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Integrated supply chain design using multi criteria mixed integer programming.

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Integrated Supply Chain Design using Multi Criteria Mixed Integer Programming

By

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ABSTRACT

This research focuses on following key Supply Chain Design questions: determining supplier selection, production quantities, inventory locations and sizes, transportation option selection and transportation quantity in a multi stage, multi level supply chain. A Novel Integrated Supply Chain Design Framework that integrates Production Costs, Transportation Costs, First Time Quality and Supplier On-Time Delivery criteria has been proposed and implemented. Mixed Integer Linear Programming models were developed and four classes of problems were solved. Real world automotive industry data was used for testing and verifying these models.

Key new knowledge, both data dependent and data independent, was gained in the course of this research. Data dependent insights include: 1) Recommendation for splitting the customer demand between two suppliers even in the absence of capacity constraints, and 2) Unit Production Cost, Unit Transportation Cost and FTQ were shown to be the most critical factors in the Total Global Supply Chain Costs. Data independent insights indicated that: 1) Supplier selection decisions at every stage and level should be made using a global integrated approach of considering both production and transportation costs across the complete supply chain avoiding the myopic approach of always looking for the cheapest part from the lowest bidding supplier, 2) Out-sourcing to a non-domestic, less expensive supplier is not always the best decision for every product when selecting suppliers, 3) The Total Global Supply Chain Costs, Production Costs and Transportation Costs all increase non-linearly with worsening FTQ of the Supply Chain links, and 4)

Supplier FTQ has the most severe impact on the supply chain stage farthest from the Demand Consumption Stage with the impact severity being higher at lower FTQ rates.

This research has clearly demonstrated the merits and benefits of taking an integrated decision making approach when selecting suppliers. A multi-criteria model that combines the cost of production, transportation, first - time quality and supplier on-time delivery has been proposed and tested. Significant savings can be achieved as a result of using the framework developed in this research. The savings in the total supply chain cost, in the automotive example used for illustration, were in excess of 15 % which translates into several Million dollars over a period of 3 Years.

DEDICATION

To my Family for their
Love and Encouragement

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CHAPTER 1

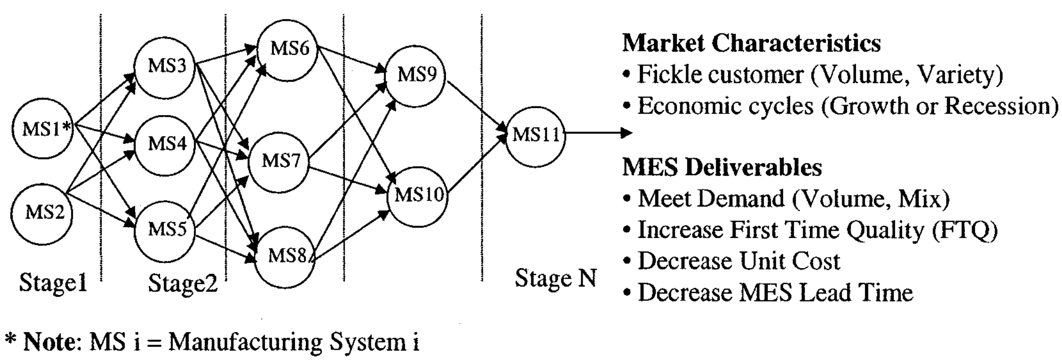
INTRODUCTION

1.1 A Look at the Automotive Industry – Where are We Today?

The Automotive industry is a mature industry. At the turn of the 20th century there were close to 100 car manufactures just in the United States alone. Only a handful of them are left in the entire world as we have just stepped into the 21st century. Consolidation is the name of the game, which is to be expected as an industry matures. Another reality as an industry matures, is that product quality becomes extremely important. Along with maturity comes intense competition, cost reduction, requirement for volume selling, reducing profit margins, shorter lead times to produce exciting and 'got to have' products. Offering heavy incentives and thereby grabbing market share (sometimes at the expense of reducing profit margins) will be a fact of life as any industry matures and the competition increases. It's already an evolving fact within the last two decades in the automotive industry. It's an established fact today in the furniture industry (Companies like Art Van & Gardner White etc.) where the products are forever on sale accompanied by heavy incentives. Negative pricing is also a fact of life for some of the products in the computer and chip making industry (Dell and Intel seem to forever be able to produce faster, cheaper computers and processors respectively!) Therefore, pricing pressures and incentives are here to stay in the automotive industry. But then, so is the ever-increasing pressure for companies to have better and higher net margins.

1.2 Manufacturing Enterprise Systems

Manufacturing Enterprise Systems (MES) deal with the design, planning and control of operations in the manufacturing enterprises from the shop floors to the associated procurement and distribution supply chains. Figure 1.1 shows a typical network of manufacturing systems (production factory) connected together in stages to form a chain with expected deliverables and characteristics of the market place in which they operate.



Manufacturing Enterprise System (MES)/Supply Chain – A Multi Stage, Multi Product Network

Figure 1.1: Manufacturing Enterprise System

A supply-chain of a manufacturing enterprise is a network of facilities performing functions of procurement, transformation of materials to intermediate and finished products and distribution of finished products to customers. Chandra [2000] suggests the following guiding principles for supply chain framework in his paper Supply Chain Integration:

- Supply chain is a cooperative system
- Supply chains exist on group dynamics of its members

- Negotiation and compromise are norms of operation in a supply chain
- Supply chain system solutions are pareto-optimal (satisfying), not optimizing, and
- Integration in the supply chain is achieved through synchronization.

1.3 Design and Operating Philosophies

Manufacturing philosophies such as Economic Order Quantity (EOQ), Material Resource Planning (MRP), Material Resource Planning II (MRP II), Just-In-Time (JIT)/Kanban/Pull Systems, Theory of Constraints (TOC), Lean and Agile have become extremely popular through the 90's and prior. Factories are already investing in agile cells, modular architectures, constraints and buffer management to consistently produce required volume of parts and also with good quality. Companies are running over time (an additional 3rd shift or a weekend) whenever necessary to better use their manufacturing systems capacity, in order to meet the volume requirements. Within the four walls of the factory, there exist limited systems design opportunities to make any dramatic improvements to the cost base.

The real cost opportunity for large manufacturing corporations may exist in leveraging their global capacities and/or supply chains. In fact, a global economy and an increase in customer expectations regarding cost and service has influenced manufacturers to strive to improve processes within their supply chain, also referred to as supply chain reengineering.

This research focuses on the problem of supply chain design for a typical product program with various suppliers that can supply raw materials, components and assemblies at different stages of production of the product. Each supplier is different in its production costs, inventory holding costs, fist time quality and overall reliability of supplier on-time delivery. Also there are multiple options of shipment from suppliers of one stage to the next with different associated costs. Different shipment options are considered because of capacity restrictions, cost differences between shipment options and variation in transportation times between shipment options. Given the different choices along the supply chain, the objective is to formulate and solve the problem of selecting the supplier at each stage, shipment options at each stage, production quantities, inventory locations and sizes such that the customer demands are met and the total supply chain costs are minimized.

Four classes of problems are considered in this research. They are essentially a combination of two factors to create all of the four classes, i.e. Split vs. No Split in Customer demand and Single vs. Multiple Criteria. Reasons for considering splitting customer demand may range from having capacity limitation in any one supplier in meeting all of the demand, to just being cheaper to split when all of the multiple criteria, i.e. regular production costs, transportation costs, cost of quality and cost of on-time delivery, are considered. Reasons for considering no splitting in customer demand include that often in the real world, entire contracts for a component are handed out to one single company for meeting all of the customer demand whether it is part production or shipment in the supply chain network.

Production costs alone, have traditionally been considered in the past for supplier selection. However, as companies began to grow in size, they started to geographically spread out their capacities, typically within the same country in the beginning and across countries over the last decade or so. This created the need to consider both production and transportation costs together during supplier selection that is called as single criterion in this dissertation.

Increasingly, as Original Equipment Manufacturers (OEM's) are focusing on their core operations and outsourcing their non-core operations, industry need is felt to have a framework that does supplier selection decisions also based on the quality of the parts supplied and their timely delivery in addition to the production and transportation costs. It is for this reason that the multiple criteria models based on Cost of Quality and Cost of On-Time Delivery, in addition to regular production and transportation costs are developed. The following explains in detail the two additional costs in multiple criteria:

- Cost of Quality – First Time Quality (FTQ) is defined as the percentage of good quality parts accepted from the total production. The remaining difference is scrap parts and is scrapped right at that location without incurring any costs for storing them in inventory and transporting them to the next stage in the supply chain. In other words, scrap parts are caught as they are produced. No supplier is ever able to consistently deliver parts at 100% FTQ. The FTQ rates are typically very low (in the 20-30% range, depending on the part) during initial production ramp-up. They are substantially higher (in the 80-99% range, depending on the part) during steady state production. A big problem can emerge, depending on the levels of FTQ's when all of the individual suppliers supply to each other in the supply chain. This is because each supplier has to produce more quantity than the requirement, to account for his own first time quality and also the first time quality of the down stream suppliers. Similarly, all these additionally produced parts need to be transported from one stage to the next in the supply chain. All this additional production and transportation creates an extra cost burden on the supply chain, which are all captured under Cost of Quality.

- Cost of On-Time Delivery – Companies entering into supplier contract agreements include sections in the contract for penalizing the suppliers if their production schedules do not meet the company requirements on time. Supplier deliveries are periodically tracked as metrics for late and on-time deliveries. Penalties are applied in case of late deliveries. Suppliers performing very poorly are black listed from future contracts. The cost of on-time delivery captures the impact of late deliveries of the suppliers. Suppliers are ranked as Low, Medium or High level of risk for late delivery. High-risk suppliers are penalized more severely than low risk suppliers. An exponential curve function for the risk level is used captures this difference in severity between high, medium and low risk suppliers. Also, a percentage of total production that is delivered late is used as an input. *Base penalty rate,* which is defined as the dollar penalty for every part that is delivered late, is derived from supplier contract agreements. The total cost of on-time delivery is finally calculated as the product of percent late delivery, production quantity, base penalty rate and exponential function of the supplier risk level. It also needs to be mentioned here that this Cost of On-Time Delivery only captures the cost penalty for late delivery. It does not directly account for transportation times for any of the shipment options. The models are set up in this way because supplier selection decisions are actually planning decisions that are made in the design phase of a product program. Actual transportation timing related issues are more operational decisions and become important during the execution phase of a product program.

These models are called multiple criteria models (as against multiple objective models which may involve more than one objective) because the impact of quality and on-time delivery are all converted into costs and captured as additional costs along with production and transportation costs. So there is only one objective function for the multiple criteria models, which is the minimization of the total supply chain costs.

1.4 Objective

The objective is to develop a framework and solutions for Supply Chain Design with single product, multiple customers, multiple stages, multiple levels, and multiple suppliers at each level, multiple transportation options, supplier first time quality and supplier on-time delivery risk, such that global supply chain costs are minimized. Also to investigate the following class of problems using the developed framework:

- Supply Chain Design that allows No Splitting in Customer Demand and considering Single Criterion, i.e. Regular Production & Transportation Costs only in decisions making (problem to be called "No Split Demand, Single Criterion" from here on.)
- Supply Chain Design that allows No Splitting in Customer Demand and considering Multiple Criteria, i.e. Production & Transportation Costs with impact of Cost of Quality and Cost of On-Time Delivery in decisions making (problem to be called "No Split Demand, Multiple Criteria" from here on.)
- Supply Chain Design that allows Splitting in Customer Demand and considering Single Criterion, i.e. Regular Production & Transportation Costs only in decisions making (problem to be called "Split Demand, Single Criterion" from here on.)

- Supply Chain Design that allows Splitting in Customer Demand and considering Multiple Criteria, i.e. Production & Transportation Costs with impact of Cost of Quality and Cost of On-Time Delivery in decisions making (problem to be called "Split Demand, Multiple Criteria" from here on.)

Further, it is desired to gain new knowledge and understanding on supplier selection decisions – if splitting the customer demand is desirable or if supplier selection decisions at different stages should be made using a local greedy approach or an integrated global supply chain approach. Also, to clearly understand the impact of the different unit costs on total global supply chain costs. Additionally, to understand the impact of supplier first time quality and supplier on-time delivery risk on production quantities and total global supply chain costs. Finally, to determine which of all the factors considered in the framework are critical from an accurate data collection standpoint. The new knowledge gained through this analysis will provide useful guidelines for the implementation community in the field of supply chain management.

