Alt	Supplier	Supplier Capacity (Units)	Build Amt (Units)	Demand (units)	μ	Build Amt (Units)	Demand (units)	TTM (days)	Build Amt (Units)	Demand (units)	η	Build Amt (Units)
1	1	1	8,177,000	57,600	57,600	0.96	11,218	57,600	600	0	39,680	0.90	0
1	1	2	7,248,000	0		0.87	0			0			0
1	1	5	4,411,000	0		0.97	46,381			0			0
1	1	6	876,000	0		0.92	0			0			0
1	2	2	7,660,000	0		0.87	0		50	0			3,968
1	2	3	9,827,000	0		0.98	0			39,680			35,712
1	2	4	5,197,000	0		0.85	0			0			0
1	3	6	8,784,000	0		0.92	0		100	0			0
2	1	3	4,206,000	288,000	288,000	0.98	288,000	288,000	110	198,400	198,400	1.00	198,400
2	2	2	8,701,000	0		0.87	0		90	0			0
2	2	4	6,623,000	0		0.85	0			0			0
2	2	6	10,014,000	0		0.92	0			0			0
3	1	1	382,000	0	864,000	0.96	0	864,000	200	0	595,200	0.90	0
3	2	1	5,575,000	0		0.96	0		80	0			59,680
3	2	3	3,490,000	864,000		0.98	864,000			595,200			537,122
4	1	1	5,927,000	230,400	230,400	0.96	44,874	230,400	150	158,720	158,720	1.00	158,720
4	1	5	5,181,000	0		0.97	185,525			0			0

The column titled "μ" lists the supplier reliability values for each supplier, which is a model input. The supplier reliability risk model restricted the selection of suppliers by requiring the overall reliability of all suppliers selected to be above a certain threshold. Table 19 shows that this caused the original selection of supplier 1 for component 1 to switch to a combination of suppliers 1 and 5. Likewise, component 4 was originally produced only by supplier 1 and is now provided by suppliers 1 and 5. The reliability of supplier 1 was too low to satisfy the constraints of the model.

The column titled "TTM" shows the TTM values for each component. Design alternative 1 was originally selected for component 1. In the TTM model, however, it was switched to alternative 2. This alternative has a much lower TTM value. However, it also has a lower design value to the customer, because demand decreased with its selection.

Finally, the column titled "η" shows the strategic exposure risk threshold value, which is the percentage of total product that can come from any one supplier. The last column of the table shows that when the strategic exposure risk constraints are added to the model, a dual sourcing scenario is required for components 1 and 3.

The results in Table 18 and Table 19 show that incorporating risk into the model is important, as it has an impact on the results. To test the magnitude of this impact, the TTM model was rerun with the design selections from the Gokhan model hard coded as inputs rather than variables. This showed profitability in the Gokhan model when TTM delays arise unexpectedly. The results of these runs are shown in Table 20. It is clear from the deltas in each case that it is extremely important to take these risks into consideration. If they are not incorporated into the decision making process, organizations can unintentionally select a solution that has an extremely long TTM. Also, Table 18 showed that the run times were not increased significantly by this addition, so it is worthwhile to include TTM risk in the model.

Table 20. "What If" TTM Analysis Results

Data Set	Objective Value of TTM Risk Model	Objective Value of TTM Risk Model with Original Design Selections as Inputs	Delta	
			$	%
4_6	$ 148,688,132	$ 147,761,107	($ 927,025)	-0.6%
5_5	$ 50,228,398	$ 46,724,986	($ 3,503,412)	-7.0%
6_7	$ 4,725,748,086	$ 4,151,074,457	($ 574,673,629)	-12.2%

5.2.1 Sensitivity Analysis

In some cases, model parameters need to be estimated, e.g. when the company does not collect such data or when the available data is based on historical records. In these cases it is important to know how the model will perform if these parameter values were estimated incorrectly. Therefore, a sensitivity analysis was completed. Gokhan performed sensitivity analysis on the following parameters in his model – supplier capacity, supplier unit manufacturing costs, supplier production times, supply chain network costs, transportation costs and demand function coefficients. In this research, sensitivity analysis is needed on the TTM and supplier reliability parameters. The strategic exposure risk limit parameter was not analyzed, because it was included as a factor in the designed experiment used to test sensitivity of the integrated model. This is discussed in the next section.

The following runs were made in CPLEX for the sensitivity analysis:

- TTM less X%: TTM values (*m*) for each component were reduced by X%.
- TTM plus X%: TTM values (*m*) for each component were increased by X%.
- Srel less X%: Supplier reliability values for each supplier (μ) were reduced by X% of (1.0 – μ). For example, if the supplier's reliability is 0.95, the sensitivity analysis reduced this value by (X%)×(1 – 0.95).
- Srel plus X%: Supplier reliability values for each supplier (μ) were increased by X% of (1.0 – μ).
- Srel threshold less X%: The overall threshold probability for suppliers (Γ) was reduced by X% of the original threshold value.
- Srel threshold plus X%: The overall threshold probability for suppliers (Γ) was increased by X% of the original threshold value.

The results of these runs for all three data sets are shown in Table 21 through Table 23. The results indicate that the TTM values can be somewhat inaccurate before they impact the results significantly. This is likely due to the fact that there are only three levels in the demand degradation schedule and it will take a large increase or decrease in the TTM value to move either up or down relative to the threshold values. This is also a function of the data set design.

In data set 4_6, a change in profitability does not occur until the TTM values are decreased by 30%, which is a fairly significant decrease. In this instance, product design component 1 switches from alternative 2 to alternative 1 and the supply chain for that component is changed from supplier 3 to supplier 1. Also, component 3 was originally sourced from suppliers 1 and 3, but is changed to sole sourcing from supplier 3.

Alternative 1 for component 1 originally had a TTM value of 600, while alternative 2 was only 50. If alternative 1 had been selected then demand would have been reduced by 50% in time period 1, due to the TTM penalty. The MIP optimization model determined that it was more profitable to select alternative 2. However, when TTM values are reduced by 30%, alternative 1 has a TTM value of 420 and it is then more profitable to select alternative 1 as it no longer has a TTM penalty associated with it.

Table 21. TTM Sensitivity Analysis Results

Data Set	Parameter Change	Objective	Delta from Original TTM Objective	Change from Original Case			Run Time (sec)
				Product Design	Price	SC Design	
4_6	TTM less 50%	$ 158,115,456	$ 9,427,324	Y	N	Y	29
	TTM less 30%	$ 158,115,456	$ 9,427,324	Y	N	Y	31
	TTM less 10%	$ 148,688,132	-	N	N	N	88
	TTM plus 10%	$ 148,688,132	-	N	N	N	83
	TTM plus 30%	$ 148,688,132	-	N	N	N	131
	TTM plus 50%	$ 148,688,132	-	N	N	N	95
5_5	TTM less 50%	$ 52,829,115	$ 2,600,717	Y	N	Y	33
	TTM less 30%	$ 52,829,115	$ 2,600,717	Y	N	Y	56
	TTM less 10%	$ 50,228,398	-	N	N	N	46
	TTM plus 10%	$ 50,228,398	-	N	N	N	40
	TTM plus 30%	$ 50,228,398	-	N	N	N	24
	TTM plus 50%	$ 50,228,398	-	N	N	N	45
6_7	TTM less 50%	$ 4,766,144,720	$ 40,396,634	Y	N	Y	60
	TTM less 30%	$ 4,763,283,833	$ 37,535,747	Y	N	Y	19
	TTM less 10%	$ 4,725,748,086	-	N	N	N	10
	TTM plus 10%	$ 4,725,748,086	-	N	N	N	21
	TTM plus 30%	$ 4,553,391,578	$(172,356,508)	Y	Y	Y	23
	TTM plus 50%	$ 4,553,391,578	$(172,356,508)	Y	Y	Y	13

This analysis shows that it is inaccurate to state that the model will not change until TTM values are reduced by 30%. Since the product design only changed for component 1 in that sensitivity analysis run, it can be deduced that the same results would be obtained when the TTM values are reduced by 17%. At that point, the TTM value for component 1, alternative 1 is reduced from 600 to 498. It falls below the 50% threshold value (as period length is 1000 in this case) and then it is optimal to select component 1 and the same results are obtained as in the 30% reduction case. Regardless, 17% still allows for a large margin of error in TTM parameter estimation.

The supplier reliability models appear to be more sensitive to changes in the parameter values. In several of the models, increasing the values by just 1% caused model results to change. If a company obtained the results in data set 4_6, they could analyze different options generated from different sensitivity analysis runs. Then they can take into consideration their risk threshold and select the supply chain design that works best for their company. Or, the company may decide to invest more time and money into determining more realistic supplier probability values so that they have a more accurate prediction for overall profitability.

Table 22. Supplier Reliability (Individual Supplier Probabilities) Sensitivity Analysis Results

Data Set	Parameter Change	Objective	Delta from Original Srel Obj	Change from Original Case			Run Time (sec)
				Product Design	Price	SC Design	
4_6	Srel less 10%	$ 108,183,449	$(24,676,951)	Y	N	Y	30
	Srel less 5%	$ 110,067,988	$(22,792,412)	Y	N	Y	22
	Srel less 1%	$ 131,600,630	$(1,259,770)	N	Y	Y	191
	Srel plus 1%	$ 134,309,569	$ 1,449,169	N	N	Y	164
	Srel plus 5%	$ 140,417,976	$ 7,557,576	N	N	Y	112
	Srel plus 10%	$ 148,832,800	$ 15,972,400	N	N	Y	89
5_5	Srel less 10%	$ 52,393,940	$ (435,175)	N	N	Y	38
	Srel less 5%	$ 52,819,430	$ (9,685)	N	N	Y	48
	Srel less 1%	$ 52,829,115	-	N	N	N	35
	Srel plus 1%	$ 52,829,115	-	N	N	N	50
	Srel plus 5%	$ 52,829,115	-	N	N	N	28
	Srel plus 10%	$ 52,829,115	-	N	N	N	23
6_7	Srel less 10%	$ 4,287,137,787	$(203,697,694)	Y	N	Y	18
	Srel less 5%	$ 4,431,996,319	$(58,839,162)	Y	N	Y	18
	Srel less 1%	$ 4,482,206,283	$ (8,629,198)	N	N	Y	20
	Srel plus 1%	$ 4,501,025,407	$ 10,189,926	N	N	Y	15
	Srel plus 5%	$ 4,526,515,594	$ 35,680,113	N	N	Y	15
	Srel plus 10%	$ 4,543,713,309	$ 52,877,828	N	N	Y	35

Table 22 shows that in many cases, the supply chain design changes, but the product design does not. When altering the supplier reliability values, the selection of some originally selected suppliers becomes infeasible. Usually, as long as an alternative supplier is available to supply the originally selected design then profitability remains highest if the original product design is unchanged. In the cases where product design and supply chain design are both changed, the original supplier(s) are no longer feasible and the only alternative is to switch to a different product design.

Table 23. Supplier Reliability (Overall Threshold Probability) Sensitivity Analysis Results

Data Set	Parameter Change	Objective	Delta from Original Srel Obj	Change from Original Case			Run Time (sec)
				Product Design	Price	SC Design	
4_6	Srel Γ less 10%	$ 158,115,456	$ 25,255,056	N	N	Y	21
	Srel Γ less 5%	$ 158,115,456	$ 25,255,056	N	N	Y	31
	Srel Γ plus 5%	-	no feasible solution	-	-	-	-
	Srel Γ plus 10%	-	no feasible solution	-	-	-	-
5_5	Srel Γ less 10%	$ 52,829,115	-	N	N	N	43
	Srel Γ less 5%	$ 52,829,115	-	N	N	N	16
	Srel Γ plus 5%	$ 45,480,697	$ (7,348,418)	Y	N	Y	157
	Srel Γ plus 10%	$ 28,130,588	$ (24,698,527)	Y	N	Y	2
6_7	Srel Γ less 10%	$ 4,766,054,813	$ 275,219,331	Y	Y	Y	41
	Srel Γ less 5%	$ 4,766,144,720	$ 275,309,238	Y	Y	Y	49
	Srel Γ plus 5%	-	no feasible solution	-	-	-	-
	Srel Γ plus 10%	-	no feasible solution	-	-	-	-

Table 23 shows the sensitivity analysis that was conducted on the overall desired supplier probability level of all components, (Γ). This parameter is also sensitive to change. However it can usually be determined with a high degree of certainty. In other words, if the decision maker's goal is to have 95% on-time delivery from suppliers, then $\Gamma = 0.95$. In Table 23, the initial Γ values were 0.90 for data set 4_6, 0.80 for 5_5 and 0.90 for 6_7. A decision maker using the model can adjust the Γ value to see how expensive it is to have a higher threshold level and based on the results choose the appropriate Γ value for the given context.

5.3 HYBRID MIP/SIMULATION MODEL ANALYSIS

The simulation model was created to analyze the capacity and market/demand risks. A solution procedure was created to facilitate this analysis which integrates the MIP and simulation models, as set forth in Section 4.4. Recall, this analysis allows the decision maker to determine the best risk mitigation plan, such as implementing a backup plan immediately or "wait to see" if capacity decreases or demand increases, then implement a backup plan.

It was hypothesized that the best risk mitigation approach is dependent on the data set, the level of demand increase or capacity decrease, or a combination of both factors. In other words, if a data set has product design and supply chain options with similar costs and supplier reliability values, then the "wait and see" strategy might perform well. The theory is that the costs of switching to a new design will be less than the costs of starting with a suboptimal supply chain. However, in the cases where the costs and supplier reliability values are different, the opposite would be true. On the other hand, the optimal risk mitigation strategy might only be dependent on the percentage of demand increase or percentage of capacity decrease, or some combination of these factors. A Design-of-Experiments (DOE) approach was employed to test this hypothesis.

5.3.1 Experimental Design

The purpose of the designed experiment was to test key model factors that were hypothesized to influence the response, namely profit. The factors analyzed in the designed experiment were:

1. Strategic Exposure Risk Limit
2. Switch Costs
3. Supply Chain Network Costs
4. Unit Manufacturing and Unit Transportation Costs
5. Supplier Reliability
6. Risk Mitigation Strategy
7. Percent Change in Demand/Capacity

The first five factors were selected so that many different experimental treatments could be created to represent different types of data sets. This facilitated analysis of the effect that the data set has on the risk mitigation strategy. The risk mitigation strategy and percent change of demand/capacity factors were included to analyze the differences between the strategies and the effect that different levels of capacity or demand change has on the profit.

Strategic exposure risk was defined in Section 4.2.2. The strategic exposure risk limit is the factor used to specify whether a single sourcing or dual sourcing strategy should be used for each component. If dual sourcing is required, then this factor (η) indicates the maximum percentage of total product that any supplier can provide. This factor was hypothesized to greatly impact profit, because single sourcing versus dual sourcing can completely change the supply chain, costs and overall system performance. The two levels of this factor analyzed were high and low. The high cases are those when $\eta = 1$, which is a single sourcing scenario. Low cases are those where $\eta < 1$, indicating the requirement of dual sourcing.

Switch costs are defined in Section 4.2.1. These costs are incurred if the design or supply chain changes for any component from one time period to the next. This factor was thought to have an impact on profit, because if switch costs are small then the model has more flexibility to change to different designs that might improve profitability. However, if switch costs are high, then it might cost too much to make the change. The two different levels analyzed for this factor are high and low.

Supply chain network costs are the fixed supply chain network costs between two suppliers. The unit manufacturing and unit transportation costs are the costs incurred on each unit for production and transportation. These costs were all believed to have a high impact on profit. The two levels of supply chain network costs analyzed were high and low. Unit manufacturing and transportation costs were analyzed together at two levels – similar and different. The similar cases are cases where most of the design and supplier alternatives have similar unit costs. Cases that are different have more variability between the options.

Supplier reliability is defined in Section 4.2.2. This factor is specified for each supplier to indicate the probability that quality product will be delivered on-time and in the quantity that was ordered. The two levels of this factor were similar and different. The similar cases are those in which the reliability values are similar between most suppliers. In the alternative case, more variability exists between the supplier reliability values.

The risk mitigation strategy factor is analyzed at three levels for demand risk and three levels for capacity risk. These levels are the possible mitigation strategies for each risk. Demand risk mitigation strategies include A (assume definite demand increase, reoptimize on day 1), B (wait and see if demand will increase, reoptimize on day 100), and C (wait and see if demand will increase, reoptimize on day 100, but only use original suppliers). Capacity risk mitigation strategies include A (do not use risky supplier), B (assume definite capacity issue, reoptimize on day 1), and C (wait and see if capacity issue, reoptimize on day 100).

The final factor in the experiment is percent change of demand or capacity. This factor is also analyzed at three levels – 10%, 20% and 30% change. The purpose of this factor is to determine if the significance of the demand increase or capacity decrease affects the profitability of each risk mitigation strategy.

The first five factors were each studied at two different levels, and the final two factors were each studied at three different levels, for a total of 288 treatments. A summary of problem treatments is shown in Table 24.

Table 24. Summary of Treatment Combinations for the Designed Experiment

Demand/Capacity Risk Mitigation Strategy

% Change in Demand/Capacity

Strategic Exposure Risk Limit	Switch Costs	S.C. Network Costs	Unit Costs	Supplier Reliability	A			B			C		
					10	20	30	10	20	30	10	20	30
H	H	H	D	D									
				S									
			S	D									
				S									
		L	D	D									
				S									
			S	D									
				S									
	L	H	D	D									
				S									
			S	D									
				S									
		L	D	D									
				S									
			S	D									
				S									
L	H	H	D	D									
				S									
			S	D									
				S									
		L	D	D									
				S									
			S	D									
				S									
	L	H	D	D									
				S									
			S	D									
				S									
		L	D	D									
				S									
			S	D									
				S									

The experiment was run with data sets 5_5 and 6_7. For each data set, capacity risk and demand risk were analyzed separately, so four experiments were completed. Twenty simulation replications were run for the data set 5_5 experiments and ten simulation replications were run for the data set 6_7 experiments. The number of simulation replications was determined by running 100 replications of a few problem treatments from each data set. The sample data was normally distributed so the following formula was used to determine the appropriate number of simulation replications to run.

$$n = \left(2z_{\alpha/2} \times \frac{\sigma}{L}\right)^2 \tag{5.1}$$

where L is the desired confidence interval length (Hogg & Ledolter, 2010). For both data sets, a 95% confidence interval with a length (L) of approximately 5% of the mean was desired. This resulted in n = 10 replications for data set 6_7, and n = 20 replications for data set 5_5.

5.3.2 Statistical Analysis of Designed Experiment Results

CPLEX 12.2 was used to solve the MIP and ARENA 12.0 was used to execute the simulations. The results of the designed experiment can be found in Appendix J. It appears from the data in Appendix J that the cases where a backup plan is implemented immediately always have greater profitability than the "wait-and-see" approaches. However, it is not clear from the table which risk mitigation strategy is optimal for different levels of demand increase or capacity decrease. To draw conclusions about the differences between the risk mitigation options, statistical analysis tools were used. The goal of the analysis was to determine if there are any statistically significant differences in profit for the risk mitigation strategies at each demand increase or capacity decrease level.

The first step was to test the data to determine if the response variable, profit, was normally distributed. The Kolmogorov-Smirnov test is a common test used to test for normality. This test was performed on the data using SPSS software and all factors failed the statistical test. Therefore, it could not be assumed that the data are normally distributed.

If data are normally distributed, then standard Analysis of Variance (ANOVA) tests can be used to determine which factors contribute significantly to variability in the response of profit. If it is not, then a transformation can usually be applied to transform the data to a normal distribution. In this analysis, many different transformations were considered, including several power transformations and a logarithmic transformation. None of the transformations worked, so non-parametric testing was used.

The significance of the first five factors were tested using the Mann-Whitney test. This test is appropriate because these factors only have two different levels. The Kruskal-Wallis test was used to test the risk mitigation strategy and percent change in demand/capacity factors. This test is appropriate for these factors because they each have three different levels. The null hypothesis of the Mann-Whitney test and Kruskal-Wallis test is that the samples come from populations with identical locations. In other words, the mean ranks of samples from the populations are expected to be the same. If the test indicates that there is a difference and rejects the null hypothesis, then a post-hoc test must be done to determine which of the levels are actually different from one another. The post-hoc test used for this analysis is based on the Mann-Whitney *U*-statistic (Sokal & Rohlf, 1995) and requires samples sizes greater than 8. The *U*-statistic is calculated in SPSS and is compared to the following critical value for *U*,

$$U_{\alpha(a,n)} = \frac{n^2}{2} + Q_{\alpha(a,n)} n \sqrt{\frac{2n+1}{24}} \qquad (5.2)$$

where $Q_{\alpha(a,n)}$ is from the Studentized Range Distribution and $n = \frac{2}{\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}$. If U is greater than the critical value, then the pairwise comparison is significant. A detailed example of this calculation is contained in Appendix L. A summary of the significance testing results for data sets 5_5 and 6_7 is shown in Table 25 and Table 26, respectively.

Table 25. Data Set 5_5 Statistical Analysis Results

	Capacity Risk Analysis		Demand Risk Analysis	
Factor	Test Result, $\alpha = 0.05$	Post Hoc Analysis, $\alpha = 0.05$	Test Result, $\alpha = 0.05$	Post Hoc Analysis, $\alpha = 0.05$
Strategic Exposure Risk Limit	Reject H_0, $p = 0.000$	N/A	Reject H_0, $p = 0.000$	N/A
Switch Costs	Reject H_0, $p = 0.000$	N/A	Reject H_0, $p = 0.000$	N/A
Unit Mfg. and Unit Transp. Costs	Reject H_0, $p = 0.000$	N/A	Reject H_0, $p = 0.000$	N/A
Supplier Reliability	Reject H_0, $p = 0.000$	N/A	Reject H_0, $p = 0.000$	N/A
Risk Mitigation Strategy	Reject H_0, $p = 0.000$	B & C same, A different	Fail to Reject H_0, $p = 0.155$	N/A
Percent Change in Demand/Capacity	Reject H_0, $p = 0.000$	70% & 80% same, 80% & 90% same	Reject H_0, $p = 0.000$	10% different, 20% & 30% same

Table 26. Data Set 6_7 Statistical Analysis Results

	Capacity Risk Analysis		Demand Risk Analysis	
Factor	Test Result, $\alpha = 0.05$	Post Hoc Analysis, $\alpha = 0.05$	Test Result, $\alpha = 0.05$	Post Hoc Analysis, $\alpha = 0.05$
Strategic Exposure Risk Limit	Fail to Reject H_0, $p = 0.623$	N/A	Fail to Reject H_0, $p = 0.138$	N/A
Switch Costs	Reject H_0, $p = 0.000$	N/A	Reject H_0, $p = 0.000$	N/A
S.C. Network Costs	Reject H_0, $p = 0.001$	N/A	Reject H_0, $p = 0.003$	N/A
Unit Mfg. and Unit Transp. Costs	Reject H_0, $p = 0.000$	N/A	Reject H_0, $p = 0.000$	N/A
Supplier Reliability	Fail to Reject H_0, $p = 0.698$	N/A	Fail to Reject H_0, $p = 0.290$	N/A
Risk Mitigation Strategy	Reject H_0, $p = 0.000$	B & C same, A different	Reject H_0, $p = 0.000$	A & B same, C different
Percent Change in Demand/Capacity	Reject H_0, $p = 0.000$	All different from one another	Reject H_0, $p = 0.000$	All different from one another

The results show that all of the factors are significant except for demand risk mitigation strategy, with data set 5_5. All factors except for strategic exposure risk limit and supplier reliability are significant with data set 6_7. This shows that the significance of the factors is dependent on the data set.

Strategic exposure risk limit was not significant in data set 6_7, which indicates that single sourcing versus dual sourcing gives statistically equivalent results for that data set. This is somewhat surprising but may be a result of the particular data values found in data set 6_7. Strategic exposure risk limit was significant in the 5_5 data set. Switch costs are significant in both data sets which is expected since higher switch costs would be expected to result in higher overall supply chain costs. This also confirms that this factor was important to add to the model. Supply chain network costs are significant in data set 6_7. This factor was removed from the data set 5_5 experiment. The reasons for this are discussed in Section 5.3.1. Unit manufacturing and unit transportation costs were significant in both data sets, which indicates that this factor always contributes significantly to variability in profit. The precise magnitude of the impact of having similar or different unit manufacturing and unit transportation costs will vary with the specific problem instance data. Supplier reliability was not significant in data set 6_7. For this data set when reliability levels of suppliers were similar versus different, the profitability was not affected. Again, the impact of having similar or different supplier reliabilities will depend on the problem instance and if the supplier with the best cost and lead time characteristics turns out to have poor reliability. Risk mitigation strategy was significant for all cases, except for the demand analysis in data set 5_5. This indicates that all three demand risk mitigation strategies for this data set are statistically equivalent. The percent change in demand/capacity was significant in all cases. Therefore, if the decision maker can make an estimate of how much demand or capacity fluctuation they expect, this will help them to make a better decision regarding a risk mitigation plan.

In general it is shown that many different factors contribute significantly to profitability. To draw conclusions about the best risk mitigation plan for these two data sets, further analysis was necessary. A limitation of non-parametric testing, compared to ANOVA is that interactions between the model factors cannot be tested. To overcome this, the interaction between the risk mitigation strategy and percent change in demand/capacity factors was analyzed by creating the groups of data shown in Table 27 and running the Kruskall-Wallis test on each group. The results of all tests are summarized in Table 28 and Table 29.

Table 27. Data Groupings

Group	Data Included
Demand Mitigation Strategy A	Results for the respective demand mitigation strategy at 0%, 10%, 20% and 30% demand increase levels.
Demand Mitigation Strategy B	
Demand Mitigation Strategy C	
10% Demand Increase	Results for risk mitigation strategy A, B and C at respective demand increase level.
20% Demand Increase	
30% Demand Increase	
Capacity Mitigation Strategy A	Results for not using the risky supplier (i.e. 0% capacity level only, so no statistical analysis necessary).
Capacity Mitigation Strategy B	Results for the respective capacity mitigation strategy at 70%, 80%, 90% and 100% capacity levels.
Capacity Mitigation Strategy C	
70% Capacity Level	Results for risk mitigation strategy A, B and C at respective capacity level.
80% Capacity Level	
90% Capacity Level	

Table 28. Data Set 5_5 Interactions Testing Results

Factor	Kruskal-Wallace Test, $\alpha = 0.05$	Post Hoc Analysis, $\alpha = 0.05$
Demand Mitigation Strategy A	Reject H_0, p = 0.000	0% & 10% same, 10% & 20% same, 20% & 30% same
Demand Mitigation Strategy B	Reject H_0, p = 0.000	0% & 10% same, 10% & 20% same, 20% & 30% same
Demand Mitigation Strategy C	Reject H_0, p = 0.005	0%, 10% & 20% same, 10%, 20% & 30% same,
10% Demand Increase	Fail to Reject H_0, p = 0.745	N/A
20% Demand Increase	Fail to Reject H_0, p = 0.479	N/A
30% Demand Increase	Fail to Reject H_0, p = 0.402	N/A
Capacity Mitigation Strategy B	Reject H_0, p = 0.000	70% & 80% same, 80% & 90% same, 90% & 100% same
Capacity Mitigation Strategy C	Fail to Reject H_0, p = 0.718	N/A
70% Capacity Level	Reject H_0, p = 0.000	All different from one another
80% Capacity Level	Reject H_0, p = 0.000	All different from one another
90% Capacity Level	Reject H_0, p = 0.000	All different from one another

Table 29. Data Set 6_7 Interactions Testing Results

Group	Kruskal-Wallace Test, $\alpha = 0.05$	Post Hoc Analysis, $\alpha = 0.05$
Demand Mitigation Strategy A	Reject H_0, p = 0.000	All different
Demand Mitigation Strategy B	Reject H_0, p = 0.000	All different
Demand Mitigation Strategy C	Reject H_0, p = 0.000	All different
10% Demand Increase	Reject H_0, p = 0.000	A & B same, C different
20% Demand Increase	Reject H_0, p = 0.000	A & B same, C different
30% Demand Increase	Reject H_0, p = 0.000	A & B same, C different
Capacity Mitigation Strategy B	Reject H_0, p = 0.000	All different
Capacity Mitigation Strategy C	Reject H_0, p = 0.000	All different
70% Capacity Level	Reject H_0, p = 0.000	B & C same, A different
80% Capacity Level	Reject H_0, p = 0.000	B & C same, A different
90% Capacity Level	Reject H_0, p = 0.000	B & C same, A different

These tables show that different results are obtained for the two different data sets. This shows that the model is dependent on the data and that risk mitigation strategies should be customized to each particular data set that is being analyzed.

For data set 5_5, the following conclusions can be drawn. If there is a reasonable likelihood that demand may increase by less than 10%, then it is acceptable to do nothing. All three risk mitigation strategies perform the same at the 0% and 10% demand increase scenarios. Therefore, it can be assumed that with at most a 10% demand increase, it is not worth implementing a backup plan. However, if demand is expected to increase more than 10%, then a backup plan should be implemented. All three strategies were found to perform the same statistically, so the decision maker should select the strategy with which they are most comfortable. The capacity analysis on this data set showed that all three of the risk mitigation strategies are different from one another. Regardless of the percentage of capacity lost, all strategies are statistically different. It can be seen in Appendix J that strategy C was infeasible for the majority of the treatments, so this strategy is not an option in most cases. Profitability of strategy B appears to be higher than profitability of strategy A, so for this data set it is recommended that strategy B should be used.

In data set 6_7, the conclusions are slightly different. When demand increases, the post-hoc tests showed that the risk mitigation plans give statistically different results at each level of demand increase – 0%, 10%, 20% and 30%. Therefore, it is not advised to take a “do nothing” approach if less than a 10% demand increase is expected, as was the recommendation for data set 5_5. Demand risk mitigation strategies A and B were found to perform the same, but C is different. Therefore, if any demand increase is expected to occur, either risk mitigation strategy A or B should be implemented, as they appear to perform better than strategy C. Although, in some situations strategy C might be the only feasible option and must be used. In this strategy, only the original set of suppliers can be used to fill the additional demand, due to contractual obligations or some other restriction. The recommendation when a capacity decrease is expected at the risky supplier is to use either strategy B or C. Regardless of the percentage of capacity lost, strategies B and C perform the same statistically, but strategy A is different. Strategies B and C appear to perform better than A, so the decision maker should select their preference of those two strategies.

One general conclusion can also be drawn about risk mitigation strategies for both data sets. Capacity decrease risk mitigation strategy A appears to always be less profitable than the other strategies. This was expected, as it eliminates the use of the risky supplier completely. In most cases it is still be better to use the risky supplier even with lower capacity. However, the decision maker should use their judgment to determine if there are other factors that affect this decision. For instance, the indirect shortage costs of working with the risky supplier might be expected to be significantly larger than those estimated in the model. Recall that shortage costs were estimated to be twelve times the unit inventory holding costs on a daily basis. However, shortage costs for different components might actually be larger or smaller than this estimate.

5.3.1 Additional Insights from the Designed Experiment

An observation gathered from the data set 6_7 experiment, which was executed first, was that the supply chain network costs did not impact the solution. In other words, the exact same product designs and supply chains were selected for the cases where the factor was high and low. The only difference between the solutions was in the overall profitability. This was shown when the significance of this factor was tested. The reason for this is because the cases with high supply chain network costs had higher costs. For example, problem instance HHHDD (high supply chain network costs) was found to have the same optimal design and supply chain as problem instance HHLDD (low supply chain network costs). The only difference between the two problem instances was that their profits differed by $34,960,000, which was the difference in their supply chain network costs. When the experiment was carried out for data set 5_5, this factor was removed from the experimental design, because its significance was already understood.

The second observation from data set 6_7 was gathered from the simulation results. In the demand analysis, Case A (re-optimization implemented on day 1) should be more profitable than Case B (wait-and-see, then re-optimize on day 100), which should be more profitable than

Case C (wait-and-see, then re-optimize on day 100, but only use original set of suppliers). Also, the 30% demand increase case should be more profitable than 20% which should be more profitable than 10%. In the capacity analysis, Case B (re-optimization implemented on day 1) should be more profitable than Case C (wait and see, then re-optimize on day 100) and both cases should be more profitable than Case A (do not use the risky supplier). Additionally, the 90% capacity case should perform better than the 80% case which should perform better than the 70% case. This was explained in Section 4.4. It was observed that some of the simulation results did not follow these trends. These instances are identified in Appendix J by gray shading.

For each of these instances where unexpected results were obtained, the simulations were re-run with 50 replications each. (Recall that originally, the simulations were run with only 10 replications each for data set 6_7.) The purpose of running more replications was to determine if the cause of these uncharacteristic results was due to the inherent variance of the simulation. The averages and standard deviations of 10, 20, 30, 40 and 50 replications each are shown in Appendix K. It is shown that the standard deviation between replications was reduced as more replications were run. These results are summarized in Table 30. They show that the unexpected results were in fact caused by the inherent variation of the simulation.

Table 30. Data Set 6_7 Uncharacteristic Results Summary

Data Set	Cases with Uncharacteristic Results	Number of Replications Until Results Show Expected Trends
HHHSD	Capacity – Case B	11
HHHSD	Demand – Cases A & B	32
HHLSD	Demand – Cases A & B	31
HLHSS	Demand – Cases A & B	29
HLLSS	Demand – Cases A & B	29

Data set 5_5 also had some of these uncharacteristic results. Some of the inconsistencies were also caused by the inherent variability within the simulation, because they stabilized after additional simulation runs. This analysis is also shown in Appendix K and is summarized in Table 31.

Table 31. Data Set 5_5 Uncharacteristic Results Summary

Data Set	Cases with Uncharacteristic Results	Number of Replications Until Results Show Expected Trends
HHDD	Capacity – Case B	36
HHSS	Capacity – Case B	22
HLDD	Capacity – Case B	31
LHDD	Demand – Case A	39
LHSD	Demand – Case A	32
LLDS	Demand – Case A	30
LLSS	Demand – Case A	22
HHSD	Demand – Case C	23
LLDD	Demand – Case C	30

Some of the cases, however, did not stabilize after additional simulation runs. These were problem instances HHDS, HHSD, HLSD, HLSS and LLDD in the capacity Case B analysis, and HLDD, HLSS and LHDD in the demand Case C analysis. For these instances, it was determined that the root cause of the behavior was the production utilization levels for some components. Data set HHDS will be used to illustrate this phenomenon. In this problem instance, the 70% capacity case performed better than the 80% case. This is the opposite of what was expected to occur. The simulation results from these cases are shown in Table 32.

Table 32. Data Set HHDS Simulation Results (avg. of 20 replications)

	Capacity Percent Reduction of Risky Supplier		Percent Change Between Cases
	70%	80%	
Revenue	$ 85,575,410	$ 88,651,290	3.5%
Manufacturing Costs	$ 21,764,775	$ 22,396,099	2.8%
Transportation Costs	$ 8,104,506	$ 8,312,301	2.5%
Inventory Holding Costs	$ 9,966,487	$ 10,256,075	2.8%
Shortage Costs	$ 7,943,036	$ 11,209,510	29.1%
SC Network Costs	$ 15,070,000	$ 15,070,000	–
Switch Costs	–	–	–
Profit	$ 22,726,606	$ 21,407,304	-6.2%

It can be deduced from the table that the amount of shortages in the 80% case was disproportionally higher than in the 70% case. This appears to be the cause of the inconsistent profit between the two cases. Testing confirmed that component 4 in the 80% case had more shortages in time periods 2 and 3, than the 70% case. This is shown in Appendix K. Next, the supply chain for component 4 was analyzed which is shown in Table 33.

Table 33. Supply Chain Data for Time Periods 2 & 3

Time Period	Component	Supplier	70%			80%		
			Build	Capacity	Utilization	Build	Capacity	Utilization
2	1	1	560,000	2,000,000	0.28	600,000	2,000,000	0.30
	2	1	200,000	200,000	1.00	200,000	200,000	1.00
	2	3	360,000	500,000	0.72	400,000	500,000	0.80
	3	4	140,000	600,000	0.23	120,000	600,000	0.20
	3	5	420,000	420,000	1.00	480,000	480,000	1.00
	4	2	560,000	600,000	0.93	600,000	600,000	1.00
	5	5	560,000	560,000	1.00	600,000	640,000	0.94
3	1	1	560,000	2,000,000	0.28	600,000	2,000,000	0.30
	2	1	200,000	200,000	1.00	200,000	200,000	1.00
	2	3	360,000	500,000	0.72	400,000	500,000	0.80
	3	4	560,000	600,000	0.93	600,000	600,000	1.00
	4	2	560,000	600,000	0.93	600,000	600,000	1.00
	5	5	560,000	560,000	1.00	600,000	640,000	0.94

It is observed that supplier 2 builds component 4 at 100% capacity utilization in the 80% case but only 93% capacity utilization in the 70% case. It was then presumed that queuing effects resulting from the 100% utilization were causing the 80% case to perform worse and incur these significant shortage costs. This was confirmed by increasing the capacity at supplier 2 in the 80% case and observing the new objective values. The results are summarized in Table 34.

Table 34. 80% Case with Increased Supplier 2 Capacity

Supplier 2 Capacity	Supplier 2 Capacity Utilization	Profit (Average of 20 replications)
600,000	1.00	$ 21,407,304
610,000	0.98	$ 22,745,101
620,000	0.97	$ 23,241,086
630,000	0.95	$23,895,109

When the capacity is increased to 620,000 units the average profitability of the 80% case exceeds the 70% case. Recall from Table 32, that the profitability in the 70% case was $22,726,606. It should be noted that Table 33 also shows that component 3 also had the same queuing effects present in time period 3, which also contributed to the increased shortage costs.

The same type of queuing effects were confirmed to occur in the other nonconforming problem instances listed previously. The identification of these queuing effects was a valuable outcome of the experiment. It showed that the simulation model is important to use in addition to the MIP model to gain a true understanding of how the solution will perform under realistic conditions. In some cases, the MIP identifies a solution as optimal, but when factors such as capacity utilization and stochastic demand are taken into consideration, the simulation might show that it is actually suboptimal. Statistical analysis was used to identify trends about the differences between the risk mitigation strategies which are described in the next section.

This analysis has shown that the overall solution obtained from the hybrid MIP/simulation model takes into consideration the five risk factors. The MIP simultaneously considers TTM, supplier reliability and strategic exposure risk while also finding the optimal product design and supply chain. Then the simulation is used to analyze capacity and market/demand risks to give the decision maker several different options to use as risk mitigation strategies. The final solution is ultimately determined by the decision maker based on their judgment and risk threshold for capacity decrease and risk of increased demand.

6.0 CONCLUSIONS AND FUTURE RESAERCH

6.1 ANSWERES TO RESEARCH QUESTIONS

The objective of this research was to answer the following research questions:

1. *Which risks to the supply chain and NPD are the most critical for companies to consider?*

    a. *Which events have the highest likelihood of occurrence and the most impact to the organization if they are to occur?*

    b. *Which risks should be included in models used to analyze NPD and supply chain design decisions?*

The analysis and identification of critical risk factors was not limited to one industry; it was broad enough to give a general set of risk factors which are important to several industry types. Observations from the literature were used to identify potential risk factors and then a survey of industry experts was used to identify candidate risk factors. Then a statistical analysis was completed to select a set of critical risk factors related to NPD and supply chain design.

The analysis suggested that the risks most critical for companies to consider in the supply chain are (1) inventory management / stock out risks, (2) strategic exposure risk, (3) market/demand risks, (4) capacity risk and (5) supplier reliability. In NPD, the top risks found are (1) organizational and project management risks (including TTM risks), (2) commercial viability risks, (3) marketing proficiency, (4) supply chain and sourcing risks, and (5) financial risk.

Although these top ten risks were all found to be critical for companies to consider, they were not all included in the DFSC risk model. Some were overlapping and including them all would have been redundant. Also, some were not within the scope of this research. The DFSC and risk model developed was a high-level strategic planning model and some of these risk factors are better suited to a more detailed, daily planning model. The risks that were included in the DFSC risk model were strategic exposure risk, market/demand risks, capacity risk, supplier reliability and TTM risk.

It is interesting to note that risk factors that currently seem to be popular, such as international terrorism, natural disasters and outsourcing risks did not appear in the list of critical risk factors. This is likely due to the fact that those types of risks have a low likelihood of occurrence and companies find it more critical to focus on risks that impose daily disruptions to the supply chain.

2. *What is the best approach for incorporating the critical risks in a DFSC Mixed Integer Programming (MIP) framework?*

    a. *Is it possible to model all of the critical risk factors in the existing Gokhan MIP framework or are risks better modeled using some other tool?*

    b. *If another tool is necessary, what is the best way to use the MIP and the new tool together?*

It was found that a hybrid approach was best for modeling risks in a DFSC model. The hybrid model is a combination of extensions to Gokhan's DFSC MIP model framework and a new simulation model. The MIP obtains the optimal product design and supply chain and was found to be an appropriate model for simultaneously analyzing TTM risks, supplier reliability and strategic exposure risk. Then the solution found in the MIP was tested in the simulation under realistic conditions, such as stochastic demand, stochastic lead times and penalties for inventory shortages. Risk mitigation strategies for capacity and demand risks were also analyzed in the simulation. The integration of the two models was achieved through the solution procedure explained in Section 4.4.

This comprehensive model for simultaneous DFSC decision making and risk analysis, is a major contribution to the DFSC knowledge base. Currently there are no DFSC models which also include risk modeling. A few of the models include a handful of risk factors, such as Lee and Sasser (1995), Arntzen (1995) and Graves and Willems (2005), but none include a comprehensive risk analysis and mitigation analysis. The integration of the two models through the solution procedure is also a contribution to the body of knowledge relate to hybrid modeling methods.

The hybrid MIP and simulation DFSC model was analyzed through an extensive designed experiment to identify trends related to risk mitigation strategies. This experiment showed that in some cases it was critical to use the simulation to capture stochastic production impacts, e.g., to determine how high utilization can affect the expected shortage costs for the supply chain and the subsequent impact on overall profitability. The experiment also showed that it is important to analyze risk when designing a new product and supply chain because the set of decisions that was optimal if risk was ignored can perform poorly when evaluated in a model that considers risks. Analysis of two different data sets also showed that the optimal risk mitigation strategy is data dependent. There are many different events that can impact the performance of the system. If they are not taken into consideration, it was shown through this analysis, that a company can make poor design and planning decisions.

In conclusion, the three main contributions from this research are: 1) The identification of a critical set of risk factors related to NPD and supply chain design. 2) Development of a DFSC and risk model using a hybrid MIP and simulation modeling methodology. 3) Analysis of data using the DFSC and risk model to draw conclusions about optimal risk mitigation strategies.

6.2 FUTURE RESEARCH

There are several different ways that this research can be expanded in future work. First, the industry survey that was used to select the critical risk factors was distributed to companies in many different industries so that a general model could be developed. However, it would be interesting to redistribute the survey to a large sample of companies from one industry and then develop a DFSC and risk model specific to that industry. This would have been especially useful to the company that assisted with the model development. They are in a highly regulated industry, and thus have specific needs. There are other industries that also have unique needs and could benefit from an industry-specific model.

Another extension is to model the supplier selection decision already in the DFSC risk model, in a more detailed manner. Currently the model is a strategic planning model and only selects suppliers and their optimal order quantities for each component. Optimal order policies and inventory strategies are not determined. However, the top supply chain risk identified through the industry survey was inventory management and stock out risks. The model can possibly be expanded to include these detailed decisions so that this critical risk is considered.

The model can also be expanded so that the market/demand risks are modeled more thoroughly. Currently commercial viability risks, marketing proficiency and financial risks are all modeled as an overall market/demand risk. However, many different extensions could be added to model the unique aspects of each of these critical risks.

The scope of this research was defined so that an efficient model could be built for the supplier selection decision and the decisions in the detailed design phase of NPD, as described in Section 1.2. A recommendation for future research is to expand the scope so that more NPD or supply chain design decisions could be taken into consideration. This was a piece of feedback that was gained from working with the small manufacturing company when developing the model. The company felt that the model would be more useful to firms in their industry if it included more of the supply chain network design decisions, such as facility location or transportation planning.

APPENDIX A

OBSERVATIONS FROM THE LITERATURE

Table 35. Risks Found in Literature

Type	Name	Description	Total Modeled	Sources
SC	Lead Time Variation Risk	Lead times on products fluctuate greatly.	13	(Vidal & Goetschalckx, 2000) (Tam & Tummala, 2001) (Liu & Hai, 2005) (Chou & Chang, 2008) (Gurmani & Shi, 2006) (Wu & Olsen, 2008) (Karpak et al., 1999) (Weber & Desai, 1996) (Liu et al., 2000) (Gaonkar & Viswanadham, 2004) (Kumar et al., 2004) (Kumar et al., 2006) (ElMaraghy and Majety, 2008)
SC	Supplier Reliability	Ability of supplier to provide quality product in a timely manner, provide customer service, have ample capacity, etc.	10	(Vidal & Goetschalckx, 2000) (Azaron et al., 2008) (Tam & Tummala, 2001) (Liu & Hai, 2005) (Kull & Talluri, 2008) (Lee, 2009) (Chou & Chang, 2008) (Weber & Desai, 1996) (Gaonkar & Viswanadham, 2004) (ElMaraghy and Majety, 2008)
SC	Quality Problems	Product (in-house or from supplier) does not meet quality standards.	10	(Liu & Hai, 2005) (Chou & Chang, 2008) (Karpak et al., 1999) (Weber & Desai, 1996) (Feng et al., 2001) (Kasilingam & Lee, 1996) (Ghodsypour & O'Brien, 2001) (Kumar et al., 2004) (Kumar et al., 2006) (ElMaraghy and Majety, 2008)
SC	Market/ Demand Risks	Changes in the market affect your demand or value - ex: customer(s) lose interest in product(s), seasonality, volatility of fads, customer(s) change orders, etc.	5	(Vidal & Goetschalckx, 2000) (Goetxchalckx et al., 2002) (Li & Kouvelis, 1999) (Kasilingam & Lee, 1996) (Gaonkar & Viswanadham, 2004)
SC	Exchange Rate Risk	Operations or an investment's value will be affected by changes in exchange rates.	5	(Huchzermeier & Cohen, 1996) (Vidal & Goetschalckx, 2000) (Goetschalckx et al., 2002) (Nembhard et al., 2005) (ElMaraghy and Majety, 2008)

Table 35. Risks Found in Literature (cont.)

Type	Name	Description	Total Modeled	Sources
SC	Capacity Risk	The inability of a system to produce a particular quantity of output in a particular time period.	3	(Lee, 2009) (Ghodsypour & O'Brien, 2001) (Gaonkar & Viswanadham, 2004)
SC	Financial Health of Suppliers	Supplier is at risk of bankruptcy.	3	(Liu & Hai, 2005) (Lee, 2009) (Gaonkar & Viswanadham, 2004)
SC	Manufacturing / Production Problems	Machine breakdowns, unavailability of plant, warehouse or office buildings.	2	(Tam & Tummala, 2001) (Gaonkar & Viswanadham, 2004)
SC	Natural Disasters	Hurricanes, floods, etc.	1	(Gaonkar & Viswanadham, 2004)
SC	International Terrorism	Risk that terrorism will occur and disrupt business or a suppliers business.	1	(Gaonkar & Viswanadham, 2004)
SC	Demand Forecast Risk	Forecasting errors.	1	(Gaonkar & Viswanadham, 2004)
SC	Transportation Risk	Delay or unavailability of either inbound or outbound transportation to move goods.	1	(Gaonkar & Viswanadham, 2004)
SC	Information Security Risks	Accidental or intentional disclosure to unauthorized persons, or unauthorized modifications or destruction	1	(Tam & Tummala, 2001)
SC	Strategic Exposure Risk	Over-reliant on a single or limited number of suppliers.	1	(ElMaraghy and Majety, 2008)
SC	Inventory Management / Stockout Risk	Risk that inventory will not be available due to stock-out because of poor management of materials, supplier deficiency, etc.	1	(Tam & Tummala, 2001)
SC	Development Risk	Difficulties transitioning to new parts, products, suppliers or processes.	1	(Tam & Tummala, 2001)
SC	Information Technology (IT) Failure	IT failure within your operation or another organization in the supply chain that disrupts the supply chain performance.	1	(Tam & Tummala, 2001)
SC	Information Distortion and Bullwhip Risks	Distortion of information leads to bullwhip risks, where the orders to the supplier tend to have larger fluctuations than sales to the customer.	0	
SC	Political Environment / Instability	Country experiences political turmoil which may affect a suppliers business - quality of product or timeliness of shipments, etc.	0	
SC	Key Staff Loss / Strikes	Strike, large number of retirees, layoffs, etc.	0	
SC	Outsourcing Risk	Any risk associated with the outsourcing of design or production - IP loss, lead time, quality, language barriers, etc.	0	
SC	Cash Flow Risks	Risk that you do not have a good flow of cash through your business - accounts receivable, accounts payable, loans, etc.	0	
SC	Infectious Disease	Bird flu, SARS, etc.	0	
SC	Technology Shift	Ex – Digital imaging has shifted market share away from film-based photography.	0	

Table 35. Risks Found in Literature (cont.)

Type	Name	Description	Total Modeled	Sources
SC	Brand Erosion	Ex – Firestone tires deemed defective, then the parent company Bridgestone suffered an 80% drop in net income in one year.	0	
SC	Environmental Requirements	Unforeseen environmental requirements negatively impact suppliers performance, ability to perform or costs.	0	
SC	Fraud	Fraudulent activity by a supplier or another organization in the supply chain.	0	
SC	Higher energy costs	Energy costs rise and cause you or your supplier's costs to rise.	0	
SC	Regulatory requirements	Unforeseen regulatory requirements negatively impact supplier's performance, ability to perform or costs.	0	
NPD	Product Technology Risk	New product fails to fulfill intended functions, assembled product fails to meet safety and technical requirements.	4	(Ahmadi & Wang, 1999) (Deyst, 2002) (Fine et al., 2005) (Raharjo et al., 2008)
NPD	Supply Chain and Sourcing Risks	Will suppliers meet required quality, capacity available to meet peak demands, financial position of each supplier is sound, etc.	2	(Germain et al., 2008) (Raharjo et al., 2008)
NPD	Organizational and Project Management Risks	Top management actively supports project, project goals and objectives are feasible, decision making process is effective, collaboration within project team is effective, required money, time and human resources will be available when needed.	1	(Ahmadi & Wang, 1999)
NPD	Time-to-Market Risk	Schedule risk.	1	(Wang & Lin, 2008)
NPD	Customer Acceptance Risks	Risk that product specifications will not meet consumer demands and standards, new product will not fit consumer habits or user conditions, and/or consumers will not feel they get good value for their money.	1	(Raharjo et al., 2008)
NPD	Financial Risk	Budget, loans and cash flow issues; correct pricing; building adequate sales, etc.	1	(Azaron et al., 2008)
NPD	Outsourcing Risk	Any risk associated with the outsourcing of design or production - IP loss, lead time, quality, language barriers, etc.	1	(Lonsdale, 1999)
NPD	Manufacturing Technology Risks	Raw materials available, production means not available, scale up potential is not possible, manufacturing efficiency standards will not be met.	1	(Raharjo et al., 2008)
NPD	Intellectual Property Risks	Risk that original know-how will not be protected, relevant patent issues not understood, trade mark registration potential unknown and not understood.	0	
NPD	Public Acceptance Risks	It is clearly understood who is responsible for the PR of the project, legal and political restrictions will be adequately anticipated.	0	

Table 35. Risks Found in Literature (cont.)

Type	Name	Description	Total Modeled	Sources
NPD	Market Research Risk	Data might not be accurate or outdated.	0	
NPD	Information Security Risks	Accidental or intentional disclosure to unauthorized persons, or unauthorized modifications or destruction	0	
NPD	Company Resources	Compatibility of firms resources with requirements of the project (capital, mfg facilities, man power).	0	
NPD	Market Competitiveness	Product will provide clear competitive advantage, introduction of new product will change existing market share positions.	0	
NPD	Marketing Proficiency	Proficiency of market development, market launch, market research, market startup, market testing.	0	
NPD	Internal/ External Communications	Coordination and cooperation with the firm and between firms.	0	
NPD	Customer Service Efficiency	Efficiency of mfg services, technical services, etc.	0	
NPD	Technological Exposure Risk	Over-reliant on a single or limited source of a product, process or technology.	0	
NPD	Product Family and Brand Positioning Risks	New product fails to achieve business strategy, new product fits with existing brand, brand image or has brand development potential.	0	
NPD	Legislation / Compliance Risk	Compliance with new standards; legal issues with competitors.	0	
NPD	Commercial Viability Risks	Risk that the market target is not clearly defined and agreed, estimated ROI will not meet companies standards, long term market potential is not to be expected.	0	

APPENDIX B

INDUSTRY SURVEY

Supply Chain and New Product Development Risk Survey

Thank you for participating in this survey. The results will be used to determine which supply chain and New Product Development (NPD) risk factors are most critical to consider during the design process.

All results will be kept anonymous and a summary of the results will be provided to your company.

The survey consists of **approximately 60 questions** and should take **15-20 minutes** to complete. You will be asked to rate the "likelihood of occurrence" and "impact of risk" for different risk factors. **When assessing these values it is preferable that you NOT focus on one particular product or project. Please think in general terms of your experiences on all projects and products related to supply chain and NPD.**

Supply Chain Knowledge Assessment

1. Your Company Name

[ ]

2. My years of experience in the Supply Chain field/area is:

- [ ] 0-5 years
- [ ] 5-10 years
- [ ] 10-15 years
- [ ] 15-20 years
- [ ] 20+ years

3. I would rate my knowledge pertaining to Supply Chain matters as:

- [ ] Excellent
- [ ] Good
- [ ] Fair
- [ ] Poor

Supply Chain Risk Factor Evaluations

(Page 1 of 2)

Directions:

1. For each risk please evaluate the likelihood that each risk would occur in your company and the associated impact that the risk would have on your company. **For example: The risk of a key supplier going out of business might have a low likelihood of occurrence, but a high impact if it were to occur.**

2. Only answer the questions which you feel comfortable answering. If you are unsure about a certain risk, please check the "unable to answer" field. If you feel that you are unable to adequately assess any of the Supply Chain risk factors, you may skip to the next page by clicking the Next button at the bottom of the page at any time.

3. A comment field is provided if you wish to clarify any responses. However, comments are not required.

Risk factors related to the manufacturing/production system and the suppliers:

1. Manufacturing / Production Problems:
Risk of machine breakdowns, plant, warehouse or office building unavailability or other issue(s) that would hinder production.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

2. Inventory Management / Stock Out Risk:
Risk of inventory stock-out due to poor management of materials, supplier deficiency, etc.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

3. Capacity Risk:
Risk that system is unable to produce a particular quantity of product(s) in a particular time period.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

4. Quality Problems:
Risk that product (in-house or from supplier) does not meet quality standards.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

5. Transportation Risk:
Risk that inbound or outbound transportation modes will be delayed or unavailable.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

6. Key Staff Loss / Strikes:
Risk of an event that will impact personnel resource availability. (Ex - strike, large number of retirees, lay offs, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

7. Supplier Reliability:
Risk that supplier is unable to provide quality product in a timely manner, has poor customer service, does not have ample capacity, etc.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

8. Financial Health of Suppliers:
Risk that supplier is facing or will face bankruptcy and/or cash flow issues.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

9. Lead Time Variation Risk:
Risk that lead times on product(s) will fluctuate greatly.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

10. Strategic Exposure Risk:
Risk of being over-reliant on a single or limited number of suppliers.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

11. Outsourcing Risk: Any risk associated with the outsourcing of *production/manufacturing* work. (Ex - Intellectual property loss, long lead time, import issues, poor quality, language barriers, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

12. Development Risk:
Risk that it will be difficult transitioning to new parts, products, suppliers or processes.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

13. Regulatory Requirements:
Unforeseen regulatory requirements negatively impact performance and/or costs within your company or a supply chain partner.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

14. Environmental Requirements:
Unforeseen environmental requirements negatively impact performance and/or costs within your company or a supply chain partner.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

Supply Chain Risk Factor Evaluations

(Page 2 of 2)

Directions:

1. For each risk please evaluate the likelihood that each risk would occur in your company and the associated impact that the risk would have on your company. **For example: The risk of a key supplier going out of business might have a low likelihood of occurrence, but a high impact if it were to occur.**

2. Only answer the questions which you feel comfortable answering. If you are unsure about a certain risk, please check the "unable to answer" field. If you feel that you are unable to adequately assess any of the Supply Chain risk factors, you may skip to the next page by clicking the Next button at the bottom of the page at any time.

3. A comment field is provided if you wish to clarify any responses. However, comments are not required.

Risk factors related to the market, information flow, costs and major catastrophes:

1. Market/Demand Risks:
Risk that a change in the market will affect demand. (Ex - customers lose interest in product, seasonality, volatility of fads, customers change orders, one-of-a-kind competitor will appear and seize market share, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

2. Technology Shift:
Risk that the market will shift to a new phase of technology before your company does. (Ex – film based photography shifted to digital imaging)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

3. Brand Erosion:
Risk that the reputation of a brand will be negatively perceived. (Ex – Company X's product deemed defective, then the parent company suffers an 80% drop in net income in one year.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

4. Demand Forecast Risk:
Risk that an error in forecast will cause a significantly inaccurate prediction of demand.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

5. Information Distortion and Bullwhip Risks:
Risk that a distortion of information will cause the bullwhip effect. The bullwhip effect is when the orders to the supplier tend to have larger fluctuations than customer sales.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

6. Information Security Risks:
Risk of accidental or intentional disclosure of sensitive information to unauthorized person(s) or unauthorized modifications or destruction of information.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

7. Information Technology (IT) Failure:
Risk that an IT failure within your company or another organization in the supply chain will disrupt supply chain performance.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

8. Exchange Rate Risk:
Risk of potential financial loss from an adverse change in exchange rates.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

9. Higher Energy Costs:
Risk that energy costs will rise.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

10. Cash Flow Risks:
Risk of poor flow of cash through company. (Ex - accounts receivable, accounts payable, loans, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Liklihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

11. International Terrorism:
Risk that a terrorist act will disrupt the operations of your company or another organization in the supply chain.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

12. Natural Disasters:
Risk that a natural phenomenon will disrupt the operations of your company or another organization in the supply chain. (Ex - hurricane, flood, earthquake, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

13. Infectious Disease:
Risk that a contagious disease will spread and disrupt the operations of your company or another organization in the supply chain. (Ex - bird flu, SARS, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

14. Political Environment / Instability:
Risk that a foreign country experiences political turmoil which would affect operations of any organization in the supply chain. (Ex - quality of product or timeliness of shipments, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

15. Fraud:
Risk that fraudulent activity by a supplier or another organization in the supply chain will disrupt supply chain performance.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

Supply chain risk factor evaluations are now complete and you are half-way finished with the survey! The remainder of the survey will focus on New Product Development.

New Product Development (NPD) Knowledge Assessment

1. My years of experience in the New Product Development (NPD) field/area is:

- 0-5 years
- 5-10 years
- 10-15 years
- 15-20 years
- 20+ years

2. I would rate my knowledge pertaining to New Product Development (NPD) as:

- Excellent
- Good
- Fair
- Poor

New Product Development (NPD) Risk Factor Evaluations

(Page 1 of 2)

Directions:

1. For each risk please evaluate the likelihood that each risk would occur in your company and the associated impact that risk would have on your company. **For example: The risk of a key product development staff member leaving the company might have a low likelihood of occurrence, but a high impact if it were to occur.**

2. Only answer the questions which you feel comfortable answering. If you are unsure about a certain risk, please check the "unable to answer" field. If you feel that you are unable to adequately assess any of the New Product Development factors, you may skip to the next page by clicking the Next button at the bottom of the page at any time.

3. A comment field is provided if you wish to clarify any responses. However, comments are not required.

Risk factors related to the design and the market:

1. Product Technology Risk:
Risk that a new product will not fulfill intended functions or will not meet safety and technical requirements.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

2. Technological Exposure Risk:
Risk of being over-reliant on a single process or technology.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

3. Legislation / Compliance Risk:
Risk that the product will not be compliant with standards, new legislation or regulations will arise that adversely affect the product, and/or that legal issues with competitor(s) will arise.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

4. Financial Risk:
Risk of incorrect pricing, and/or inability to build adequate sales (with respect to the new product).

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

5. Product Family and Brand Positioning Risks:
Risk that a new product will not help to achieve business strategy, will not fit with existing brand(s), and/or will not have brand image or brand development potential.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

6. Market Research Risk:
Risk that market research data will not be tested/measured accurately and/or adequately.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

7. Marketing Proficiency:
Risk that proficiency of market development, market launch, market research, market startup, and/or market testing will not be adequate.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

8. Time-to-Market Risk:
Risk that the new product development will take too long and cause late entry to the market.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

9. Market Competitiveness:
Risk that product will not provide clear competitive advantage or introduction of new product will not change existing market share positions.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

10. Commercial Viability Risks:
Risk that the market target will not be clearly defined and agreed upon, estimated ROI will not meet company standards, and/or long term market potential is not realized.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence	○	○	○	○	○
Impact of Risk	○	○	○	○	○

Comments:

11. Public Acceptance Risks:
Risk that public relations (PR) will not be successfully handled and/or legal and political restrictions will not be adequately anticipated.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

12. Customer Acceptance Risks:
Risk that product specifications will not meet consumer demands and standards, new product will not fit consumer habits or user conditions, and/or consumers will not feel they get good value for their money.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

New Product Development (NPD) Risk Factor Evaluations

(Page 2 of 2)

Directions:

1. For each risk please evaluate the likelihood that each risk would occur in your company and the associated impact that risk would have on your company. **For example: The risk of a key product development staff member leaving the company might have a low likelihood of occurrence, but a high impact if it were to occur.**

2. Only answer the questions which you feel comfortable answering. If you are unsure about a certain risk, please check the "unable to answer" field. If you feel that you are unable to adequately assess any of the New Product Development factors, you may skip to the next page by clicking the Next button at the bottom of the page at any time.

3. A comment field is provided if you wish to clarify any responses. However, comments are not required.

Risk factors related to project management, security and sourcing:

1. Organizational and Project Management Risks:
Risk that top management will not actively support project, project goals and objectives are not feasible, decision making process is not effective, and/or collaboration within project team is not effective.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

2. Company Resources:
Risk that company resources will not be compatible with requirements of the new product development project (capital, time, manufacturing facilities, and/or manpower).

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

3. Internal/ External Communications:
Risk that there will not be coordination and cooperation within the new product development (NPD) team.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

4. Intellectual Property Risks:
Risk that original know-how will not be protected, relevant patent issues will not be understood, and/or trade mark registration potential unknown / not understood.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

5. Information Security Risks:
Risk of accidental or intentional disclosure of sensitive information to unauthorized person(s), and/or unauthorized modifications or destruction of information.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

6. Customer Service Efficiency:
Risk that service functions will not be efficient and/or effective.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

7. Supply Chain and Sourcing Risks:
Risk that supplier(s) will not meet required quality standards, not have required capacity, their financial position will not be sound, etc.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

8. Manufacturing Technology Risks:
Risk that raw materials will not be available, production means not available, scale up potential will not be possible, and/or manufacturing efficiency standards will not be met, etc.

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

9. Outsourcing Risk:
Any risk associated with the outsourcing of design/development work. (Ex - Intellectual property loss, long lead time, poor quality, language barriers, etc.)

	Low	Medium	High	Very High	*Unable to Answer*
Likelihood of Occurrence					
Impact of Risk					

Comments:

Thank You!

Thank you for completing the survey. Your responses will be very helpful in identifying critical risk factors!

APPENDIX C

INDUSTRY SURVEY DATA

Table 36. NPD Weighted Averages and Calculated Correlation Values

NEW PRODUCT DEVELOPMENT				
Risk	Impact of Risk		Likelihood of Occurrence	
	0-15 yrs	15+ yrs	0-15 yrs	15+ yrs
	N = 13	N = 11	N = 13	N = 11
Product Technology Risk	3.00	2.82	1.50	1.36
Technological Exposure Risk	2.18	2.09	1.67	1.73
Legislation / Compliance Risk	2.73	2.60	1.36	1.20
Financial Risk	2.45	2.50	2.09	2.20
Product Family / Brand Positioning Risks	2.00	2.20	1.73	1.50
Market Research Risk	2.18	2.70	1.91	2.50
Marketing Proficiency	2.27	2.70	2.27	2.30
Time-to-Market Risk	2.08	2.50	2.08	2.60
Market Competitiveness	2.42	2.60	2.17	2.00
Commercial Viability Risks	2.58	2.89	2.17	2.44
Public Acceptance Risks	2.00	1.89	1.60	1.44
Customer Acceptance Risks	2.27	2.60	1.75	1.70
Org. and Project Mgmt Risks	2.73	2.82	2.17	2.36
Company Resources	2.33	2.64	2.00	2.00
Internal/ External Communications	2.33	2.45	1.67	1.73
Intellectual Property Risks	2.27	2.10	1.50	1.50
Information Security Risks	2.60	2.36	1.27	1.73
Customer Service Efficiency	2.27	2.33	1.55	1.56
Supply Chain and Sourcing Risks	2.58	3.00	1.83	2.00
Manufacturing Technology Risks	2.67	2.73	1.75	1.82
Outsourcing Risk	2.42	2.55	1.42	1.82
	Correlation	0.656	Correlation	0.812

Table 37. Supply Chain Weighted Averages and Calculated Correlation Values

SUPPLY CHAIN				
Risk	Impact of Risk		Likelihood of Occurrence	
	0-15 yrs	15+ yrs	0-15 yrs	15+ yrs
	N = 22	N = 13	N = 22	N = 13
Manufacturing / Production Problems	3.00	2.62	1.86	1.54
Inventory Management / Stock Out Risk	3.14	3.31	2.00	2.31
Capacity Risk	2.81	3.00	1.90	2.38
Quality Problems	3.05	2.77	1.73	2.00
Transportation Risk	2.14	2.33	1.36	1.42
Key Staff Loss / Strikes	2.09	2.31	1.36	1.77
Supplier Reliability	3.18	2.77	1.95	2.00
Financial Health of Suppliers	2.76	2.17	1.38	1.58
Lead Time Variation Risk	2.32	2.08	1.64	1.77
Strategic Exposure Risk	2.81	2.92	2.33	2.46
Outsourcing Risk	2.36	2.69	1.68	2.15
Development Risk	2.00	1.92	1.86	2.08
Regulatory Requirements	2.10	2.17	1.43	1.83
Environmental Requirements	2.14	2.10	1.33	1.40
Market/Demand Risks	2.72	2.90	2.16	2.20
Technology Shift	2.44	2.10	1.44	1.30
Brand Erosion	2.76	1.30	1.17	1.00
Demand Forecast Risk	2.52	2.36	1.95	2.09
Information Distortion and Bullwhip Risks	2.00	2.00	1.53	1.67
Information Security Risks	2.50	2.40	1.21	1.60
Information Technology (IT) Failure	2.21	2.30	1.53	1.80
Exchange Rate Risk	1.86	2.25	1.73	1.63
Higher Energy Costs	1.76	2.10	2.00	2.20
Cash Flow Risks	2.13	2.00	1.32	1.18
International Terrorism	2.12	1.60	1.32	1.27
Natural Disasters	2.41	1.82	1.21	1.27
Infectious Disease	1.89	1.91	1.13	1.18
Political Environment / Instability	2.00	1.55	1.22	1.09
Fraud	1.82	1.73	1.56	1.88
	Correlation	0.636	Correlation	0.869

Table 38. NPD Scatter Plot Data

NEW PRODUCT DEVELOPMENT					
Risk		Impact of Risk		Likelihood of Occurrence	
		AVG	SDEV	AVG	SDEV
1	Product Technology Risk	2.91	0.95	1.43	0.59
2	Technological Exposure Risk	2.14	0.89	1.70	0.70
3	Legislation / Compliance Risk	2.67	1.06	1.29	0.46
4	Financial Risk	2.48	1.03	2.14	0.73
5	Product Family and Brand Positioning Risks	2.10	0.89	1.62	0.74
6	Market Research Risk	2.43	1.03	2.19	1.12
7	Marketing Proficiency	2.48	0.81	2.29	0.96
8	Time-to-Market Risk	2.27	0.83	2.32	0.72
9	Market Competitiveness	2.50	0.67	2.09	0.75
10	Commercial Viability Risks	2.71	0.85	2.29	0.72
11	Public Acceptance Risks	1.95	1.08	1.53	0.90
12	Customer Acceptance Risks	2.43	0.87	1.73	0.63
13	Organizational and Project Management Risks	2.77	0.75	2.26	0.81
14	Company Resources	2.48	0.85	2.00	0.85
15	Internal/ External Communications	2.39	0.84	1.70	0.63
16	Intellectual Property Risks	2.19	0.87	1.50	0.69
17	Information Security Risks	2.48	1.08	1.50	0.67
18	Customer Service Efficiency	2.30	0.73	1.55	0.60
19	Supply Chain and Sourcing Risks	2.78	0.80	1.91	0.60
20	Manufacturing Technology Risks	2.70	0.93	1.78	0.80
21	Outsourcing Risk	2.48	1.04	1.61	0.72
	Overall Average =	2.46		1.83	

Table 39. Supply Chain Scatter Plot Data

SUPPLY CHAIN					
Risk		Impact of Risk		Likelihood of Occurrence	
		Avg	Sdev	Avg	Sdev
1	Manufacturing / Production Problems	2.85	0.86	1.74	0.75
2	Inventory Management / Stock Out Risk	3.20	0.63	2.11	0.90
3	Capacity Risk	2.88	0.77	2.09	0.87
4	Quality Problems	2.94	0.84	1.83	0.71
5	Transportation Risk	2.21	0.86	1.38	0.78
6	Key Staff Loss / Strikes	2.17	0.79	1.51	0.78
7	Supplier Reliability	3.03	0.71	1.97	0.79
8	Financial Health of Suppliers	2.55	0.87	1.45	0.71
9	Lead Time Variation Risk	2.23	0.94	1.69	0.90
10	Strategic Exposure Risk	2.85	1.05	2.38	1.04
11	Outsourcing Risk	2.49	0.95	1.86	0.77
12	Development Risk	1.97	0.79	1.94	0.76
13	Regulatory Requirements	2.13	0.87	1.58	0.66
14	Environmental Requirements	2.13	0.96	1.35	0.55
15	Market/Demand Risks	2.79	0.83	2.17	0.89
16	Technology Shift	2.32	1.12	1.39	0.74
17	Brand Erosion	2.22	1.28	1.11	0.31
18	Demand Forecast Risk	2.47	0.92	2.00	0.76
19	Information Distortion and Bullwhip Risks	2.00	0.72	1.57	0.63
20	Information Security Risks	2.46	1.07	1.34	0.72
21	Information Technology (IT) Failure	2.24	0.83	1.62	0.82
22	Exchange Rate Risk	2.00	0.98	1.70	0.63
23	Higher Energy Costs	1.89	0.89	2.07	0.87
24	Cash Flow Risks	2.09	0.90	1.67	0.92
25	International Terrorism	1.93	1.07	1.27	0.58
26	Natural Disasters	2.18	1.06	1.30	0.53
27	Infectious Disease	1.90	0.82	1.23	0.50
28	Political Environment / Instability	1.81	0.98	1.15	0.36
29	Fraud	1.79	0.88	1.17	0.38
	Overall Average =	2.33		1.64	