CHAPTER 2

LITERATURE REVIEW

Literature in this area is broadly categorized under the following sections, which touch on the various aspects pertaining to different issues involved in the topic.

2.1 Supply Chain Design, Modeling and Analysis

According to Global Supply Chain Associates [2003], 10% improvements in supply chain costs and 25% improvements in supply chain cycle time are typical to achieve in supply chain projects. Some of the questions that their clients have asked include:

- How many plants? Where should they be located?
- How much production capacity of each process in each plant?
- How vertically integrated?
- What products should be produced in each plant?
- What demand regions should each plant serve?
- Which vendors should serve each plant?
- Which parts should be purchased from each vendor?
- Should we ship direct from the plants or use warehouses?
- How many warehouses should be operated and where should each be located?
- What is the service area for each distribution center?
- What modes of transportation to use?

- How best to use in-transit merge to fulfill orders?
- Should I outsource logistics? Which functions?

Swaminathan et. al. [1998] in their paper on modeling supply chain dynamics have described a simulation-based framework for developing customized supply chain models from a library of software components. Figure 2.1 shows a typical supply chain

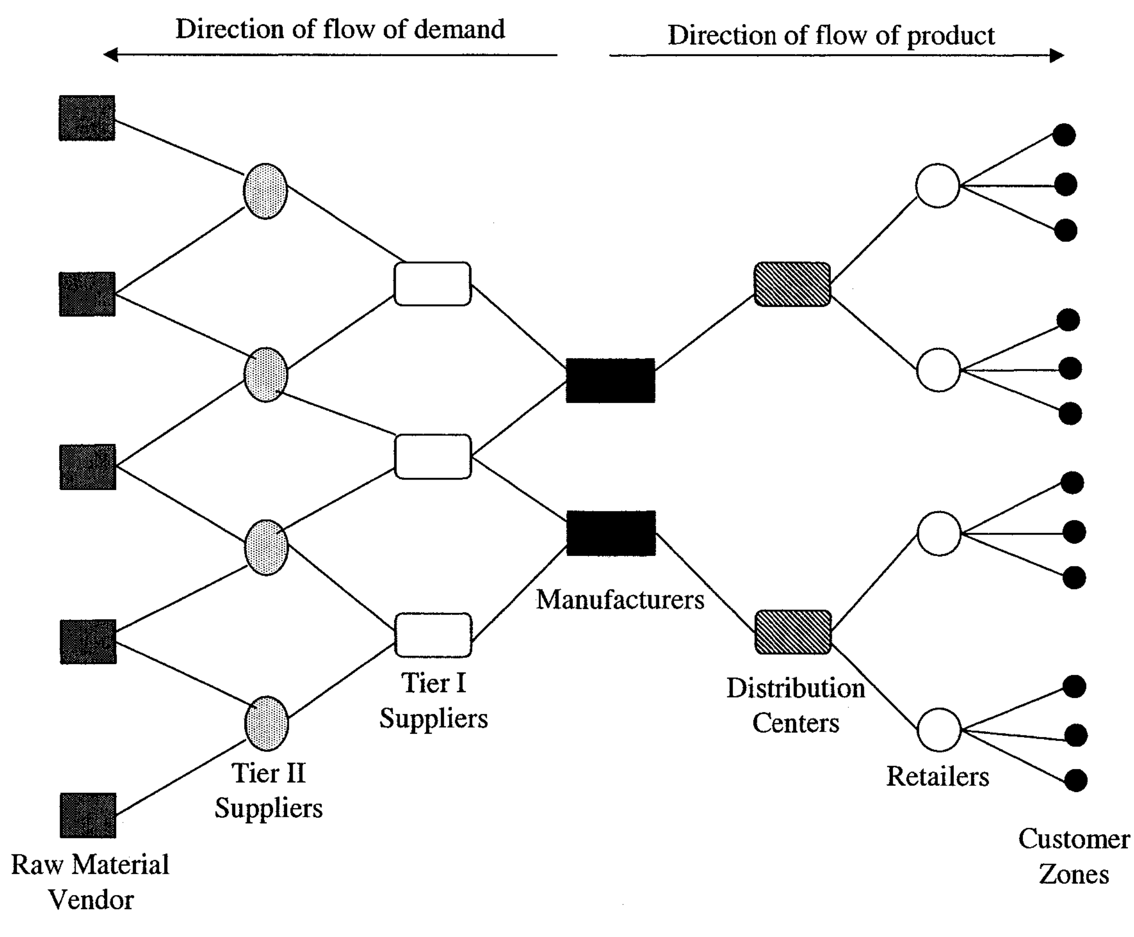


Figure 2.1: Supply Chain Network, Source – Swaminathan et al. [1998]

network as described by them. Among the factors considered in their model were Bill of Material (BOM), demand, lead-time, transportation time and costs. While no mention is made to the limitations of the work, one can only surmise that the framework would involve the typical limitations of simulation projects such as long development time and, at times, being too cumbersome to implement.

Arntzen et. al. [1995] in their paper on Supply Chain implementations at Digital Equipment Corporation discussed the internal development of a Global Supply Chain Model (GSCM) to investigate issues relating to the location of customers and suppliers, transit time and cost of various transportation modes, significance of tax heavens, offset trades and export regulations. Some of the decisions they were trying to make using this tool were how many plants they need, where to locate the plants, what technologies and capacities should they have, should a product be built at one plant, two plants or three, and at what volume do the answers change. They developed mixed integer linear program models to capture all of the multiple objectives and constraints. One of the limitations of their work is the requirement to select appropriate weights for linear combination of the multiple criteria, which can be a big limitation in the real world because of a lack of good data or the subjectivity of the weights. Also, impacts of factors like supplier quality and on-time delivery risk are not considered in their models.

Archibald et al. [1999] in their paper on Supply Chain analysis to Compete Beyond the Four Walls did a case study on a hypothetical global food manufacturing organization with facilities and suppliers spread all over North America. They considered Transportation options with a full and partial truck load, continuous replenishment of inventories with shifting management to manufacturer or wholesaler and collaborative planning by sharing of information among all participants of supply chain. Some of their output measures include Return on Investment, Inventory turns and Stock out delays. They develop simulation models for the case study and in their results graph the relationship between the input and output parameters.

Cachon and Zipkin [1999] in their paper on Inventory policies in Supply Chain investigate a two-stage serial supply chain with stochastic demand and fixed transportation times. Inventory holding costs are charged at each stage with optional backorder penalty costs. They develop a mathematical formulation to investigate competitive and cooperative inventory policies where in the former case, inventories are tracked locally at each stage and in the later case inventories are jointly tracked and maintained. Their work, however, does not focus on the design aspect of the supply chain in terms of selection of suppliers.

Sean Willems [1999] in his work on Supply Chain Design focuses on configuration of the supply chain for a new product program. Different sourcing options at each stage of the supply chain along with the associated costs are considered. However, this work focuses only on imposing the criteria of not allowing splitting in customer demand and does not investigate the effect of allowing splitting in customer demand along with the inclusion of supplier quality and on-time delivery risk factors. The goal of the design is to minimize the total supply chain costs. A Dynamic programming formulation is used for solving the design problem.

Jain et al. [2000] in their paper on Bottleneck based Modeling of Semiconductor Supply Chains study the multiple wafer fabrication facilities supplying an assembly and test facility at AT&T. They developed a C++ discrete event simulation model for studying and include multiple manufacturing facilities, transportation between successive stage and customer orders for fulfillment. They develop a bottleneck identification approach to abstract the detailed simulation model and compare results.

Joines et al [2000] in their research review of systems dynamic modeling in supply chain management say that current research in supply chain management focuses on inventory decision and policy development, time compression, demand amplification, supply chain design and integration, and international supply chain management. Their paper gives an overview of recent research work in those areas, followed by a discussion of research issues that have evolved in terms of modeling for theory building. They also find that Casual Loop Programming, Continuous Loop Simulation and Operation Research (OR) Techniques are the 3 main approaches and techniques currently employed to solve problems relating to supply chain design.

According to Lin et. al. [2000], IBM began to reengineer its global supply chain in 1994. It wanted to achieve quick responsiveness to customers with minimal inventories. To support that effort they developed the extended enterprise supply chain analysis tool, the Asset Management Tool (AMT.) The later integrates graphical process modeling, simulation modeling, analytical performance optimization, activity based costing and enterprise database connectivity into a system that allows quantitative analysis of extended supply chains. The tool primarily helps determine the safety stock for each product at each location to minimize the investment in total inventory. It views the supply chain as a multi echelon network in which each stocking location is modeled as queuing system. This work however does not include supplier selection and multiple criteria for optimization like supplier quality and delivery risk.

Karbakal et al. [2000] in their work at Volkswagen look at the vehicle distribution system with two major objectives: to reduce total distribution and inventory holding costs; and to improve delivery lead times and market responsiveness. Among the different transportation options they looked at were replacing more expensive truck routes by cheaper rail and sea routes for delivery. They develop a simulation based mixed integer optimization approach to solve the problem.

Tomlin [2000] in his work on Supply Chain Design evaluates capacity decisions in multiple product multiple stage supply chains. Multiple product supply chains are subject to floating bottlenecks in which the set of stages that limit throughput is dependent on the product realizations. Mathematical solution approaches to the capacity investment problem, in which an expected shortfall bound or service level bound, are developed.

Chandra [2000] in his paper on Supply Chain Modeling and Optimization developed a general framework for a cooperative supply chain system. The supply chain is made up of a manufacturer and two level hierarchy of suppliers. Each subsystem in the supply chain incurs ordering and holding costs. Each level in the supply chain incurs a delay for procurement activity. The model assumes that demand for final product and raw material is already known. Raw material orders are initiated based on predicted demand from level to level. A distinct supplier is assumed to provide each raw material. Inventory and ordering costs are assumed to have a quadratic relationship. The model seeks to optimize the global cost of the supply chain. However, this work does not include any transportation costs, supplier first time quality and on-time delivery risk.

Shah and Singh [2001] in their paper on benchmarking internal supply chain analysis develop a simple rough-cut framework for supply chain analysis and improvements by using information from public databases. The information collected includes cost of raw materials, cost of production, cost of distribution, raw inventory, semi-finished and finished inventory. They apply that framework to case studies done in the paint industry.

Novak and Eppinger [2001] in their paper on Supplier Sourcing by design focus on the connection between product complexity and vertical integration using empirical evidence from the auto industry. They address the choices of internal production and external sourcing for components in the auto industry. They hypothesize that in-house production is more attractive when product complexity is high, as firms seek to capture the benefits of their investment in the skills needed to coordinate the development of complex designs. They present a simultaneous equations model and a statistical analysis to test their hypothesis.

Ramcharran [2001] in his paper on Inter-Firm Linkages and Profitability in the automotive industry studies the degree of linkages between automotive part suppliers and automotive manufacturers. Regression analysis is done using data from the Price to Earnings (P/E) ratios for auto parts suppliers and manufacturers. Risk assessment, utilizing information on linkages, is important for demand management and developing profit-maximizing strategies.

Kim et al. [2002] in their paper on configuring a manufacturing firm's supply network develop a single period mathematical model and algorithm to solve a supply chain management problem, that is, how much of each raw material and/or component part to order from which supplier, given capacity limits of suppliers as well as the manufacturer. They take an example of a manufacturer that assembles and sells multiple products using materials procured from several suppliers or parts outsourced to contract manufacturers. Their work is partially similar to the focus of this dissertation in the sense of determining supplier choice, quantities and inventories. However, this dissertation also includes transportation factors along with supplier quality and on-time delivery risk in the models and determines transportation choice and quantities as well.

Chan et al. [2002] in their paper on a simulation approach in Supply Chain Management develop simulation model for a typical single channel logistic network and examine the applicability of order release mechanisms for monitoring the performance of supply chains. Delivery speed and on-time delivery reliability are used to measure the performance of the supply chains. Several existing order release mechanisms (Constant Work in Process – CONWIP) are evaluated and some new ones are proposed.

Looman et. al. [2002] in their paper on designing ordering and inventory management methodologies present methods for redesigning ordering and inventory management practices for purchased parts in a manufacturing firm from the perspective of integrating purchasing and logistics functions. They decompose their methodology by developing individual flow chart based methods for Order triggering, lot sizing and order expediting. Qualitative evaluations using the Analytical Hierarchy Process (AHP) are used for developing the methods. The design methodology is tested for a Dutch manufacturer of Kitchen equipment.

Muralidharan et. al. [2002] in their paper on Multi criteria group decision making model for supplier rating identify supplier quality, costs and on-time delivery as the three most important criteria in supplier selection. They present excellent literature survey on multi criteria decision making and using analytical hierarchy process (AHP) for multiple criteria problems. They develop a practical useful methodology for carrying out supplier ratings in a commercial organization.

Joines et al. [2002] in their paper on Supply Chain Multi Objective Simulation Optimization focus on Sourcing decisions in the supply chain. The decisions they focus on are of the type "How much to order" and/or "How often to order." One of the performance measures used is Gross Margin Return on Investment. They interface simulation with Genetic Algorithms to solve the problem.

Zsidisin [2003] in his paper on managerial perceptions of supply risk studies characteristics of inbound supply that affect perceptions of risk and creates a classification of supply risk sources. Supplier product quality, number of qualified suppliers, supplier capacity and supplier delivery reliability are listed as some of the major sources of risk in his research findings. The idea is that by understanding characteristics of supply risk, supply chain management professionals can implement strategies for better management of that risk.

Reiner and Trcka [2003] in their paper on Customized Supply Chain Design study a product-specific supply chain in the food industry by building a discrete event simulation model of the supply chain. They analyze the effect of making continuous improvement changes in the supply chain and also show how demand uncertainties are dealt with. They use work in process and lead time as the performance measures.

Tang et. al. [2004] in their paper on Heuristics-based Integrated Decisions in a Global Manufacturing Environment develop heuristics for integrated decisions for production assignment, lot sizing, transportation and order quantity for multiple suppliers/multiple destinations logistic network in a global manufacturing system. The cost components considered in their model include production and inventory costs at the suppliers, transportation costs between the suppliers and destination and ordering costs and inventory costs at the destinations. While these costs are similar to the costs that are considered in this dissertation, taking impact of supplier quality and supplier on-time delivery risk into consideration enhances the models in this dissertation further and results are investigated. Also a real world automotive industry example is taken for case study in this dissertation unlike case studies from the electronics and computers industry in the rest of the literature. This is important because the magnitude of customer demand and all of the individual costs (production, transportation etc.) are much larger than the relatively smaller size parts in other industries. This can potentially lead to different generalized conclusions.

Bredststrom et. al. [2004] study the supply chain problem in the pulp mill industry in Scandinavia. They develop mixed integer models that determine daily supply chain decisions over a planning period of three months. Detailed production schedules are developed using the models with an accuracy of usually single days. These schedules are supposed to balance production with a supply of raw materials. One of the limitations of their work is that transportation and distribution to customers is not included.

Chiang and Russell [2004] study the integration problem of purchasing and routing in a propane gas supply chain. They develop solution methods using Tabu search for optimal and near optimal solutions. Their study results in a real-world propane distribution problem indicates that integration of purchasing and routing decisions can result in annual costs savings of millions of dollars for large distributors.

Some of the other work that was done relating to integrated production and distribution systems in the context of supply chain management are also relatively recent [Glover 1979, Thomas 1996, Cohen 1998 and Tayur 1999]. In particular integrated decisions for production and transportation [Blumenfeld 1991, Hahm 1992, Chien 1993, Hall 1996, Fumero 1999], production and inventory [Williams 1981, Cohen 1988], transportation and inventory [Speranze 1994, Bertazzi 1999, Qu 1999] are also very relevant. However, their formulations and solutions are mostly Economic Order Quantity (EOQ) based.

2.2 Optimization Solution Approaches

Generally, the Optimization Technology Center (OTC) defines the following optimization tree for optimization solution approaches:

- Discrete
    - Integer Programming
    - Stochastic Programming
- Continuous
    - Constrained
        - Non-Linear equations
        - Non-Linear least squares
        - Global optimization
        - Non differentiable optimization
    - Unconstrained

- Linear Programming
- Semi definite Programming
- Non linearly constrained
- Bound constrained
- Quadratic Programming
- Network Programming
- Stochastic Programming

As seen from Literature on Supply Chain Optimization, the below are some of the approaches used.

2.3 Solution Approaches to Supply Chain Problems

2.3.1 Linear and Integer Programming

Linear Programming (LP) approaches allow for optimization of a linear function subject to linear constraints with real variables. Where some or all of the variables are constrained to be integers, rounding real numbers to integers can result in infeasibility. Integer Programming (IP) is therefore used for optimization in which some or all of the variables are integers. When all of the variables are required to be integer, the formulation is called a Pure Integer program. However, when only some of the variables are integers, the formulation is called Mixed Integer Programming (MIP.) The representation of the variables as Integer or Real is driven by the requirements of modeling. For example, representing the decision of "number of machines to be purchased" in a design example by a real variable may result in a decimal answer which will have to be rounded up or down and that may or may not necessarily optimize the objective function. An integer variable representation is better suited for such modeling requirement. However in a different example if the decision variable is "production throughput" a real variable representation is acceptable even if it gives a decimal answer as rounding up in this case is likely to have little effect on the objective function. Linear and Integer programming has been successfully applied to a number of fields in production and distribution. Some of the examples include the blending problem [1977], capital budgeting [1992], production scheduling [1982] and crew scheduling [1991]. There has been some work done in applying LP/IP/MIP to supply chain problems. Yan et. al. [2003] present a MIP model of supply chain design by including consideration of product structure, in the form a bill of materials.

2.3.2 Non-Linear Programming

Non-Linear Programming (NLP) approaches allow for optimization of a non-linear function subject to non-linear constraints with real variables. Generally, NLP problems are intrinsically more difficult to solve than LP and IP problems. Because of the possibility of multiple feasible regions and multiple locally optimal points within such regions, there is no way to determine with certainty that the problem is infeasible, the objective is unbounded, or that an optimal solution is the "global optimum" across all feasible regions. Some nonlinear programming algorithms such as sequential quadratic programming (SQP), the method of moving asymptotes (MMA) and the generalized reduced gradient method (GRG) have been used in structural design problems [1999]. Some research has been done in applying NLP approaches to design of supply chains. This include the pooling problem for a refinery model [1993] and operation of a network of plants and markets by Cohen et. al. [1989]. Also applying NLP approaches to supply chain problems are extremely challenging because:

- The NLP approach involves significant complexity with unwieldy models and extensive computational complexity. The development and maintenance of the models is also cumbersome.
- The NLP approaches may converge to a local optimal solution and may not necessarily converge to a global optimal solution. This is a property of all mathematical algorithms and happens because nonlinear optimization models may have several solutions that are locally optimal and it is hard to guarantee, when searching in the dark, that the current solution found is globally optimal.

2.4 Literature Review Matrix

Table 2.1 summarizes the critical literature collected on supply chain design into a literature review matrix to show the topics, references, dates and solution methods used:

Table 2.1: Literature Review Matrix

Authors	Year	Work Done	Methods/Approach Used	Limitations/Issues Not Addressed
Arntzen et. al.	1995	Development of Global Supply Chain Model (GSCM) to investigate issues relating to location of customers and suppliers, transit time & cost of various transportation times, significance of tax heavens, offset trades and export regulations. Included multiple criteria	Mixed Integer Program	Does not include First Time Quality and On-Time Delivery Risk. Requirement to select appropriate weights for linear combination of the multiple criteria
Swaminathan et. al.	1998	Modeling supply chain dynamics, Factors considered in their model were BOM, demand, lead-time, transportation time and costs	Simulation-based framework for developing customized supply chain models from a library of software components	No details offered on Objective functions. Simulation modeling - too time consuming to build, too cumbersome to implement
Archibald et al.	1999	Distribution and Collaborative planning of inventory in a multi plant hypothetical food processing organization, Output measures include Return on Investment, Inventory turns and Stock out delays	Simulation modeling	Simulation modeling - too time consuming to build, too cumbersome to implement, Not a Real World Case study
Cachon and Zipkin	1999	Inventory policies in Supply Chain investigate a two-stage serial supply chain with stochastic demand and fixed transportation times. Inventory holding costs are charged at each stage with optional backorder penalty costs	Develop a mathematical formulation to investigate competitive and cooperative inventory policies	Does not focus on design aspect of the supply chain in terms of selection of suppliers and multiple criteria of quality and on-time delivery risk
Sean Williams	1999	Supply Chain Design focuses on configuration of the supply chain for a new product program. Different sourcing options at each stage of the supply chain along with the associated costs are considered	Dynamic programming formulation	Single Criteria - Does not include Quality and Delivery Risk. Also does not include Capacity constraints and that Customer demand is met by only one single supplier at every stage without splitting
Lin et. al.	2000	Extended enterprise supply chain analysis tool, the Asset management Tool (AMT), AMT primarily helps to determine the safety stock for each product at each location to minimize the investment in total inventory	System that includes Graphical process modeling, simulation modeling, analytical performance optimization, activity based costing and enterprise database connectivity	Does not address supplier selection and multiple criteria for optimization

Table 2.1: Literature Review Matrix continued

Authors	Year	Work Done	Methods/Approach Used	Limitations/Issues Not Addressed
Jain et. al.	2000	Bottleneck based modeling of Semiconductor Supply Chains where multi wafer fabrication facilities supply to an assembly and test facility at AT&T	C++ Discrete Event Simulation Model	Semiconductor Industry, Does not look at optimizing multiple criteria
Karbakal et. al.	2000	Work at Volkswagen look at the vehicle distribution system with two major objectives: reduce total distribution and inventory holding costs; improve delivery lead times and market responsiveness	Simulation based mixed integer optimization approach	Does not focus on design aspect of the supply chain in terms of selection of suppliers and multiple criteria of quality and on-time delivery risk
Brian Tomlin	2000	Evaluates capacity decisions in multiple product multiple stage supply chains. Develops Mathematical solution approaches to the capacity investment problem in which there is an expected shortfall bound or service level bound	Mixed Integer Programming	Does not include supplier selection and multiple criteria for optimization
Charu Chandra	2000	General framework for Supply Chain Modeling and Optimization, supply chain is made up of a manufacturer and two level hierarchy of suppliers, ordering and holding costs considered & have quadratic relationship, delay for procurement activity, demand for final product and raw material is already known. Model seeks to optimize the global cost of the supply chain	Mixed Integer Program	Does not include any transportation costs, single criteria optimization of the supply chain costs
Novak & Eppinger	2001	Study Supply sourcing by design by investigating the connection between product complexity and vertical integration	Simultaneous Equations model	Does not include transportation factors including determining transportation choice and quantities, Supplier Quality and On-Time Delivery Risk
Kim, Zhang et. al.	2002	Configuring manufacturing firm's supply network with development of a single period mathematical model and algorithms to determine how much of raw material/component should be ordered from which supplier given capacity limits of suppliers and manufacturers. Real World case study from Computer Industry demonstrated	Mathematical model	Does not include transportation factors including determining transportation choice and quantities, Supplier Quality and On-Time Delivery Risk

Table 2.1: Literature Review Matrix continued

Authors	Year	Work Done	Methods/Approach Used	Limitations/Issues Not Addressed
Chan et. al.	2002	Investigate single channel logistic network and examine the applicability of order release mechanisms for monitoring the performance of supply chains	Simulation Approach	Does not include transportation factors including determining transportation choice and quantities and Supplier Quality
Looman et. al.	2002	Investigate designing ordering and inventory management practices for purchased parts from the perspective of integrating purchasing and logistics functions	Quantitative evaluations using AHP used	Does not include supplier selection and multiple criteria for optimization
Muralidharan et. al.	2002	Literature survey on multi criteria group decision making identify supplier quality, cost and on-time delivery as three most important criteria in supplier selection	Use AHP for multi criteria decision making	No rigid optimization modeling done
Zsidisin	2003	Studies and identifies sources of supply risk and concludes supplier quality, number of qualified suppliers, supplier capacity and supplier delivery reliability are identified as major sources of risk	Literature survey	No rigid optimization modeling done
Tang, Yung and Ip	2004 Working Paper	Develop Heuristics for Integrated decisions for production assignment, lot sizing, transportation and order quantity for multiple supplier/destinations logistics network in a global manufacturing system	Mathematical model	Partially similar to focus of this work. However this research extends further by considering Impact of Supplier Quality and Supplier On-Time Delivery Risk into consideration. Real World Automotive Industry Case Study taken to demonstrate
Bredststrom	2004	Develops daily supply chain decisions by developing production schedules that are supposed to balance production and supply of raw materials	Mixed Integer models	Does not include any transportation costs, single criteria optimization of the supply chain costs

2.5 Motivation for the Proposed Research

The following summarizes the justification for the proposed research:

- Supply Chain design is a new and growing area of applied research. Industry recognizes potential opportunity for significant cost benefits.
- As seen from the literature review, very little work has been done on the development of an integrated framework for Supply Chain Design, which takes into consideration supplier selection factors, production factors, inventory factors, logistics factors along with supplier quality and on-time delivery risk.
- As a result, there exists a need for new knowledge and understanding of supplier selection decisions; if splitting the customer demand is desirable or if supplier selection decisions at different stages should done using a local greedy approach or an integrated global supply chain approach. Furthermore, to clearly understand the impact of the different unit costs on total global supply chain costs. Further, to understand the impact of supplier first time quality and supplier on-time delivery risk on production quantities and total global supply chain costs. And finally to determine which of all the factors considered in the framework are critical from an accurate data collection standpoint. The new knowledge gained through this analysis will provide useful guidelines for the implementation community in the field of supply chain management.
- Linear Mixed Integer Programming (MIP) models will be developed for the different supply chain design framework scenarios because they represent the best choice to model and solve for all of the different factors considered.