APPENDIX D

GOKHAN'S MODEL FORMULATION

Parameters:

- F: Total number of components used in the product
- $\mathcal{I}$: Set of components, $\mathcal{I} = \{1, 2,\ldots, F\}$
- A_i: Number of design alternatives for component i
- $\mathcal{A}_i$: Set of design alternatives for component i, $i \in \mathcal{I}$
- S: Total number of available suppliers
- $\mathcal{J}$: Set of suppliers, $\mathcal{J} = \{1, 2,\ldots, S\}$
- T: Number of time periods (each representing a product life cycle phase)
- $\mathcal{T}$: Set of time periods, $\mathcal{T} = \{1, 2, 3, 4\}$
- N: Number of lead time – demand binary variables (γ and δ) that cover all possible $LT_{1t} \times D_{1t}$ values in a binary representation
- $n \in \mathcal{N}$: Set of binary factorization elements of lead time – demand multiplication
- $c_{ij\alpha_i t}$: Unit manufacturing costs of design α_i of component i at supplier j in time period t
- $C_{ij\alpha_i t}$: Total production capacity of supplier j for design α_i of component i in time period t
- W_{jl}: Fixed supply chain network costs between suppliers j and l
- $Relation_{ik}$: Number of components k required to manufacture component i
- $pt_{ij\alpha_i t}$: Production time of design α_i of component i at supplier j in time period t

- $val_{i\alpha_i t}$: Value of design α_i of component i for the demand in time period t (% of total contribution)
- $S_{jkl\alpha_k t}$: Unit transportation cost of design α_k of component k from supplier l to j in time period t
- ω_{1t}, ω_{2t}, ω_{3t}: Allowed values that price can take in time period t
- h_t: Unit inventory holding cost of the final product in time period t
- β_1, β_2: Demand function coefficients
- Φ_t: A parameter value in order to adjust demand value according to the time period t (based on what life cycle phase t is)
- l_t: Length of the time period t (same units as lead time)
- z: z-value from the normal distribution corresponding to the given safety stock ratio
- ρ_1, ρ_2: Constant coefficients of variation for demand over lead time and lead time, respectively
- $Mcap_{i\alpha_i t}$: Total available capacity for design α_i of component i in time period t over all suppliers ($\sum_{j=1}^{P} C_{ij\alpha_i t}$)
- M: Maximum potential demand over all periods (calculated by using maximum of $timemultiplier_t$ and lowest $price_t$ with $\upsilon_t=1$)

Decision Variables:

- $x_{ij\alpha_i t}$: Total production quantity of design α_i of component i built at supplier j in time period t
- $price_t$: Price of the final product in time period t
- y_{jl}: 1, if suppliers j and l have a direct relationship; 0, otherwise
- $u_{jkl\alpha_k t}$: Total amount of design α_k of component k manufactured at supplier l and transported to supplier j in time period t
- $\pi_{i\alpha_i t}$: 1, if design α_i of component i is selected for time period t; 0, otherwise
- υ_t: Total value of the final product design for time period t (between 0 and 1)

- D_{it}: Total demand for component *i* in time period *t*
- ϕ_{1t}: 1, if price values are increased to ω_{2t}; 0, otherwise
- ϕ_{2t}: 1, if price values are increased to ω_{3t}; 0, otherwise
- λ_{1t}, λ_{2t}: Variables that reflects pricing decision onto demand generation via ϕ_{1t}, ϕ_{2t}, *and* υ in time period *t*
- τ_t^+: 1, if *total production* > *demand*; 0, otherwise
- τ_t^-: 1, if *demand* > *total production*; 0, otherwise
- k_t^+: Equal to *demand*, if *total production* > *demand*; 0, otherwise
- k_t^-: Equal to *total production*, if *demand* > *total production*; 0, otherwise
- ψ_{1t}, ψ_{2t}, ψ_{3t}, ψ_{4t}: Control variables that link pricing decisions and demand or total production values for revenue calculation in time period *t*
- LT_{it}: Total lead time for component *i* in time period *t*
- $LTint_t$: LT_{1t} value rounded up to the nearest integer
- Ω_{it}: Maximum production time for component *i* in time period *t*
- γ_{nt}: 1, if n^{th} binary factor for LT_{1t} is selected for time period *t*; 0, otherwise
- δ_{nt}: A variable to reflect lead time-demand multiplication via binary factorization in time period *t*

The complete DFSC model is described below:

Objective Function

The objective of this model is to maximize the total profit throughout the product's life cycle. Two components of the total profit are total revenue and total cost and total profit is defined as

$$Total\ Profit = Total\ Revenue - Total\ Cost$$

Since the model is not restricted to satisfy all the demand, the *Total Revenue* would be

Total Revenue = Price × Satisfied Demand

where,

Satisfied Demand = min(Demand, Total Production)

Since both demand and production amounts are variables in the model, for the *Total Revenue* calculation, a linearization schema is developed. The details of this linearization are found in Gokhan (2007). According to this schema, *Total Revenue* over the product's life cycle is

$$Total\ Revenue = \sum_{t=1}^{T} \omega_{1t}(k_t^+ + k_t^-) + (\omega_{2t} - \omega_{1t})(\psi_{1t} + \psi_{3t}) + (\omega_{3t} - \omega_{1t})(\psi_{2t} + \psi_{4t}) \qquad (1)$$

On the other hand, *Total Cost* consists of all supply chain related costs, namely production, supply chain network, transportation, and inventory costs. The *Total Production Cost* is the summation of all manufacturing costs incurred by all the suppliers for all selected component design alternatives over the planning horizon. Therefore, it can be expressed by

$$Total\ Production\ Cost = \sum_{t=1}^{T}\sum_{i=1}^{F}\sum_{j=1}^{S}\sum_{\alpha_i=1}^{A_i}(c_{ij\alpha_i t}x_{ij\alpha_i t}) \qquad (2)$$

The supply chain network costs are incurred whenever there is a direct relationship between two suppliers. Hence, *Total Supply Chain Network Cost* is the summation of these costs over all supplier pairs and given as

$$Total\ Supply\ Chain\ Newtork\ Cost = \sum_{j=1}^{S}\sum_{l=1}^{S} y_{jl}W_{jl} \qquad (3)$$

The transportation costs are incurred per unit transported, so the *Total Transportation Cost* is the summation of costs incurred per item for each component design alternative between all supplier pairs over the planning horizon as represented below.

$$Total\,Transportation\,Cost = \sum_{t=1}^{T}\sum_{j=1}^{S}\sum_{k=1}^{F}\sum_{l=1}^{S}\sum_{\alpha_k}^{A_k} u_{jkl\alpha_k t} S_{jkl\alpha_k t} \tag{4}$$

Finally, *Total Inventory Cost* constitutes the last group of cost drivers. Due to the non-linear nature of the safety stock calculations, the *Total Inventory Cost* function is linearized. The details of the linearization schema are given in Gokhan (2007). The *Total Inventory Cost* is the summation of *Inventory Costs* over all time periods and given below.

$$Total\ Inventory\ \ Cost = \sum_{t=1}^{T} \frac{1}{2} h_t (1 + (z \times \rho_2)) \sum_{n=0}^{N} 2^n \delta_{nt} \tag{5}$$

Given these components of the objective function, the DFSC model is presented below.

$$\max\sum_{t=1}^{T}\omega_{1t}(k_t^{+}+k_t^{-})+(\omega_{2t}-\omega_{1t})(\psi_{1t}+\psi_{3t})+(\omega_{3t}-\omega_{1t})(\psi_{2t}+\psi_{4t})-\Bigg(\sum_{t=1}^{T}\sum_{i=1}^{F}\sum_{j=1}^{S}\sum_{\alpha_i=1}^{A_i}c^1_{ij\alpha_i t}x^1_{ij\alpha_i t}+$$

$$\sum_{j=1}^{S}\sum_{l=1}^{S}y_{jl}W_{jl}+\sum_{t=1}^{T}\sum_{j=1}^{S}\sum_{k=1}^{F}\sum_{l=1}^{S}\sum_{\alpha_k}^{A_k}u_{jkl\alpha_k t}S_{jkl\alpha_k t}+\sum_{t=1}^{T}\frac{1}{2}h_t(1+(z\times\rho_2))\sum_{n=0}^{N}2^n\delta_{nt}\Bigg) \tag{D.1}$$

s.t.

$$D_{1t}=\left((\beta_1\omega_{1t}^2+\beta_2)\upsilon_t+\beta_1\lambda_{1t}(\omega_{2t}^2-\omega_{1t}^2)+\beta_1\lambda_{2t}(\omega_{3t}^2-\omega_{1t}^2)\right)\times\Phi_t\quad\forall t \tag{D.2}$$

$$D_{kt}=\sum_{i=1}^{k-1}D_{it}Relation_{ik}\qquad\forall k(k>1),t \tag{D.3}$$

$$\sum_{\alpha_k=1}^{A_k}\sum_{j=1}^{S}x^1_{kj\alpha_k t}\geq\sum_{i=1}^{k-1}\sum_{\alpha_i=1}^{A_i}\sum_{j=1}^{S}x^1_{ij\alpha_i t}Relation_{ik}\qquad\forall k(k>1),t \tag{D.4}$$

$$\sum_{j=1}^{S}x^1_{ij\alpha_i t}\leq\pi_{i\alpha_i t}Mcap_{i\alpha_i t}\qquad\forall i,\alpha_i,t \tag{D.5}$$

$$\sum_{\alpha_i=1}^{A_i}\pi_{i\alpha_i t}=1\qquad\forall i,t \tag{D.6}$$

$$\upsilon_t=\sum_{i=1}^{F}\sum_{\alpha_i=1}^{A_i}\pi_{i\alpha_i t}val_{i\alpha_i t}\qquad\forall t \tag{D.7}$$

$$x^1_{ij\alpha_i t}\leq C^1_{ij\alpha_i t}\qquad\forall i,j,\alpha_i,t \tag{D.8}$$

$$y_{jl}C^1_{kl\alpha_k t}\geq u_{jkl\alpha_k t}\qquad\forall j,k,l,\alpha_k,t \tag{D.9}$$

$$\sum_{j=1}^{S}u_{jkl\alpha_k t}\leq x^1_{kl\alpha_k t}\qquad\forall k,l,\alpha_k,t \tag{D.10}$$

$$\sum_{\alpha_k=1}^{A_k}\sum_{l=1}^{S}u_{jkl\alpha_k t}\geq Relation_{ik}\sum_{\alpha_i=1}^{A_i}x^1_{ij\alpha_i t}\qquad\forall i,j,k,t\mid Relation_{ik}>0 \tag{D.11}$$

$$\Omega_{it}\geq\frac{pt_{ij\alpha_i t}x^1_{ij\alpha_i t}}{C^1_{ij\alpha_i t}}\qquad\forall i,j,\alpha_i,t\mid Capacity^1_{ij\alpha t}>0 \tag{D.12}$$

$$LT_{it}\geq LT_{kt}Relation_{ik}+\Omega_{it}\qquad\forall i,k,t\mid Relation_{ik}>0 \tag{D.13}$$

$$LT_{it}\geq\Omega_{it}\qquad\forall i,t\mid Relation_{ik}=0\text{ for }\forall k>i \tag{D.14}$$

$$LT_{1t}=\sum_{n=0}^{N}2^n\gamma_{nt}\qquad\forall t \tag{D.15}$$

$$\delta_{nt}\leq D_{1t}\qquad n\in[0,\mathrm{N}],\ \forall t \tag{D.16}$$

$$\delta_{nt}\leq M\times\gamma_{nt}\qquad n\in[0,\mathrm{N}],\ \forall t \tag{D.17}$$

$$D_{1t}-M(1-\gamma_{nt})\leq\delta_{nt}\qquad n\in[0,\mathrm{N}],\ \forall t \tag{D.18}$$

$$\phi_{1t} + \phi_{2t} \leq 1 \qquad \forall t \qquad \text{(D.19)}$$

$$\lambda_{qt} \leq \phi_{qt} \qquad \forall t, q \in \{1,2\} \qquad \text{(D.20)}$$

$$\lambda_{qt} \leq \upsilon_t \qquad \forall t, q \in \{1,2\} \qquad \text{(D.21)}$$

$$\phi_{qt} + \upsilon_t \leq \lambda_{qt} + 1 \qquad \forall t, q \in \{1,2\} \qquad \text{(D.22)}$$

$$\tau_t^+ \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \geq \sum_{\alpha_1=1}^{A_1}\sum_{j=1}^{S}(x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) - D_{1t} \qquad \forall t \qquad \text{(D.23)}$$

$$\tau_t^- M \geq D_{1t} - \sum_{\alpha_1=1}^{A_1}\sum_{j=1}^{S}(x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) \qquad \forall t \qquad \text{(D.24)}$$

$$\tau_t^+ + \tau_t^- \leq 1 \qquad \forall t \qquad \text{(D.25)}$$

$$k_t^+ \leq D_{1t} \qquad \forall t \qquad \text{(D.26)}$$

$$k_t^+ \leq \tau_t^+ M \qquad \forall t \qquad \text{(D.27)}$$

$$D_{1t} + \tau_t^+ M \leq k_t^+ + M \qquad \forall t \qquad \text{(D.28)}$$

$$k_t^- \leq \sum_{\alpha_1=1}^{A_1}\sum_{j=1}^{S}(x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) \qquad \forall t \qquad \text{(D.29)}$$

$$k_t^- \leq \tau_t^- \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \qquad \text{(D.30)}$$

$$\sum_{\alpha_1=1}^{A_1}\sum_{j=1}^{S}(x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) + \tau_t^- \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \leq k_t^- + \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \qquad \text{(D.31)}$$

$$\psi_{1t} \leq k_t^+ \qquad \forall t \qquad \text{(D.32)}$$

$$\psi_{1t} \leq \phi_{1t} M \qquad \forall t \qquad \text{(D.33)}$$

$$\phi_{1t} M + k_t^+ \leq \psi_{1t} + M \qquad \forall t \qquad \text{(D.34)}$$

$$\psi_{2t} \leq k_t^+ \qquad \forall t \qquad \text{(D.35)}$$

$$\psi_{2t} \leq \phi_{2t} M \qquad \forall t \qquad \text{(D.36)}$$

$$\phi_{2t} M + k_t^+ \leq \psi_{2t} + M \qquad \forall t \qquad \text{(D.37)}$$

$$\psi_{3t} \leq k_t^- \qquad \forall t \qquad \text{(D.38)}$$

$$\psi_{3t} \leq \phi_{1t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \qquad \text{(D.39)}$$

$$\phi_{1t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} + k_t^- \leq \psi_{3t} + \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \qquad \text{(D.40)}$$

$$\psi_{4t} \leq k_t^- \qquad \forall t \qquad \text{(D.41)}$$

$$\psi_{4t} \leq \phi_{2t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \qquad \text{(D.42)}$$

$$\phi_{2t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} + k_t^- \leq \psi_{4t} + \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \qquad \text{(D.43)}$$

$$\begin{aligned} & x_{ij\alpha_i t}, u_{jkl\alpha_k t}, LT_{it}, \Omega_{it}, \lambda_{1t}, \lambda_{2t}, \psi_{1t}, \psi_{2t}, \psi_{3t}, \psi_{4t}, k_t^+, k_t^-, D_{kt}, \upsilon_t, \delta_{nt} \geq 0 \\ & \pi_{i\alpha_i t}, y_{jl}, \tau_t^+, \tau_t^-, \phi_{1t}, \phi_{2t}, \gamma_{nt} \in \{0,1\} \end{aligned} \qquad \text{(D.44)}$$

Equation (D.2) calculates the demand of the final product for each time period based on selected component design alternatives, price, and the time period adjustment parameter. The original demand function in non-linear form is given below.

$$D_{1t} = (\beta_1 price_t^2 + \beta_2) \times \upsilon_t \times \Phi_t \quad (6)$$

Since this equation is non-linear due to multiplication of the *price* and υ variables, a linearization schema is presented in Gokhan (2007). Equation (D.3) does not necessarily constrain the feasible region, but instead is used to evaluate the demand for each selected component alternative design based on the demand for the final product and BOM data. Similarly, equation (D.4) makes sure that each component that is assembled into another one is manufactured in at least an amount required by the BOM data. The difference between these two equations is that equation (D.4) constrains the minimum manufacturing quantity of a component where equation (D.3) only calculates the demand for this component but does not enforce any limits on the manufacturing amounts. The next three constraints incorporate the product design decisions into the model. The first constraint (D.5) ensures that only selected component alternative designs (for which $\pi_{i\alpha_i t} = 1$) are manufactured. The second product design constraint (D.6) requires that exactly one component design alternative is selected for each component in each time period. The last product design constraint (D.7) is used to calculate total value of the final product based on component design alternative selections. Equation (D.8) establishes supplier capacity limits. The supply chain network design is set up by the equation (D.9) by making sure that two suppliers are linked (that is $y_{jl} = 1$) if any transportation occurs between them (that is $u_{jkl\alpha_k t} > 0$) for a component. Equation (D.10) guarantees that the total amount of a component transported from a supplier is at most the manufactured quantity by this supplier. The next constraint (D.11) makes sure that for a component manufactured at a certain supplier, all required subcomponents are transported to this supplier from other suppliers. Equations (D.12) through (D.15) are used to calculate the lead times. Equation (D.12), makes sure that the production time of a component is at least equal to the longest time it takes for manufacturing this component among all the suppliers that manufacture this particular component. This constraint is necessary since it is assumed that the production of a component starts only after all of its subcomponents are delivered to the manufacturer. Therefore, the longest production time among all of a component's suppliers is defined as the production time of this component. However, different from the preliminary modeling, in this complete model it is assumed that production time data ($pt_{ij\alpha_i t}$) is given for the total capacity of the supplier, hence the final production time of a component at a particular supplier is determined relative to the capacity utilization of this supplier. For example, if a supplier states that it takes 10 days to manufacture the complete batch in full capacity utilization, then the model decides that the production time of this component at this supplier is 5 days if half the capacity is used. Equations (D.13) and (D.14) are used to calculate the final lead time of a component in the same fashion described in the preliminary models where the former constraint (only defined for components which have subcomponents) ensures that the lead time of a component is equal to the summation of its own manufacturing time and the maximum lead time of its subcomponents. The latter constraint is used only for the components which do not have any subcomponents to make sure that their final lead time is at least equal to their production times. In the lead time constraints set, the last equation (D.15) is used to represent the final lead time of the main product with binary variables for inventory cost linearization.

Constraints (D.16) through (D.43) are used for linearization of the model and do not impose any actual limits on the product and supply chain design. Equations (D.16), (D.17), and

(D.18) ensure that δ_{nt} variables take values to truly represent demand – lead time multiplication in a binary format. Similarly, while equation (D.19) ensures that only one of the second or third price levels is selected, the following three equations (D.20), (D.21), and (D.22) ensure that the λ_{1t} and λ_{2t} variables take correct values to capture price and product design value multiplications.

In order to calculate the satisfied demand, which is the minimum of demand and total production, equations (D.23), (D.24), and (D.25) control the τ_t^+ and τ_t^- variable values to represent whether the demand or the total production is larger. Based on these τ_t^+ and τ_t^- values, k_t^+ and k_t^- variables take the minimum of the demand or the total production via equations (D.26) through (D.31). The following twelve constraints, equations (D.32) through (D.43), control the ψ variables that are used in revenue calculation and described in revenue linearization. Finally, equation (D.44) establishes the required variable types and bounds.

APPENDIX E

DFSC RISK MIP FORMULATION

Parameters:

- F: Total number of components used in the product
- $\mathcal{I}$: Set of components, $\mathcal{I} = \{1, 2, \ldots, F\}$
- A_i: Number of design alternatives for component i
- $\mathcal{A}_i$: Set of design alternatives for component i, $i \in \mathcal{I}$
- S: Total number of available suppliers
- $\mathcal{J}$: Set of suppliers, $\mathcal{J} = \{1, 2, \ldots, S\}$
- T: Number of time periods (each representing a product life cycle phase)
- $\mathcal{T}$: Set of time periods, $\mathcal{T} = \{1, 2, 3, 4\}$
- N: Number of lead time – demand binary variables (γ and δ) that cover all possible $LT_{1t} \times D_{1t}$ values in a binary representation
- $n \in \mathcal{N}$: Set of binary factorization elements of lead time – demand multiplication
- $c_{ij\alpha_i t}$: Unit manufacturing costs of design α_i of component i at supplier j in time period t
- $C_{ij\alpha_i t}$: Total production capacity of supplier j for design α_i of component i in time period t
- W_{jl}: Fixed supply chain network costs between suppliers j and l
- $Relation_{ik}$: Number of components k required to manufacture component i
- $val_{i\alpha_i t}$: Value of design α_i of component i for the demand in time period t (% of total contribution)

- $S_{jkl\alpha_k t}$: Unit transportation cost of design α_k of component *k* from supplier *l* to *j* in time period *t*
- ω_{1t}, ω_{2t}, ω_{3t}: Allowed values that price can take in time period *t*
- h_t: Unit inventory holding cost of the final product in time period *t*
- β_1, β_2: Demand function coefficients
- Φ_τ: A parameter value in order to adjust demand value according to the time period *t* (based on what life cycle phase *t* is)
- l_t: Length of the time period *t* (same units as lead time)
- *z*: z-value from the normal distribution corresponding to the given safety stock ratio
- ρ_1, ρ_2: Constant coefficients of variation for demand over lead time and lead time, respectively
- $Mcap_{i\alpha_i t}$: Total available capacity for design α_i of component *i* in time period *t* over all suppliers ($\sum_{j=1}^{P} C_{ij\alpha_i t}$)
- *M*: Maximum potential demand over all periods (calculated by using maximum of $timemultiplier_t$ and lowest $price_t$ with $\upsilon_t=1$)
- $mfgt_{ij\alpha_i t}$: Production time of design α_i of component *i* at supplier *j* in time period *t*
- $shipt_{ij\alpha_i t}$: Transportation time of design α_i of component *i* at supplier *j* in time period *t*
- $\mu_{ij\alpha_i t}$: Probability that supplier *j* will deliver a quality product (design α_i of component *i*) in time period *t* to satisfy demand requirements
- Γ_t: Overall desired probability of timely delivery of all components of the complete assembly
- $\sigma_{p1,i}$: BOM relationship of component *i* to component 1 (final product)
- $m_{i\alpha_i 1}$: Time-to-market for alternative α_i of component *i* in time period 1
- θ: Fixed cost of switching between different product designs
- θ': Fixed cost of switching between different suppliers
- η_{it}: Maximum percentage of total demand that any supplier can supply for component *i* in time period *t*

Decision Variables:

- $x_{ij\alpha_i t}$: Total production quantity of design α_i of component *i* built at supplier *j* in time period *t*
- $price_t$: Price of the final product in time period *t*
- y_{jl}: 1, if suppliers *j* and *l* have a direct relationship; 0, otherwise
- $u_{jkl\alpha_k t}$: Total amount of design α_k of component *k* manufactured at supplier *l* and transported to supplier *j* in time period *t*
- $\pi_{i\alpha_i t}$: 1, if design α_i of component *i* is selected for time period *t*; 0, otherwise
- υ_t: Total value of the final product design for time period *t* (between 0 and 1)
- D_{it}: Total demand for component *i* in time period *t*
- ϕ_{1t}: 1, if price values are increased to ω_{2t}; 0, otherwise
- ϕ_{2t}: 1, if price values are increased to ω_{3t}; 0, otherwise
- λ_{1t}, λ_{2t}: Variables that reflects pricing decision onto demand generation via ϕ_{1t}, ϕ_{2t}, *and* υ in time period *t*
- τ_t^+: 1, if *total production* > *demand*; 0, otherwise
- τ_t^-: 1, if *demand* > *total production*; 0, otherwise
- k_t^+: Equal to *demand*, if *total production* > *demand*; 0, otherwise
- k_t^-: Equal to *total production*, if *demand* > *total production*; 0, otherwise
- ψ_{1t}, ψ_{2t}, ψ_{3t}, ψ_{4t}: Control variables that link pricing decisions and demand or total production values for revenue calculation in time period *t*
- LT_{it}: Total lead time for component *i* in time period *t*
- $LTint_t$: LT_{1t} value rounded up to the nearest integer
- Ω_{it}: Maximum production time for component *i* in time period *t*

- γ_{nt}: 1, if nth binary factor for LT_{1t} is selected for time period t; 0, otherwise
- δ_{nt}: A variable to reflect lead time-demand multiplication via binary factorization in time period t
- m_{max}: Maximum time-to-market for the final product
- m_{b1}: 1, if $\frac{m_{max}}{l_1} < 0.5$; 0, otherwise
- m_{b2}: 1, if $0.5 \leq \frac{m_{max}}{l_1} < 0.8$; 0, otherwise
- m_{b3}: 1, if $\frac{m_{max}}{l_1} \geq 0.8$; 0, otherwise
- d'_1 ,d'_2: Variables to indicate the amount of demand lost (dependent on TTM value)
- $x'_{ij\alpha_i t}$: 1 if $x_{ij\alpha_i t}$ is positive; 0, otherwise
- $B_{t,t+1}$: 1 if a design change occurred between time period t and t+1; 0, otherwise
- $G_{t,t+1}$: 1 if a supplier change occurred between time period t and t+1; 0, otherwise

Objective Function:

$$max\left(\sum_{t=1}^{T}\omega_{1t}(k_t^+ + k_t^-) + (\omega_{2t}-\omega_{1t})(\psi_{1t}+\psi_{3t}) + (\omega_{3t}-\omega_{1t})(\psi_{2t}+\psi_{4t}) - \right.$$

$$\sum_{t=1}^{T}\sum_{i=1}^{F}\sum_{j=1}^{S}\sum_{\alpha_i=1}^{A_i}(c_{ij\alpha_i t}x_{ij\alpha_i t}) - \sum_{j=1}^{S}\sum_{l=1}^{S} y_{jl}W_{jl} - \sum_{t=1}^{T}\sum_{j=1}^{S}\sum_{k=1}^{F}\sum_{l=1}^{S}\sum_{\alpha_k=1}^{A_k} u_{jkl\alpha_k t}S_{jkl\alpha_k t} -$$

$$\left.\sum_{t=1}^{T}\frac{1}{2}h_t(1+(z\times\rho_2))\sum_{n=0}^{N}2^n\delta_{nt} - \theta\sum_{t=1}^{T}B_{t,t+1} - \theta'\sum_{t=1}^{T}G_{t,t+1}\right) \qquad \text{(E.1)}$$

$$D_{1t} = \left((\beta_1 \omega_{1,1}^2 + \beta_2)\upsilon_1 + \beta_1 \lambda_{1t} (\omega_{2,1}^2 - \omega_{1,1}^2) + \beta_1 \lambda_{2,1} (\omega_{3,1}^2 - \omega_{1,1}^2) \right) \times \Phi_1 - d_1' - d_2' \tag{E.2}$$

$$D_{1t} = \left((\beta_1 \omega_{1t}^2 + \beta_2)\upsilon_t + \beta_1 \lambda_{1t} (\omega_{2t}^2 - \omega_{1t}^2) + \beta_1 \lambda_{2t} (\omega_{3t}^2 - \omega_{1t}^2) \right) \times \Phi_t \quad \forall t > 1 \in \mathcal{T} \tag{E.3}$$

$$D_{kt} = \sum_{i=1}^{k-1} D_{it} Relation_{ik} \qquad \forall k (k > 1), t \in \mathcal{T} \tag{E.4}$$

$$\sum_{\alpha_k=1}^{A_k} \sum_{j=1}^{S} x_{kj\alpha_k t} = \sum_{i=1}^{k-1} \sum_{\alpha_i=1}^{A_i} \sum_{j=1}^{S} x_{ij\alpha_i t} Relation_{ik} \qquad \forall k (k > 1), t \in \mathcal{T} \tag{E.5}$$

$$\sum_{j=1}^{S} x_{ij\alpha_i t} \le \pi_{i\alpha_i t} Mcap_{i\alpha_i t} \qquad \forall i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.6}$$

$$\sum_{\alpha_i=1}^{A_i} \pi_{i\alpha_i t} = 1 \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \tag{E.7}$$

$$\upsilon_t = \sum_{i=1}^{F} \sum_{\alpha_i=1}^{A_i} \pi_{i\alpha_i t} val_{i\alpha_i t} \qquad \forall t \in \mathcal{T} \tag{E.8}$$

$$x_{ij\alpha_i t} \le C_{ij\alpha_i t} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.9}$$

$$y_{jl} C_{kl\alpha_k t} \ge u_{jkl\alpha_k t} \qquad \forall j \in J, k \in \mathcal{I}, l \in \mathcal{J}, \alpha_k \in \mathcal{A}_k, t \in \mathcal{T} \tag{E.10}$$

$$\sum_{j=1}^{S} u_{jkl\alpha_k t} \le x_{kl\alpha_k t} \qquad \forall k \in \mathcal{I}, l \in \mathcal{J}, \alpha_k \in \mathcal{A}_k, t \in \mathcal{T} \tag{E.11}$$

$$\sum_{\alpha_k=1}^{A_k} \sum_{l=1}^{S} u_{jkl\alpha_k t} \ge Relation_{ik} \sum_{\alpha_i=1}^{A_i} x_{ij\alpha_i t} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, k \in \mathcal{I}, t \in \mathcal{T}, s.t.\ Relation_{ik} > 0 \tag{E.12}$$

$$\Omega_{it} \ge (mfgt_{ij\alpha_i t} + shipt_{ij\alpha_i t}) x'_{ij\alpha_i t} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T}, s.t.\ C_{ij\alpha t} > 0 \tag{E.13}$$

$$LT_{it} \ge LT_{kt} + \Omega_{it} \qquad \forall i \in \mathcal{I}, k \in \mathcal{I}, t \in \mathcal{T}, s.t.\ Relation_{ik} > 0 \tag{E.14}$$

$$LT_{it} \ge \Omega_{it} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T}, s.t.\ Relation_{ik} = 0 \text{ for } \forall k > i \tag{E.15}$$

$$LT_{1t} = \sum_{n=0}^{N} 2^n \gamma_{nt} \qquad \forall t \in \mathcal{T} \tag{E.16}$$

$$\delta_{nt} \le \sum_{\alpha_k=1}^{A_k} \sum_{j=1}^{S} x_{1j\alpha_k t} \qquad n \in [0, \mathrm{N}],\ \forall t \in \mathcal{T} \tag{E.17}$$

$$\delta_{nt} \le M \times \gamma_{nt} \qquad n \in [0, \mathrm{N}],\ \forall t \in \mathcal{T} \tag{E.18}$$

$$\sum_{\alpha_k=1}^{A_k} \sum_{j=1}^{S} x_{1j\alpha_k t} - M(1 - \gamma_{nt}) \le \delta_{nt} \qquad n \in [0, \mathrm{N}],\ \forall t \in \mathcal{T} \tag{E.19}$$

$$\sum_{i=1}^{F} \sum_{j=1}^{S} \sum_{\alpha_i \in Q} \left(\frac{x_{ij\alpha_i t}}{\sigma_{1,i}} \times \left| \log \mu_{ij\alpha_i t} \right| \right) \le \left| \log \Gamma_t \right| \times \sum_{\alpha_i \in Q} \sum_{j=1}^{S} x_{1j\alpha_i t} \qquad \forall t \in \mathcal{T} \tag{E.20}$$

$$\text{where}, Q = \left\{ \alpha_i \mid \mu_{ij\alpha_i t} > 0,\ i \in \mathcal{I}, j \in \mathcal{J}, t \in \mathcal{T} \right\}$$

$$m_{\max} \geq m_{i\alpha_i 1} \times \pi_{i\alpha_i 1} \qquad \forall i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i \tag{E.21}$$

$$0.8 \geq \frac{m_{\max}}{l_1} - m_{b3} \tag{E.22}$$

$$0.5 \geq \frac{m_{\max}}{l_1} - m_{b3} - m_{b2} \tag{E.23}$$

$$m_{b1} + m_{b2} + m_{b3} = 1 \tag{E.24}$$

$$d_1' \geq 0.5 \times D_{1,1} - (1 - m_{b2}) \times M \tag{E.25}$$

$$d_2' \geq 0.8 \times D_{1,1} - (1 - m_{b3}) \times M \tag{E.26}$$

$$B_{t,t+1} \geq \pi_{i\alpha_i t} - \pi_{i\alpha_i t+`} \qquad \forall i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.27}$$

$$B_{t,t+1} \geq \pi_{i\alpha_i t+1} - \pi_{i\alpha_i t} \qquad \forall i \in \mathcal{I}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.28}$$

$$x_{ij\alpha_i t} \leq x'_{ij\alpha_i t} \times C_{ij\alpha_i t} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.29}$$

$$G_{t,t+1} \geq x'_{ij\alpha_i t} - x'_{ij\alpha_i t+1} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.30}$$

$$G_{t,t+1} \geq x'_{ij\alpha_i t+1} - x'_{ij\alpha_i t} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.31}$$

$$x_{ij\alpha_i t} \leq \eta_{it} \times \sum_{\alpha_i=1}^{A_i} \sum_{j=1}^{S} x_{ij\alpha_i t} \qquad \forall i \in \mathcal{I}, j \in \mathcal{J}, \alpha_i \in \mathcal{A}_i, t \in \mathcal{T} \tag{E.32}$$

$$\phi_{1t} + \phi_{2t} \le 1 \qquad \forall t \in \mathcal{T} \qquad \text{(E.33)}$$

$$\lambda_{qt} \le \phi_{qt} \qquad \forall t \in \mathcal{T}, q \in \{1,2\} \qquad \text{(E.34)}$$

$$\lambda_{qt} \le \upsilon_t \qquad \forall t \in \mathcal{T}, q \in \{1,2\} \qquad \text{(E.35)}$$

$$\phi_{qt} + \upsilon_t \le \lambda_{qt} + 1 \qquad \forall t \in \mathcal{T}, q \in \{1,2\} \qquad \text{(E.36)}$$

$$\tau_t^+ \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \ge \sum_{\alpha_1=1}^{A_1} \sum_{j=1}^{S} (x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) - D_{1t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.37)}$$

$$\tau_t^- M \ge D_{1t} - \sum_{\alpha_1=1}^{A_1} \sum_{j=1}^{S} (x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) \qquad \forall t \in \mathcal{T} \qquad \text{(E.38)}$$

$$\tau_t^+ + \tau_t^- \le 1 \qquad \forall t \in \mathcal{T} \qquad \text{(E.39)}$$

$$k_t^+ \le D_{1t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.40)}$$

$$k_t^+ \le \tau_t^+ M \qquad \forall t \in \mathcal{T} \qquad \text{(E.41)}$$

$$D_{1t} + \tau_t^+ M \le k_t^+ + M \qquad \forall t \in \mathcal{T} \qquad \text{(E.42)}$$

$$k_t^- \le \sum_{\alpha_1=1}^{A_1} \sum_{j=1}^{S} (x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) \qquad \forall t \in \mathcal{T} \qquad \text{(E.43)}$$

$$k_t^- \le \tau_t^- \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.44)}$$

$$\sum_{\alpha_1=1}^{A_1} \sum_{j=1}^{S} (x_{1j\alpha_1 t}^1 + x_{1j\alpha_1 t}^2) + \tau_t^- \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \le k_t^- + \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.45)}$$

$$\psi_{1t} \le k_t^+ \qquad \forall t \in \mathcal{T} \qquad \text{(E.46)}$$

$$\psi_{1t} \le \phi_{1t} M \qquad \forall t \in \mathcal{T} \qquad \text{(E.47)}$$

$$\phi_{1t} M + k_t^+ \le \psi_{1t} + M \qquad \forall t \in \mathcal{T} \qquad \text{(E.48)}$$

$$\psi_{2t} \le k_t^+ \qquad \forall t \in \mathcal{T} \qquad \text{(E.49)}$$

$$\psi_{2t} \le \phi_{2t} M \qquad \forall t \in \mathcal{T} \qquad \text{(E.50)}$$

$$\phi_{2t} M + k_t^+ \le \psi_{2t} + M \qquad \forall t \in \mathcal{T} \qquad \text{(E.51)}$$

$$\psi_{3t} \le k_t^- \qquad \forall t \in \mathcal{T} \qquad \text{(E.52)}$$

$$\psi_{3t} \le \phi_{1t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.53)}$$

$$\phi_{1t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} + k_t^- \le \psi_{3t} + \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.54)}$$

$$\psi_{4t} \le k_t^- \qquad \forall t \in \mathcal{T} \qquad \text{(E.55)}$$

$$\psi_{4t} \le \phi_{2t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.56)}$$

$$\phi_{2t} \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} + k_t^- \le \psi_{4t} + \sum_{\alpha_1=1}^{A_1} Mcap_{1\alpha_1 t} \qquad \forall t \in \mathcal{T} \qquad \text{(E.57)}$$

$$\begin{aligned} & x_{ij\alpha_i t}, u_{jkl\alpha_k t}, LT_{it}, \Omega_{it}, \lambda_{1t}, \lambda_{2t}, \psi_{1t}, \psi_{2t}, \psi_{3t}, \psi_{4t}, k_t^+, k_t^-, D_{kt}, \upsilon_t, \delta_{nt} \ge 0 \\ & \pi_{i\alpha_i t}, y_{jl}, \tau_t^+, \tau_t^-, \phi_{1t}, \phi_{2t}, \gamma_{nt} \in \{0,1\} \end{aligned} \qquad \text{(E.58)}$$

The differences between the DFSC risk MIP formulation shown here and Gokhan's MIP formulation shown in Appendix D are as follows:

1. Equation (E.1) – Objective function includes switch costs.
2. Equation (E.5) – Changed to an equality to prevent overproduction per discussion in Section 4.3.
3. Equations (E.13) – (E.15) – Lead time equations changed per discussion in Section 4.2.1.
4. Equations (E.17) – (E.19) – Inventory equations changed per discussion in Section 4.5.2.
5. Equations (E.20) – Supplier reliability constraint as shown in Section 4.2.2.
6. Equations (E.21) – (E.26) – TTM constraints as shown in Section 4.2.2.
7. Equations (E.27) – (E.31) – Switch cost constraints as shown in Section 4.2.1.
8. Equation (E.32) – Strategic exposure risk constraint as shown in Section 4.2.2.