- In conclusion, a real world case study example from the Automotive Industry, with real-world data is also new as much of existing literature, is focused on the Electronics & Computer Industry. This also helps to gain knowledge and insights that are particularly relevant to the automotive industry.

CHAPTER 3

PROPOSED SUPPLY CHAIN FRAMEWORK

3.1 An Overview

Supply Chain issues in the United States are estimated to consume 10 percent of the U.S. Gross National Product. The Automotive Industry, with its increasing pressure to control costs and grow market share, is elevating its focus from a manufacturing systems level to the supply chain level as one of the ways to achieve cost reductions. As a result, designing the right supply chain becomes a key issue for both large corporations with multiple facilities and small corporations dealing with multiple suppliers.

This research focuses on development of a framework for supply chain design. The supply network is established starting from customers through manufacturers and multi–tier (levels) suppliers. At each level, multiple supplier options are considered for all of the different stages. Also, different transportation options are considered between different levels. The objective of the design problem is to determine the appropriate:

- Supplier selection(s) at each level
- Production quantities at different stages and levels in the supply chain
- Inventory locations and sizes in the supply chain
- Transport choice between stages in the supply chain,

such that the total global supply chain costs through the supply chain are minimized. Mathematical programming based linear/non-linear multi criteria optimization will be used for solving the design problem. A real world case study from the Automotive Industry will be used as an example for demonstration.

3.2 Problem Definition

3.2.1 Supply Chain Network

Figure 3.1 shows a generic supply chain network for a single product with multiple customers, multiple stages and levels of processing, multiple suppliers at each level and multiple modes of transportation from one stage to the next. A stage is defined as a processing step in the process flow of a product that receives raw material from a previous step and the processed part is sent to the next step in the process flow. A level in a stage is defined all the processing steps that need to be completed before the next processing step in the process flow can be executed. So, each level in a stage receives a semi-finished part from a previous stage and feed the finished part to the next stage and not to any of the levels in that particular stage. The concept of stages and levels will be further explained using an example in Chapter 4. A similar supply network can be set up for another different product. Each of the multiple customers has a separate demand in every time period for the product. Each supplier at every stage and level has production costs, inventory carrying costs, supplier first time quality, supplier on-time delivery risk and capacity limitations to meet the customer demand. Each of the multiple modes of transportation has transportation costs involved in shipping parts from one stage to the next. The supply chain network is organized based on the classic Bill of Material (BOM) as shown in Figure 3.2. So, one unit of product P requires one unit of assemblies A, B, C and D which in turn require components U, V, W and X and finally all the way to the raw materials.

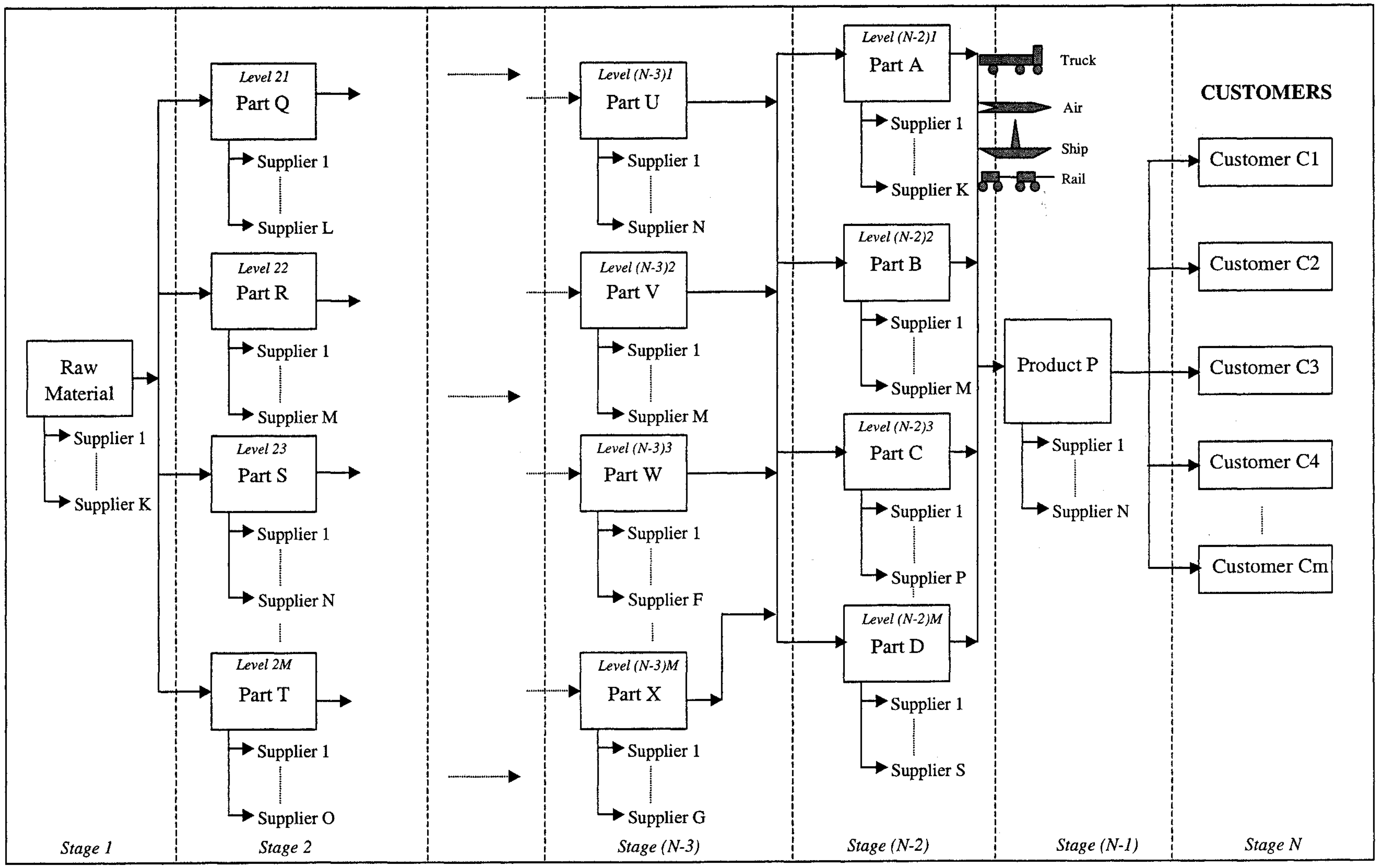


Figure 3.1: Generic Supply Chain Network

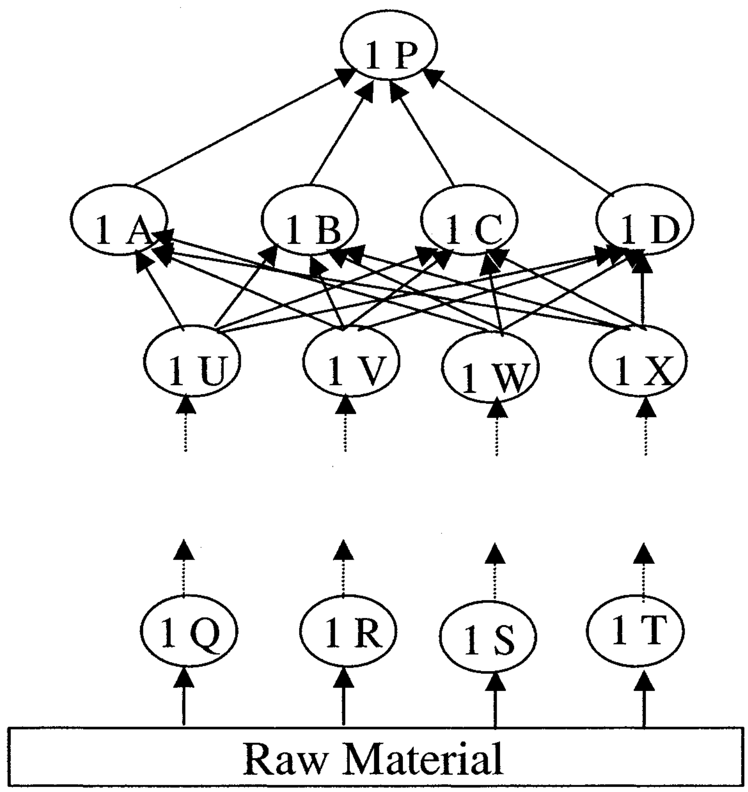


Figure 3.2: Classic Bill of Material for Product P

3.2.2 Problem Formulation

Four classes of problems are considered in this research. They are essentially a combination of two factors to create all of the four classes, i.e. Split vs. No Split in Customer demand and Single vs. Multiple Criteria. Generalized models are developed in the following sections to cover for Split Demand, Single/Multi Criteria and No Split Demand, Single/Multi Criteria.

3.2.2.1 Models Classification

The Generalized Split Demand Single/Multi Criteria models are characterized as Linear Programming models. All of the data variables are constants. All of the decision variables are continuous variables. The Generalized No Split Demand Single/Multi Criteria models are characterized as Linear Mixed Integer Programming models. Again, all of the data variables are constants. The decision variables are a mix of continuous variables and binary integer variables. The Data and Decision Variables section in the Generic models identifies the detailed characterization for each variable.

3.2.2.2 Generalized Split Demand, Single/Multi Criteria Model

The supply chain design problem is formulated as a combination of an advanced transportation problem and a multi-stage production-planning problem. This model allows for splitting of customer demand between multiple suppliers, if that represents the optimal supply chain design solution. It is organized into model variables, data, formulation and objectives.

<u>Model Variables & Data</u>

Indices

i is a stage index (i = 1, 2, ……, nst)

l is a level index (l = 1, 2, ……., L_i)

j is a supplier index (j = 1, 2, …., S_{l_i})

o is a transport origin index

d is a transport destination index

Derived Transportation indices are:

o_i - Origin stage

o_l - Origin level at origin stage o_i

o_j - Origin supplier at origin level o_l and origin stage o_i

d_l - Destination level at destination stage (o_i+1)

d_j - Destination supplier at destination level d_l and destination stage (o_i+1)

m is a transport mode index

t is a time index (t = 1, 2, ..., T) where T is the length of the planning horizon

c is a customer index (c = 1, 2, ..., C_m) where C_m is the maximum number of customers

Z – Total Supply Chain costs inclusive of Single/Multi Criteria in the Planning Horizon

Data

This section lists the individual data variables used in the model formulation along with their representation (Constant or Variable.)

D_{ct} - Constant - Forecasted Demand at customer c, period t

P_{iljt} - Constant - Production Capacity at stage i, level l, supplier j, period t

H_{iljt} - Constant - Max inventory holding capacity at stage i, level l, supplier j, period t

F_{iljt} - Constant - First Time Quality (FTQ) at stage i, level l, supplier j in period t (= 1 for Single Criteria; < 1 for Multi Criteria)

LD_{iljt} - Constant - Late Delivery of parts (expressed as percentage) by supplier i, level l, supplier j, in period t

$Risk_{iljt}$ – Constant - Risk of supplier i, level l, supplier j in period t (expressed as Low = 1/ Medium = 2/ High = 3) for supplying parts late to their customer

PenRt - Constant - Base penalty rate is defined as the dollar penalty for every part that is delivered late is derived from supplier contract agreements.