APPENDIX F

LINEAR BEHAVIOR OF LOG FUNCTION

PR	log(PR)	% mtl from supplier	%*log(PR)
0.85	-0.0706	0.4	-0.0282
0.92	-0.0362	0.6	-0.0217
		sum =	-0.0500
		10^{sum} =	0.8913
		Σ(%*PR) =	0.8920

PR	log(PR)	% mtl from supplier	%*log(PR)
0.90	-0.0458	0.25	-0.0114
0.99	-0.0044	0.75	-0.0033
		sum =	-0.0147
		10^{sum} =	0.9667
		Σ(%*PR) =	0.9675

This experiment shows that these two equations are close to equivalent when PR is close to the number one.

1. Σ (% * PR)
2. $10^{(\text{sum of log(PR)*\%})}$

APPENDIX G

INDUSTRY DATA SET

Design	Supplier	Capacity				Unit Mfg Cost			
		T1	T2	T3	T4	T1	T2	T3	T4
Initial	1	100,000	250,000	500,000	1,000,000	$1.06	$1.01	$0.97	$0.92
Final	1	100,000	250,000	500,000	1,000,000	$1.21	$1.16	$1.12	$1.07
Initial	2	300,000	540,000	972,000	1,700,000	$2.28	$2.28	$1.53	$1.43
Final	2	300,000	540,000	972,000	1,700,000	$2.43	$2.43	$1.68	$1.58

Design	Supplier	Unit Transp. Cost	Unit Production Time	Design Value
		T1-T4	T1-T4	T1-T4
Initial	1	$0.021	56 days	1.00
Final	1	$0.021	56 days	1.00
Initial	2	$0.025	35 days	1.00
Final	2	$0.025	35 days	1.00

Selling Price of Final Product	
Low	$4.44
Medium	$5.00
High	$5.13

Supplier	Design & Development Costs	Supplier Reliability
1	$92,000	0.75
2	$239,820	1

Design	Time-to-Market
Initial	121 days (~4 mo)
Final	121 days (~4 mo)

Unit Inventory Holding Cost of Final Product = $0.02

APPENDIX H

HYBRID MIP/SIMULATION PROCEDURE

1. Obtain data from decision maker and create data set.
2. Write a .lp file and solve MIP in CPLEX.
3. Put the CPLEX output into the Simulation Excel Input File.
4. Run the simulation in ARENA.
5. Capacity Risk Analysis – Option A
    a. Use MIP and simulation output to identify a “risky supplier.”
    a. Remove risky supplier as an option from the optimization by removing it from the data set.
    b. Create new .lp file and solve in CPLEX.
    c. Use the results to create a new Excel Simulation Input File.
    d. Run the simulation in ARENA to obtain the Option A results.
6. Capacity Risk Analysis - Option B
    a. Create modified data sets, where the capacity level for the “risky supplier” is set to 90%, 80% and 70% of original capacity.
    b. Create new .lp files and solve in CPLEX.
    c. Use the results to create a new Excel Simulation Input File.
    d. Run the simulation in ARENA to obtain the Option B results.
7. Capacity Risk Analysis – Option C
    a. Create modified .lp files by using the .lp files that were created for Option B (90%, 80% and 70% cases) and adding constraints to force MIP to select original production values for all non-risky suppliers and to force MIP to use the risky supplier up to the modified capacity level (this is basically a re-optimization of a portion of the problem – the portion that the risky supplier is unable to provide.)
    b. Solve modified .lp files in CPLEX.

c. Use a combination of the original results and the results from step b to create a new Excel Simulation Input File, because assume that the supplier changeover will take place after day 100 of the simulation. This will show what happens when a decision maker realizes there is a problem and then has the backup plan in place by day 100.
d. Run the simulation in ARENA with modified Excel Simulation Input File to obtain the Option C results.

8. Demand Risk Analysis – Option A
    a. Create modified .lp files by adding constraints to force larger demand (10%, 20% and 30% increase). When a larger demand value is forced, constraints also need to be added to keep the price and product selection the same. (The price and product selection are a function of demand, so since demand is now an input, price and product selection also need to become inputs.)
    b. Solve modified .lp files in CPLEX.
    c. Use the results to create a new Excel Simulation Input File.
    d. Run the simulation in ARENA to obtain the Option A results.
9. Demand Risk Analysis – Option B
    a. Create modified .lp files (for 10%, 20% and 30% cases) by using the files that were created for Option A and adding constraints to force MIP to use the original set of suppliers. The MIP can also select other suppliers in addition to these if more capacity is needed. (This is basically a re-optimization of a portion of the problem – the portion of increased demand that the current suppliers are unable to provide.)
    b. Solve modified .lp files in CPLEX.
    c. Use a combination of the original results and the results from step b to create a new Excel Simulation Input File, because assume that the supplier changeover will take place after day 100 of the simulation. This will show what happens when a decision maker realizes there is a problem and then has the backup plan in place by day 100.
    d. Run the simulation in ARENA with modified Excel Simulation Input File to obtain the Option B results.
10. Demand Risk Analysis – Option C
    a. Create modified .lp files (for 10%, 20% and 30% cases) by using the files that were created for Option B and adding constraints to force MIP to *only* use the original set of suppliers. (This is basically a re-optimization of a portion of the problem – the portion of increased demand that the current suppliers are unable to provide.)
    b. Solve modified .lp files in CPLEX.

c. Use a combination of the original results and the results from step b to create a new Excel Simulation Input File, because assume that the supplier changeover will take place after day 100 of the simulation. This will show what happens when a decision maker realizes there is a problem and then has the backup plan in place by day 100.
d. Run the simulation in ARENA with modified Excel Simulation Input File to obtain the Option C results.

APPENDIX I

DATA SETS

Data Set 4_6

Component	Alternative	Time Period	Design Value
1	1	1	0.32
1	1	2	0.32
1	1	3	0.32
1	1	4	0.32
1	2	1	0.04
1	2	2	0.04
1	2	3	0.04
1	2	4	0.04
1	3	1	0.12
1	3	2	0.12
1	3	3	0.12
1	3	4	0.12
2	1	1	0.38
2	1	2	0.38
2	1	3	0.38
2	1	4	0.38
2	2	1	0.34
2	2	2	0.34
2	2	3	0.34
2	2	4	0.34
3	1	1	0.23
3	1	2	0.23
3	1	3	0.23
3	1	4	0.23
3	2	1	0.13
3	2	2	0.13
3	2	3	0.13
3	2	4	0.13
4	1	1	0.07
4	1	2	0.07
4	1	3	0.07
4	1	4	0.07

Component	Time Period	Strategic Exp
1	1	0.95
1	2	0.95
1	3	0.95
1	4	0.95
2	1	1
2	2	1
2	3	1
2	4	1
3	1	0.95
3	2	0.95
3	3	0.95
3	4	0.95
4	1	1
4	2	1
4	3	1
4	4	1

Supplier 1	Supplier 2	Network Costs
1	2	5020000
1	3	3050000
1	4	2750000
1	5	3170000
1	6	540000
2	3	1020000
2	4	1510000
2	5	190000
2	6	860000
3	4	2200000
3	5	2840000
3	6	2890000
4	5	4000000
4	6	310000
5	6	2120000

Component	Alternative	Time Period	TTM
1	1	1	600
1	2	1	50
1	3	1	100
2	1	1	110
2	2	1	90
3	1	1	200
3	2	1	80
4	1	1	150

	Cost
Design Switch	$ 100,000
Supplier Switch	$ 100,000

Time Period	Length (Days)	*Γ*	*Φ*	Inv Hold Cost	Selling Price 1	Selling Price 2	Selling Price 3
1	1000	0.9	1	3	200	600	800
2	1000	0.9	2	2	200	600	800
3	1000	0.9	3	1	200	600	800
4	1000	0.9	1	1	200	600	800

Data Set 4_6 Lead Times, Unit Costs, Supplier Reliability and Capacity

Component	Alternative	Supplier	Time Period	Mfg Time	Ship Time	Mfg Cost	Supplier Reliability	Capacity
1	1	1	1	2	1	10	0.96	8177000
1	1	1	2	2	1	10	0.96	8177000
1	1	1	3	2	1	10	0.96	8177000
1	1	1	4	2	1	10	0.96	8177000
1	1	2	1	11	10	6	0.87	7248000
1	1	2	2	11	10	6	0.87	7248000
1	1	2	3	11	10	6	0.87	7248000
1	1	2	4	11	10	6	0.87	7248000
1	1	5	1	10	8	3	0.97	4411000
1	1	5	2	10	8	3	0.97	4411000
1	1	5	3	10	8	3	0.97	4411000
1	1	5	4	10	8	3	0.97	4411000
1	1	6	1	10	8	10	0.92	876000
1	1	6	2	10	8	10	0.92	876000
1	1	6	3	10	8	10	0.92	876000
1	1	6	4	10	8	10	0.92	876000
1	2	2	1	6	2	5	0.87	7660000
1	2	2	2	6	2	5	0.87	7660000
1	2	2	3	6	2	5	0.87	7660000
1	2	2	4	6	2	5	0.87	7660000
1	2	3	1	4	1	7	0.98	9827000
1	2	3	2	4	1	7	0.98	9827000
1	2	3	3	4	1	7	0.98	9827000
1	2	3	4	4	1	7	0.98	9827000
1	2	4	1	21	2	2	0.85	5197000
1	2	4	2	21	2	2	0.85	5197000
1	2	4	3	21	2	2	0.85	5197000
1	2	4	4	21	2	2	0.85	5197000
1	3	6	1	10	2	3	0.92	8784000
1	3	6	2	10	2	3	0.92	8784000
1	3	6	3	10	2	3	0.92	8784000
1	3	6	4	10	2	3	0.92	8784000
2	1	3	1	21	5	8	0.98	4206000
2	1	3	2	21	5	8	0.98	4206000
2	1	3	3	21	5	8	0.98	4206000
2	1	3	4	21	5	8	0.98	4206000
2	2	2	1	9	3	5	0.87	8701000
2	2	2	2	9	3	5	0.87	8701000
2	2	2	3	9	3	5	0.87	8701000
2	2	2	4	9	3	5	0.87	8701000
2	2	4	1	8	10	3	0.85	6623000
2	2	4	2	8	10	3	0.85	6623000
2	2	4	3	8	10	3	0.85	6623000
2	2	4	4	8	10	3	0.85	6623000
2	2	6	1	3	1	1	0.92	10014000
2	2	6	2	3	1	1	0.92	10014000
2	2	6	3	3	1	1	0.92	10014000
2	2	6	4	3	1	1	0.92	10014000
3	1	1	1	3	1	8	0.96	382000
3	1	1	2	3	1	8	0.96	382000
3	1	1	3	3	1	8	0.96	382000
3	1	1	4	3	1	8	0.96	382000
3	2	1	1	25	3	10	0.96	5575000
3	2	1	2	25	3	10	0.96	5575000
3	2	1	3	25	3	10	0.96	5575000
3	2	1	4	25	3	10	0.96	5575000
3	2	3	1	7	5	2	0.98	3490000
3	2	3	2	7	5	2	0.98	3490000
3	2	3	3	7	5	2	0.98	3490000
3	2	3	4	7	5	2	0.98	3490000
4	1	1	1	11	12	5	0.96	5927000
4	1	1	2	11	12	5	0.96	5927000
4	1	1	3	11	12	5	0.96	5927000
4	1	1	4	11	12	5	0.96	5927000
4	1	5	1	10	10	9	0.97	5181000
4	1	5	2	10	10	9	0.97	5181000
4	1	5	3	10	10	9	0.97	5181000
4	1	5	4	10	10	9	0.97	5181000

Data Set 4_6 Transportation Costs

Component	Alternative	Ship From	Ship To	Time Period	Transp $
1	1	1	2	1	13
1	1	1	2	2	13
1	1	1	2	3	13
1	1	1	2	4	13
1	1	1	5	1	8
1	1	1	5	2	8
1	1	1	5	3	8
1	1	1	5	4	8
1	1	1	6	1	16
1	1	1	6	2	16
1	1	1	6	3	16
1	1	1	6	4	16
1	1	2	1	1	7
1	1	2	1	2	7
1	1	2	1	3	7
1	1	2	1	4	7
1	1	2	5	1	16
1	1	2	5	2	16
1	1	2	5	3	16
1	1	2	5	4	16
1	1	2	6	1	5
1	1	2	6	2	5
1	1	2	6	3	5
1	1	2	6	4	5
1	1	3	1	1	8
1	1	3	1	2	8
1	1	3	1	3	8
1	1	3	1	4	8
1	1	3	2	1	7
1	1	3	2	2	7
1	1	3	2	3	7
1	1	3	2	4	7
1	1	3	5	1	3
1	1	3	5	2	3
1	1	3	5	3	3
1	1	3	5	4	3
1	1	3	6	1	7
1	1	3	6	2	7
1	1	3	6	3	7
1	1	3	6	4	7
1	1	4	1	1	3
1	1	4	1	2	3
1	1	4	1	3	3
1	1	4	1	4	3

Component	Alternative	Ship From	Ship To	Time Period	Transp $
1	1	4	2	1	15
1	1	4	2	2	15
1	1	4	2	3	15
1	1	4	2	4	15
1	1	4	5	1	11
1	1	4	5	2	11
1	1	4	5	3	11
1	1	4	5	4	11
1	1	4	6	1	7
1	1	4	6	2	7
1	1	4	6	3	7
1	1	4	6	4	7
1	1	5	1	1	3
1	1	5	1	2	3
1	1	5	1	3	3
1	1	5	1	4	3
1	1	5	2	1	13
1	1	5	2	2	13
1	1	5	2	3	13
1	1	5	2	4	13
1	1	5	6	1	6
1	1	5	6	2	6
1	1	5	6	3	6
1	1	5	6	4	6
1	1	6	1	1	4
1	1	6	1	2	4
1	1	6	1	3	4
1	1	6	1	4	4
1	1	6	2	1	3
1	1	6	2	2	3
1	1	6	2	3	3
1	1	6	2	4	3
1	1	6	5	1	3
1	1	6	5	2	3
1	1	6	5	3	3
1	1	6	5	4	3
1	2	1	2	1	6
1	2	1	2	2	6
1	2	1	2	3	6
1	2	1	2	4	6
1	2	1	3	1	16
1	2	1	3	2	16
1	2	1	3	3	16
1	2	1	3	4	16

Component	Alternative	Ship From	Ship To	Time Period	Transp $
1	2	1	4	1	7
1	2	1	4	2	7
1	2	1	4	3	7
1	2	1	4	4	7
1	2	2	3	1	13
1	2	2	3	2	13
1	2	2	3	3	13
1	2	2	3	4	13
1	2	2	4	1	6
1	2	2	4	2	6
1	2	2	4	3	6
1	2	2	4	4	6
1	2	3	2	1	2
1	2	3	2	2	2
1	2	3	2	3	2
1	2	3	2	4	2
1	2	3	4	1	13
1	2	3	4	2	13
1	2	3	4	3	13
1	2	3	4	4	13
1	2	4	2	1	9
1	2	4	2	2	9
1	2	4	2	3	9
1	2	4	2	4	9
1	2	4	3	1	8
1	2	4	3	2	8
1	2	4	3	3	8
1	2	4	3	4	8
1	2	5	2	1	13
1	2	5	2	2	13
1	2	5	2	3	13
1	2	5	2	4	13
1	2	5	3	1	2
1	2	5	3	2	2
1	2	5	3	3	2
1	2	5	3	4	2
1	2	5	4	1	8
1	2	5	4	2	8
1	2	5	4	3	8
1	2	5	4	4	8
1	2	6	2	1	14
1	2	6	2	2	14
1	2	6	2	3	14
1	2	6	2	4	14

Component	Alternative	Ship From	Ship To	Time Period	Transp $
1	2	6	3	1	4
1	2	6	3	2	4
1	2	6	3	3	4
1	2	6	3	4	4
1	2	6	4	1	5
1	2	6	4	2	5
1	2	6	4	3	5
1	2	6	4	4	5
1	3	1	6	1	2
1	3	1	6	2	2
1	3	1	6	3	2
1	3	1	6	4	2
1	3	2	6	1	13
1	3	2	6	2	13
1	3	2	6	3	13
1	3	2	6	4	13
1	3	3	6	1	14
1	3	3	6	2	14
1	3	3	6	3	14
1	3	3	6	4	14
1	3	4	6	1	6
1	3	4	6	2	6
1	3	4	6	3	6
1	3	4	6	4	6
1	3	5	6	1	12
1	3	5	6	2	12
1	3	5	6	3	12
1	3	5	6	4	12
2	1	1	3	1	4
2	1	1	3	2	4
2	1	1	3	3	4
2	1	1	3	4	4
2	1	2	3	1	10
2	1	2	3	2	10
2	1	2	3	3	10
2	1	2	3	4	10
2	1	4	3	1	5
2	1	4	3	2	5
2	1	4	3	3	5
2	1	4	3	4	5
2	1	5	3	1	16
2	1	5	3	2	16
2	1	5	3	3	16
2	1	5	3	4	16

Data Set 4_6 Transportation Costs (cont.)

Component	Alternative	Ship From	Ship To	Time Period	Transp $	Component	Alternative	Ship From	Ship To	Time Period	Transp $	Component	Alternative	Ship From	Ship To	Time Period	Transp $	Component	Alternative	Ship From	Ship To	Time Period	Transp $
2	1	6	3	1	3	2	2	5	2	1	5	3	2	2	1	1	8	4	1	2	5	1	3
2	1	6	3	2	3	2	2	5	2	2	5	3	2	2	1	2	8	4	1	2	5	2	3
2	1	6	3	3	3	2	2	5	2	3	5	3	2	2	1	3	8	4	1	2	5	3	3
2	1	6	3	4	3	2	2	5	2	4	5	3	2	2	1	4	8	4	1	2	5	4	3
2	2	1	2	1	7	2	2	5	4	1	5	3	2	2	3	1	10	4	1	3	1	1	7
2	2	1	2	2	7	2	2	5	4	2	5	3	2	2	3	2	10	4	1	3	1	2	7
2	2	1	2	3	7	2	2	5	4	3	5	3	2	2	3	3	10	4	1	3	1	3	7
2	2	1	2	4	7	2	2	5	4	4	5	3	2	2	3	4	10	4	1	3	1	4	7
2	2	1	4	1	8	2	2	5	6	1	10	3	2	3	1	1	14	4	1	3	5	1	8
2	2	1	4	2	8	2	2	5	6	2	10	3	2	3	1	2	14	4	1	3	5	2	8
2	2	1	4	3	8	2	2	5	6	3	10	3	2	3	1	3	14	4	1	3	5	3	8
2	2	1	4	4	8	2	2	5	6	4	10	3	2	3	1	4	14	4	1	3	5	4	8
2	2	1	6	1	7	2	2	6	2	1	3	3	2	4	1	1	16	4	1	4	1	1	2
2	2	1	6	2	7	2	2	6	2	2	3	3	2	4	1	2	16	4	1	4	1	2	2
2	2	1	6	3	7	2	2	6	2	3	3	3	2	4	1	3	16	4	1	4	1	3	2
2	2	1	6	4	7	2	2	6	2	4	3	3	2	4	1	4	16	4	1	4	1	4	2
2	2	2	4	1	4	2	2	6	4	1	12	3	2	4	3	1	6	4	1	4	5	1	12
2	2	2	4	2	4	2	2	6	4	2	12	3	2	4	3	2	6	4	1	4	5	2	12
2	2	2	4	3	4	2	2	6	4	3	12	3	2	4	3	3	6	4	1	4	5	3	12
2	2	2	4	4	4	2	2	6	4	4	12	3	2	4	3	4	6	4	1	4	5	4	12
2	2	2	6	1	4	3	1	2	1	1	10	3	2	5	1	1	5	4	1	5	1	1	6
2	2	2	6	2	4	3	1	2	1	2	10	3	2	5	1	2	5	4	1	5	1	2	6
2	2	2	6	3	4	3	1	2	1	3	10	3	2	5	1	3	5	4	1	5	1	3	6
2	2	2	6	4	4	3	1	2	1	4	10	3	2	5	1	4	5	4	1	5	1	4	6
2	2	3	2	1	6	3	1	3	1	1	14	3	2	5	3	1	14	4	1	6	1	1	16
2	2	3	2	2	6	3	1	3	1	2	14	3	2	5	3	2	14	4	1	6	1	2	16
2	2	3	2	3	6	3	1	3	1	3	14	3	2	5	3	3	14	4	1	6	1	3	16
2	2	3	2	4	6	3	1	3	1	4	14	3	2	5	3	4	14	4	1	6	1	4	16
2	2	3	4	1	11	3	1	4	1	1	10	3	2	6	1	1	4	4	1	6	5	1	8
2	2	3	4	2	11	3	1	4	1	2	10	3	2	6	1	2	4	4	1	6	5	2	8
2	2	3	4	3	11	3	1	4	1	3	10	3	2	6	1	3	4	4	1	6	5	3	8
2	2	3	4	4	11	3	1	4	1	4	10	3	2	6	1	4	4	4	1	6	5	4	8
2	2	3	6	1	16	3	1	5	1	1	5	3	2	6	3	1	6						
2	2	3	6	2	16	3	1	5	1	2	5	3	2	6	3	2	6						
2	2	3	6	3	16	3	1	5	1	3	5	3	2	6	3	3	6						
2	2	3	6	4	16	3	1	5	1	4	5	3	2	6	3	4	6						
2	2	4	2	1	10	3	1	6	1	1	5	4	1	1	5	1	8						
2	2	4	2	2	10	3	1	6	1	2	5	4	1	1	5	2	8						
2	2	4	2	3	10	3	1	6	1	3	5	4	1	1	5	3	8						
2	2	4	2	4	10	3	1	6	1	4	5	4	1	1	5	4	8						
2	2	4	6	1	15	3	2	1	3	1	7	4	1	2	1	1	6						
2	2	4	6	2	15	3	2	1	3	2	7	4	1	2	1	2	6						
2	2	4	6	3	15	3	2	1	3	3	7	4	1	2	1	3	6						
2	2	4	6	4	15	3	2	1	3	4	7	4	1	2	1	4	6						

Data Set 5-5

Component	Alternative	Time Period	Design Value
1	1	1	0
1	1	2	0
1	1	3	0
1	1	4	0
2	1	1	0.34
2	1	2	0.34
2	1	3	0.34
2	1	4	0.34
2	2	1	0.276
2	2	2	0.272
2	2	3	0.242
2	2	4	0.208
3	1	1	0.26
3	1	2	0.26
3	1	3	0.26
3	1	4	0.26
3	2	1	0.209
3	2	2	0.184
3	2	3	0.134
3	2	4	0.084
4	1	1	0.22
4	1	2	0.22
4	1	3	0.22
4	1	4	0.22
4	2	1	0.181
4	2	2	0.17
4	2	3	0.17
4	2	4	0.148
5	1	1	0.18
5	1	2	0.18
5	1	3	0.18
5	1	4	0.18
5	2	1	0.146
5	2	2	0.146
5	2	3	0.146
5	2	4	0.146

Component	Time Period	Strategic Exp (H)	Strategic Exp (L)
1	1	1	1
1	2	1	1
1	3	1	1
1	4	1	1
2	1	1	0.8
2	2	1	0.8
2	3	1	0.8
2	4	1	0.8
3	1	1	0.8
3	2	1	0.8
3	3	1	0.8
3	4	1	0.8
4	1	1	0.8
4	2	1	0.8
4	3	1	0.8
4	4	1	0.8
5	1	1	0.8
5	2	1	0.8
5	3	1	0.8
5	4	1	0.8

Supplier 1	Supplier 2	Network Costs
1	2	3360000
1	3	5060000
1	4	4670000
1	5	1410000
2	3	430000
2	4	2850000
2	5	570000
3	4	2130000
3	5	4290000
4	5	4510000

Component	Alternative	Time Period	TTM
1	1	1	100
2	1	1	260
2	2	1	600
3	1	1	20
3	2	1	80
4	1	1	150
4	2	1	178
5	1	1	250
5	2	1	385

	Cost (H)	Cost (L)
Design Switch	$100,000,000	$ 100,000
Supplier Switch	$ 10,000,000	$ 10,000

Time Period	Length (Days)	Γ	Φ	Inv Hold Cost	Selling Price 1	Selling Price 2	Selling Price 3
1	1000	0.9	1	1	10	20	40
2	1000	0.9	2	0.75	10	20	40
3	1000	0.9	3	0.5	10	20	40
4	1000	0.9	1	0.4	10	20	40

Data Set 5_5 Lead Times, Unit Costs, Supplier Reliability and Capacity

Component	Alternative	Supplier	Time Period	Mfg Time	Ship Time	Mfg Cost (S)	Mfg Cost (D)	Supplier Reliability (S)	Supplier Reliability (D)	Capacity
1	1	1	1	1	1	1	1	0.99	0.99	2000000
1	1	1	2	1	1	1	1	0.99	0.99	2000000
1	1	1	3	1	1	1	1	0.99	0.99	2000000
1	1	1	4	1	1	1	1	0.99	0.99	2000000
2	1	1	1	4	1	3	3	0.99	0.99	200000
2	1	1	2	4	1	2	2	0.99	0.99	200000
2	1	1	3	4	1	2	2	0.99	0.99	200000
2	1	1	4	4	1	1.5	1.5	0.99	0.99	200000
2	1	3	1	3	2	4	6	0.987	0.987	500000
2	1	3	2	3	2	3	5	0.987	0.987	500000
2	1	3	3	3	2	1.5	3.5	0.987	0.987	500000
2	1	3	4	3	2	1.5	3.5	0.987	0.987	500000
2	2	1	1	1	1	1.5	4	0.99	0.99	400000
2	2	1	2	1	1	1.5	4	0.99	0.99	400000
2	2	1	3	1	1	1	3	0.99	0.99	400000
2	2	1	4	1	1	0.5	2.5	0.99	0.99	400000
2	2	3	1	1	1	1	2	0.987	0.987	100000
2	2	3	2	1	1	1	2	0.987	0.987	100000
2	2	3	3	1	1	1	2	0.987	0.987	100000
2	2	3	4	1	1	1	2	0.987	0.987	100000
2	2	4	1	1	1	0.7	0.7	0.98	0.98	600000
2	2	4	2	1	1	0.7	0.7	0.98	0.98	600000
2	2	4	3	1	1	0.5	0.5	0.98	0.98	600000
2	2	4	4	1	1	0.5	0.5	0.98	0.98	600000
3	1	4	1	3	4	3	3	0.98	0.98	200000
3	1	4	2	3	4	3	3	0.98	0.98	200000
3	1	4	3	3	4	2.5	2.5	0.98	0.98	200000
3	1	4	4	3	4	2	2	0.98	0.98	200000
3	1	5	1	3	3	4	6	0.975	0.961	500000
3	1	5	2	3	3	3.5	5.5	0.975	0.961	500000
3	1	5	3	3	3	3.5	5.5	0.975	0.961	500000
3	1	5	4	3	3	2.5	4.5	0.975	0.961	500000
3	2	4	1	1	1	1.5	3.5	0.98	0.98	600000
3	2	4	2	1	1	1.5	3.5	0.98	0.98	600000
3	2	4	3	1	1	1	3	0.98	0.98	600000
3	2	4	4	1	1	0.5	2.5	0.98	0.98	600000
3	2	5	1	1	1	1	1	0.975	0.961	600000
3	2	5	2	1	1	1	1	0.975	0.961	600000
4	1	2	1	5	3	4	4	0.978	0.97	600000
4	1	2	2	5	3	3	3	0.978	0.97	600000
4	1	2	3	5	3	3	3	0.978	0.97	600000
4	1	2	4	5	3	2.5	2.5	0.978	0.97	600000
4	1	3	1	5	3	6	9	0.987	0.987	200000
4	1	3	2	5	3	5	8	0.987	0.987	200000
4	1	3	3	5	3	5	8	0.987	0.987	200000
4	1	3	4	5	3	4	7	0.987	0.987	200000
4	2	2	1	2	1	3	5	0.978	0.97	400000
4	2	2	2	2	1	2	4	0.978	0.97	400000
4	2	3	1	2	1	2	2	0.987	0.987	900000
4	2	3	2	2	1	2	2	0.987	0.987	900000
4	2	3	3	2	1	2	2	0.987	0.987	900000
4	2	3	4	2	1	2	2	0.987	0.987	900000
4	2	4	1	1	1	2	3	0.98	0.98	1000000
4	2	4	2	1	1	2	3	0.98	0.98	1000000
4	2	4	3	1	1	2	3	0.98	0.98	1000000
4	2	4	4	1	1	2	3	0.98	0.98	1000000
5	1	1	1	4	3	0.5	1	0.99	0.99	100000
5	1	1	2	4	3	0.5	1	0.99	0.99	100000
5	1	1	3	4	3	0.5	1	0.99	0.99	100000
5	1	1	4	4	3	0.5	1	0.99	0.99	100000
5	1	5	1	4	2	0.4	0.4	0.975	0.961	1000000
5	1	5	2	4	2	0.4	0.4	0.975	0.961	1000000
5	1	5	3	4	2	0.4	0.4	0.975	0.961	1000000
5	1	5	4	4	2	0.4	0.4	0.975	0.961	1000000
5	2	1	1	4	1	0.3	0.8	0.99	0.99	500000
5	2	1	2	4	1	0.3	0.8	0.99	0.99	500000
5	2	1	3	4	1	0.3	0.8	0.99	0.99	500000
5	2	1	4	4	1	0.3	0.8	0.99	0.99	500000
5	2	5	1	1	1	0.2	0.2	0.975	0.961	800000
5	2	5	2	1	1	0.2	0.2	0.975	0.961	800000
5	2	5	3	1	1	0.2	0.2	0.975	0.961	800000
5	2	5	4	1	1	0.2	0.2	0.975	0.961	800000

Data Set 5_5 Transportation Costs

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
2	1	1	1	1	0.5	0.7
2	1	1	1	2	0.5	0.7
2	1	1	1	3	0.5	0.7
2	1	1	1	4	0.5	0.7
2	1	1	3	1	0.5	0.5
2	1	1	3	2	0.5	0.5
2	1	1	3	3	0.5	0.5
2	1	1	3	4	0.5	0.5
2	2	1	1	1	2	4
2	2	1	1	2	2	4
2	2	1	1	3	2	4
2	2	1	1	4	2	4
2	2	1	3	1	1	1
2	2	1	3	2	1	1
2	2	1	3	3	1	1
2	2	1	3	4	1	1
2	2	1	4	1	2	3
2	2	1	4	2	2	3
2	2	1	4	3	2	3
2	2	1	4	4	2	3
3	1	1	4	1	1.2	2
3	1	1	4	2	1.2	2
3	1	1	4	3	1.2	2
3	1	1	4	4	1.2	2
3	1	1	5	1	0.6	0.6
3	1	1	5	2	0.6	0.6
3	1	1	5	3	0.6	0.6
3	1	1	5	4	0.6	0.6
3	2	1	4	1	1.2	2
3	2	1	4	2	1.2	2
3	2	1	4	3	1.2	2
3	2	1	4	4	1.2	2
3	2	1	5	1	1	1
3	2	1	5	2	1	1
3	2	1	5	3	1	1
3	2	1	5	4	1	1
4	1	1	2	1	0.6	0.6
4	1	1	2	2	0.6	0.6
4	1	1	2	3	0.6	0.6
4	1	1	2	4	0.6	0.6
4	1	1	3	1	1.4	2.4
4	1	1	3	2	1.4	2.4
4	1	1	3	3	1.4	2.4
4	1	1	3	4	1.4	2.4
4	2	1	2	1	1	1
4	2	1	2	2	1	1
4	2	1	2	3	1	1
4	2	1	2	4	1	1
4	2	1	3	1	3	5
4	2	1	3	2	3	5
4	2	1	3	3	3	5
4	2	1	3	4	3	5
4	2	1	4	1	2	3
4	2	1	4	2	2	3
4	2	1	4	3	2	3
4	2	1	4	4	2	3
5	1	2	1	1	1.1	1.1
5	1	2	1	2	1.1	1.1
5	1	2	1	3	1.1	1.1
5	1	2	1	4	1.1	1.1
5	1	2	5	1	2	4
5	1	2	5	2	2	4
5	1	2	5	3	2	4
5	1	2	5	4	2	4
5	1	3	1	1	2	2
5	1	3	1	2	2	2
5	1	3	1	3	2	2
5	1	3	1	4	2	2
5	1	3	5	1	3	4
5	1	3	5	2	3	4
5	1	3	5	3	3	4
5	1	3	5	4	3	4
5	1	4	1	1	0.8	0.8
5	1	4	1	2	0.8	0.8
5	1	4	1	3	0.8	0.8
5	1	4	1	4	0.8	0.8
5	1	4	5	1	2	3
5	1	4	5	2	2	3
5	1	4	5	3	2	3
5	1	4	5	4	2	3
5	2	2	1	1	2.5	4
5	2	2	1	2	2.5	4
5	2	2	1	3	2.5	4
5	2	2	1	4	2.5	4
5	2	2	5	2	1	1
5	2	2	5	3	1	1
5	2	2	5	4	1	1
5	2	3	1	1	1.6	1.6
5	2	3	1	2	1.6	1.6
5	2	3	1	3	1.6	1.6
5	2	3	1	4	1.6	1.6
5	2	3	5	1	4	7
5	2	3	5	2	4	7
5	2	3	5	3	4	7
5	2	3	5	4	4	7
5	2	4	1	1	1.1	1.1
5	2	4	1	2	1.1	1.1
5	2	4	1	3	1.1	1.1
5	2	4	1	4	1.1	1.1
5	2	4	5	1	1.5	3
5	2	4	5	2	1.5	3
5	2	4	5	3	1.5	3
5	2	4	5	4	1.5	3
5	2	5	5	4	0	0