C_{iljt} - Constant – Cost to produce a unit part at stage i, level l, supplier j, period t

h_{iljt} - Constant – Cost to hold inventory at stage i, level l, supplier j, period t

$g_{o\_io\_lo\_jd\_ld\_jmt}$ – Constant - Cost to transport a unit from origin stage (o_i), origin level (o_l), origin supplier (o_j) to destination stage (o_i+1), destination level (d_l), destination supplier (d_j) using transport option m in same time period t

$C\_V_{o\_io\_lo\_jd\_ld\_jmt}$ - Constant - Transport Capacity from origin (o_i, o_l, o_j) to destination (o_i+1, d_l, d_j) with transport mode m in period t

$M_{o\_io\_lo\_jd\_ld\_j}$ - Constant - Maximum number of transport options between the indicated origin (o_i, o_l, o_j) and destination (o_i+1, d_l, d_j)

Decision Variables

This section lists the individual decision variables used in the model formulation along with their representation (Continuous or Integer.)

X_{iljt} - Continuous Variable - Number of units produced at stage i, level l, supplier j, period t

I_{iljt} - Continuous Variable - Inventory at stage i, level l, supplier j, period t

$V_{o\_io\_lo\_jd\_ld\_jmt}$ - Continuous Variable - Number of units transported from origin stage o_i, origin level o_l, origin supplier o_j to destination stage (o_i+1), destination level d_l, destination supplier d_j using transport option m in period t

Model Objective and Formulation

This section shows the model formulation along with the explanations.

Model Explanation

The objective function Z lists the individual cost components for Production costs, Inventory costs, Late Delivery costs and Transportation costs. The impact of Supplier On-Time Delivery Risk is captured as Cost of On-Time Delivery that is the product of Percent late delivery rate, Production quantity, Base penalty rate and Exponential function of Supplier on-time delivery risk level. Data for percent late delivery and Supplier on-time delivery risk level can be obtained from current and past historical databases. Data for Base penalty rates can be obtained from previous Supplier Contract Agreements that are issued when the purchase orders are cut.

Equation 3.2 balances the inventory between production and shipment at every stage. This constraint also captures the impact of Supplier First Time Quality. Changing data values for First Time Quality and On-Time Delivery Risk variables does switching from Single to Multiple criteria. Initial starting inventory at time period zero is assumed to be zero.

Equation 3.3 ensures that production at every stage gets the raw material shipments from the previous stage.

Equation 3.4 ensures that the customer demand for all of the customers is shipped from the last production stage.

Equation 3.5 deals with Supplier Capacity restrictions and Non-Negativity restrictions.

Equation 3.6 deals with Inventory Storage Capacity restrictions and Non-Negativity restrictions.

Equation 3.7 deals with Transportation Option Capacity restrictions and Non-Negativity restrictions.

Model Formulation

Minimize the Total Supply Chain Costs in the Planning Horizon with Single/Multiple Criteria. The Total Cost is the sum of Production Costs, Inventory Carrying Costs, Cost of On-Time Delivery and Transportation Costs in the complete Supply Chain.

Minimize Z =

$$\sum_{t=1}^{T}\sum_{i=1}^{(nst-1)}\sum_{l=1}^{L_i}\sum_{j=1}^{S_{l_i}} \left[C_{iljt}.X_{iljt} + h_{iljt}.I_{iljt} + LD_{iljt}.X_{iljt}.PenRt.Exp\left(Risk_{iljt}\right)\right] +$$

$$\sum_{t=1}^{T}\sum_{o\_i=1}^{(nst-1)}\sum_{o\_l=1}^{L_{o\_i}}\sum_{d\_l=1}^{L_{o\_i+1}}\sum_{o\_j=1}^{S_{o\_l_{o\_i}}}\sum_{d\_j=1}^{S_{d\_l_{o\_i+1}}}\sum_{m=1}^{M_{o\_io\_lo\_jd\_ld\_j}} \left[g_{o\_io\_lo\_jd\_ld\_jmt}V_{o\_io\_lo\_jd\_ld\_jmt}\right] \quad - \quad (3.1)$$

Subject to

Inventory Balance Constraint – Inventory at all stages, levels, suppliers and time periods is equal to the inventory from the previous time period plus the quantity produced in the current time period with the inclusion of First Time Quality less the quantity shipped to the downstream stage in the supply chain. The variable F_{iljt} represents the First Time Quality of the supplier.

$$I_{iljt} = I_{ilj(t-1)} + X_{iljt}.F_{iljt} - \sum_{d\_l=1}^{L_{i+1}} \sum_{d\_j=1}^{S_{d\_l_{i+1}}} \sum_{m=1}^{M_{i,l,j,d\_l,d\_j}} V_{iljd\_ld\_jmt} \qquad -(3.2)$$

$$\begin{aligned} &i = 1,2,\dots,(nst-1) \\ &l = 1,2,\dots,L_i \\ &j = 1,2,\dots,S_{l_i} \\ &\forall t \end{aligned}$$

Flow Constraint – This constraint models that the transport shipments received from the upstream stage as raw materials at a current stage is equal to the production quantity at that current stage.

$$\sum_{o\_j=1}^{S_{o\_l_{o\_i}}} \sum_{m=1}^{M_{o\_io\_lo\_jd\_ld\_j}} V_{o\_io\_lo\_jd\_ld\_jmt} = X_{iljt} \qquad -(3.3)$$

$$\begin{aligned} &o\_i = 1,2,\dots,(nst-2) \\ &o\_l = 1,2,\dots,o\_l_{o\_i} \\ &i = (o\_i+1),\dots,(nst-1) \\ &d\_l, l = 1,2,\dots,L_i \\ &d\_j, j = 1,2,\dots,S_{l_i} \\ &\forall t \end{aligned}$$

Meeting Customer Demand Constraint – The transport shipments from the assembly stage or the last stage before the customer's stage is equal to the customer demand. This constraint ensures that all of the customers demands are met.

$$\sum_{o\_l=1}^{L_{(nst-1)}} \sum_{o\_j=1}^{S_{o\_l(nst-1)}} \sum_{m=1}^{M_{(nst-1)o\_lo\_jc1}} V_{(nst-1)o\_lo\_jclmt} \quad = \quad D_{c,t} \qquad -(3.4)$$

$$\forall\, c\, t$$

Supplier Capacity and Non Negativity Constraint – This constraint models the suppliers capacity limits and ensures that the production quantities are greater than or equal to zero and below the suppliers capacity limits.

$$0 \le X_{iljt} \le P_{iljt} \qquad \forall i\, l\, j\, t \qquad -(3.5)$$

Inventory Capacity and Non Negativity Constraint – This constraint models the inventory carrying capacity limits and ensures that the inventory quantities are greater than or equal to zero and below the inventory carrying capacity limits.

$$0 \le I_{iljt} \le H_{iljt} \qquad \forall i\, l\, j\, t \qquad -(3.6)$$

Transport Capacity and Non Negativity Constraint – This constraint models the transport capacity limits for each transport option and ensures that the transport quantities are greater than or equal to zero and below the transport carrying capacity limits.

$$0 \leq V_{o\_io\_lo\_jd\_ld\_jmt} \leq C\_V_{o\_io\_lo\_jd\_ld\_jmt} \qquad -(3.7)$$

$$\begin{aligned}
o_i &= 1,2,...,(nst-1) \\
o_l &= 1,2,...,L_{o_i} \\
o_j &= 1,2,...,S_{o_l_{o_i}} \\
d_i &= (o_i+1),...,nst \\
d_l &= 1,2,...,L_{d_i} \\
d_j &= 1,2,...,S_{d_l_{d_i}} \\
m &= 1,2,...,M_{o_io_lo_jd_ld_j} \\
\forall\, t
\end{aligned}$$

3.2.2.3 Generalized No Split Demand, Single/Multi Criteria Model

This model allows for No splitting of customer demand between multiple suppliers (i.e. a single supplier is selected for each component in the supply chain to meet all of the customer demand.) It is organized into model variables, formulation and objectives.

<u>Model Variables & Data</u>

Indices

i is a stage index (i = 1, 2, ……, nst)

l is a level index (l = 1, 2, ……., L_i)

j is a supplier index (j = 1, 2, …., S_{l_i})

o is a transport origin index

d is a transport destination index

Derived Transportation indices are:

- o_i - Origin stage
- o_l - Origin level at origin stage o_i
- o_j - Origin supplier at origin level o_l and origin stage o_i
- d_l - Destination level at destination stage (o_i+1)
- d_j - Destination supplier at destination level d_l and destination stage (o_i+1)

m is a transport mode index

t is a time index (t = 1, 2, …., T) where T is the length of the planning horizon

c is a customer index (c = 1, 2, …., C_m) where C_m is the maximum number of customers

Z – Total Supply Chain costs inclusive of Single/Multi Criteria in the Planning Horizon

Data

This section lists the individual data variables used in the model formulation along with their representation (Constant or Variable.)

D_{ct} - Constant - Forecasted Demand at customer c, period t

P_{iljt} - Constant - Production Capacity at stage i, level l, supplier j, period t

H_{iljt} - Constant - Max inventory holding capacity at stage i, level l, supplier j, period t

F_{iljt} - Constant - First Time Quality (FTQ) at stage i, level l, supplier j in period t (= 1 for Single Criteria; < 1 for Multi Criteria)

LD_{iljt} - Constant - Late Delivery of parts (expressed as percentage) by supplier i, level l, supplier j, in period t

$Risk_{iljt}$ – Constant - Risk of supplier i, level l, supplier j in period t (expressed as Low = 1/ Medium = 2/ High = 3) for supplying parts late to their customer

PenRt - Constant - Base penalty rate is defined as the dollar penalty for every part that is delivered late is derived from supplier contract agreements.

C_{iljt} - Constant – Cost to produce a unit part at stage i, level l, supplier j, period t

h_{iljt} - Constant – Cost to hold inventory at stage i, level l, supplier j, period t

$g_{o\_io\_lo\_jd\_ld\_jmt}$ – Constant - Cost to transport a unit from origin stage (o_i), origin level (o_l), origin supplier (o_j) to destination stage (o_i+1), destination level (d_l), destination supplier (d_j) using transport option m in period t

$C\_V_{o\_io\_lo\_jd\_ld\_jmt}$ - Constant - Transport Capacity from origin (o_i, o_l, o_j) to destination (o_i+1, d_l, d_j) with transport mode m in period t

$M_{o\_io\_lo\_jd\_ld\_j}$ - Constant - Maximum number of transport options between the indicated origin (o_i, o_l, o_j) and destination (o_i+1, d_l, d_j)

Decision Variables

This section lists the individual decision variables used in the model formulation along with their representation (Continuous or Integer.)

X_{iljt} - Continuous Variable - Number of units produced at stage i, level l, supplier j, period t

I_{iljt} - Continuous Variable - Inventory at stage i, level l, supplier j, period t

$V_{o\_io\_lo\_jd\_ld\_jmt}$ - Continuous Variable - Number of units transported from origin stage o_i, origin level o_l, origin supplier o_j to destination stage (o_i+1), destination level d_l, destination supplier d_j using transport option m in same time period t

BX_{iljt} - Integer Binary Variable - Binary Variable to choose only 1 supplier at stage i, level l, supplier j, period t

$BV_{o\_io\_lo\_jd\_ld\_jmt}$ - Integer Binary Variable - Binary Variable to choose one transport option from origin stage o_i, origin level o_l, origin supplier o_j to destination stage (o_i+1), destination level d_l, destination supplier d_j using transport option m in period t

Model Objective and Formulation

This section shows the model formulation along with the explanations.

Model Explanation

The objective function Z lists the individual cost components for Production costs, Inventory costs, Late Delivery costs and Transportation costs. The impact of Supplier On-Time Delivery Risk is captured as Cost of On-Time Delivery that is the product of Percent late delivery rate, Production quantity, Base penalty rate and Exponential function of Supplier on-time delivery risk level. Data for Percent late delivery and Supplier on-time delivery risk level can be obtained from current and past historical databases. Data for Base penalty rates can be obtained from previous Supplier Contract Agreements that are issued when the purchase orders are cut.

Constraint 3.9 balances the inventory between production and shipment at every stage. This constraint also captures the impact of Supplier First Time Quality. Changing data values for First Time Quality and On-Time Delivery Risk variables does switching from Single to Multiple criteria. Initial starting inventory at time period zero is assumed to be zero.

Constraint 3.10 ensures that production at every stage gets the raw material shipments from the previous stage.

Constraint 3.11 ensures that the customer demand for all of the customers is shipped from the last production stage.

Constraint 3.12 deals with Supplier Capacity restrictions and non-negativity restrictions.

Constraint 3.13 deals with Inventory storage capacity restrictions and non-negativity restrictions.

Constraint 3.14 deals with Transportation option capacity restrictions and non-negativity restrictions.