Data Set 6_7

Component	Alternative	Time Period	Design Value
1	1	1	0
1	1	2	0
1	1	3	0
1	1	4	0
2	1	1	0.4
2	1	2	0.4
2	1	3	0.4
2	1	4	0.4
2	2	1	0.34
2	2	2	0.28
2	2	3	0.22
2	2	4	0.12
3	1	1	0.14
3	1	2	0.14
3	1	3	0.14
3	1	4	0.14
3	2	1	0.1
3	2	2	0.08
3	2	3	0.06
3	2	4	0.03
4	1	1	0.13
4	1	2	0.13
4	1	3	0.13
4	1	4	0.13
4	2	1	0.1
4	2	2	0.1
4	2	3	0.07
4	2	4	0.02
5	1	1	0.16
5	1	2	0.16
5	1	3	0.16
5	1	4	0.16
5	2	1	0.1
5	2	2	0.09
5	2	3	0.04
5	2	4	0.01
6	1	1	0.17
6	1	2	0.17
6	1	3	0.17
6	1	4	0.17
6	2	1	0.13
6	2	2	0.13
6	2	3	0.09
6	2	4	0.06

Component	Time Period	Strategic Exp (H)	Strategic Exp (L)
1	1	1	1
1	2	1	1
1	3	1	1
1	4	1	1
2	1	1	0.8
2	2	1	0.8
2	3	1	0.8
2	4	1	0.8
3	1	1	0.8
3	2	1	0.8
3	3	1	0.8
3	4	1	0.8
4	1	1	0.8
4	2	1	0.8
4	3	1	0.8
4	4	1	0.8
5	1	1	0.8
5	2	1	0.8
5	3	1	0.8
5	4	1	0.8
6	1	1	0.8
6	2	1	0.8
6	3	1	0.8
6	4	1	0.8

Supplier 1	Supplier 2	Network Costs (H)	Network Costs (L)
1	2	11100000	3700000
1	3	11610000	3870000
1	4	7620000	2540000
1	5	10830000	3610000
1	6	360000	120000
1	7	10920000	3640000
2	3	7020000	2340000
2	4	9510000	3170000
2	5	2610000	870000
2	6	13110000	4370000
2	7	7410000	2470000
3	4	6150000	2050000
3	5	7950000	2650000
3	6	15030000	5010000
3	7	11790000	3930000
4	5	11490000	3830000
4	6	15180000	5060000
4	7	2370000	790000
5	6	11340000	3780000
5	7	11670000	3890000
6	7	6720000	2240000

Component	Alternative	Time Period	TTM
1	1	1	100
2	1	1	150
2	1	2	250
3	1	1	320
3	1	2	400
4	1	1	850
4	1	2	100
5	1	1	580
5	1	2	350
6	1	1	600
6	1	2	450

	Cost (H)	Cost (L)
Design Switch	$ 1,000,000,000	$100,000,000
Supplier Switch	$ 1,000,000,000	$100,000,000

Time Period	Length (Days)	Γ	Φ	Inv Hold Cost	Selling Price 1	Selling Price 2	Selling Price 3
1	1000	0.9	1	4	200	400	800
2	1000	0.9	1.2	3	200	400	800
3	1000	0.9	1.6	2	200	400	800
4	1000	0.9	1	1	200	400	800

Data Set 6_7 Lead Times, Unit Costs, Supplier Reliability and Capacity

Component	Alternative	Supplier	Time Period	Mfg Time	Ship Time	Mfg Cost (S)	Mfg Cost (D)	Supplier Reliability (S)	Supplier Reliability (D)	Capacity
1	1	1	1	1	1	6	6	0.99	0.99	10000000
1	1	1	2	1	1	6	6	0.99	0.99	15000000
1	1	1	3	1	1	6	6	0.99	0.99	25000000
1	1	1	4	1	1	6	6	0.99	0.99	30000000
2	1	2	1	1	1	60	60	0.982	0.979	500000
2	1	2	2	1	1	60	60	0.982	0.979	1000000
2	1	2	3	1	1	48	48	0.982	0.979	1800000
2	1	2	4	1	1	42	42	0.982	0.979	2000000
2	1	3	1	4	1	72	36	0.985	0.98	250000
2	1	3	2	4	1	72	36	0.985	0.98	800000
2	1	3	3	4	1	54	27	0.985	0.98	1200000
2	1	3	4	4	1	48	24	0.985	0.98	2000000
2	1	7	1	1	1	78	78	0.991	0.991	400000
2	1	7	2	1	1	60	60	0.991	0.991	1000000
2	1	7	3	1	1	42	42	0.991	0.991	1500000
2	1	7	4	1	1	36	36	0.991	0.991	2000000
2	2	2	1	1	1	42	42	0.982	0.979	1000000
2	2	2	2	1	1	30	30	0.982	0.979	2000000
2	2	3	1	1	1	36	18	0.985	0.98	1000000
2	2	3	2	1	1	30	15	0.985	0.98	2000000
2	2	3	3	1	1	18	9	0.985	0.98	2000000
2	2	3	4	1	1	18	9	0.985	0.98	2000000
2	2	7	1	3	1	54	54	0.991	0.991	1500000
2	2	7	2	3	1	36	36	0.991	0.991	1500000
2	2	7	3	3	1	18	18	0.991	0.991	1500000
3	1	1	1	2	1	60	60	0.99	0.99	600000
3	1	1	2	2	1	54	54	0.99	0.99	1000000
3	1	1	3	2	1	42	42	0.99	0.99	2000000
3	1	1	4	2	1	36	36	0.99	0.99	3000000
3	1	2	1	1	1	48	48	0.982	0.979	250000
3	1	2	2	1	1	48	48	0.982	0.979	800000
3	1	2	3	1	1	36	36	0.982	0.979	1600000
3	1	2	4	1	1	24	24	0.982	0.979	3000000
3	1	5	1	3	1	42	42	0.986	0.98	400000
3	1	5	2	3	1	36	36	0.986	0.98	1200000
3	1	5	3	3	1	30	30	0.986	0.98	1600000
3	1	5	4	3	1	24	24	0.986	0.98	2400000
3	2	1	1	4	1	42	21	0.99	0.99	1000000
3	2	1	2	4	1	36	18	0.99	0.99	2000000
3	2	1	3	4	1	24	12	0.99	0.99	3000000
3	2	1	4	4	1	12	6	0.99	0.99	3000000
3	2	2	1	1	1	30	30	0.982	0.979	2000000
3	2	2	2	1	1	30	30	0.982	0.979	2000000
3	2	2	3	1	1	18	18	0.982	0.979	2000000
3	2	5	1	4	1	24	24	0.986	0.98	1000000
4	1	3	1	3	1	48	24	0.985	0.98	600000
4	1	3	2	3	1	42	21	0.985	0.98	1200000
4	1	3	3	3	1	36	18	0.985	0.98	2000000
4	1	3	4	3	1	24	12	0.985	0.98	2000000
4	1	5	1	2	1	48	48	0.986	0.98	800000
4	1	5	2	2	1	42	42	0.986	0.98	1200000
4	1	5	3	2	1	30	30	0.986	0.98	1600000
4	1	5	4	2	1	18	18	0.986	0.98	2000000
4	1	6	1	1	1	36	36	0.982	0.975	1000000
4	1	6	2	1	1	30	30	0.982	0.975	1500000
4	1	6	3	1	1	30	30	0.982	0.975	2000000
4	1	6	4	1	1	24	24	0.982	0.975	2000000
4	2	3	1	4	1	36	18	0.985	0.98	1000000
4	2	3	2	4	1	30	15	0.985	0.98	2000000
4	2	3	3	4	1	24	12	0.985	0.98	2000000
4	2	3	4	4	1	12	6	0.985	0.98	2000000
4	2	5	1	4	1	30	30	0.986	0.98	1000000
4	2	5	2	4	1	24	24	0.986	0.98	1400000
4	2	5	3	4	1	18	18	0.986	0.98	1400000
4	2	6	1	1	1	24	24	0.982	0.975	3000000
4	2	6	2	1	1	18	18	0.982	0.975	3000000
5	1	3	2	0	0	72	36	0.985	0.98	800000
5	1	3	3	0	0	60	30	0.985	0.98	1200000
5	1	3	4	0	0	54	27	0.985	0.98	2000000
5	1	4	1	3	1	84	84	0.991	0.991	1000000
5	1	4	2	3	1	72	72	0.991	0.991	1000000
5	1	4	3	3	1	66	66	0.991	0.991	1600000

Data Set 6_7 Lead Times, Unit Costs, Supplier Reliability and Capacity (cont.)

Component	Alternative	Supplier	Time Period	Mfg Time	Ship Time	Mfg Cost (S)	Mfg Cost (D)	Supplier Reliability (S)	Supplier Reliability (D)	Capacity
5	1	4	4	3	1	54	54	0.991	0.991	2400000
5	1	5	1	1	1	60	60	0.986	0.98	1000000
5	1	5	2	1	1	54	54	0.986	0.98	1600000
5	1	5	3	1	1	48	48	0.986	0.98	2000000
5	1	5	4	1	1	36	36	0.986	0.98	2000000
5	2	1	1	3	1	66	66	0.99	0.99	2000000
5	2	1	2	3	1	54	54	0.99	0.99	2000000
5	2	1	3	3	1	48	48	0.99	0.99	2000000
5	2	1	4	3	1	36	36	0.99	0.99	2000000
5	2	3	1	1	1	48	24	0.985	0.98	3000000
5	2	3	2	1	1	42	21	0.985	0.98	3000000
5	2	4	1	1	1	60	30	0.991	0.991	1000000
5	2	4	2	1	1	48	24	0.991	0.991	1000000
5	2	4	3	1	1	42	21	0.991	0.991	2000000
5	2	4	4	1	1	30	15	0.991	0.991	2000000
6	1	2	1	1	1	30	30	0.982	0.979	800000
6	1	2	2	1	1	30	30	0.982	0.979	1200000
6	1	2	3	1	1	24	24	0.982	0.979	2000000
6	1	2	4	1	1	24	24	0.982	0.979	2000000
6	1	6	1	2	1	24	12	0.982	0.975	1000000
6	1	6	2	2	1	18	9	0.982	0.975	1600000
6	1	6	3	2	1	18	9	0.982	0.975	2000000
6	1	6	4	2	1	18	9	0.982	0.975	2000000
6	1	7	1	1	1	30	30	0.991	0.991	700000
6	1	7	2	1	1	24	24	0.991	0.991	1400000
6	1	7	3	1	1	18	18	0.991	0.991	2000000
6	1	7	4	1	1	18	18	0.991	0.991	2000000
6	2	2	1	1	1	18	9	0.982	0.979	3000000
6	2	2	2	1	1	12	6	0.982	0.979	3000000
6	2	2	3	1	1	12	6	0.982	0.979	2000000
6	2	6	1	4	1	18	9	0.982	0.975	2000000
6	2	6	2	4	1	12	6	0.982	0.975	3000000
6	2	6	3	4	1	12	6	0.982	0.975	3000000
6	2	6	4	4	1	12	6	0.982	0.975	3000000
6	2	7	1	1	0	12	12	0.991	0.991	3000000
6	2	7	2	1	0	6	6	0.991	0.991	3000000

Data Set 6_7 Transportation Costs

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
1	1	1	1	1	4	4
1	1	1	1	2	4	4
1	1	1	1	3	4	4
1	1	1	1	4	4	4
1	1	2	1	1	2	2
1	1	2	1	2	2	2
1	1	2	1	3	2	2
1	1	2	1	4	2	2
1	1	3	1	1	8	8
1	1	3	1	2	8	8
1	1	3	1	3	8	8
1	1	3	1	4	8	8
1	1	4	1	1	4	4
1	1	4	1	2	4	4
1	1	4	1	3	4	4
1	1	4	1	4	4	4
1	1	5	1	1	8	8
1	1	5	1	2	8	8
1	1	5	1	3	8	8
1	1	5	1	4	8	8
1	1	6	1	1	6	6
1	1	6	1	2	6	6
1	1	6	1	3	6	6
1	1	6	1	4	6	6
1	1	7	1	1	2	2
1	1	7	1	2	2	2
1	1	7	1	3	2	2
1	1	7	1	4	2	2
2	1	1	2	1	6	6
2	1	1	2	2	6	6
2	1	1	2	3	6	6
2	1	1	2	4	6	6
2	1	1	3	1	2	1
2	1	1	3	2	2	1
2	1	1	3	3	2	1
2	1	1	3	4	2	1
2	1	1	7	1	6	6
2	1	1	7	2	6	6
2	1	1	7	3	6	6
2	1	1	7	4	6	6
2	1	2	2	1	4	4
2	1	2	2	2	4	4
2	1	2	2	3	4	4
2	1	2	2	4	4	4
2	1	2	3	1	4	2
2	1	2	3	2	4	2
2	1	2	3	3	4	2
2	1	2	3	4	4	2
2	1	2	7	1	6	6
2	1	2	7	2	6	6
2	1	2	7	3	6	6
2	1	2	7	4	6	6
2	1	3	2	1	2	2
2	1	3	2	2	2	2
2	1	3	2	3	2	2
2	1	3	2	4	2	2
2	1	3	3	1	6	3
2	1	3	3	2	6	3
2	1	3	3	3	6	3
2	1	3	3	4	6	3
2	1	3	7	1	8	8
2	1	3	7	2	8	8
2	1	3	7	3	8	8
2	1	3	7	4	8	8
2	1	4	2	1	4	4
2	1	4	2	2	4	4
2	1	4	2	3	4	4
2	1	4	2	4	4	4
2	1	4	3	1	2	1
2	1	4	3	2	2	1
2	1	4	3	3	2	1
2	1	4	3	4	2	1
2	1	4	7	1	6	6
2	1	4	7	2	6	6
2	1	4	7	3	6	6
2	1	4	7	4	6	6
2	1	5	2	1	4	4
2	1	5	2	2	4	4
2	1	5	2	3	4	4
2	1	5	2	4	4	4
2	1	5	3	1	4	2
2	1	5	3	2	4	2
2	1	5	3	3	4	2
2	1	5	3	4	4	2
2	1	5	7	1	6	6
2	1	5	7	2	6	6
2	1	5	7	3	6	6
2	1	5	7	4	6	6
2	1	6	2	1	8	8
2	1	6	2	2	8	8
2	1	6	2	3	8	8
2	1	6	2	4	8	8
2	1	6	3	1	8	4
2	1	6	3	2	8	4
2	1	6	3	3	8	4
2	1	6	3	4	8	4
2	1	6	7	1	8	8
2	1	6	7	2	8	8
2	1	6	7	3	8	8
2	1	6	7	4	8	8
2	1	7	2	1	2	2
2	1	7	2	2	2	2
2	1	7	2	3	2	2
2	1	7	2	4	2	2
2	1	7	3	1	8	4
2	1	7	3	2	8	4
2	1	7	3	3	8	4
2	1	7	3	4	8	4
2	1	7	7	1	4	4
2	1	7	7	2	4	4
2	1	7	7	3	4	4
2	1	7	7	4	4	4
2	2	1	2	1	6	6
2	2	1	2	2	6	6
2	2	1	2	3	6	6
2	2	1	2	4	6	6
2	2	1	3	1	2	1
2	2	1	3	2	2	1
2	2	1	3	3	2	1
2	2	1	3	4	2	1
2	2	1	7	1	8	8
2	2	1	7	2	8	8
2	2	1	7	3	8	8
2	2	1	7	4	8	8
2	2	2	2	1	6	6
2	2	2	2	2	6	6
2	2	2	2	3	6	6
2	2	2	2	4	6	6
2	2	2	3	1	2	1
2	2	2	3	2	2	1
2	2	2	3	3	2	1
2	2	2	3	4	2	1
2	2	2	7	1	4	4
2	2	2	7	2	4	4
2	2	2	7	3	4	4
2	2	2	7	4	4	4
2	2	3	2	1	4	4
2	2	3	2	2	4	4
2	2	3	2	3	4	4
2	2	3	2	4	4	4
2	2	3	3	1	8	4
2	2	3	3	2	8	4
2	2	3	3	3	8	4
2	2	3	3	4	8	4
2	2	3	7	1	8	8
2	2	3	7	2	8	8
2	2	3	7	3	8	8
2	2	3	7	4	8	8
2	2	4	2	1	4	4
2	2	4	2	2	4	4
2	2	4	2	3	4	4
2	2	4	2	4	4	4
2	2	4	3	1	2	1
2	2	4	3	2	2	1
2	2	4	3	3	2	1
2	2	4	3	4	2	1
2	2	4	7	1	4	4
2	2	4	7	2	4	4
2	2	4	7	3	4	4
2	2	4	7	4	4	4
2	2	5	2	1	4	4
2	2	5	2	2	4	4
2	2	5	2	3	4	4
2	2	5	2	4	4	4
2	2	5	3	1	4	2
2	2	5	3	2	4	2
2	2	5	3	3	4	2
2	2	5	3	4	4	2
2	2	5	7	1	4	4
2	2	5	7	2	4	4
2	2	5	7	3	4	4
2	2	5	7	4	4	4
2	2	6	2	1	6	6
2	2	6	2	2	6	6
2	2	6	2	3	6	6
2	2	6	2	4	6	6
2	2	6	3	1	2	1
2	2	6	3	2	2	1
2	2	6	3	3	2	1
2	2	6	3	4	2	1

Data Set 6_7 Transportation Costs (cont.)

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
2	2	6	7	1	6	6	3	1	3	2	2	4	4	3	1	7	1	3	4	4	3	2	3	5	4	6	6
2	2	6	7	2	6	6	3	1	3	2	3	4	4	3	1	7	1	4	4	4	3	2	4	1	1	8	4
2	2	6	7	3	6	6	3	1	3	2	4	4	4	3	1	7	2	1	6	6	3	2	4	1	2	8	4
2	2	6	7	4	6	6	3	1	3	5	1	4	4	3	1	7	2	2	6	6	3	2	4	1	3	8	4
2	2	7	2	1	6	6	3	1	3	5	2	4	4	3	1	7	2	3	6	6	3	2	4	1	4	8	4
2	2	7	2	2	6	6	3	1	3	5	3	4	4	3	1	7	2	4	6	6	3	2	4	2	1	8	8
2	2	7	2	3	6	6	3	1	3	5	4	4	4	3	1	7	5	1	8	8	3	2	4	2	2	8	8
2	2	7	2	4	6	6	3	1	4	1	1	8	8	3	1	7	5	2	8	8	3	2	4	2	3	8	8
2	2	7	3	1	8	4	3	1	4	1	2	8	8	3	1	7	5	3	8	8	3	2	4	2	4	8	8
2	2	7	3	2	8	4	3	1	4	1	3	8	8	3	1	7	5	4	8	8	3	2	4	5	1	4	4
2	2	7	3	3	8	4	3	1	4	1	4	8	8	3	2	1	1	1	6	3	3	2	4	5	2	4	4
2	2	7	3	4	8	4	3	1	4	2	1	8	8	3	2	1	1	2	6	3	3	2	4	5	3	4	4
2	2	7	7	1	8	8	3	1	4	2	2	8	8	3	2	1	1	3	6	3	3	2	4	5	4	4	4
2	2	7	7	2	8	8	3	1	4	2	3	8	8	3	2	1	1	4	6	3	3	2	5	1	1	6	3
2	2	7	7	3	8	8	3	1	4	2	4	8	8	3	2	1	2	1	8	8	3	2	5	1	2	6	3
2	2	7	7	4	8	8	3	1	4	5	1	4	4	3	2	1	2	2	8	8	3	2	5	1	3	6	3
3	1	1	1	1	4	4	3	1	4	5	2	4	4	3	2	1	2	3	8	8	3	2	5	1	4	6	3
3	1	1	1	2	4	4	3	1	4	5	3	4	4	3	2	1	2	4	8	8	3	2	5	2	1	8	8
3	1	1	1	3	4	4	3	1	4	5	4	4	4	3	2	1	5	1	4	4	3	2	5	2	2	8	8
3	1	1	1	4	4	4	3	1	5	1	1	8	8	3	2	1	5	2	4	4	3	2	5	2	3	8	8
3	1	1	2	1	6	6	3	1	5	1	2	8	8	3	2	1	5	3	4	4	3	2	5	2	4	8	8
3	1	1	2	2	6	6	3	1	5	1	3	8	8	3	2	1	5	4	4	4	3	2	5	5	1	6	6
3	1	1	2	3	6	6	3	1	5	1	4	8	8	3	2	2	1	1	4	2	3	2	5	5	2	6	6
3	1	1	2	4	6	6	3	1	5	2	1	8	8	3	2	2	1	2	4	2	3	2	5	5	3	6	6
3	1	1	5	1	2	2	3	1	5	2	2	8	8	3	2	2	1	3	4	2	3	2	5	5	4	6	6
3	1	1	5	2	2	2	3	1	5	2	3	8	8	3	2	2	1	4	4	2	3	2	6	1	1	4	2
3	1	1	5	3	2	2	3	1	5	2	4	8	8	3	2	2	2	1	2	2	3	2	6	1	2	4	2
3	1	1	5	4	2	2	3	1	5	5	1	6	6	3	2	2	2	2	2	2	3	2	6	1	3	4	2
3	1	2	1	1	2	2	3	1	5	5	2	6	6	3	2	2	2	3	2	2	3	2	6	1	4	4	2
3	1	2	1	2	2	2	3	1	5	5	3	6	6	3	2	2	2	4	2	2	3	2	6	2	1	4	4
3	1	2	1	3	2	2	3	1	5	5	4	6	6	3	2	2	5	1	8	8	3	2	6	2	2	4	4
3	1	2	1	4	2	2	3	1	6	1	1	4	4	3	2	2	5	2	8	8	3	2	6	2	3	4	4
3	1	2	2	1	8	8	3	1	6	1	2	4	4	3	2	2	5	3	8	8	3	2	6	2	4	4	4
3	1	2	2	2	8	8	3	1	6	1	3	4	4	3	2	2	5	4	8	8	3	2	6	5	1	4	4
3	1	2	2	3	8	8	3	1	6	1	4	4	4	3	2	3	1	1	4	2	3	2	6	5	2	4	4
3	1	2	2	4	8	8	3	1	6	2	1	6	6	3	2	3	1	2	4	2	3	2	6	5	3	4	4
3	1	2	5	1	4	4	3	1	6	2	2	6	6	3	2	3	1	3	4	2	3	2	6	5	4	4	4
3	1	2	5	2	4	4	3	1	6	2	3	6	6	3	2	3	1	4	4	2	3	2	7	1	1	2	1
3	1	2	5	3	4	4	3	1	6	2	4	6	6	3	2	3	2	1	2	2	3	2	7	1	2	2	1
3	1	2	5	4	4	4	3	1	6	5	1	6	6	3	2	3	2	2	2	2	3	2	7	1	3	2	1
3	1	3	1	1	4	4	3	1	6	5	2	6	6	3	2	3	2	3	2	2	3	2	7	1	4	2	1
3	1	3	1	2	4	4	3	1	6	5	3	6	6	3	2	3	2	4	2	2	3	2	7	2	1	6	6
3	1	3	1	3	4	4	3	1	6	5	4	6	6	3	2	3	5	1	6	6	3	2	7	2	2	6	6
3	1	3	1	4	4	4	3	1	7	1	1	4	4	3	2	3	5	2	6	6	3	2	7	2	3	6	6
3	1	3	2	1	4	4	3	1	7	1	2	4	4	3	2	3	5	3	6	6	3	2	7	2	4	6	6

Data Set 6_7 Transportation Costs (cont.)

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
3	2	7	5	1	2	2	4	1	4	5	2	8	8	4	2	1	3	3	4	2	4	2	4	6	4	6	6
3	2	7	5	2	2	2	4	1	4	5	3	8	8	4	2	1	3	4	4	2	4	2	5	3	1	4	2
3	2	7	5	3	2	2	4	1	4	5	4	8	8	4	2	1	5	1	6	6	4	2	5	3	2	4	2
3	2	7	5	4	2	2	4	1	4	6	1	8	8	4	2	1	5	2	6	6	4	2	5	3	3	4	2
4	1	1	3	1	2	1	4	1	4	6	2	8	8	4	2	1	5	3	6	6	4	2	5	3	4	4	2
4	1	1	3	2	2	1	4	1	4	6	3	8	8	4	2	1	5	4	6	6	4	2	5	5	1	6	6
4	1	1	3	3	2	1	4	1	4	6	4	8	8	4	2	1	6	1	2	2	4	2	5	5	2	6	6
4	1	1	3	4	2	1	4	1	5	3	1	8	4	4	2	1	6	2	2	2	4	2	5	5	3	6	6
4	1	1	5	1	8	8	4	1	5	3	2	8	4	4	2	1	6	3	2	2	4	2	5	5	4	6	6
4	1	1	5	2	8	8	4	1	5	3	3	8	4	4	2	1	6	4	2	2	4	2	5	6	1	8	8
4	1	1	5	3	8	8	4	1	5	3	4	8	4	4	2	2	3	1	8	4	4	2	5	6	2	8	8
4	1	1	5	4	8	8	4	1	5	5	1	4	4	4	2	2	3	2	8	4	4	2	5	6	3	8	8
4	1	1	6	1	2	2	4	1	5	5	2	4	4	4	2	2	3	3	8	4	4	2	5	6	4	8	8
4	1	1	6	2	2	2	4	1	5	5	3	4	4	4	2	2	3	4	8	4	4	2	6	3	1	8	4
4	1	1	6	3	2	2	4	1	5	5	4	4	4	4	2	2	5	1	6	6	4	2	6	3	2	8	4
4	1	1	6	4	2	2	4	1	5	6	1	4	4	4	2	2	5	2	6	6	4	2	6	3	3	8	4
4	1	2	3	1	8	4	4	1	5	6	2	4	4	4	2	2	5	3	6	6	4	2	6	3	4	8	4
4	1	2	3	2	8	4	4	1	5	6	3	4	4	4	2	2	5	4	6	6	4	2	6	5	1	4	4
4	1	2	3	3	8	4	4	1	5	6	4	4	4	4	2	2	6	1	4	4	4	2	6	5	2	4	4
4	1	2	3	4	8	4	4	1	6	3	1	8	4	4	2	2	6	2	4	4	4	2	6	5	3	4	4
4	1	2	5	1	4	4	4	1	6	3	2	8	4	4	2	2	6	3	4	4	4	2	6	5	4	4	4
4	1	2	5	2	4	4	4	1	6	3	3	8	4	4	2	2	6	4	4	4	4	2	6	6	1	6	6
4	1	2	5	3	4	4	4	1	6	3	4	8	4	4	2	3	3	1	6	3	4	2	6	6	2	6	6
4	1	2	5	4	4	4	4	1	6	5	1	8	8	4	2	3	3	2	6	3	4	2	6	6	3	6	6
4	1	2	6	1	2	2	4	1	6	5	2	8	8	4	2	3	3	3	6	3	4	2	6	6	4	6	6
4	1	2	6	2	2	2	4	1	6	5	3	8	8	4	2	3	3	4	6	3	4	2	7	3	1	4	2
4	1	2	6	3	2	2	4	1	6	5	4	8	8	4	2	3	5	1	2	2	4	2	7	3	2	4	2
4	1	2	6	4	2	2	4	1	6	6	1	8	8	4	2	3	5	2	2	2	4	2	7	3	3	4	2
4	1	3	3	1	8	4	4	1	6	6	2	8	8	4	2	3	5	3	2	2	4	2	7	3	4	4	2
4	1	3	3	2	8	4	4	1	6	6	3	8	8	4	2	3	5	4	2	2	4	2	7	5	1	6	6
4	1	3	3	3	8	4	4	1	6	6	4	8	8	4	2	3	6	1	4	4	4	2	7	5	2	6	6
4	1	3	3	4	8	4	4	1	7	3	1	6	3	4	2	3	6	2	4	4	4	2	7	5	3	6	6
4	1	3	5	1	2	2	4	1	7	3	2	6	3	4	2	3	6	3	4	4	4	2	7	5	4	6	6
4	1	3	5	2	2	2	4	1	7	3	3	6	3	4	2	3	6	4	4	4	4	2	7	6	1	4	4
4	1	3	5	3	2	2	4	1	7	3	4	6	3	4	2	4	3	1	4	2	4	2	7	6	2	4	4
4	1	3	5	4	2	2	4	1	7	5	1	2	2	4	2	4	3	2	4	2	4	2	7	6	3	4	4
4	1	3	6	1	4	4	4	1	7	5	2	2	2	4	2	4	3	3	4	2	4	2	7	6	4	4	4
4	1	3	6	2	4	4	4	1	7	5	3	2	2	4	2	4	3	4	4	2	5	1	1	3	1	8	4
4	1	3	6	3	4	4	4	1	7	5	4	2	2	4	2	4	5	1	2	2	5	1	1	3	2	8	4
4	1	3	6	4	4	4	4	1	7	6	1	4	4	4	2	4	5	2	2	2	5	1	1	3	3	8	4
4	1	4	3	1	8	4	4	1	7	6	2	4	4	4	2	4	5	3	2	2	5	1	1	3	4	8	4
4	1	4	3	2	8	4	4	1	7	6	3	4	4	4	2	4	5	4	2	2	5	1	1	4	1	8	8
4	1	4	3	3	8	4	4	1	7	6	4	4	4	4	2	4	6	1	6	6	5	1	1	4	2	8	8
4	1	4	3	4	8	4	4	2	1	3	1	4	2	4	2	4	6	2	6	6	5	1	1	4	3	8	8
4	1	4	5	1	8	8	4	2	1	3	2	4	2	4	2	4	6	3	6	6	5	1	1	4	4	8	8

Data Set 6_7 Transportation Costs (cont.)

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
5	1	1	5	1	8	8
5	1	1	5	2	8	8
5	1	1	5	3	8	8
5	1	1	5	4	8	8
5	1	2	3	1	2	1
5	1	2	3	2	2	1
5	1	2	3	3	2	1
5	1	2	3	4	2	1
5	1	2	4	1	2	2
5	1	2	4	2	2	2
5	1	2	4	3	2	2
5	1	2	4	4	2	2
5	1	2	5	1	2	2
5	1	2	5	2	2	2
5	1	2	5	3	2	2
5	1	2	5	4	2	2
5	1	3	3	1	3	1
5	1	3	3	2	3	1
5	1	3	3	3	3	1
5	1	3	3	4	3	1
5	1	3	4	1	2	2
5	1	3	4	2	2	2
5	1	3	4	3	2	2
5	1	3	4	4	2	2
5	1	3	5	1	4	4
5	1	3	5	2	4	4
5	1	3	5	3	4	4
5	1	3	5	4	4	4
5	1	4	3	1	2	1
5	1	4	3	2	2	1
5	1	4	3	3	2	1
5	1	4	3	4	2	1
5	1	4	4	1	2	2
5	1	4	4	2	2	2
5	1	4	4	3	2	2
5	1	4	4	4	2	2
5	1	4	5	1	8	8
5	1	4	5	2	8	8
5	1	4	5	3	8	8
5	1	4	5	4	8	8
5	1	5	3	1	2	1
5	1	5	3	2	2	1
5	1	5	3	3	2	1
5	1	5	3	4	2	1
5	1	5	4	1	2	2

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
5	1	5	4	2	2	2
5	1	5	4	3	2	2
5	1	5	4	4	2	2
5	1	5	5	1	2	2
5	1	5	5	2	2	2
5	1	5	5	3	2	2
5	1	5	5	4	2	2
5	1	6	3	1	6	3
5	1	6	3	2	6	3
5	1	6	3	3	6	3
5	1	6	3	4	6	3
5	1	6	4	1	8	8
5	1	6	4	2	8	8
5	1	6	4	3	8	8
5	1	6	4	4	8	8
5	1	6	5	1	2	2
5	1	6	5	2	2	2
5	1	6	5	3	2	2
5	1	6	5	4	2	2
5	1	7	3	1	4	2
5	1	7	3	2	4	2
5	1	7	3	3	4	2
5	1	7	3	4	4	2
5	1	7	4	1	6	6
5	1	7	4	2	6	6
5	1	7	4	3	6	6
5	1	7	4	4	6	6
5	1	7	5	1	2	2
5	1	7	5	2	2	2
5	1	7	5	3	2	2
5	1	7	5	4	2	2
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5	2	1	1	2	2	2
5	2	1	1	3	2	2
5	2	1	1	4	2	2
5	2	1	3	1	2	1
5	2	1	3	2	2	1
5	2	1	3	3	2	1
5	2	1	3	4	2	1
5	2	1	4	1	8	4
5	2	1	4	2	8	4
5	2	1	4	3	8	4
5	2	1	4	4	8	4
5	2	2	1	1	2	2
5	2	2	1	2	2	2

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
5	2	2	1	3	2	2
5	2	2	1	4	2	2
5	2	2	3	1	2	1
5	2	2	3	2	2	1
5	2	2	3	3	2	1
5	2	2	3	4	2	1
5	2	2	4	1	8	4
5	2	2	4	2	8	4
5	2	2	4	3	8	4
5	2	2	4	4	8	4
5	2	3	1	1	6	6
5	2	3	1	2	6	6
5	2	3	1	3	6	6
5	2	3	1	4	6	6
5	2	3	3	1	4	2
5	2	3	3	2	4	2
5	2	3	3	3	4	2
5	2	3	3	4	4	2
5	2	3	4	1	2	1
5	2	3	4	2	2	1
5	2	3	4	3	2	1
5	2	3	4	4	2	1
5	2	4	1	1	2	2
5	2	4	1	2	2	2
5	2	4	1	3	2	2
5	2	4	1	4	2	2
5	2	4	3	1	2	1
5	2	4	3	2	2	1
5	2	4	3	3	2	1
5	2	4	3	4	2	1
5	2	4	4	1	4	2
5	2	4	4	2	4	2
5	2	4	4	3	4	2
5	2	4	4	4	4	2
5	2	5	1	1	8	8
5	2	5	1	2	8	8
5	2	5	1	3	8	8
5	2	5	1	4	8	8
5	2	5	3	1	8	4
5	2	5	3	2	8	4
5	2	5	3	3	8	4
5	2	5	3	4	8	4
5	2	5	4	1	8	4
5	2	5	4	2	8	4
5	2	5	4	3	8	4

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
5	2	5	4	4	8	4
5	2	6	1	1	4	4
5	2	6	1	2	4	4
5	2	6	1	3	4	4
5	2	6	1	4	4	4
5	2	6	3	1	8	4
5	2	6	3	2	8	4
5	2	6	3	3	8	4
5	2	6	3	4	8	4
5	2	6	4	1	6	3
5	2	6	4	2	6	3
5	2	6	4	3	6	3
5	2	6	4	4	6	3
5	2	7	1	1	6	6
5	2	7	1	2	6	6
5	2	7	1	3	6	6
5	2	7	1	4	6	6
5	2	7	3	1	2	1
5	2	7	3	2	2	1
5	2	7	3	3	2	1
5	2	7	3	4	2	1
5	2	7	4	1	8	4
5	2	7	4	2	8	4
5	2	7	4	3	8	4
5	2	7	4	4	8	4
6	1	1	2	1	8	8
6	1	1	2	2	8	8
6	1	1	2	3	8	8
6	1	1	2	4	8	8
6	1	1	6	1	8	4
6	1	1	6	2	8	4
6	1	1	6	3	8	4
6	1	1	6	4	8	4
6	1	1	7	1	4	4
6	1	1	7	2	4	4
6	1	1	7	3	4	4
6	1	1	7	4	4	4
6	1	2	2	1	2	2
6	1	2	2	2	2	2
6	1	2	2	3	2	2
6	1	2	2	4	2	2
6	1	2	6	1	6	3
6	1	2	6	2	6	3
6	1	2	6	3	6	3
6	1	2	6	4	6	3

Data Set 6_7 Transportation Costs (cont.)

Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $	Component	Alternative	Ship From	Ship To	Time Period	Similar Transp $	Diff Transp $
6	1	2	7	1	8	8	6	1	6	6	2	2	1	6	2	3	2	3	2	1	6	2	6	7	4	8	8
6	1	2	7	2	8	8	6	1	6	6	3	2	1	6	2	3	2	4	2	1	6	2	7	2	1	4	2
6	1	2	7	3	8	8	6	1	6	6	4	2	1	6	2	3	6	1	4	2	6	2	7	2	2	4	2
6	1	2	7	4	8	8	6	1	6	7	1	8	8	6	2	3	6	2	4	2	6	2	7	2	3	4	2
6	1	3	2	1	8	8	6	1	6	7	2	8	8	6	2	3	6	3	4	2	6	2	7	2	4	4	2
6	1	3	2	2	8	8	6	1	6	7	3	8	8	6	2	3	6	4	4	2	6	2	7	6	1	8	4
6	1	3	2	3	8	8	6	1	6	7	4	8	8	6	2	3	7	1	4	4	6	2	7	6	2	8	4
6	1	3	2	4	8	8	6	1	7	2	1	8	8	6	2	3	7	2	4	4	6	2	7	6	3	8	4
6	1	3	6	1	4	2	6	1	7	2	2	8	8	6	2	3	7	3	4	4	6	2	7	6	4	8	4
6	1	3	6	2	4	2	6	1	7	2	3	8	8	6	2	3	7	4	4	4	6	2	7	7	1	4	4
6	1	3	6	3	4	2	6	1	7	2	4	8	8	6	2	4	2	1	8	4	6	2	7	7	2	4	4
6	1	3	6	4	4	2	6	1	7	6	1	8	4	6	2	4	2	2	8	4	6	2	7	7	3	4	4
6	1	3	7	1	6	6	6	1	7	6	2	8	4	6	2	4	2	3	8	4	6	2	7	7	4	4	4
6	1	3	7	2	6	6	6	1	7	6	3	8	4	6	2	4	2	4	8	4							
6	1	3	7	3	6	6	6	1	7	6	4	8	4	6	2	4	6	1	4	2							
6	1	3	7	4	6	6	6	1	7	7	1	8	8	6	2	4	6	2	4	2							
6	1	4	2	1	4	4	6	1	7	7	2	8	8	6	2	4	6	3	4	2							
6	1	4	2	2	4	4	6	1	7	7	3	8	8	6	2	4	6	4	4	2							
6	1	4	2	3	4	4	6	1	7	7	4	8	8	6	2	4	7	1	4	4							
6	1	4	2	4	4	4	6	2	1	2	1	4	2	6	2	4	7	2	4	4							
6	1	4	6	1	2	1	6	2	1	2	2	4	2	6	2	4	7	3	4	4							
6	1	4	6	2	2	1	6	2	1	2	3	4	2	6	2	4	7	4	4	4							
6	1	4	6	3	2	1	6	2	1	2	4	4	2	6	2	5	2	1	6	3							
6	1	4	6	4	2	1	6	2	1	6	1	4	2	6	2	5	2	2	6	3							
6	1	4	7	1	8	8	6	2	1	6	2	4	2	6	2	5	2	3	6	3							
6	1	4	7	2	8	8	6	2	1	6	3	4	2	6	2	5	2	4	6	3							
6	1	4	7	3	8	8	6	2	1	6	4	4	2	6	2	5	6	1	4	2							
6	1	4	7	4	8	8	6	2	1	7	1	2	2	6	2	5	6	2	4	2							
6	1	5	2	1	2	2	6	2	1	7	2	2	2	6	2	5	6	3	4	2							
6	1	5	2	2	2	2	6	2	1	7	3	2	2	6	2	5	6	4	4	2							
6	1	5	2	3	2	2	6	2	1	7	4	2	2	6	2	5	7	1	6	6							
6	1	5	2	4	2	2	6	2	2	2	1	2	1	6	2	5	7	2	6	6							
6	1	5	6	1	6	3	6	2	2	2	2	2	1	6	2	5	7	3	6	6							
6	1	5	6	2	6	3	6	2	2	2	3	2	1	6	2	5	7	4	6	6							
6	1	5	6	3	6	3	6	2	2	2	4	2	1	6	2	6	2	1	8	4							
6	1	5	6	4	6	3	6	2	2	6	1	4	2	6	2	6	2	2	8	4							
6	1	5	7	1	6	6	6	2	2	6	2	4	2	6	2	6	2	3	8	4							
6	1	5	7	2	6	6	6	2	2	6	3	4	2	6	2	6	2	4	8	4							
6	1	5	7	3	6	6	6	2	2	6	4	4	2	6	2	6	6	1	4	2							
6	1	5	7	4	6	6	6	2	2	7	1	2	2	6	2	6	6	2	4	2							
6	1	6	2	1	6	6	6	2	2	7	2	2	2	6	2	6	6	3	4	2							
6	1	6	2	2	6	6	6	2	2	7	3	2	2	6	2	6	6	4	4	2							
6	1	6	2	3	6	6	6	2	2	7	4	2	2	6	2	6	7	1	8	8							
6	1	6	2	4	6	6	6	2	3	2	1	2	1	6	2	6	7	2	8	8							
6	1	6	6	1	2	1	6	2	3	2	2	2	1	6	2	6	7	3	8	8							

APPENDIX J

DESIGNED EXPERIMENT RESULTS

Table 40 and Table 41 in this appendix show the profit obtained for each treatment in data sets 5_5 and 6_7. The profit shown for the simulations is the average of all replications. Table 42 and Table 43 show the percent change of each treatment from a baseline case. The baseline cases were not part of the experimental design (first three rows of the table). The percentage change was calculated by the following formula:

(Treatment Profit – Baseline Profit) / Baseline Profit.

Table 40. Data Set 6_7 Designed Experiment Results - Profit

				HHHDD	HHHDS	HHHSD	HHHSS	HHLDD	HHLDS	HHLSD	HHLSS
	Original MIP			$ 4,397,563,976	$ 4,406,989,168	$ 4,019,860,468	$ 4,021,923,168	$ 4,432,523,976	$ 4,441,949,168	$ 4,054,820,468	$ 4,056,883,168
	Deterministic Simulation			$ 4,386,684,696	$ 4,396,109,889	$ 4,008,981,185	$ 4,011,043,884	$ 4,421,644,696	$ 4,431,069,889	$ 4,043,941,185	$ 4,046,003,884
	Stochastic Simulation			$ 4,231,843,593	$ 4,238,000,757	$ 3,862,893,875	$ 3,859,236,992	$ 4,266,803,593	$ 4,278,027,780	$ 3,897,853,875	$ 3,892,546,232
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		$ 3,904,186,872	$ 3,915,989,200	$ 3,603,297,174	$ 3,603,460,400	$ 3,931,406,872	$ 3,943,209,200	$ 3,631,037,174	$ 3,631,200,400
		Simulation		$ 3,754,984,198	$ 3,769,051,994	$ 3,466,932,453	$ 3,475,072,778	$ 3,782,204,198	$ 3,794,993,751	$ 3,492,956,497	$ 3,506,865,158
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	$ 4,332,466,256	$ 4,342,910,968	$ 3,968,004,401	$ 3,969,697,968	$ 4,367,426,256	$ 4,377,870,968	$ 4,002,964,401	$ 4,004,657,968
			Risky supplier at 80%	$ 4,267,236,815	$ 4,278,760,768	$ 3,916,068,333	$ 3,917,312,768	$ 4,302,196,815	$ 4,313,720,768	$ 3,951,028,333	$ 3,952,272,768
			Risky supplier at 70%	$ 4,202,007,374	$ 4,214,610,568	$ 3,891,486,707	$ 3,893,001,054	$ 4,236,967,374	$ 4,249,570,568	$ 3,926,446,675	$ 3,927,961,054
		Simulation	Risky supplier at 90%	$ 4,172,215,146	$ 4,180,795,982	$ 3,827,535,541	$ 3,807,385,594	$ 4,207,175,146	$ 4,215,755,982	$ 3,862,495,541	$ 3,859,144,185
			Risky supplier at 80%	$ 4,113,149,709	$ 4,122,404,927	$ 3,765,094,526	$ 3,770,680,276	$ 4,148,109,709	$ 4,157,364,927	$ 3,800,054,526	$ 3,805,640,276
			Risky supplier at 70%	$ 4,040,240,756	$ 4,061,084,901	$ 3,766,417,790	$ 3,750,061,323	$ 4,075,200,756	$ 4,096,044,901	$ 3,798,496,743	$ 3,785,841,271
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	$ 4,332,466,256	$ 4,342,910,968	$ 3,968,004,401	$ 3,969,697,968	$ 4,367,426,256	$ 4,377,870,968	$ 4,002,964,401	$ 4,004,657,968
			Risky supplier at 80%	$ 4,267,236,815	$ 4,278,760,768	$ 3,916,068,333	$ 3,917,312,768	$ 4,302,196,815	$ 4,313,720,768	$ 3,951,028,333	$ 3,952,272,768
			Risky supplier at 70%	$ 4,202,007,374	$ 4,214,610,568	$ 3,863,232,687	$ 3,864,159,568	$ 4,236,967,374	$ 4,249,570,568	$ 3,898,192,687	$ 3,899,119,568
		Simulation	Risky supplier at 90%	$ 4,172,215,146	$ 4,180,795,982	$ 3,827,535,541	$ 3,807,385,594	$ 4,207,175,146	$ 4,215,755,982	$ 3,862,495,541	$ 3,859,144,185
			Risky supplier at 80%	$ 4,113,149,709	$ 4,122,404,927	$ 3,765,094,526	$ 3,770,680,276	$ 4,148,109,709	$ 4,157,364,927	$ 3,800,054,526	$ 3,805,640,276
			Risky supplier at 70%	$ 4,040,240,756	$ 4,061,084,901	$ 3,702,472,964	$ 3,698,919,355	$ 4,075,200,756	$ 4,096,044,901	$ 3,737,432,964	$ 3,733,829,397
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	$ 4,680,418,314	$ 4,689,710,685	$ 4,288,523,549	$ 4,290,023,885	$ 4,715,378,314	$ 4,724,670,685	$ 4,323,483,549	$ 4,324,983,885
			Increase Demand 20%	$ 4,962,492,859	$ 4,971,419,402	$ 4,556,642,646	$ 4,557,836,602	$ 4,997,452,859	$ 5,006,379,402	$ 4,591,602,646	$ 4,592,796,602
			Increase Demand 30%	$ 5,238,340,577	$ 5,244,190,518	$ 4,821,352,467	$ 4,822,524,518	$ 5,273,300,577	$ 5,279,150,518	$ 4,856,312,467	$ 4,857,484,518
		Simulation	Increase Demand 10%	$ 4,505,642,504	$ 4,524,600,053	$ 4,122,361,093	$ 4,123,427,045	$ 4,540,602,504	$ 4,559,560,053	$ 4,157,321,093	$ 4,158,387,045
			Increase Demand 20%	$ 4,787,183,763	$ 4,790,390,036	$ 4,386,418,454	$ 4,380,888,905	$ 4,822,143,763	$ 4,825,350,036	$ 4,416,939,625	$ 4,415,848,905
			Increase Demand 30%	$ 5,041,712,390	$ 5,050,616,309	$ 4,639,288,268	$ 4,634,167,646	$ 5,076,672,390	$ 5,085,576,309	$ 4,674,248,268	$ 4,669,127,646
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	$ 4,680,418,314	$ 4,689,710,685	$ 4,288,263,555	$ 4,290,023,885	$ 4,715,378,314	$ 4,724,670,685	$ 4,323,223,555	$ 4,324,983,885
			Increase Demand 20%	$ 4,962,492,859	$ 4,971,419,402	$ 4,556,394,642	$ 4,557,836,602	$ 4,997,452,859	$ 5,006,379,402	$ 4,591,354,642	$ 4,592,796,602
			Increase Demand 30%	$ 5,237,087,547	$ 5,244,190,518	$ 4,821,219,883	$ 4,822,524,518	$ 5,272,047,547	$ 5,279,150,518	$ 4,856,179,883	$ 4,857,484,518
		Simulation	Increase Demand 10%	$ 4,505,642,504	$ 4,524,600,053	$ 4,126,855,898	$ 4,123,427,045	$ 4,540,602,504	$ 4,559,560,053	$ 4,161,815,898	$ 4,158,387,045
			Increase Demand 20%	$ 4,787,183,763	$ 4,790,390,036	$ 4,365,545,084	$ 4,380,888,905	$ 4,822,143,763	$ 4,825,350,036	$ 4,400,505,084	$ 4,415,848,905
			Increase Demand 30%	$ 5,027,583,909	$ 5,050,616,309	$ 4,619,518,973	$ 4,634,167,646	$ 5,062,543,909	$ 5,085,576,309	$ 4,654,478,973	$ 4,669,127,646
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	$ 4,531,623,414	$ 4,540,804,691	$ 4,288,263,555	$ 4,290,023,885	$ 4,566,583,414	$ 4,575,764,691	$ 4,323,223,555	$ 4,324,983,885
			Increase Demand 20%	$ 4,646,554,608	$ 4,655,515,200	$ 4,540,700,181	$ 4,542,148,538	$ 4,681,514,608	$ 4,690,475,200	$ 4,575,660,181	$ 4,577,108,538
			Increase Demand 30%	$ 4,646,554,608	$ 4,655,515,200	$ 4,630,946,447	$ 4,632,146,800	$ 4,681,514,608	$ 4,690,475,200	$ 4,665,906,447	$ 4,667,106,800
		Simulation	Increase Demand 10%	$ 4,356,665,853	$ 4,368,283,787	$ 4,126,855,898	$ 4,123,427,045	$ 4,391,625,853	$ 4,394,120,703	$ 4,161,815,898	$ 4,158,387,045
			Increase Demand 20%	$ 4,456,558,253	$ 4,474,170,405	$ 4,350,260,699	$ 4,351,038,426	$ 4,491,518,253	$ 4,513,374,045	$ 4,385,220,699	$ 4,397,888,934
			Increase Demand 30%	$ 4,456,558,253	$ 4,474,170,405	$ 4,429,218,242	$ 4,441,983,885	$ 4,491,518,253	$ 4,513,374,045	$ 4,464,178,242	$ 4,469,574,020

Table 40. Data Set 6_7 Designed Experiment Results - Profit (cont.)

				HLHDD	HLHDS	HLHSD	HLHSS	HLLDD	HLLDS	HLLSD	HLLSS
	Original MIP			$ 5,073,041,768	$ 5,078,435,718	$ 4,645,311,342	$ 4,646,933,195	$ 5,108,001,768	$ 5,113,395,718	$ 4,680,271,342	$ 4,681,893,195
	Deterministic Simulation			$ 5,059,936,529	$ 5,065,330,480	$ 4,632,320,176	$ 4,633,942,030	$ 5,094,896,529	$ 5,100,290,480	$ 4,667,280,175	$ 4,668,902,030
	Stochastic Simulation			$ 4,872,254,478	$ 4,880,802,235	$ 4,460,037,271	$ 4,446,597,361	$ 4,907,214,478	$ 4,909,110,904	$ 4,494,370,027	$ 4,481,557,361
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		$ 4,538,163,321	$ 4,546,606,235	$ 4,328,573,529	$ 4,330,470,084	$ 4,565,383,321	$ 4,573,826,235	$ 4,356,313,533	$ 4,358,210,067
		Simulation		$ 4,374,794,257	$ 4,386,206,550	$ 4,153,074,762	$ 4,163,126,785	$ 4,402,014,257	$ 4,412,684,051	$ 4,177,370,658	$ 4,190,405,870
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	$ 5,005,046,175	$ 5,011,582,518	$ 4,592,480,761	$ 4,593,910,433	$ 5,040,006,175	$ 5,046,542,518	$ 4,627,440,756	$ 4,628,870,433
			Risky supplier at 80%	$ 4,936,918,861	$ 4,944,657,318	$ 4,539,533,317	$ 4,541,685,217	$ 4,971,878,861	$ 4,979,617,318	$ 4,574,493,317	$ 4,576,645,217
			Risky supplier at 70%	$ 4,868,791,547	$ 4,877,732,118	$ 4,486,608,799	$ 4,488,932,017	$ 4,903,751,552	$ 4,912,692,118	$ 4,521,568,799	$ 4,523,892,017
		Simulation	Risky supplier at 90%	$ 4,809,052,567	$ 4,815,454,149	$ 4,412,921,510	$ 4,392,824,372	$ 4,844,012,567	$ 4,854,455,557	$ 4,458,241,686	$ 4,428,686,546
			Risky supplier at 80%	$ 4,742,978,016	$ 4,750,634,469	$ 4,363,304,731	$ 4,349,989,827	$ 4,777,938,016	$ 4,785,594,469	$ 4,396,193,780	$ 4,384,949,827
			Risky supplier at 70%	$ 4,687,942,484	$ 4,682,220,951	$ 4,292,259,904	$ 4,302,795,501	$ 4,716,807,998	$ 4,718,930,504	$ 4,327,168,730	$ 4,336,151,593
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	$ 5,005,046,175	$ 5,011,582,518	$ 4,592,480,756	$ 4,593,910,417	$ 5,040,006,175	$ 5,046,542,518	$ 4,627,440,756	$ 4,628,845,915
			Risky supplier at 80%	$ 4,936,918,861	$ 4,944,657,318	$ 4,539,533,317	$ 4,541,685,217	$ 4,971,878,861	$ 4,979,617,318	$ 4,574,493,317	$ 4,576,645,217
			Risky supplier at 70%	$ 4,868,791,547	$ 4,877,732,118	$ 4,486,608,799	$ 4,488,932,017	$ 4,903,751,547	$ 4,912,692,118	$ 4,521,568,799	$ 4,523,892,017
		Simulation	Risky supplier at 90%	$ 4,809,052,567	$ 4,815,454,149	$ 4,369,519,853	$ 4,358,069,809	$ 4,844,012,567	$ 4,854,455,557	$ 4,458,241,686	$ 4,395,174,838
			Risky supplier at 80%	$ 4,742,978,016	$ 4,750,634,469	$ 4,363,304,731	$ 4,349,989,827	$ 4,777,938,016	$ 4,785,594,469	$ 4,396,193,780	$ 4,384,949,827
			Risky supplier at 70%	$ 4,687,942,484	$ 4,682,220,951	$ 4,292,259,904	$ 4,302,795,501	$ 4,628,029,021	$ 4,718,930,504	$ 4,327,168,730	$ 4,336,151,593
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	$ 5,419,906,013	$ 5,425,136,890	$ 4,972,822,544	$ 4,974,177,279	$ 5,454,866,013	$ 5,460,096,890	$ 5,007,782,544	$ 5,009,137,279
			Increase Demand 20%	$ 5,766,018,539	$ 5,770,857,262	$ 5,303,024,970	$ 5,304,887,343	$ 5,800,978,539	$ 5,805,817,262	$ 5,337,984,970	$ 5,339,847,343
			Increase Demand 30%	$ 6,106,170,937	$ 6,107,944,034	$ 5,626,337,594	$ 5,628,801,174	$ 6,141,130,937	$ 6,142,904,034	$ 5,661,297,594	$ 5,663,761,174
		Simulation	Increase Demand 10%	$ 5,219,206,026	$ 5,219,019,779	$ 4,776,712,623	$ 4,775,490,395	$ 5,254,166,026	$ 5,253,979,779	$ 4,811,672,623	$ 4,810,450,395
			Increase Demand 20%	$ 5,542,208,578	$ 5,554,143,240	$ 5,076,134,479	$ 5,071,983,559	$ 5,577,168,578	$ 5,579,150,064	$ 5,109,369,013	$ 5,106,943,559
			Increase Demand 30%	$ 5,871,574,415	$ 5,862,640,001	$ 5,385,211,689	$ 5,367,036,387	$ 5,906,534,415	$ 5,899,461,328	$ 5,423,626,550	$ 5,401,974,219
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	$ 5,419,856,933	$ 5,425,136,890	$ 4,972,759,901	$ 4,974,177,279	$ 5,454,816,933	$ 5,460,096,890	$ 5,007,719,901	$ 5,009,137,279
			Increase Demand 20%	$ 5,765,920,380	$ 5,770,857,262	$ 5,302,833,038	$ 5,304,055,940	$ 5,800,880,380	$ 5,805,817,262	$ 5,337,793,038	$ 5,339,015,940
			Increase Demand 30%	$ 6,104,770,669	$ 6,107,944,034	$ 5,626,037,894	$ 5,627,066,320	$ 6,139,730,669	$ 6,142,904,034	$ 5,660,997,894	$ 5,662,026,320
		Simulation	Increase Demand 10%	$ 5,207,814,365	$ 5,219,019,779	$ 4,745,507,723	$ 4,775,490,395	$ 5,242,774,365	$ 5,253,979,779	$ 4,779,625,445	$ 4,810,450,395
			Increase Demand 20%	$ 5,516,929,264	$ 5,554,143,240	$ 5,052,645,984	$ 5,053,062,307	$ 5,551,889,264	$ 5,579,150,064	$ 5,092,625,602	$ 5,088,022,307
			Increase Demand 30%	$ 5,851,566,134	$ 5,862,640,001	$ 5,369,171,315	$ 5,379,171,250	$ 5,886,526,134	$ 5,899,461,328	$ 5,406,712,052	$ 5,414,131,250
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	$ 5,188,768,663	$ 5,276,230,897	$ 4,897,086,473	$ 4,898,853,233	$ 5,223,728,663	$ 5,311,190,897	$ 4,932,046,473	$ 4,933,813,233
			Increase Demand 20%	$ 5,287,113,270	$ 5,456,708,913	$ 5,110,678,965	$ 5,112,642,353	$ 5,322,073,270	$ 5,491,668,913	$ 5,145,638,965	$ 5,147,602,353
			Increase Demand 30%	$ 5,287,113,270	$ 5,539,461,023	$ 5,188,318,766	$ 5,190,478,783	$ 5,322,073,270	$ 5,574,421,023	$ 5,223,278,766	$ 5,225,438,783
		Simulation	Increase Demand 10%	$ 4,992,536,284	$ 5,061,432,946	$ 4,673,896,809	$ 4,679,899,481	$ 5,027,496,284	$ 5,089,893,635	$ 4,708,094,704	$ 4,714,859,481
			Increase Demand 20%	$ 5,084,298,176	$ 5,217,964,010	$ 4,857,529,070	$ 4,861,023,710	$ 5,119,258,176	$ 5,246,272,552	$ 4,895,190,552	$ 4,895,983,710
			Increase Demand 30%	$ 5,084,298,176	$ 5,288,634,259	$ 4,933,073,568	$ 4,935,610,859	$ 5,119,258,176	$ 5,330,260,724	$ 4,966,882,784	$ 4,970,570,859

Table 40. Data Set 6_7 Designed Experiment Results - Profit (cont.)

				LHHDD	LHHDS	LHHSD	LHHSS	LHLDD	LHLDS	LHLSD	LHLSS
	Original MIP			$ 4,394,937,392	$ 4,402,621,168	$ 4,016,498,651	$ 4,018,159,968	$ 4,429,897,392	$ 4,437,581,168	$ 4,051,458,651	$ 4,053,119,968
	Deterministic Simulation			$ 4,384,058,113	$ 4,391,741,889	$ 4,005,619,369	$ 4,007,280,685	$ 4,419,018,113	$ 4,426,701,889	$ 4,040,579,369	$ 4,042,240,684
	Stochastic Simulation			$ 4,230,388,378	$ 4,243,859,120	$ 3,865,399,618	$ 3,874,241,992	$ 4,265,348,378	$ 4,274,328,065	$ 3,904,558,695	$ 3,891,557,933
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		$ 3,889,332,864	$ 3,897,643,600	$ 3,429,221,648	$ 3,429,221,648	$ 3,916,552,864	$ 3,924,863,600	$ 3,456,961,648	$ 3,456,961,648
		Simulation		$ 3,744,653,011	$ 3,768,117,927	$ 3,308,883,585	$ 3,302,537,548	$ 3,771,873,011	$ 3,795,337,927	$ 3,336,780,512	$ 3,336,623,585
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	$ 4,329,839,672	$ 4,338,542,968	$ 3,964,642,584	$ 3,965,934,768	$ 4,364,799,672	$ 4,373,502,968	$ 3,999,602,584	$ 4,000,894,768
			Risky supplier at 80%	$ 4,264,610,231	$ 4,274,392,768	$ 3,912,786,517	$ 3,913,709,568	$ 4,299,570,231	$ 4,309,352,768	$ 3,947,746,517	$ 3,948,669,568
			Risky supplier at 70%	$ 4,199,380,790	$ 4,210,242,568	$ 3,860,349,455	$ 3,860,956,368	$ 4,234,340,790	$ 4,245,202,568	$ 3,895,309,455	$ 3,895,916,368
		Simulation	Risky supplier at 90%	$ 4,174,491,295	$ 4,188,600,499	$ 3,823,260,237	$ 3,815,727,434	$ 4,209,451,295	$ 4,216,034,080	$ 3,858,220,237	$ 3,853,027,175
			Risky supplier at 80%	$ 4,114,315,194	$ 4,119,136,991	$ 3,761,735,511	$ 3,775,866,820	$ 4,141,255,660	$ 4,161,181,349	$ 3,797,582,837	$ 3,810,826,820
			Risky supplier at 70%	$ 4,046,725,460	$ 4,042,601,934	$ 3,719,884,616	$ 3,719,923,183	$ 4,081,685,460	$ 4,110,087,796	$ 3,759,358,879	$ 3,741,797,367
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	$ 4,329,839,672	$ 4,338,542,968	$ 3,964,642,584	$ 3,965,934,768	$ 4,364,799,672	$ 4,373,502,968	$ 3,999,602,584	$ 4,000,894,768
			Risky supplier at 80%	$ 4,264,610,231	$ 4,274,392,768	$ 3,912,786,517	$ 3,913,709,568	$ 4,299,570,231	$ 4,309,352,768	$ 3,947,746,517	$ 3,948,669,568
			Risky supplier at 70%	$ 4,199,380,790	$ 4,210,242,568	$ 3,860,349,455	$ 3,860,956,368	$ 4,234,340,790	$ 4,245,202,568	$ 3,895,309,455	$ 3,895,916,368
		Simulation	Risky supplier at 90%	$ 4,174,491,295	$ 4,188,600,499	$ 3,823,260,237	$ 3,815,727,434	$ 4,209,451,295	$ 4,216,034,080	$ 3,858,220,237	$ 3,853,027,175
			Risky supplier at 80%	$ 4,114,315,194	$ 4,119,136,991	$ 3,761,735,511	$ 3,775,866,820	$ 4,141,255,660	$ 4,161,181,349	$ 3,797,582,837	$ 3,810,826,820
			Risky supplier at 70%	$ 4,046,725,460	$ 4,042,601,934	$ 3,719,884,616	$ 3,719,923,183	$ 4,081,685,460	$ 4,110,087,796	$ 3,759,358,879	$ 3,741,797,367
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	$ 4,677,529,071	$ 4,684,905,885	$ 4,284,825,551	$ 4,285,884,365	$ 4,712,489,071	$ 4,719,865,885	$ 4,319,785,551	$ 4,320,844,365
			Increase Demand 20%	$ 4,959,369,032	$ 4,966,209,802	$ 4,552,624,466	$ 4,553,352,762	$ 4,994,329,032	$ 5,001,169,802	$ 4,587,584,466	$ 4,588,312,762
			Increase Demand 30%	$ 5,235,248,865	$ 5,238,880,118	$ 4,817,211,372	$ 4,818,000,358	$ 5,270,208,865	$ 5,273,840,118	$ 4,852,171,372	$ 4,852,960,358
		Simulation	Increase Demand 10%	$ 4,512,287,849	$ 4,513,485,898	$ 4,124,548,128	$ 4,132,208,193	$ 4,547,247,849	$ 4,548,445,898	$ 4,159,508,128	$ 4,167,168,193
			Increase Demand 20%	$ 4,774,215,785	$ 4,775,299,526	$ 4,381,498,141	$ 4,384,650,225	$ 4,809,175,785	$ 4,810,259,526	$ 4,416,458,141	$ 4,419,610,225
			Increase Demand 30%	$ 5,042,563,150	$ 5,052,956,562	$ 4,640,534,857	$ 4,640,846,844	$ 5,077,523,150	$ 5,087,916,562	$ 4,675,494,857	$ 4,675,806,844
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	$ 4,677,529,071	$ 4,684,905,885	$ 4,284,565,557	$ 4,285,884,365	$ 4,712,489,071	$ 4,719,865,885	$ 4,319,525,557	$ 4,320,844,365
			Increase Demand 20%	$ 4,959,369,032	$ 4,966,209,802	$ 4,552,376,462	$ 4,553,352,762	$ 4,994,329,032	$ 5,001,169,802	$ 4,587,336,462	$ 4,588,312,762
			Increase Demand 30%	$ 5,233,995,834	$ 5,238,880,118	$ 4,817,211,372	$ 4,818,000,358	$ 5,268,955,834	$ 5,273,840,118	$ 4,852,171,372	$ 4,852,960,358
		Simulation	Increase Demand 10%	$ 4,512,287,849	$ 4,513,485,898	$ 4,120,224,562	$ 4,132,208,193	$ 4,547,247,849	$ 4,548,445,898	$ 4,149,226,035	$ 4,167,168,193
			Increase Demand 20%	$ 4,774,215,785	$ 4,775,299,526	$ 4,380,131,373	$ 4,384,650,225	$ 4,809,175,785	$ 4,810,259,526	$ 4,413,722,984	$ 4,419,610,225
			Increase Demand 30%	$ 5,030,028,724	$ 5,052,956,562	$ 4,640,534,857	$ 4,640,846,844	$ 5,064,988,724	$ 5,087,916,562	$ 4,675,494,857	$ 4,675,806,844
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	$ 4,528,734,172	$ 4,535,999,891	$ 4,284,565,557	$ 4,285,884,365	$ 4,563,694,172	$ 4,570,959,891	$ 4,319,525,557	$ 4,320,844,365
			Increase Demand 20%	$ 4,645,148,664	$ 4,652,061,453	$ 4,538,351,451	$ 4,539,327,750	$ 4,680,108,664	$ 4,687,021,453	$ 4,573,311,451	$ 4,574,287,750
			Increase Demand 30%	$ 4,663,218,549	$ 4,670,397,107	$ 4,645,958,761	$ 4,646,747,747	$ 4,698,178,549	$ 4,705,357,107	$ 4,680,918,761	$ 4,681,707,747
		Simulation	Increase Demand 10%	$ 4,352,928,911	$ 4,364,266,875	$ 4,120,224,562	$ 4,132,208,193	$ 4,387,888,911	$ 4,405,696,447	$ 4,149,226,035	$ 4,167,168,193
			Increase Demand 20%	$ 4,461,173,084	$ 4,474,697,055	$ 4,358,742,145	$ 4,364,351,814	$ 4,496,133,084	$ 4,503,762,603	$ 4,402,277,286	$ 4,391,930,763
			Increase Demand 30%	$ 4,472,523,325	$ 4,478,256,441	$ 4,464,683,388	$ 4,459,580,787	$ 4,507,483,325	$ 4,515,538,113	$ 4,500,160,803	$ 4,499,650,621

Table 40. Data Set 6_7 Designed Experiment Results - Profit (cont.)