Being No Split Demand scenarios, Constraints 3.15 and 3.16 capture the selection of one single supplier and transportation option at different stages. This is done using the binary integer variables.

Model Formulation

Minimize the Total Supply Chain Costs in the Planning Horizon with Single/Multiple Criteria. The Total Costs is equal to the sum of Production Costs, Inventory Carrying Costs, Cost of On-Time Delivery and Transportation Costs in the complete Supply Chain.

Minimize Z =

$$\sum_{t=1}^{T}\sum_{i=1}^{(nst-1)}\sum_{l=1}^{L_i}\sum_{j=1}^{S_{l_i}} \left[C_{iljt}.X_{iljt} + h_{iljt}.I_{iljt} + LD_{iljt}.X_{iljt}.PenRt.Exp\left(Risk_{iljt}\right)\right] +$$

$$\sum_{t=1}^{T}\sum_{o\_i=1}^{(nst-1)}\sum_{o\_l=1}^{L_{o\_i}}\sum_{d\_l=1}^{L_{o\_i+1}}\sum_{o\_j=1}^{S_{o\_l_{o\_i}}}\sum_{d\_j=1}^{S_{d\_l_{o\_i+1}}}\sum_{m=1}^{M_{o\_io\_lo\_jd\_ld\_j}} \left[g_{o\_io\_lo\_jd\_ld\_jmt}V_{o\_io\_lo\_jd\_ld\_jmt}\right] \quad -(3.8)$$

subject to

Inventory Balance Constraint – Inventory at all stages, levels, suppliers and time periods is equal to the inventory from the previous time period plus the quantity produced in the current time period with the inclusion of First Time Quality less the quantity shipped to downstream stage in the supply chain. The variable F_{iljt} represents the First Time Quality of the supplier.

$$I_{iljt} = I_{ilj(t-1)} + X_{iljt}.F_{iljt} - \sum_{d\_l=1}^{L_{i+1}}\sum_{d\_j=1}^{S_{d\_l_{i+1}}}\sum_{m=1}^{M_{iljd\_ld\_j}} V_{iljd\_ld\_jmt} \quad -(3.9)$$

$i = 1,2,\ldots,(nst-1)$
$l = 1,2,\ldots,L_i$
$j = 1,2,\ldots,S_{l_i}$
$\forall t$

Flow Constraint – This constraint models that the transport shipments received from the upstream stage as raw materials at a current stage is equal to the production quantity at that current stage.

$$\sum_{o\_j=1}^{S_{o\_l_{o\_i}}} \sum_{m=1}^{M_{o\_io\_lo\_jd\_ld\_j}} V_{o\_io\_lo\_jd\_ld\_jmt} = X_{i,l,j,t} \qquad -(3.10)$$

$$\begin{aligned} & o\_i = 1,2,\ldots,(nst-2) \\ & o\_l = 1,2,\ldots,o\_l_{o\_i} \\ & i \ = (o\_i+1),\ldots,(nst-1) \\ & d\_l, l = 1,2,\ldots,L_i \\ & d\_j, j = 1,2,\ldots,S_{l_i} \\ & \forall t \end{aligned}$$

Meeting Customer Demand Constraint – The transport shipments from the assembly stage or the last stage before the customer's stage is equal to the customer demand. This constraint ensures that all of the customers' demands are met.

$$\sum_{o\_l=1}^{L_{(nst-1)}} \sum_{o\_j=1}^{S_{o\_l(nst-1)}} \sum_{m=1}^{M_{(nst-1)o\_lo\_jd1}} V_{(nst-1)o\_lo\_jd1mt} = D_{ct} \qquad -(3.11)$$

$$\forall\ ct$$

Supplier Capacity and Non Negativity Constraint – This constraint models the suppliers' capacity limits and ensures that the production quantities are greater than or equal to zero and below the suppliers capacity limits.

$$0 \leq X_{iljt} \leq P_{iljt}.BX_{iljt} \qquad \forall iljt \qquad -(3.12)$$

Inventory Capacity and Non Negativity Constraint – This constraint models the inventory carrying capacity limits and ensures that the inventory quantities are greater than or equal to zero and below the inventory carrying capacity limits.

$$0 \leq I_{i,l,j,t} \leq H_{i,l,j,t}.BX_{i,l,j,t} \qquad \forall iljt \qquad -(3.13)$$

Transport Capacity and Non Negativity Constraint – This constraint models the transport capacity limits for each transport option and ensures that the transport quantities are greater than or equal to zero and below the transport carrying capacity limits.

$$0 \leq V_{o\_io\_lo\_jd\_ld\_jmt} \leq C\_V_{o\_io\_lo\_jd\_ld\_jmt}.BV_{o\_io\_lo\_jd\_ld\_jmt} \qquad -(3.14)$$

$$o\_i = 1,2,...,(nst-1)$$
$$o\_l = 1,2,...,L_{o\_i}$$
$$o\_j = 1,2,...,S_{o\_l_{o\_i}}$$
$$d\_i \ = (o\_i+1),...,nst$$
$$d\_l \ = 1,2,...,L_{d\_i}$$
$$d\_j \ = 1,2,...,S_{d\_l_{d\_i}}$$
$$m \ = 1,2,...,M_{o\_io\_lo\_jd\_ld\_j}$$
$$\forall t$$

Single Supplier Selection Constraint – This constraint uses binary integer variables and ensures that only one supplier is selected for production at all of the different stages in the supply chain.

$$\sum_{j=1}^{S_{l_i}} BX_{iljt} \quad = \quad 1 \qquad \forall i,l,t \qquad -(3.15)$$

Single Transport Option Selection Constraint – This constraint uses binary variables and ensures that only one single transport option is selected for transportation between different stages in the supply chain. The reason for this constraint is similar in nature to single supplier selection which is that often in the real world contracts are handed out to just one transport company.

$$\sum_{m=1}^{M_{o\_io\_lo\_jd\_ld\_j}} BV_{o\_io\_lo\_jd\_ld\_jmt} \quad \leq \quad 1 \qquad \forall o\_io\_lo\_jd\_ld\_jt \quad -(3.16)$$

3.3 Model Validation, Data Collection and Solutions

A real world automotive industry powertrain process is taken as a supply chain study and for demonstrating the Supply Chain Design framework and solutions. Real world data is used for design and analysis. Sources of data come from a combination of electronic data collection systems, experiential knowledge in supply chain projects, collected literature and using interview methods for determining the remaining unknowns. Commercial Linear/Non-Linear/Integer Programming Software tool, LINGO is used in solving the supply chain design problems. LINGO linear mixed integer programs are developed for all four scenarios (Split Demand – Single Criterion, Split Demand – Multiple Criteria, No Split Demand – Single Criterion and No Split Demand – Multiple Criteria) to be investigated in this research. An Excel based front end is developed to interface with the LINGO models for data input and results. This helped tremendously during the analysis phase of the research. Validation of results for each of the four scenarios is done by including a validation table that compares the total customer demand by stage and by time period to actual production by the supplier(s) chosen to ensure that the required demand is met completely.

CHAPTER 4

SUPPLY CHAIN DESIGN – EXAMPLE CASE STUDY

4.1 An Overview

To illustrate application of the proposed supply chain framework, a real world automotive powertrain engine process and manufacturing system is taken as an example case study for supply chain design in this chapter. Chapter 5 focuses on the analysis phase by varying the values of the different variables and studying its impact on the solution. Automotive powertrain forms the heart of the automobile and in that sense represents the most important component of the car. The following section shows the major components and the typical process of an automobile powertrain engine.

4.2 Automobile Powertrain Manufacturing Process and Suppliers

The major components of an automobile's powertrain are Blocks, Heads, Crankshafts, Cams and Piston Rod Assembly. Figures 4.1 through 4.6 show a typical powertrain assembled engine and the above major components. While there are many other small components that go into the final assembly, this example only considers the above major components to illustrate the use of supply chain framework. Figure 4.7 shows the engine manufacturing process. There are multiple types of powertrains depending upon capacity (horse power), displacement and their final application (cars, trucks, SUV's.) The automotive powertrain industry typically supplies these powertrains to the final vehicle assembly industry depending on the demand received from them.

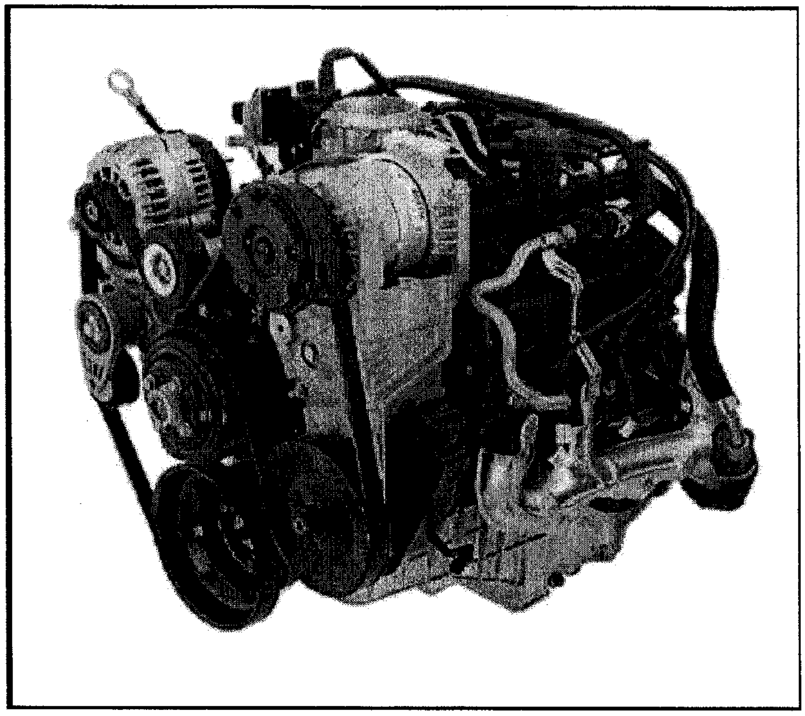


Figure 4.1 – Automobile Powertrain Engine

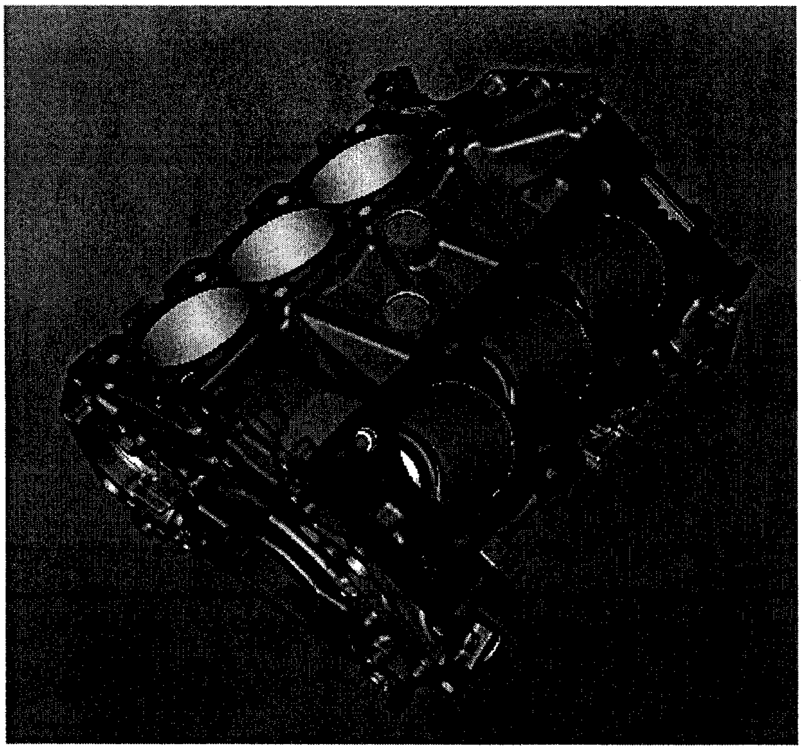


Figure 4.2 – Engine Block

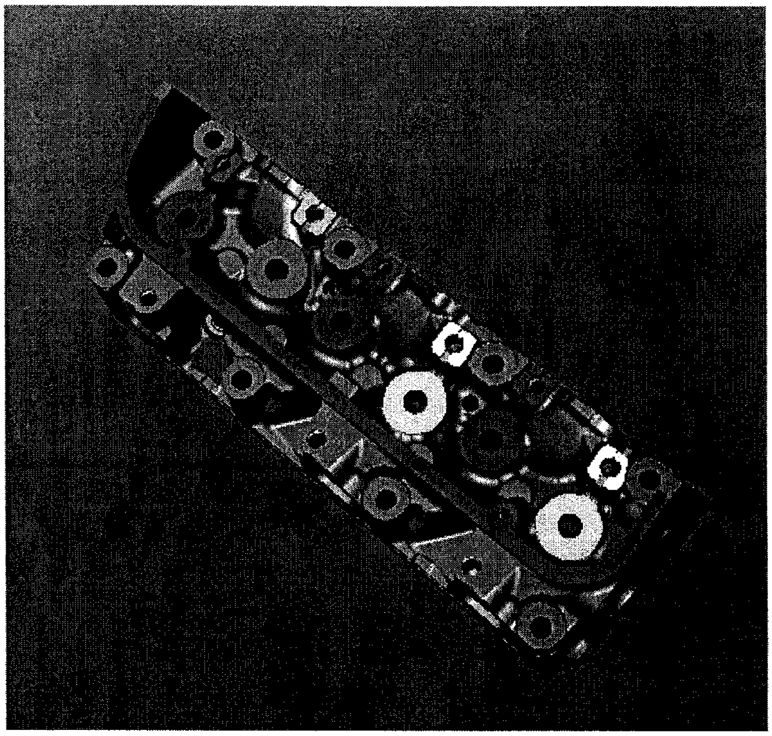


Figure 4.3 – Engine Head

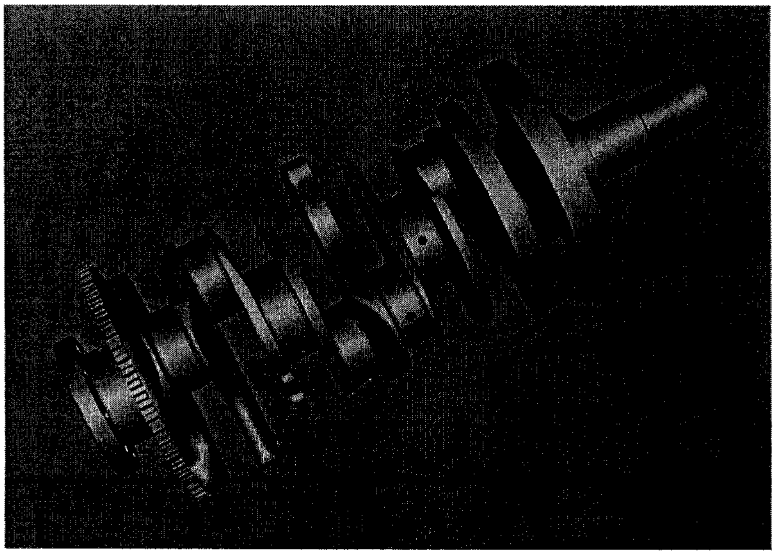


Figure 4.4 – Engine Crank

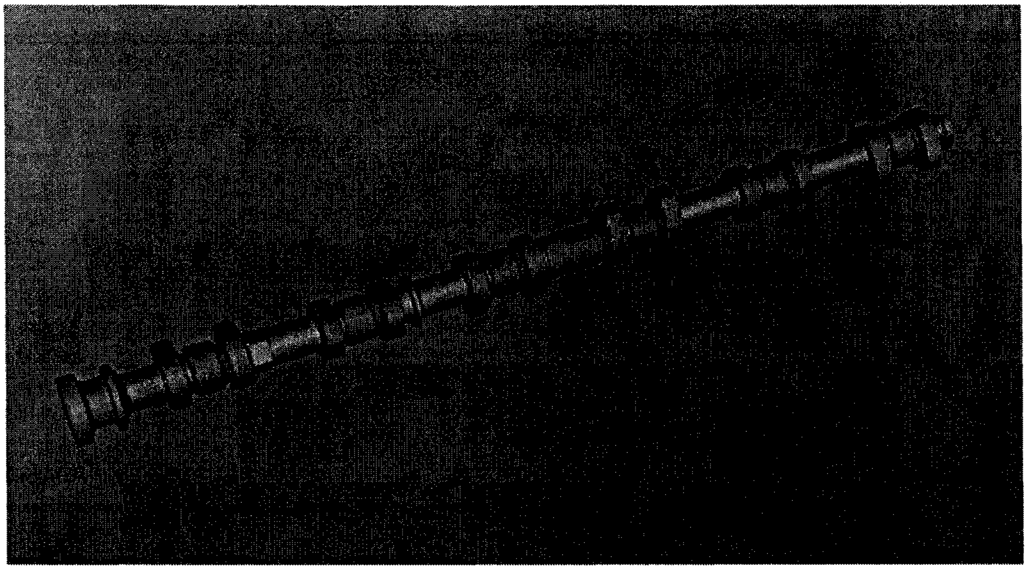


Figure 4.5 – Engine Camshaft

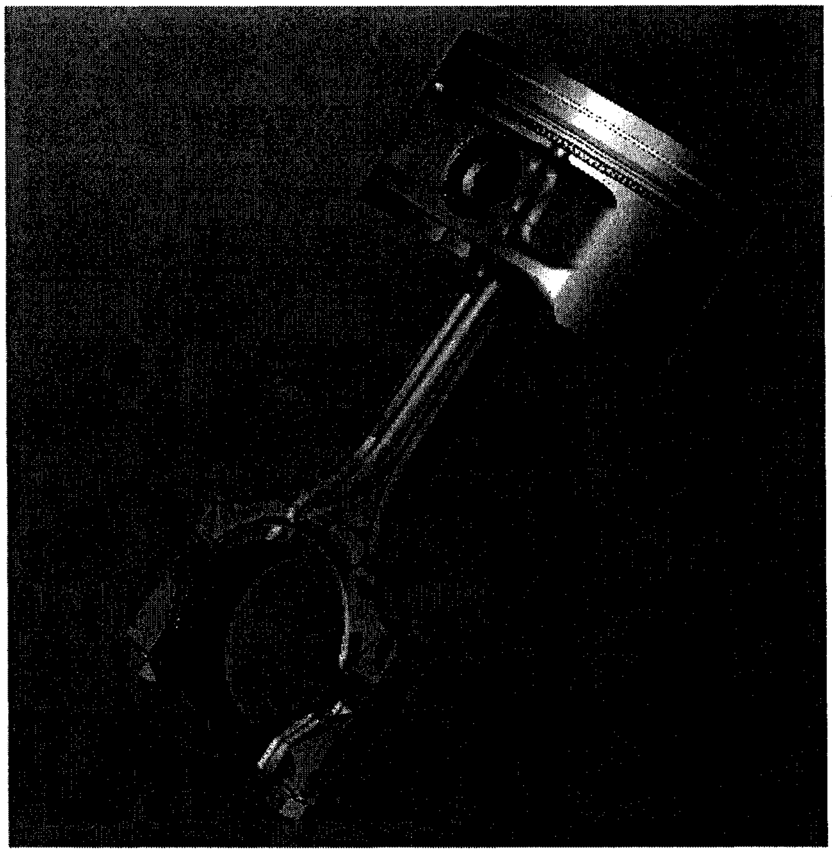


Figure 4.6 – Engine Piston Rod Assembly

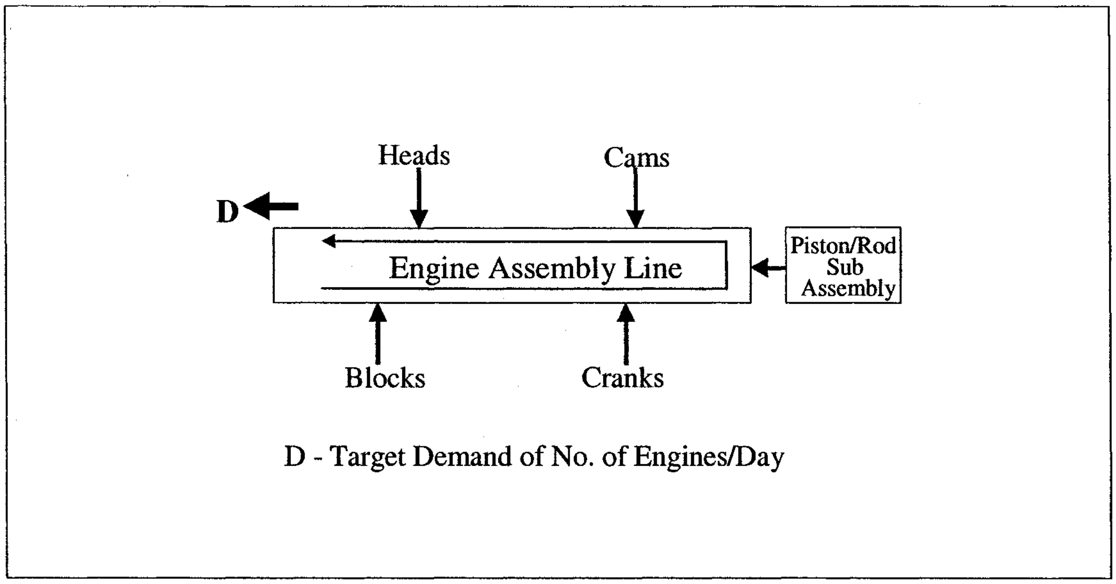


Figure 4.7: Automobile Powertrain Engine Manufacturing Process

Each of the individual components can either be purchased from an outside supplier or produced at an OEM facility. The suppliers and/or OEM facilities could be geographically spread out over the globe, thus creating what is called a 'Global Manufacturing System.' The supplier companies typically include North American and overseas companies that have facilities worldwide and operate globally. The major companies are: Delphi Corp., Visteon Corp., Lear Corp., Johnson Controls Inc., Magna International Inc., Comau Corp., Lamb Corp. and Ex-CELL-O. Some of the major logistics companies that transport parts between different geographic locations include Federal Express, United Postal Service (UPS), DHL and Yellow Truck. These are in addition to any other state/privately owned transportation services, like Trains (Rail Cars), Sea Shipping etc.

Figure 4.8 shows the earlier powertrain manufacturing process from a supply chain network point of view. Supplier locations are specified for individual components as against actual suppliers from one of the above listed companies. Raw castings represent the 1st stage of the supply chain network. The raw castings are fed as raw materials to all the machining steps - Blocks, Heads, Cranks, Camshafts and Piston/Rod assembly. All these machining steps represent the individual levels of the 2nd stage of the supply chain network. Each step is called a level because all of them need raw castings from 1st stage for further processing and the machined part is not fed as a raw material input to any of the other machining steps. Assembly represents the 3rd stage in the supply chain and needs the machined parts from each of the five levels of the 2nd stage to continue processing. Finally, the last customer stage is the 4th stage in the supply chain.