				LLHDD	LLHDS	LLHSD	LLHSS	LLLDD	LLLDS	LLLSD	LLLSS
	Original MIP			$ 5,070,798,909	$ 5,076,107,238	$ 4,634,947,427	$ 4,636,001,835	$ 5,105,758,909	$ 5,111,067,238	$ 4,669,907,427	$ 4,670,961,835
	Deterministic Simulation			$ 5,057,693,670	$ 5,063,002,000	$ 4,621,848,442	$ 4,620,611,814	$ 5,092,653,670	$ 5,097,962,000	$ 4,656,808,442	$ 4,655,571,810
	Stochastic Simulation			$ 4,874,394,398	$ 4,879,126,750	$ 4,438,444,583	$ 4,436,794,207	$ 4,909,354,398	$ 4,914,491,984	$ 4,471,444,975	$ 4,472,772,307
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		$ 4,517,387,835	$ 4,523,087,389	$ 4,291,881,805	$ 4,291,881,788	$ 4,544,607,835	$ 4,550,307,385	$ 4,319,621,788	$ 4,319,621,793
		Simulation		$ 4,342,328,228	$ 4,346,658,981	$ 4,151,483,866	$ 4,158,258,283	$ 4,369,548,228	$ 4,376,707,496	$ 4,185,148,611	$ 4,181,605,948
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	$ 5,002,954,419	$ 5,009,254,038	$ 4,582,091,359	$ 4,582,776,630	$ 5,037,914,414	$ 5,044,214,038	$ 4,617,051,359	$ 4,617,736,630
			Risky supplier at 80%	$ 4,934,978,198	$ 4,942,328,838	$ 4,529,235,292	$ 4,529,551,430	$ 4,969,938,198	$ 4,977,288,838	$ 4,564,195,297	$ 4,564,511,435
			Risky supplier at 70%	$ 4,866,935,643	$ 4,875,403,643	$ 4,475,798,230	$ 4,475,798,235	$ 4,901,895,643	$ 4,910,363,638	$ 4,510,758,235	$ 4,510,758,230
		Simulation	Risky supplier at 90%	$ 4,813,810,616	$ 4,819,224,346	$ 4,403,941,058	$ 4,388,215,657	$ 4,848,770,674	$ 4,858,419,670	$ 4,438,901,058	$ 4,431,752,163
			Risky supplier at 80%	$ 4,748,849,126	$ 4,748,046,171	$ 4,349,731,304	$ 4,339,698,867	$ 4,777,597,093	$ 4,778,682,295	$ 4,388,307,675	$ 4,382,163,472
			Risky supplier at 70%	$ 4,673,692,509	$ 4,675,606,779	$ 4,300,159,934	$ 4,303,124,874	$ 4,708,652,509	$ 4,716,642,256	$ 4,338,084,874	$ 4,339,796,663
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	$ 5,002,954,414	$ 5,009,254,038	$ 4,582,091,359	$ 4,582,776,630	$ 5,037,914,414	$ 5,044,214,038	$ 4,617,051,359	$ 4,617,736,630
			Risky supplier at 80%	$ 4,934,978,198	$ 4,942,328,838	$ 4,529,235,292	$ 4,529,551,430	$ 4,969,938,198	$ 4,977,288,838	$ 4,564,195,292	$ 4,564,511,435
			Risky supplier at 70%	$ 4,866,935,643	$ 4,875,403,638	$ 4,475,798,230	$ 4,475,798,230	$ 4,901,895,643	$ 4,910,363,638	$ 4,510,748,230	$ 4,510,758,230
		Simulation	Risky supplier at 90%	$ 4,772,535,939	$ 4,819,224,346	$ 4,403,941,058	$ 4,388,215,657	$ 4,848,770,674	$ 4,858,419,670	$ 4,438,901,058	$ 4,431,752,163
			Risky supplier at 80%	$ 4,748,849,126	$ 4,748,046,171	$ 4,349,731,304	$ 4,339,698,867	$ 4,777,597,093	$ 4,778,682,295	$ 4,305,675,058	$ 4,382,163,472
			Risky supplier at 70%	$ 4,673,692,509	$ 4,600,460,192	$ 4,300,159,934	$ 4,205,525,223	$ 4,708,652,509	$ 4,716,642,256	$ 4,238,744,741	$ 4,339,796,663
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	$ 5,417,839,964	$ 5,422,575,562	$ 4,963,131,204	$ 4,963,522,413	$ 5,452,799,964	$ 5,457,535,562	$ 4,998,091,204	$ 4,998,482,413
			Increase Demand 20%	$ 5,763,856,409	$ 5,768,063,086	$ 5,290,786,996	$ 5,290,786,996	$ 5,798,816,409	$ 5,803,023,086	$ 5,325,746,996	$ 5,325,746,996
			Increase Demand 30%	$ 6,103,449,503	$ 6,104,917,010	$ 5,611,183,298	$ 5,611,173,298	$ 6,138,872,703	$ 6,139,877,010	$ 5,646,133,298	$ 5,646,143,298
		Simulation	Increase Demand 10%	$ 5,221,960,462	$ 5,215,060,988	$ 4,759,586,705	$ 4,764,363,744	$ 5,256,920,462	$ 5,252,890,766	$ 4,798,165,503	$ 4,799,541,592
			Increase Demand 20%	$ 5,552,933,632	$ 5,552,198,075	$ 5,093,492,902	$ 5,094,530,746	$ 5,587,903,632	$ 5,587,158,075	$ 5,128,452,902	$ 5,129,500,746
			Increase Demand 30%	$ 5,865,531,395	$ 5,895,046,721	$ 5,395,680,817	$ 5,396,498,758	$ 5,910,348,085	$ 5,926,031,105	$ 5,430,568,201	$ 5,431,468,758
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	$ 5,417,839,964	$ 5,422,575,562	$ 4,962,871,210	$ 4,963,522,413	$ 5,452,799,964	$ 5,457,535,562	$ 4,997,831,210	$ 4,998,482,413
			Increase Demand 20%	$ 5,763,816,868	$ 5,768,063,086	$ 5,290,538,993	$ 5,290,786,996	$ 5,798,776,868	$ 5,803,023,086	$ 5,325,498,993	$ 5,325,746,996
			Increase Demand 30%	$ 6,102,554,500	$ 6,104,917,010	$ 5,611,183,298	$ 5,611,173,298	$ 6,137,514,500	$ 6,139,877,010	$ 5,646,133,298	$ 5,646,143,298
		Simulation	Increase Demand 10%	$ 5,221,960,462	$ 5,215,060,988	$ 4,752,977,619	$ 4,764,363,744	$ 5,256,920,462	$ 5,252,890,766	$ 4,777,622,006	$ 4,799,541,592
			Increase Demand 20%	$ 5,516,868,336	$ 5,552,198,075	$ 5,048,973,648	$ 5,094,530,746	$ 5,551,828,336	$ 5,587,158,075	$ 5,084,490,529	$ 5,129,500,746
			Increase Demand 30%	$ 5,834,876,898	$ 5,895,046,721	$ 5,395,680,817	$ 5,396,498,758	$ 5,869,836,898	$ 5,926,031,105	$ 5,430,568,201	$ 5,431,468,758
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	$ 5,269,045,065	$ 5,273,669,569	$ 4,962,871,210	$ 4,963,522,413	$ 5,304,005,065	$ 5,308,629,569	$ 4,997,831,210	$ 4,998,482,413
			Increase Demand 20%	$ 5,448,715,088	$ 5,453,914,737	$ 5,276,484,183	$ 5,276,732,187	$ 5,483,675,088	$ 5,488,874,737	$ 5,311,444,183	$ 5,311,692,187
			Increase Demand 30%	$ 5,530,040,404	$ 5,536,433,999	$ 5,443,635,487	$ 5,443,635,487	$ 5,565,000,404	$ 5,571,393,999	$ 5,478,595,487	$ 5,478,595,487
		Simulation	Increase Demand 10%	$ 5,047,066,405	$ 5,049,916,812	$ 4,752,977,619	$ 4,764,363,744	$ 5,082,026,405	$ 5,084,161,684	$ 4,777,622,006	$ 4,799,541,592
			Increase Demand 20%	$ 5,208,382,465	$ 5,222,743,669	$ 5,033,756,777	$ 5,028,435,316	$ 5,243,342,465	$ 5,244,601,921	$ 5,064,906,272	$ 5,067,985,970
			Increase Demand 30%	$ 5,277,019,065	$ 5,286,749,224	$ 5,178,800,646	$ 5,192,839,127	$ 5,311,979,065	$ 5,314,312,182	$ 5,220,161,242	$ 5,220,540,523

Table 41. Data Set 5_5 Designed Experiment Results - Profit

Analysis	Option	Method	Scenario	HHDD	HHDS	HHSD	HHSS	HLDD	HLDS	HLSD	HLSS
	Original MIP			$ 25,644,128	$ 33,392,718	$ 41,528,202	$ 42,183,384	$ 30,829,460	$ 36,191,673	$ 45,428,631	$ 49,792,712
	Deterministic Simulation			$ 24,841,644	$ 32,552,343	$ 40,643,733	$ 41,077,407	$ 29,791,775	$ 34,136,139	$ 43,437,467	$ 47,633,431
	Stochastic Simulation			$ 15,547,433	$ 22,445,237	$ 29,210,752	$ 29,578,456	$ 16,976,650	$ 25,160,524	$ 31,697,036	$ 34,844,566
Capacity Analysis	Risky Supplier			5	5	5	5	5	5	5	5
	Option A - Remove risky supplier from data set.	MIP		$ 21,043,221	$ 21,043,221	$ 33,685,558	$ 33,685,558	$ 21,160,718	$ 21,160,718	$ 33,735,558	$ 33,735,558
		Simulation		$ 14,238,125	$ 14,238,125	$ 23,857,018	$ 23,857,018	$ 11,388,884	$ 11,388,884	$ 23,759,206	$ 23,759,206
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	$ 25,434,128	$ 33,151,218	$ 41,528,202	$ 42,141,384	$ 29,740,410	$ 35,950,173	$ 44,177,581	$ 47,167,175
			Risky supplier at 80%	$ 25,224,128	$ 32,731,218	$ 40,401,014	$ 40,624,794	$ 28,931,760	$ 35,530,173	$ 44,065,731	$ 44,904,177
			Risky supplier at 70%	$ 25,014,128	$ 30,724,418	$ 38,376,714	$ 38,686,466	$ 28,511,760	$ 32,758,304	$ 43,839,531	$ 44,073,518
		Simulation	Risky supplier at 90%	$ 15,577,810	$ 21,999,977	$ 29,210,752	$ 29,293,376	$ 16,160,055	$ 24,694,573	$ 30,673,177	$ 32,974,548
			Risky supplier at 80%	$ 14,221,322	$ 21,407,304	$ 27,573,311	$ 29,434,760	$ 16,920,368	$ 24,483,816	$ 30,635,796	$ 29,738,988
			Risky supplier at 70%	$ 14,881,298	$ 22,726,606	$ 27,994,690	$ 28,274,542	$ 15,657,052	$ 24,152,789	$ 30,928,739	$ 31,471,727
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	$ 25,434,128	$ 33,151,218	$ 41,528,202	infeasible	infeasible	infeasible	infeasible	infeasible
			Risky supplier at 80%	$ 25,224,128	$ 32,731,218	$ 40,081,159	infeasible	infeasible	infeasible	infeasible	infeasible
			Risky supplier at 70%	$ 25,014,128	$ 30,724,418	$ 38,376,714	infeasible	infeasible	infeasible	infeasible	infeasible
		Simulation	Risky supplier at 90%	$ 15,577,810	$ 21,999,977	$ 29,210,752	-	-	-	-	-
			Risky supplier at 80%	$ 14,221,322	$ 21,407,304	$ 28,774,594	-	-	-	-	-
			Risky supplier at 70%	$ 14,881,298	$ 22,726,606	$ 27,994,690	-	-	-	-	-
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	$ 27,783,128	$ 35,405,697	$ 33,894,685	$ 43,406,231	$ 33,582,182	$ 36,509,740	$ 49,390,469	$ 51,982,763
			Increase Demand 20%	$ 29,011,585	$ 36,515,160	$ 36,261,167	$ 44,990,689	$ 35,316,842	$ 36,509,740	$ 51,946,884	$ 54,551,746
			Increase Demand 30%	$ 30,240,042	$ 37,245,440	$ 38,627,650	$ 46,575,146	$ 36,975,062	$ 36,509,740	$ 54,503,299	$ 56,507,725
		Simulation	Increase Demand 10%	$ 15,201,740	$ 21,070,985	$ 29,637,618	$ 33,239,504	$ 16,745,190	$ 27,230,160	$ 31,797,297	$ 33,531,214
			Increase Demand 20%	$ 15,791,303	$ 22,026,866	$ 31,959,554	$ 34,411,321	$ 18,030,194	$ 27,230,160	$ 33,537,702	$ 35,912,247
			Increase Demand 30%	$ 16,213,478	$ 22,639,923	$ 33,301,175	$ 34,635,558	$ 18,434,390	$ 27,230,160	$ 35,319,201	$ 36,877,591
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	$ 27,783,128	$ 35,405,697	$ 33,894,685	$ 43,406,231	$ 33,582,182	$ 36,509,740	$ 49,390,469	$ 51,982,763
			Increase Demand 20%	$ 29,011,585	$ 36,515,160	$ 36,261,167	$ 44,990,689	$ 35,316,842	$ 36,509,740	$ 51,946,884	$ 54,551,746
			Increase Demand 30%	$ 30,240,042	$ 37,245,440	$ 38,627,650	$ 46,575,146	$ 36,975,062	$ 36,509,740	$ 54,503,299	$ 56,507,725
		Simulation	Increase Demand 10%	$ 15,201,740	$ 21,070,985	$ 29,637,618	$ 33,239,504	$ 16,745,190	$ 27,230,160	$ 31,797,297	$ 33,531,214
			Increase Demand 20%	$ 15,791,303	$ 22,026,866	$ 31,959,554	$ 34,411,321	$ 18,030,194	$ 27,230,160	$ 33,537,702	$ 35,912,247
			Increase Demand 30%	$ 16,213,478	$ 22,639,923	$ 33,301,175	$ 34,635,558	$ 18,434,390	$ 27,230,160	$ 35,319,201	$ 36,877,591
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	$ 27,783,128	$ 35,405,697	$ 33,894,685	$ 43,406,231	$ 33,582,182	$ 36,509,740	$ 49,390,469	$ 51,982,763
			Increase Demand 20%	$ 29,011,585	$ 36,515,160	$ 35,786,789	$ 44,990,689	$ 34,930,938	$ 36,509,740	$ 51,946,884	$ 53,875,108
			Increase Demand 30%	$ 30,240,042	$ 37,245,440	$ 36,948,307	$ 46,575,146	$ 35,928,899	$ 36,509,740	$ 54,503,299	$ 54,673,400
		Simulation	Increase Demand 10%	$ 15,201,740	$ 21,070,985	$ 28,009,626	$ 33,239,504	$ 13,769,781	$ 27,230,160	$ 31,797,297	$ 31,924,273
			Increase Demand 20%	$ 15,791,303	$ 22,026,866	$ 28,537,734	$ 34,411,321	$ 12,783,182	$ 27,230,160	$ 33,537,702	$ 31,718,449
			Increase Demand 30%	$ 16,213,478	$ 22,639,923	$ 28,481,171	$ 34,635,558	$ 12,773,213	$ 27,230,160	$ 35,319,201	$ 32,378,513

Table 41. Data Set 5_5 Designed Experiment Results - Profit (cont.)

				LHDD	LHDS	LHSD	LHSS	LLDD	LLDS	LLSD	LLSS
	Original MIP			$ 19,407,401	$ 23,108,339	$ 34,913,573	$ 35,159,245	$ 26,215,554	$ 31,553,645	$ 42,103,117	$ 43,221,629
	Deterministic Simulation			$ 18,442,523	$ 22,169,396	$ 33,927,817	$ 34,194,364	$ 24,390,283	$ 30,427,727	$ 40,164,334	$ 41,121,938
	Stochastic Simulation			$ 8,716,261	$ 14,596,957	$ 25,365,766	$ 25,838,228	$ 17,617,285	$ 19,130,786	$ 33,561,094	$ 30,788,173
Capacity Analysis	Risky Supplier			5	5	5	5	5	5	5	5
	Option A - Remove risky supplier from data set.	MIP		infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
		Simulation		-	-	-	-	-	-	-	-
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	$ 18,376,151	$ 21,478,964	$ 32,858,623	$ 32,926,995	$ 25,177,190	$ 30,436,895	$ 40,933,491	$ 42,051,511
			Risky supplier at 80%	$ 17,092,901	$ 19,849,589	$ 30,787,461	$ 30,787,461	$ 24,149,256	$ 29,320,145	$ 39,755,840	$ 40,867,761
			Risky supplier at 70%	$ 15,489,947	$ 17,321,025	$ 28,441,107	$ 28,441,107	$ 23,891,970	$ 27,591,718	$ 38,453,436	$ 38,921,598
		Simulation	Risky supplier at 90%	$ 7,553,700	$ 13,551,501	$ 22,135,872	$ 23,011,020	$ 17,044,978	$ 16,582,350	$ 32,925,785	$ 28,143,624
			Risky supplier at 80%	$ 6,972,918	$ 12,505,679	$ 20,726,610	$ 20,726,610	$ 13,486,607	$ 16,081,241	$ 31,554,470	$ 27,566,062
			Risky supplier at 70%	$ 5,666,448	$ 12,153,119	$ 18,019,896	$ 18,589,896	$ 13,705,681	$ 14,188,796	$ 30,607,112	$ 25,532,996
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
			Risky supplier at 80%	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
			Risky supplier at 70%	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
		Simulation	Risky supplier at 90%	-	-	-	-	-	-	-	-
			Risky supplier at 80%	-	-	-	-	-	-	-	-
			Risky supplier at 70%	-	-	-	-	-	-	-	-
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	$ 21,002,391	$ 24,869,048	$ 37,261,234	$ 37,542,019	$ 28,952,812	$ 33,414,409	$ 46,188,145	$ 46,732,227
			Increase Demand 20%	$ 22,475,029	$ 26,629,757	$ 39,608,895	$ 39,923,299	$ 31,674,617	$ 35,375,174	$ 50,471,313	$ 50,930,770
			Increase Demand 30%	$ 23,806,550	$ 26,765,850	$ 41,545,884	$ 41,883,474	$ 33,427,935	$ 36,233,822	$ 52,900,479	$ 53,383,042
		Simulation	Increase Demand 10%	$ 9,015,165	$ 16,253,209	$ 26,178,442	$ 25,562,260	$ 18,254,007	$ 19,929,446	$ 35,486,688	$ 35,232,706
			Increase Demand 20%	$ 11,270,999	$ 16,830,795	$ 28,399,453	$ 28,168,460	$ 18,749,050	$ 23,251,127	$ 37,542,090	$ 39,469,361
			Increase Demand 30%	$ 9,897,292	$ 17,522,745	$ 27,630,780	$ 28,526,881	$ 21,194,409	$ 22,700,971	$ 40,660,672	$ 39,279,366
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	$ 21,002,391	$ 24,869,048	$ 37,261,234	$ 37,542,019	$ 28,950,261	$ 33,414,409	$ 46,172,838	$ 46,732,227
			Increase Demand 20%	$ 22,289,336	$ 26,629,757	$ 39,608,895	$ 39,923,299	$ 31,669,837	$ 35,375,174	$ 50,442,630	$ 50,930,770
			Increase Demand 30%	$ 23,198,063	$ 26,765,850	$ 41,545,884	$ 41,883,474	$ 33,423,154	$ 36,233,822	$ 52,871,795	$ 53,383,042
		Simulation	Increase Demand 10%	$ 6,290,909	$ 16,253,209	$ 26,178,442	$ 25,562,260	$ 16,617,905	$ 19,929,446	$ 33,837,739	$ 35,232,706
			Increase Demand 20%	$ 3,660,414	$ 16,830,795	$ 28,399,453	$ 28,168,460	$ 15,998,606	$ 23,251,127	$ 34,768,418	$ 39,469,361
			Increase Demand 30%	$ 1,116,997	$ 17,522,745	$ 27,630,780	$ 28,526,881	$ 16,564,336	$ 22,700,971	$ 36,007,842	$ 39,279,366
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	$ 21,002,391	$ 24,869,048	$ 37,261,234	$ 37,542,019	$ 28,950,261	$ 33,414,409	$ 46,172,838	$ 46,732,227
			Increase Demand 20%	$ 22,289,336	$ 26,629,757	$ 39,608,895	$ 39,923,299	$ 31,669,837	$ 35,375,174	$ 50,442,630	$ 50,930,770
			Increase Demand 30%	$ 23,198,063	$ 26,765,850	$ 41,545,884	$ 41,883,474	$ 33,423,154	$ 36,233,822	$ 52,871,795	$ 53,383,042
		Simulation	Increase Demand 10%	$ 6,290,909	$ 16,253,209	$ 26,178,442	$ 25,562,260	$ 16,617,905	$ 19,929,446	$ 33,837,739	$ 35,232,706
			Increase Demand 20%	$ 3,660,414	$ 16,830,795	$ 28,399,453	$ 28,168,460	$ 15,998,606	$ 23,251,127	$ 34,768,418	$ 39,469,361
			Increase Demand 30%	$ 1,116,997	$ 17,522,745	$ 27,630,780	$ 28,526,881	$ 16,564,336	$ 22,700,971	$ 36,007,842	$ 39,279,366

Table 42. Data Set 6_7 Designed Experiment Results - % Change

				HHHDD	HHHDS	HHHSD	HHHSS	HHLDD	HHLDS	HHLSD	HHLSS
	Original MIP			$ 4,397,563,976	$ 4,406,989,168	$ 4,019,860,468	$ 4,021,923,168	$ 4,432,523,976	$ 4,441,949,168	$ 4,054,820,468	$ 4,056,883,168
	Deterministic Simulation			$ 4,386,684,696	$ 4,396,109,889	$ 4,008,981,185	$ 4,011,043,884	$ 4,421,644,696	$ 4,431,069,889	$ 4,043,941,185	$ 4,046,003,884
	Stochastic Simulation			$ 4,231,843,593	$ 4,238,000,757	$ 3,862,893,875	$ 3,859,236,992	$ 4,266,803,593	$ 4,278,027,780	$ 3,897,853,875	$ 3,892,546,232
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		-11.2%	-11.1%	-10.4%	-10.4%	-11.3%	-11.2%	-10.5%	-10.5%
		Simulation		-11.3%	-11.1%	-10.3%	-10.0%	-11.4%	-11.3%	-10.4%	-9.9%
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	-1.5%	-1.5%	-1.3%	-1.3%	-1.5%	-1.4%	-1.3%	-1.3%
			Risky supplier at 80%	-3.0%	-2.9%	-2.6%	-2.6%	-2.9%	-2.9%	-2.6%	-2.6%
			Risky supplier at 70%	-4.4%	-4.4%	-3.2%	-3.2%	-4.4%	-4.3%	-3.2%	-3.2%
		Simulation	Risky supplier at 90%	-1.4%	-1.3%	-0.9%	-1.3%	-1.4%	-1.5%	-0.9%	-0.9%
			Risky supplier at 80%	-2.8%	-2.7%	-2.5%	-2.3%	-2.8%	-2.8%	-2.5%	-2.2%
			Risky supplier at 70%	-4.5%	-4.2%	-2.5%	-2.8%	-4.5%	-4.3%	-2.5%	-2.7%
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	-1.5%	-1.5%	-1.3%	-1.3%	-1.5%	-1.4%	-1.3%	-1.3%
			Risky supplier at 80%	-3.0%	-2.9%	-2.6%	-2.6%	-2.9%	-2.9%	-2.6%	-2.6%
			Risky supplier at 70%	-4.4%	-4.4%	-3.9%	-3.9%	-4.4%	-4.3%	-3.9%	-3.9%
		Simulation	Risky supplier at 90%	-1.4%	-1.3%	-0.9%	-1.3%	-1.4%	-1.5%	-0.9%	-0.9%
			Risky supplier at 80%	-2.8%	-2.7%	-2.5%	-2.3%	-2.8%	-2.8%	-2.5%	-2.2%
			Risky supplier at 70%	-4.5%	-4.2%	-4.2%	-4.2%	-4.5%	-4.3%	-4.1%	-4.1%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	6.4%	6.4%	6.7%	6.7%	6.4%	6.4%	6.6%	6.6%
			Increase Demand 20%	12.8%	12.8%	13.4%	13.3%	12.7%	12.7%	13.2%	13.2%
			Increase Demand 30%	19.1%	19.0%	19.9%	19.9%	19.0%	18.8%	19.8%	19.7%
		Simulation	Increase Demand 10%	6.5%	6.8%	6.7%	6.8%	6.4%	6.6%	6.7%	6.8%
			Increase Demand 20%	13.1%	13.0%	13.6%	13.5%	13.0%	12.8%	13.3%	13.4%
			Increase Demand 30%	19.1%	19.2%	20.1%	20.1%	19.0%	18.9%	19.9%	20.0%
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	6.4%	6.4%	6.7%	6.7%	6.4%	6.4%	6.6%	6.6%
			Increase Demand 20%	12.8%	12.8%	13.3%	13.3%	12.7%	12.7%	13.2%	13.2%
			Increase Demand 30%	19.1%	19.0%	19.9%	19.9%	18.9%	18.8%	19.8%	19.7%
		Simulation	Increase Demand 10%	6.5%	6.8%	6.8%	6.8%	6.4%	6.6%	6.8%	6.8%
			Increase Demand 20%	13.1%	13.0%	13.0%	13.5%	13.0%	12.8%	12.9%	13.4%
			Increase Demand 30%	18.8%	19.2%	19.6%	20.1%	18.6%	18.9%	19.4%	20.0%
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	3.0%	3.0%	6.7%	6.7%	3.0%	3.0%	6.6%	6.6%
			Increase Demand 20%	5.7%	5.6%	13.0%	12.9%	5.6%	5.6%	12.8%	12.8%
			Increase Demand 30%	5.7%	5.6%	15.2%	15.2%	5.6%	5.6%	15.1%	15.0%
		Simulation	Increase Demand 10%	2.9%	3.1%	6.8%	6.8%	2.9%	2.7%	6.8%	6.8%
			Increase Demand 20%	5.3%	5.6%	12.6%	12.7%	5.3%	5.5%	12.5%	13.0%
			Increase Demand 30%	5.3%	5.6%	14.7%	15.1%	5.3%	5.5%	14.5%	14.8%

Table 42. Data Set 6_7 Designed Experiment Results - % Change (cont.)

				HLHDD	HLHDS	HLHSD	HLHSS	HLLDD	HLLDS	HLLSD	HLLSS
	Original MIP			$ 5,073,041,768	$ 5,078,435,718	$ 4,645,311,342	$ 4,646,933,195	$ 5,108,001,768	$ 5,113,395,718	$ 4,680,271,342	$ 4,681,893,195
	Deterministic Simulation			$ 5,059,936,529	$ 5,065,330,480	$ 4,632,320,176	$ 4,633,942,030	$ 5,094,896,529	$ 5,100,290,480	$ 4,667,280,175	$ 4,668,902,030
	Stochastic Simulation			$ 4,872,254,478	$ 4,880,802,235	$ 4,460,037,271	$ 4,446,597,361	$ 4,907,214,478	$ 4,909,110,904	$ 4,494,370,027	$ 4,481,557,361
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		-10.5%	-10.5%	-6.8%	-6.8%	-10.6%	-10.6%	-6.9%	-6.9%
		Simulation		-10.2%	-10.1%	-6.9%	-6.4%	-10.3%	-10.1%	-7.1%	-6.5%
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.1%	-1.3%	-1.3%	-1.1%	-1.1%
			Risky supplier at 80%	-2.7%	-2.6%	-2.3%	-2.3%	-2.7%	-2.6%	-2.3%	-2.2%
			Risky supplier at 70%	-4.0%	-4.0%	-3.4%	-3.4%	-4.0%	-3.9%	-3.4%	-3.4%
		Simulation	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.2%	-1.3%	-1.1%	-0.8%	-1.2%
			Risky supplier at 80%	-2.7%	-2.7%	-2.2%	-2.2%	-2.6%	-2.5%	-2.2%	-2.2%
			Risky supplier at 70%	-3.8%	-4.1%	-3.8%	-3.2%	-3.9%	-3.9%	-3.7%	-3.2%
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.1%	-1.3%	-1.3%	-1.1%	-1.1%
			Risky supplier at 80%	-2.7%	-2.6%	-2.3%	-2.3%	-2.7%	-2.6%	-2.3%	-2.2%
			Risky supplier at 70%	-4.0%	-4.0%	-3.4%	-3.4%	-4.0%	-3.9%	-3.4%	-3.4%
		Simulation	Risky supplier at 90%	-1.3%	-1.3%	-2.0%	-2.0%	-1.3%	-1.1%	-0.8%	-1.9%
			Risky supplier at 80%	-2.7%	-2.7%	-2.2%	-2.2%	-2.6%	-2.5%	-2.2%	-2.2%
			Risky supplier at 70%	-3.8%	-4.1%	-3.8%	-3.2%	-5.7%	-3.9%	-3.7%	-3.2%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	6.8%	6.8%	7.1%	7.0%	6.8%	6.8%	7.0%	7.0%
			Increase Demand 20%	13.7%	13.6%	14.2%	14.2%	13.6%	13.5%	14.1%	14.1%
			Increase Demand 30%	20.4%	20.3%	21.1%	21.1%	20.2%	20.1%	21.0%	21.0%
		Simulation	Increase Demand 10%	7.1%	6.9%	7.1%	7.4%	7.1%	7.0%	7.1%	7.3%
			Increase Demand 20%	13.8%	13.8%	13.8%	14.1%	13.7%	13.6%	13.7%	14.0%
			Increase Demand 30%	20.5%	20.1%	20.7%	20.7%	20.4%	20.2%	20.7%	20.5%
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	6.8%	6.8%	7.0%	7.0%	6.8%	6.8%	7.0%	7.0%
			Increase Demand 20%	13.7%	13.6%	14.2%	14.1%	13.6%	13.5%	14.0%	14.0%
			Increase Demand 30%	20.3%	20.3%	21.1%	21.1%	20.2%	20.1%	21.0%	20.9%
		Simulation	Increase Demand 10%	6.9%	6.9%	6.4%	7.4%	6.8%	7.0%	6.3%	7.3%
			Increase Demand 20%	13.2%	13.8%	13.3%	13.6%	13.1%	13.6%	13.3%	13.5%
			Increase Demand 30%	20.1%	20.1%	20.4%	21.0%	20.0%	20.2%	20.3%	20.8%
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	2.3%	3.9%	5.4%	5.4%	2.3%	3.9%	5.4%	5.4%
			Increase Demand 20%	4.2%	7.4%	10.0%	10.0%	4.2%	7.4%	9.9%	9.9%
			Increase Demand 30%	4.2%	9.1%	11.7%	11.7%	4.2%	9.0%	11.6%	11.6%
		Simulation	Increase Demand 10%	2.5%	3.7%	4.8%	5.2%	2.5%	3.7%	4.8%	5.2%
			Increase Demand 20%	4.4%	6.9%	8.9%	9.3%	4.3%	6.9%	8.9%	9.2%
			Increase Demand 30%	4.4%	8.4%	10.6%	11.0%	4.3%	8.6%	10.5%	10.9%

Table 42. Data Set 6_7 Designed Experiment Results - % Change (cont.)

				LHHDD	LHHDS	LHHSD	LHHSS	LHLDD	LHLDS	LHLSD	LHLSS
	Original MIP			$ 4,394,937,392	$ 4,402,621,168	$ 4,016,498,651	$ 4,018,159,968	$ 4,429,897,392	$ 4,437,581,168	$ 4,051,458,651	$ 4,053,119,968
	Deterministic Simulation			$ 4,384,058,113	$ 4,391,741,889	$ 4,005,619,369	$ 4,007,280,685	$ 4,419,018,113	$ 4,426,701,889	$ 4,040,579,369	$ 4,042,240,684
	Stochastic Simulation			$ 4,230,388,378	$ 4,243,859,120	$ 3,865,399,618	$ 3,874,241,992	$ 4,265,348,378	$ 4,274,328,065	$ 3,904,558,695	$ 3,891,557,933
Capacity Analysis	Risky Supplier			3	3	5	5	3	3	5	5
	Option A - Remove risky supplier from data set.	MIP		-11.5%	-11.5%	-14.6%	-14.7%	-11.6%	-11.6%	-14.7%	-14.7%
		Simulation		-11.5%	-11.2%	-14.4%	-14.8%	-11.6%	-11.2%	-14.5%	-14.3%
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	-1.5%	-1.5%	-1.3%	-1.3%	-1.5%	-1.4%	-1.3%	-1.3%
			Risky supplier at 80%	-3.0%	-2.9%	-2.6%	-2.6%	-2.9%	-2.9%	-2.6%	-2.6%
			Risky supplier at 70%	-4.4%	-4.4%	-3.9%	-3.9%	-4.4%	-4.3%	-3.9%	-3.9%
		Simulation	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.5%	-1.3%	-1.4%	-1.2%	-1.0%
			Risky supplier at 80%	-2.7%	-2.9%	-2.7%	-2.5%	-2.9%	-2.6%	-2.7%	-2.1%
			Risky supplier at 70%	-4.3%	-4.7%	-3.8%	-4.0%	-4.3%	-3.8%	-3.7%	-3.8%
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	-1.5%	-1.5%	-1.3%	-1.3%	-1.5%	-1.4%	-1.3%	-1.3%
			Risky supplier at 80%	-3.0%	-2.9%	-2.6%	-2.6%	-2.9%	-2.9%	-2.6%	-2.6%
			Risky supplier at 70%	-4.4%	-4.4%	-3.9%	-3.9%	-4.4%	-4.3%	-3.9%	-3.9%
		Simulation	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.5%	-1.3%	-1.4%	-1.2%	-1.0%
			Risky supplier at 80%	-2.7%	-2.9%	-2.7%	-2.5%	-2.9%	-2.6%	-2.7%	-2.1%
			Risky supplier at 70%	-4.3%	-4.7%	-3.8%	-4.0%	-4.3%	-3.8%	-3.7%	-3.8%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	6.4%	6.4%	6.7%	6.7%	6.4%	6.4%	6.6%	6.6%
			Increase Demand 20%	12.8%	12.8%	13.3%	13.3%	12.7%	12.7%	13.2%	13.2%
			Increase Demand 30%	19.1%	19.0%	19.9%	19.9%	19.0%	18.8%	19.8%	19.7%
		Simulation	Increase Demand 10%	6.7%	6.4%	6.7%	6.7%	6.6%	6.4%	6.5%	7.1%
			Increase Demand 20%	12.9%	12.5%	13.4%	13.2%	12.7%	12.5%	13.1%	13.6%
			Increase Demand 30%	19.2%	19.1%	20.1%	19.8%	19.0%	19.0%	19.7%	20.2%
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	6.4%	6.4%	6.7%	6.7%	6.4%	6.4%	6.6%	6.6%
			Increase Demand 20%	12.8%	12.8%	13.3%	13.3%	12.7%	12.7%	13.2%	13.2%
			Increase Demand 30%	19.1%	19.0%	19.9%	19.9%	18.9%	18.8%	19.8%	19.7%
		Simulation	Increase Demand 10%	6.7%	6.4%	6.6%	6.7%	6.6%	6.4%	6.3%	7.1%
			Increase Demand 20%	12.9%	12.5%	13.3%	13.2%	12.7%	12.5%	13.0%	13.6%
			Increase Demand 30%	18.9%	19.1%	20.1%	19.8%	18.7%	19.0%	19.7%	20.2%
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	3.0%	3.0%	6.7%	6.7%	3.0%	3.0%	6.6%	6.6%
			Increase Demand 20%	5.7%	5.7%	13.0%	13.0%	5.6%	5.6%	12.9%	12.9%
			Increase Demand 30%	6.1%	6.1%	15.7%	15.6%	6.1%	6.0%	15.5%	15.5%
		Simulation	Increase Demand 10%	2.9%	2.8%	6.6%	6.7%	2.9%	3.1%	6.3%	7.1%
			Increase Demand 20%	5.5%	5.4%	12.8%	12.7%	5.4%	5.4%	12.7%	12.9%
			Increase Demand 30%	5.7%	5.5%	15.5%	15.1%	5.7%	5.6%	15.3%	15.6%

Table 42. Data Set 6_7 Designed Experiment Results - % Change (cont.)

				LLHDD	LLHDS	LLHSD	LLHSS	LLLDD	LLLDS	LLLSD	LLLSS
	Original MIP			$ 5,070,798,909	$ 5,076,107,238	$ 4,634,947,427	$ 4,636,001,835	$ 5,105,758,909	$ 5,111,067,238	$ 4,669,907,427	$ 4,670,961,835
	Deterministic Simulation			$ 5,057,693,670	$ 5,063,002,000	$ 4,621,848,442	$ 4,620,611,814	$ 5,092,653,670	$ 5,097,962,000	$ 4,656,808,442	$ 4,655,571,810
	Stochastic Simulation			$ 4,874,394,398	$ 4,879,126,750	$ 4,438,444,583	$ 4,436,794,207	$ 4,909,354,398	$ 4,914,491,984	$ 4,471,444,975	$ 4,472,772,307
	Risky Supplier			3	3	5	5	3	3	5	5
Capacity Analysis	Option A - Remove risky supplier from data set.	MIP		-10.9%	-10.9%	-7.4%	-7.4%	-11.0%	-11.0%	-7.5%	-7.5%
		Simulation		-10.9%	-10.9%	-6.5%	-6.3%	-11.0%	-10.9%	-6.4%	-6.5%
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.1%	-1.3%	-1.3%	-1.1%	-1.1%
			Risky supplier at 80%	-2.7%	-2.6%	-2.3%	-2.3%	-2.7%	-2.6%	-2.3%	-2.3%
			Risky supplier at 70%	-4.0%	-4.0%	-3.4%	-3.5%	-4.0%	-3.9%	-3.4%	-3.4%
		Simulation	Risky supplier at 90%	-1.2%	-1.2%	-0.8%	-1.1%	-1.2%	-1.1%	-0.7%	-0.9%
			Risky supplier at 80%	-2.6%	-2.7%	-2.0%	-2.2%	-2.7%	-2.8%	-1.9%	-2.0%
			Risky supplier at 70%	-4.1%	-4.2%	-3.1%	-3.0%	-4.1%	-4.0%	-3.0%	-3.0%
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	-1.3%	-1.3%	-1.1%	-1.1%	-1.3%	-1.3%	-1.1%	-1.1%
			Risky supplier at 80%	-2.7%	-2.6%	-2.3%	-2.3%	-2.7%	-2.6%	-2.3%	-2.3%
			Risky supplier at 70%	-4.0%	-4.0%	-3.4%	-3.5%	-4.0%	-3.9%	-3.4%	-3.4%
		Simulation	Risky supplier at 90%	-2.1%	-1.2%	-0.8%	-1.1%	-1.2%	-1.1%	-0.7%	-0.9%
			Risky supplier at 80%	-2.6%	-2.7%	-2.0%	-2.2%	-2.7%	-2.8%	-3.7%	-2.0%
			Risky supplier at 70%	-4.1%	-5.7%	-3.1%	-5.2%	-4.1%	-4.0%	-5.2%	-3.0%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	6.8%	6.8%	7.1%	7.1%	6.8%	6.8%	7.0%	7.0%
			Increase Demand 20%	13.7%	13.6%	14.1%	14.1%	13.6%	13.5%	14.0%	14.0%
			Increase Demand 30%	20.4%	20.3%	21.1%	21.0%	20.2%	20.1%	20.9%	20.9%
		Simulation	Increase Demand 10%	7.1%	6.9%	7.2%	7.4%	7.1%	6.9%	7.3%	7.3%
			Increase Demand 20%	13.9%	13.8%	14.8%	14.8%	13.8%	13.7%	14.7%	14.7%
			Increase Demand 30%	20.3%	20.8%	21.6%	21.6%	20.4%	20.6%	21.4%	21.4%
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	6.8%	6.8%	7.1%	7.1%	6.8%	6.8%	7.0%	7.0%
			Increase Demand 20%	13.7%	13.6%	14.1%	14.1%	13.6%	13.5%	14.0%	14.0%
			Increase Demand 30%	20.3%	20.3%	21.1%	21.0%	20.2%	20.1%	20.9%	20.9%
		Simulation	Increase Demand 10%	7.1%	6.9%	7.1%	7.4%	7.1%	6.9%	6.8%	7.3%
			Increase Demand 20%	13.2%	13.8%	13.8%	14.8%	13.1%	13.7%	13.7%	14.7%
			Increase Demand 30%	19.7%	20.8%	21.6%	21.6%	19.6%	20.6%	21.4%	21.4%
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	3.9%	3.9%	7.1%	7.1%	3.9%	3.9%	7.0%	7.0%
			Increase Demand 20%	7.5%	7.4%	13.8%	13.8%	7.4%	7.4%	13.7%	13.7%
			Increase Demand 30%	9.1%	9.1%	17.4%	17.4%	9.0%	9.0%	17.3%	17.3%
		Simulation	Increase Demand 10%	3.5%	3.5%	7.1%	7.4%	3.5%	3.5%	6.8%	7.3%
			Increase Demand 20%	6.9%	7.0%	13.4%	13.3%	6.8%	6.7%	13.3%	13.3%
			Increase Demand 30%	8.3%	8.4%	16.7%	17.0%	8.2%	8.1%	16.7%	16.7%

Table 43. Data Set 5_5 Designed Experiment Results - % Change

				HHDD	HHDS	HHSD	HHSS	HLDD	HLDS	HLSD	HLSS
	Original MIP			$ 25,644,128	$ 33,392,718	$ 41,528,202	$ 42,183,384	$ 30,829,460	$ 36,191,673	$ 45,428,631	$ 49,792,712
	Deterministic Simulation			$ 24,841,644	$ 32,552,343	$ 40,643,733	$ 41,077,407	$ 29,791,775	$ 34,136,139	$ 43,437,467	$ 47,633,431
	Stochastic Simulation			$ 15,547,433	$ 22,445,237	$ 29,210,752	$ 29,578,456	$ 16,976,650	$ 25,160,524	$ 31,697,036	$ 34,844,566
Capacity Analysis	Risky Supplier			5	5	5	5	5	5	5	5
Capacity Analysis	Option A - Remove risky supplier from data set.	MIP		-17.9%	-37.0%	-18.9%	-20.1%	-31.4%	-41.5%	-25.7%	-32.2%
Capacity Analysis	Option A - Remove risky supplier from data set.	Simulation		-8.4%	-36.6%	-18.3%	-19.3%	-32.9%	-54.7%	-25.0%	-31.8%
Capacity Analysis	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	-0.8%	-0.7%	0.0%	-0.1%	-3.5%	-0.7%	-2.8%	-5.3%
Capacity Analysis	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 80%	-1.6%	-2.0%	-2.7%	-3.7%	-6.2%	-1.8%	-3.0%	-9.8%
Capacity Analysis	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 70%	-2.5%	-8.0%	-7.6%	-8.3%	-7.5%	-9.5%	-3.5%	-11.5%
Capacity Analysis	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	Simulation	Risky supplier at 90%	0.2%	-2.0%	0.0%	-1.0%	-4.8%	-1.9%	-3.2%	-5.4%
Capacity Analysis	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	Simulation	Risky supplier at 80%	-8.5%	-4.6%	-5.6%	-0.5%	-0.3%	-2.7%	-3.3%	-14.7%
Capacity Analysis	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	Simulation	Risky supplier at 70%	-4.3%	1.3%	-4.2%	-4.4%	-7.8%	-4.0%	-2.4%	-9.7%
Capacity Analysis	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	-0.8%	-0.7%	0.0%	infeasible	infeasible	infeasible	infeasible	infeasible
Capacity Analysis	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 80%	-1.6%	-2.0%	-3.5%	infeasible	infeasible	infeasible	infeasible	infeasible
Capacity Analysis	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 70%	-2.5%	-8.0%	-7.6%	infeasible	infeasible	infeasible	infeasible	infeasible
Capacity Analysis	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	Simulation	Risky supplier at 90%	0.2%	-2.0%	0.0%	-	-	-	-	-
Capacity Analysis	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	Simulation	Risky supplier at 80%	-8.5%	-4.6%	-1.5%	-	-	-	-	-
Capacity Analysis	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	Simulation	Risky supplier at 70%	-4.3%	1.3%	-4.2%	-	-	-	-	-
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	8.3%	6.0%	-18.4%	2.9%	8.9%	0.9%	8.7%	4.4%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 20%	13.1%	9.4%	-12.7%	6.7%	14.6%	0.9%	14.3%	9.6%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 30%	17.9%	11.5%	-7.0%	10.4%	19.9%	0.9%	20.0%	13.5%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	Simulation	Increase Demand 10%	-2.2%	-6.1%	1.5%	12.4%	-1.4%	8.2%	0.3%	-3.8%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	Simulation	Increase Demand 20%	1.6%	-1.9%	9.4%	16.3%	6.2%	8.2%	5.8%	3.1%
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	Simulation	Increase Demand 30%	4.3%	0.9%	14.0%	17.1%	8.6%	8.2%	11.4%	5.8%
Demand Analysis	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	8.3%	6.0%	-18.4%	2.9%	8.9%	0.9%	8.7%	4.4%
Demand Analysis	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 20%	13.1%	9.4%	-12.7%	6.7%	14.6%	0.9%	14.3%	9.6%
Demand Analysis	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 30%	17.9%	11.5%	-7.0%	10.4%	19.9%	0.9%	20.0%	13.5%
Demand Analysis	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	Simulation	Increase Demand 10%	-2.2%	-6.1%	1.5%	12.4%	-1.4%	8.2%	0.3%	-3.8%
Demand Analysis	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	Simulation	Increase Demand 20%	1.6%	-1.9%	9.4%	16.3%	6.2%	8.2%	5.8%	3.1%
Demand Analysis	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	Simulation	Increase Demand 30%	4.3%	0.9%	14.0%	17.1%	8.6%	8.2%	11.4%	5.8%
Demand Analysis	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	8.3%	6.0%	-18.4%	2.9%	8.9%	0.9%	8.7%	4.4%
Demand Analysis	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 20%	13.1%	9.4%	-13.8%	6.7%	13.3%	0.9%	14.3%	8.2%
Demand Analysis	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 30%	17.9%	11.5%	-11.0%	10.4%	16.5%	0.9%	20.0%	9.8%
Demand Analysis	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	Simulation	Increase Demand 10%	-2.2%	-6.1%	-4.1%	12.4%	-18.9%	8.2%	0.3%	-8.4%
Demand Analysis	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	Simulation	Increase Demand 20%	1.6%	-1.9%	-2.3%	16.3%	-24.7%	8.2%	5.8%	-9.0%
Demand Analysis	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	Simulation	Increase Demand 30%	4.3%	0.9%	-2.5%	17.1%	-24.8%	8.2%	11.4%	-7.1%

Table 43. Data Set 5_5 Designed Experiment Results - % Change (cont.)

				LHDD	LHDS	LHSD	LHSS	LLDD	LLDS	LLSD	LLSS
	Original MIP			$ 19,407,401	$ 23,108,339	$ 34,913,573	$ 35,159,245	$ 26,215,554	$ 31,553,645	$ 42,103,117	$ 43,221,629
	Deterministic Simulation			$ 18,442,523	$ 22,169,396	$ 33,927,817	$ 34,194,364	$ 24,390,283	$ 30,427,727	$ 40,164,334	$ 41,121,938
	Stochastic Simulation			$ 8,716,261	$ 14,596,957	$ 25,365,766	$ 25,838,228	$ 17,617,285	$ 19,130,786	$ 33,561,094	$ 30,788,173
Capacity Analysis	Risky Supplier			5	5	5	5	5	5	5	5
	Option A - Remove risky supplier from data set.	MIP		infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
		Simulation		-	-	-	-	-	-	-	-
	Option B - Assume definite capacity risk. Reoptimize and implement on Day 1.	MIP	Risky supplier at 90%	-5.3%	-7.1%	-5.9%	-6.3%	-4.0%	-3.5%	-2.8%	-2.7%
			Risky supplier at 80%	-11.9%	-14.1%	-11.8%	-12.4%	-7.9%	-7.1%	-5.6%	-5.4%
			Risky supplier at 70%	-20.2%	-25.0%	-18.5%	-19.1%	-8.9%	-12.6%	-8.7%	-9.9%
		Simulation	Risky supplier at 90%	-13.3%	-7.2%	-12.7%	-10.9%	-3.2%	-13.3%	-1.9%	-8.6%
			Risky supplier at 80%	-20.0%	-14.3%	-18.3%	-19.8%	-23.4%	-15.9%	-6.0%	-10.5%
			Risky supplier at 70%	-35.0%	-16.7%	-29.0%	-28.1%	-22.2%	-25.8%	-8.8%	-17.1%
	Option C - Wait and see if capacity issue. Reoptimize on Day 100.	MIP	Risky supplier at 90%	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
			Risky supplier at 80%	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
			Risky supplier at 70%	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible	infeasible
		Simulation	Risky supplier at 90%	-	-	-	-	-	-	-	-
			Risky supplier at 80%	-	-	-	-	-	-	-	-
			Risky supplier at 70%	-	-	-	-	-	-	-	-
Demand Analysis	Option A - Assume definite demand increase. Reoptimize and implement on Day 1.	MIP	Increase Demand 10%	8.2%	7.6%	6.7%	6.8%	10.4%	5.9%	9.7%	8.1%
			Increase Demand 20%	15.8%	15.2%	13.4%	13.5%	20.8%	12.1%	19.9%	17.8%
			Increase Demand 30%	22.7%	15.8%	19.0%	19.1%	27.5%	14.8%	25.6%	23.5%
		Simulation	Increase Demand 10%	3.4%	11.3%	3.2%	-1.1%	3.6%	4.2%	5.7%	14.4%
			Increase Demand 20%	29.3%	15.3%	12.0%	9.0%	6.4%	21.5%	11.9%	28.2%
			Increase Demand 30%	13.5%	20.0%	8.9%	10.4%	20.3%	18.7%	21.2%	27.6%
	Option B - Wait and see if demand will increase. Reoptimize on Day 100.	MIP	Increase Demand 10%	8.2%	7.6%	6.7%	6.8%	10.4%	5.9%	9.7%	8.1%
			Increase Demand 20%	14.8%	15.2%	13.4%	13.5%	20.8%	12.1%	19.8%	17.8%
			Increase Demand 30%	19.5%	15.8%	19.0%	19.1%	27.5%	14.8%	25.6%	23.5%
		Simulation	Increase Demand 10%	-27.8%	11.3%	3.2%	-1.1%	-5.7%	4.2%	0.8%	14.4%
			Increase Demand 20%	-58.0%	15.3%	12.0%	9.0%	-9.2%	21.5%	3.6%	28.2%
			Increase Demand 30%	-87.2%	20.0%	8.9%	10.4%	-6.0%	18.7%	7.3%	27.6%
	Option C - Wait and see if demand will increase. Reoptimize on Day 100 but only use original suppliers.	MIP	Increase Demand 10%	8.2%	7.6%	6.7%	6.8%	10.4%	5.9%	9.7%	8.1%
			Increase Demand 20%	14.8%	15.2%	13.4%	13.5%	20.8%	12.1%	19.8%	17.8%
			Increase Demand 30%	19.5%	15.8%	19.0%	19.1%	27.5%	14.8%	25.6%	23.5%
		Simulation	Increase Demand 10%	-27.8%	11.3%	3.2%	-1.1%	-5.7%	4.2%	0.8%	14.4%
			Increase Demand 20%	-58.0%	15.3%	12.0%	9.0%	-9.2%	21.5%	3.6%	28.2%
			Increase Demand 30%	-87.2%	20.0%	8.9%	10.4%	-6.0%	18.7%	7.3%	27.6%

APPENDIX K

ADDITIONAL SIMULATION ANALYSIS

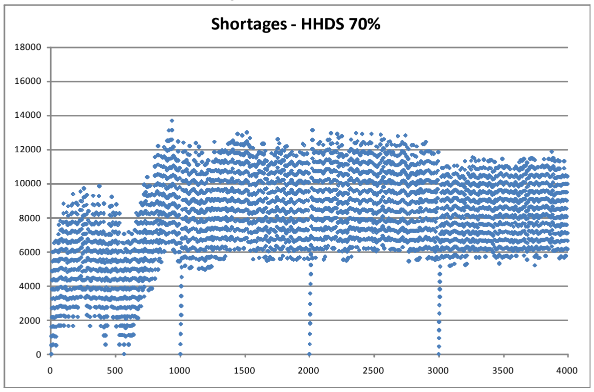
Table 44. Data Set 6_7 Cases with Uncharacteristic Results – 50 replications

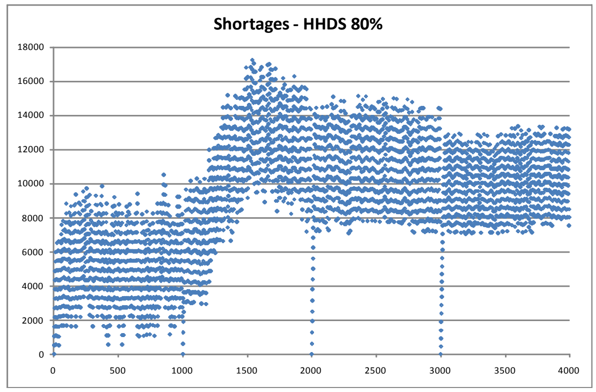
Results corresponding to Table 28		Average of 10 Replications	Average of 20 Replications	Average of 30 Replications	Average of 40 Replications	Average of 50 Replications
HHHSD 10% Demand - Case A	Profit	$ 4,122,361,093	$ 4,126,909,620	$ 4,126,416,937	$ 4,127,459,099	$ 4,128,564,818
HHHSD 10% Demand - Case A	Standard Deviation	$ 29,135,549	$ 23,338,683	$ 25,764,323	$ 26,454,579	$ 25,721,058
HHHSD 10% Demand - Case B	Profit	$ 4,126,855,898	$ 4,127,213,647	$ 4,126,817,718	$ 4,125,089,249	$ 4,124,079,642
HHHSD 10% Demand - Case B	Standard Deviation	$ 25,816,901	$ 20,966,858	$ 20,633,932	$ 19,078,019	$ 20,114,033
HHLSD 10% Demand - Case A	Profit	$ 4,157,321,093	$ 4,161,869,620	$ 4,161,376,937	$ 4,162,419,099	$ 4,163,524,818
HHLSD 10% Demand - Case A	Standard Deviation	$ 29,135,549	$ 23,338,683	$ 25,764,323	$ 26,454,579	$ 25,721,058
HHLSD 10% Demand - Case B	Profit	$ 4,161,815,898	$ 4,162,173,647	$ 4,161,777,718	$ 4,160,049,249	$ 4,159,039,642
HHLSD 10% Demand - Case B	Standard Deviation	$ 25,816,901	$ 20,966,858	$ 20,633,932	$ 19,078,019	$ 20,114,033
HLHSS 30% Demand - Case A	Profit	$ 5,367,036,387	$ 5,375,755,046	$ 5,379,497,469	$ 5,381,478,452	$ 5,380,406,924
HLHSS 30% Demand - Case A	Standard Deviation	$ 31,765,130	$ 27,060,842	$ 25,406,311	$ 24,442,011	$ 24,883,466
HLHSS 30% Demand - Case B	Profit	$ 5,371,846,000	$ 5,377,102,346	$ 5,376,475,025	$ 5,372,886,531	$ 5,374,220,818
HLHSS 30% Demand - Case B	Standard Deviation	$ 16,350,473	$ 23,803,491	$ 27,240,680	$ 28,254,594	$ 27,842,489
HLLSS 30% Demand - Case A	Profit	$ 5,401,974,219	$ 5,410,613,402	$ 5,414,066,506	$ 5,417,340,484	$ 5,415,923,852
HLLSS 30% Demand - Case A	Standard Deviation	$ 31,148,015	$ 26,795,777	$ 24,517,798	$ 24,493,435	$ 24,866,371
HLLSS 30% Demand - Case B	Profit	$ 5,406,806,000	$ 5,412,062,346	$ 5,411,435,025	$ 5,407,846,531	$ 5,409,180,818
HLLSS 30% Demand - Case B	Standard Deviation	$ 16,350,473	$ 23,803,491	$ 27,240,680	$ 28,254,594	$ 27,842,489
HHHSD 70% Capacity Case B	Profit	$ 3,766,417,790	$ 3,765,178,991	$ 3,765,050,211	$ 3,769,138,831	$ 3,769,783,663
HHHSD 70% Capacity Case B	Standard Deviation	$ 27,834,370	$ 23,205,525	$ 23,608,134	$ 23,585,980	$ 23,571,068
HHHSD 80% Capacity Case B	Profit	$ 3,765,094,526	$ 3,772,705,368	$ 3,775,075,010	$ 3,772,946,505	$ 3,774,780,831
HHHSD 80% Capacity Case B	Standard Deviation	$ 28,313,132	$ 23,928,923	$ 24,354,737	$ 23,560,136	$ 22,704,473
HHHSD 90% Capacity Case B	Profit	$ 3,827,535,541	$ 3,822,574,868	$ 3,824,665,220	$ 3,822,689,723	$ 3,820,728,191
HHHSD 90% Capacity Case B	Standard Deviation	$ 26,189,549	$ 22,931,187	$ 23,499,628	$ 23,379,337	$ 23,643,049

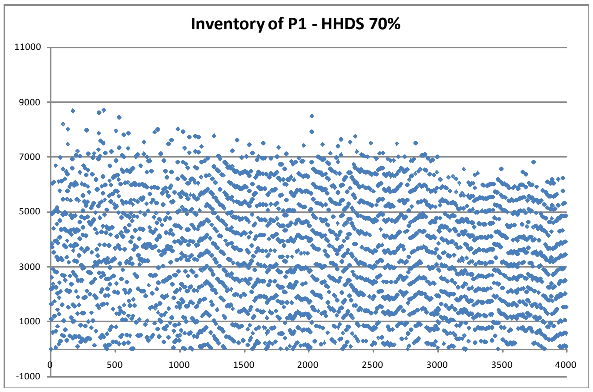
Table 45. Data Set 5_5 Cases with Uncharacteristic Results – 50 replications

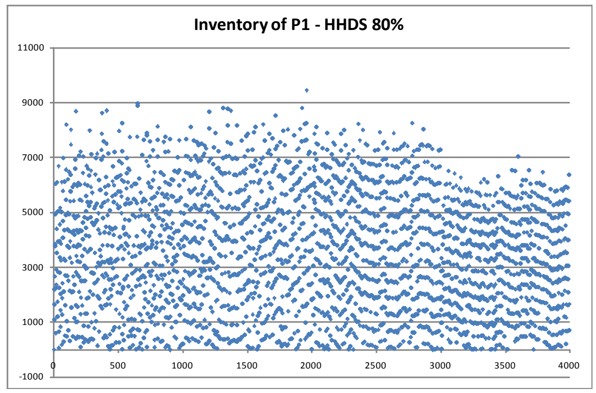
Results corresponding to Table 29		Average of 10 Replications	Average of 20 Replications	Average of 30 Replications	Average of 40 Replications	Average of 50 Replications
HHDD 70% Capacity Case B	Profit	$ 14,391,125	$ 14,881,298	$ 14,670,038	$ 14,762,583	$ 14,721,280
	Standard Deviation	$ 2,005,960	$ 2,050,763	$ 1,787,291	$ 1,788,301	$ 1,923,283
HHDD 80% Capacity Case B	Profit	$ 13,670,902	$ 14,221,322	$ 14,650,959	$ 14,780,761	$ 14,833,510
	Standard Deviation	$ 979,649	$ 1,648,646	$ 1,864,221	$ 1,894,684	$ 1,844,818
HHSS 80% Capacity Case B	Profit	$ 29,256,254	$ 29,434,760	$ 29,286,769	$ 29,160,010	$ 29,003,868
	Standard Deviation	$ 2,902,255	$ 2,809,516	$ 2,531,530	$ 2,288,819	$ 2,227,692
HHSS 90% Capacity Case B	Profit	$ 29,091,187	$ 29,293,376	$ 29,707,723	$ 29,864,856	$ 29,842,578
	Standard Deviation	$ 2,928,059	$ 3,084,042	$ 2,704,534	$ 2,738,158	$ 2,644,864
HLDD 80% Capacity Case B	Profit	$ 17,220,672	$ 16,920,368	$ 16,461,492	$ 16,094,848	$ 16,196,269
	Standard Deviation	$ 3,191,561	$ 2,613,622	$ 2,594,453	$ 2,742,912	$ 2,897,721
HLDD 90% Capacity Case B	Profit	$ 15,603,746	$ 16,160,055	$ 16,283,024	$ 16,203,358	$ 16,118,419
	Standard Deviation	$ 1,905,064	$ 2,344,192	$ 2,323,082	$ 2,215,785	$ 2,226,449
LHDD 20% Demand Case A	Profit	$ 10,734,003	$ 11,270,999	$ 11,220,856	$ 10,882,981	$ 10,885,758
	Standard Deviation	$ 2,672,084	$ 2,433,281	$ 2,415,440	$ 2,446,885	$ 2,520,615
LHDD 30% Demand Case A	Profit	$ 10,182,881	$ 9,897,292	$ 10,581,034	$ 11,025,797	$ 11,204,695
	Standard Deviation	$ 1,910,252	$ 3,014,908	$ 3,393,280	$ 3,565,809	$ 3,510,679
LHSD 20% Demand Case A	Profit	$ 27,861,733	$ 28,399,453	$ 28,349,781	$ 28,012,362	$ 28,015,329
	Standard Deviation	$ 2,673,807	$ 2,433,936	$ 2,416,515	$ 2,447,241	$ 2,520,856
LHSD 30% Demand Case A	Profit	$ 27,915,403	$ 27,630,780	$ 28,315,151	$ 28,760,270	$ 28,939,179
	Standard Deviation	$ 1,911,150	$ 3,015,376	$ 3,394,375	$ 3,567,403	$ 3,512,158
LLDS 20% Demand Case A	Profit	$ 23,293,778	$ 23,251,127	$ 22,914,622	$ 22,799,143	$ 22,940,026
	Standard Deviation	$ 1,778,317	$ 1,816,358	$ 2,382,455	$ 3,016,712	$ 3,090,550
LLDS 30% Demand Case A	Profit	$ 23,057,468	$ 22,700,971	$ 22,920,579	$ 22,911,441	$ 22,969,909
	Standard Deviation	$ 2,382,217	$ 2,331,718	$ 2,488,415	$ 2,591,371	$ 2,605,209
LLSS 20% Demand Case A	Profit	$ 39,237,764	$ 39,469,361	$ 38,888,838	$ 39,145,787	$ 39,338,823
	Standard Deviation	$ 2,063,648	$ 2,373,645	$ 3,466,572	$ 3,222,351	$ 3,307,048
LLSS 30% Demand Case A	Profit	$ 39,750,501	$ 39,279,366	$ 39,920,136	$ 40,131,193	$ 40,285,514
	Standard Deviation	$ 2,882,818	$ 3,715,409	$ 3,492,978	$ 3,669,798	$ 3,629,263
HHSD 20% Demand Case C	Profit	$ 28,336,639	$ 28,537,734	$ 28,748,016	$ 28,973,379	$ 29,036,760
	Standard Deviation	$ 1,767,666	$ 2,072,557	$ 1,885,563	$ 2,064,896	$ 2,041,627
HHSD 30% Demand Case C	Profit	$ 28,677,757	$ 28,481,171	$ 28,786,359	$ 28,941,764	$ 28,979,971
	Standard Deviation	$ 1,573,917	$ 1,445,880	$ 1,675,882	$ 1,832,922	$ 1,868,033
LLDD 10% Demand Case B	Profit	$ 16,582,279	$ 16,617,905	$ 16,550,008	$ 16,429,837	$ 16,494,525
	Standard Deviation	$ 1,378,856	$ 1,672,949	$ 1,564,351	$ 1,712,710	$ 1,850,032
LLDD 20% Demand Case B	Profit	$ 14,669,947	$ 15,998,606	$ 16,549,497	$ 16,790,132	$ 16,932,770
	Standard Deviation	$ 4,096,952	$ 3,381,004	$ 3,248,840	$ 3,094,168	$ 3,060,511

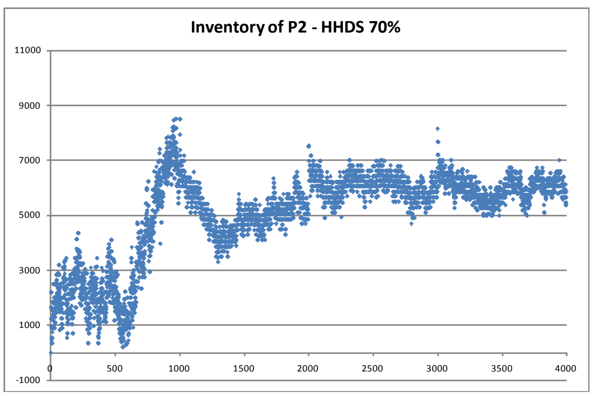
Plots used to identify issues in the HHDS case:

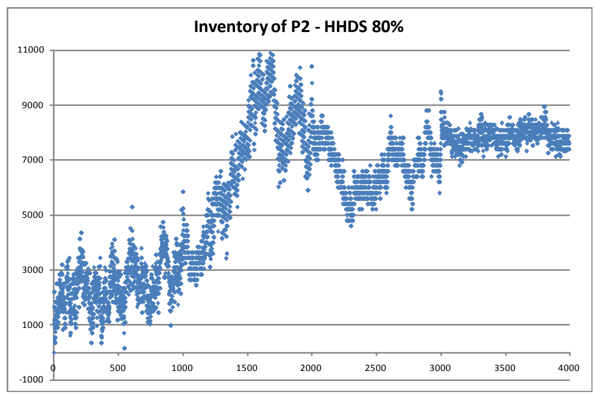


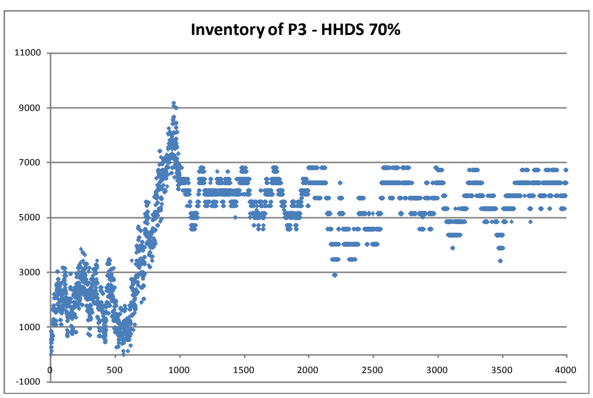


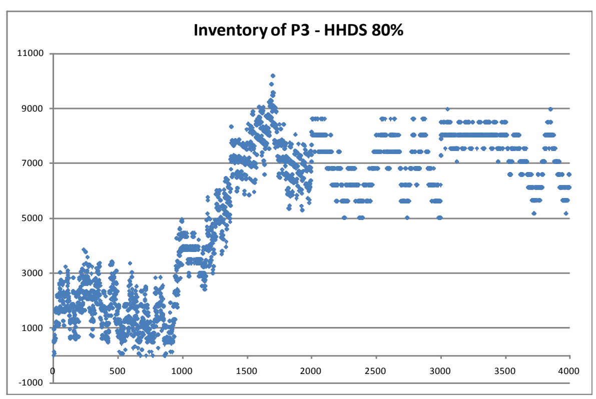


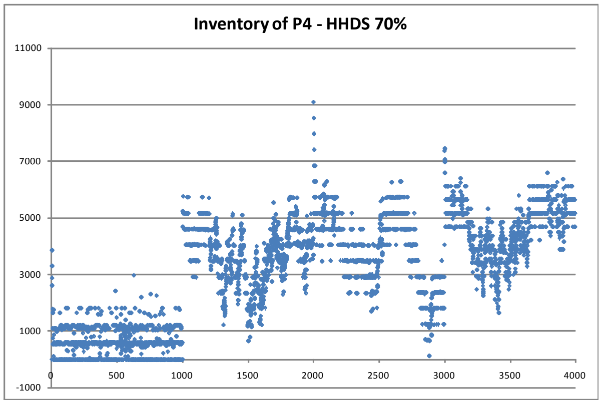


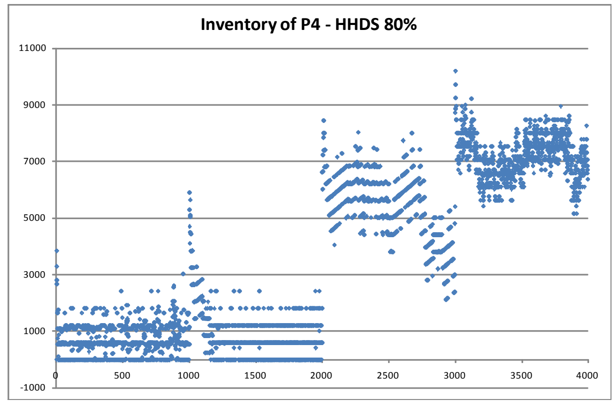


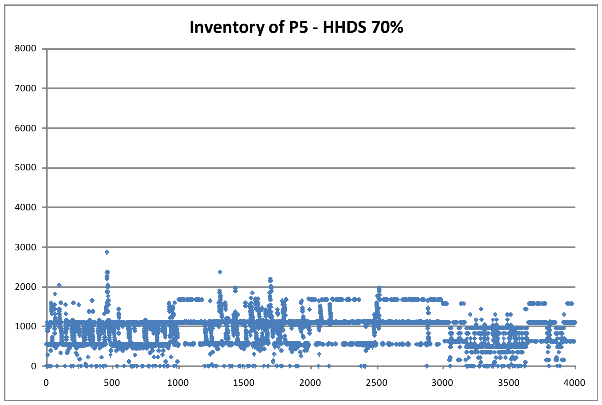


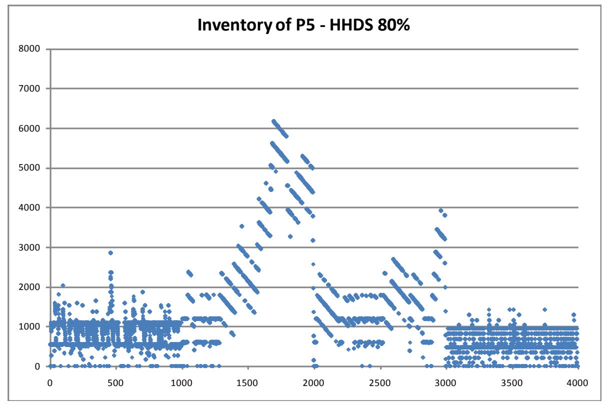












These plots show:

- 80% case has more shortages than 70% case, with a spike in TP2 and TP3, slight increase in TP4.
- 80% case shows increased inventory levels of components 2 and 3 in TP2 and a decrease in component 4. This confirms that Component 4 is the "problem component." This component can't be built, so inventory of components 2 and 3 increases while they are waiting to be consumed into component 1 (final product) with the missing component 4's.
- 80% case also shows a major spike in the inventory level of component 5 halfway through TP2. This is because component 4 consumes component 5. While there is a bottleneck at component 4, inventory of component 5 increases, because they are not being consumed.

APPENDIX L

POST-HOC TESTING EXAMPLE

The following test was performed on the Data Set 5_5 Demand Mitigation Strategy A data group. The purpose of the post-hoc test is to identify which of the 0%, 10%, 20% and 30% groups are statistically different from one another.

Critical value for *U*,

$$U_{\alpha(a,n)} = \frac{n^2}{2} + Q_{\alpha(a,n)} n \sqrt{\frac{2n+1}{24}}$$

where $Q_{\alpha(a,n)}$ is from the Studentized Range Distribution. In this example, $Q_{0.05(4,\infty)} = 3.63$.

$$U_{.05(4,320)} = \frac{320^2}{2} + n(320)\sqrt{\frac{2(320)+1}{24}}$$

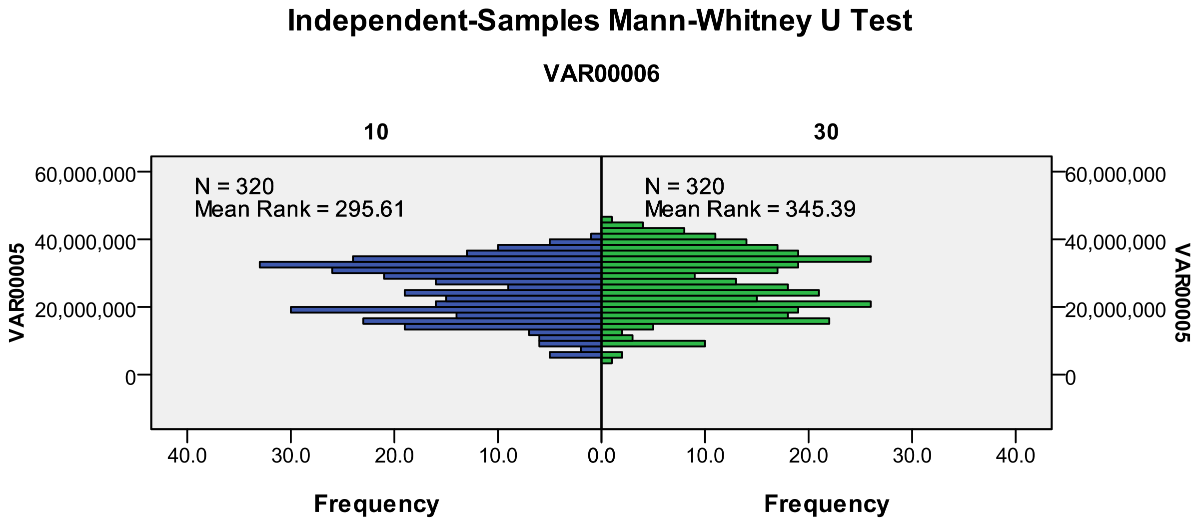
$$U_{.05(4,320)} = 57{,}203$$

The *U* statistics for the comparisons are calculated in SPSS and shown in the following table. Figure 21, on the following page, shows an example of the output obtained from SPSS for the *U* calculation.

Table 46. U statistics calculated in SPSS

	0%	10%	20%	30%
0%				
10%	54,594			
20%	59,995*	57,125		
30%	61,730*	59,165*	53,311	

If the *U* statistic is greater than the critical *U* value then the pairwise comparison is significant. Significant comparisons are marked with an asterisk in Table 46. For this data group, the post-hoc test indicates that 0% and 10% are statistically equivalent, 10% and 20% are statistically equivalent and 20% and 30% are statistically equivalent.



Total N	640
Mann-Whitney U	59,165.000
Wilcoxon W	110,525.000
Test Statistic	59,165.000
Standard Error	2,338.774
Standardized Test Statistic	3.406
Asymptotic Sig. (2-sided test)	.001

Figure 21. Sample SPSS Output - Mann-Whitney U Calculation

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