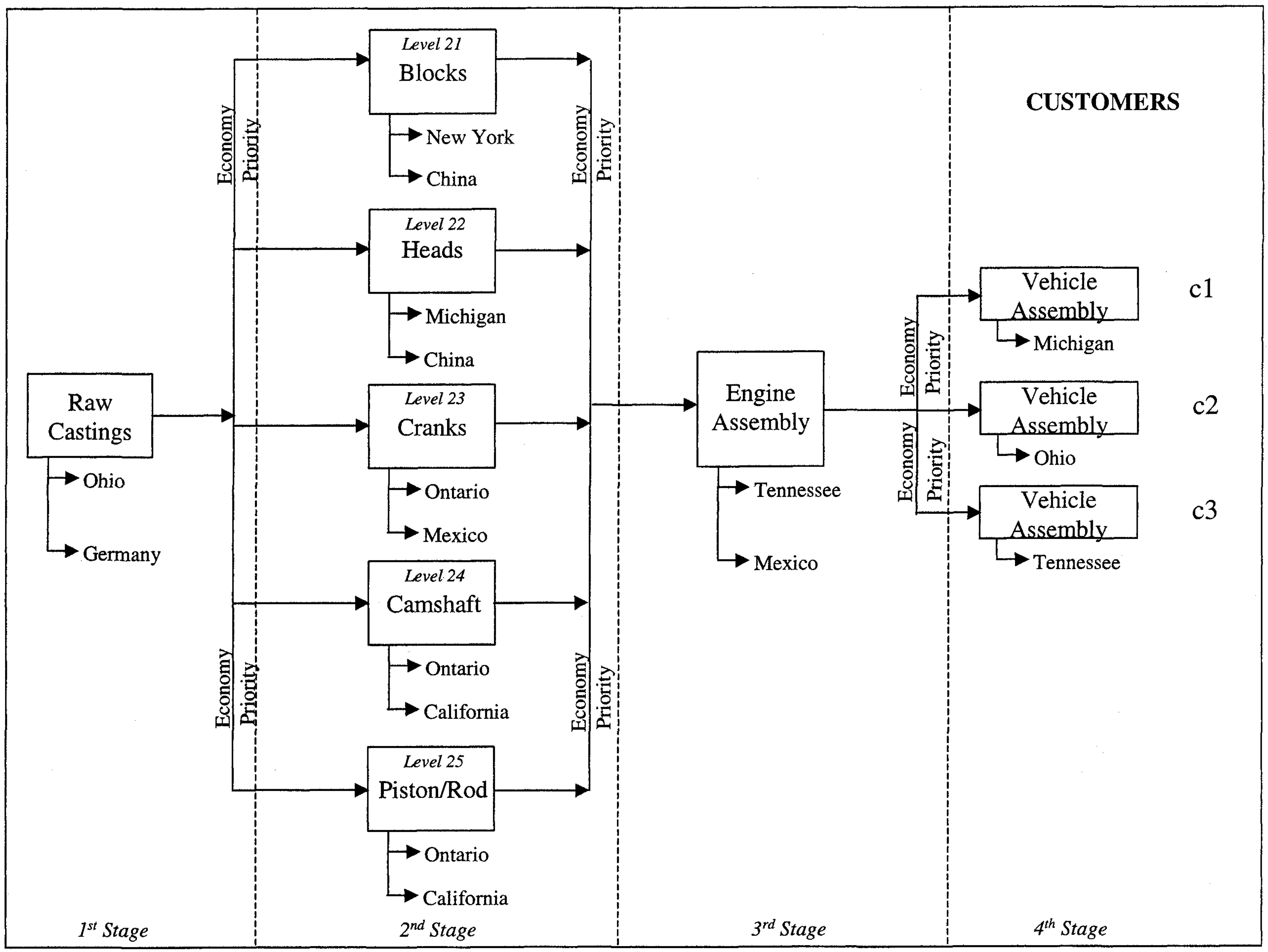


Figure 4.8: Supply Chain for Automobile Powertrain Engine Manufacturing Process

Figure 4.9 shows the Bill of Materials for the powertrain engine.

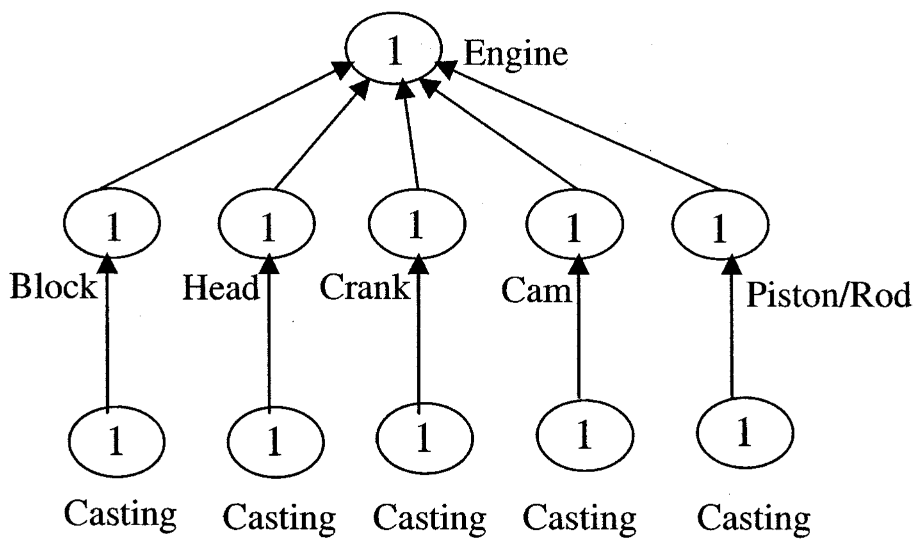


Figure 4.9: Bill of Material for Automobile Powertrain Engine

4.3 Problem Scenarios

The following four problems are developed and solved by using the proposed framework for making sourcing decisions:

1. No Split Demand, Single Criterion - Selecting one supplier and transport option to meet all of the demand for every component without splitting the demand between suppliers and between transport options. Each supplier and transport option has large enough capacity to meet all of the demand. Supplier selection is based on Single Criterion, which is just the sum of regular production and transportation costs.
2. No Split Demand, Multiple Criteria - Selecting one supplier and transport option to meet all of the demand for every component without splitting the demand

between suppliers and between transport options. Each supplier and transport option has a large enough capacity to meet all of the demand. Supplier selection is based on Multiple Criteria, which is the sum of regular production and transportation costs and Cost of Quality and Cost of On-Time Delivery.

3. Split Demand, Single Criterion - Selecting suppliers and transport options for every component while allowing splitting of demand between suppliers and between transport options. This includes suppliers and transport options having restricted capacity to meet all of the demand. Supplier selection is based on Single Criterion, which is just the sum of regular production and transportation costs.

4. Split Demand, Multiple Criteria - Selecting suppliers and transport options for every component while allowing splitting of demand between suppliers and between transport options. This includes suppliers and transport options having restricted capacity to meet all of the demand. Supplier selection is based on Multiple criteria, which is the sum of regular production and transportation costs and Cost of Quality and Cost of On-Time Delivery.

4.4 Software System and Computational Details

The commercial Linear/Non-Linear/Integer Programming Software package, "LINGO" is used to solve the supply chain design problems. An Excel based front-end interface was developed for ease of use during data input and in the analysis phase. Figure 4.10 shows the block diagram of the software system.

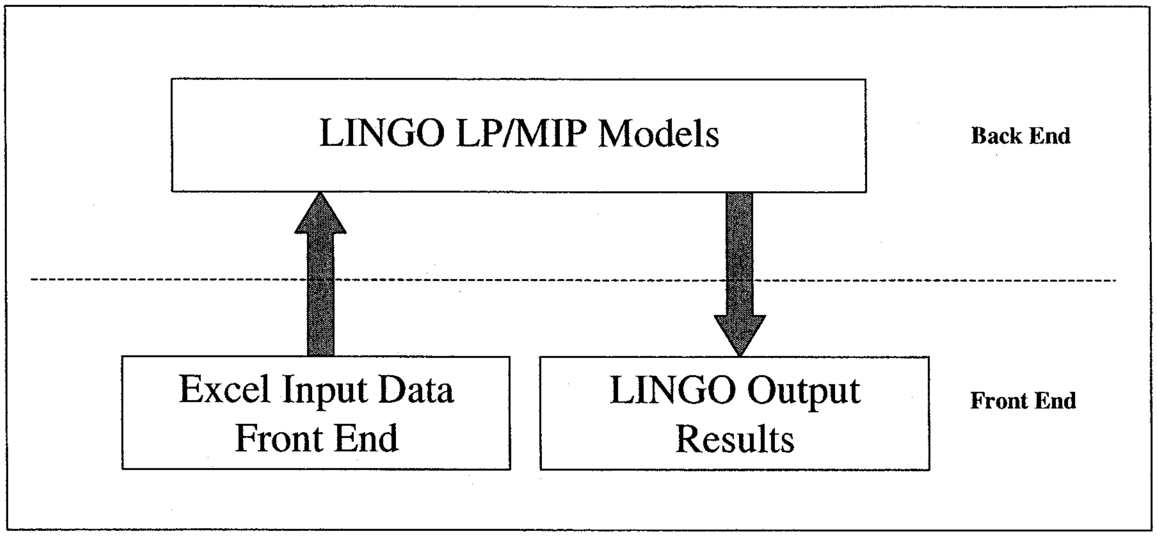


Figure 4.10 – Block diagram of Software System Components

Figure 4.11 shows an actual screen shot of the system details. The Excel Input data sheet acts as an interface to the LINGO models on the right side of the screen shot. Different sets of models and interfaces are used depending on which of the four problem scenarios is being solved. The interface allows inputting all of the data required for any of the problem scenarios. When solving single criterion models, data for the First Time Quality for all suppliers is set to 100% and data for Late Delivery Percentage, Base Penalty Rate and Risk level for all suppliers is set to zero in their respective units. While solving multi criteria models, data for the above variables including Supplier Risk level and Base penalty rate are set to the appropriate values for the suppliers. Again, as mentioned earlier, all of the input data used in this supply chain framework is typically available in the real world through historical databases, electronic data collection systems and experiential knowledge of the people working in the field.

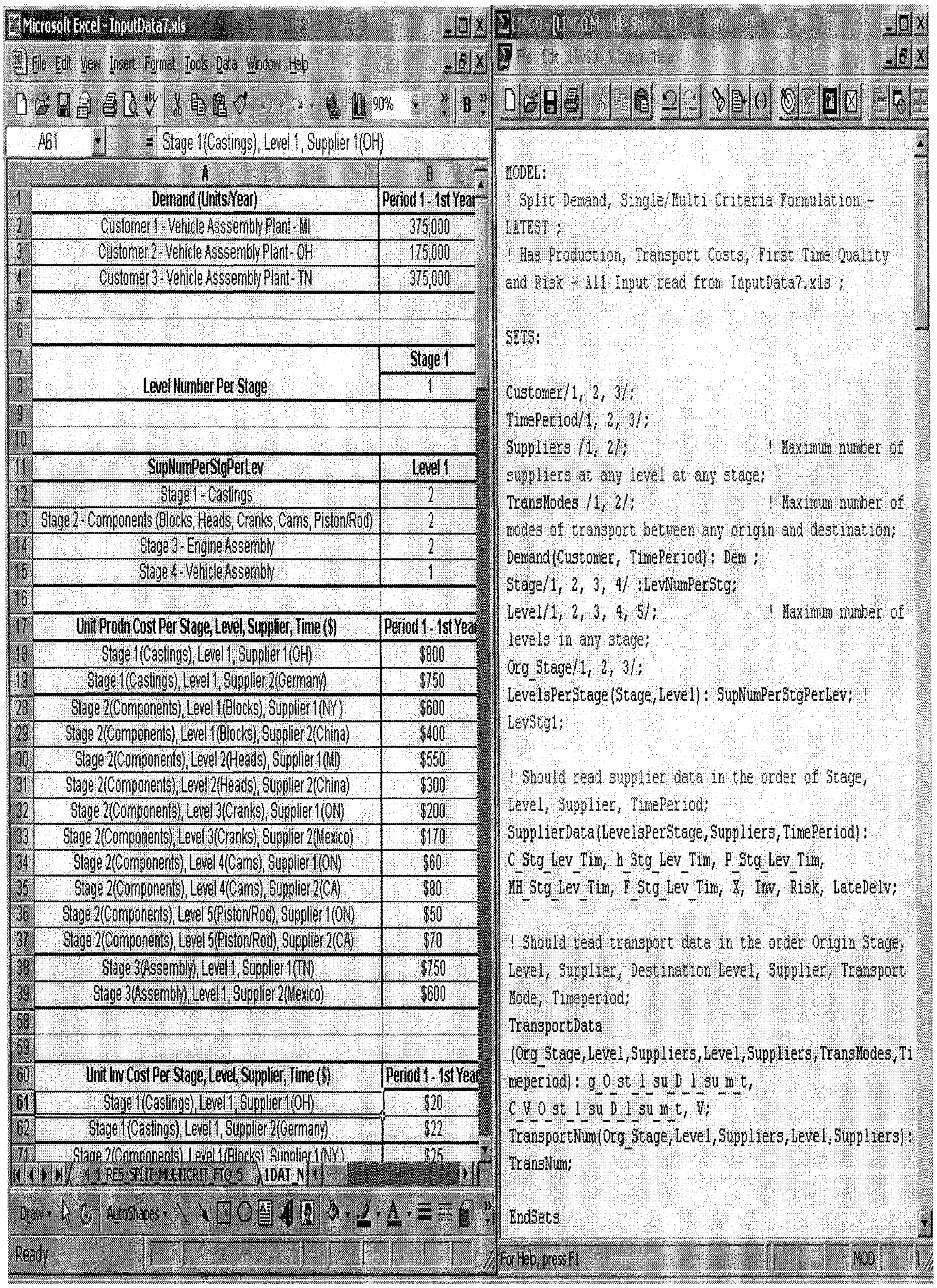


Figure 4.11 – Actual Screen Shot of Software System

The solutions of all of the four problem scenarios discussed earlier are presented in this chapter. Chapter 5 focuses on the analysis phase by varying the values of the different variables and studying its impact on the solution. From a computation time standpoint, the time taken to solve the majority of the problem scenarios and test case analysis takes up to two minutes on a laptop computer with an Intel Pentium III Mobile 1 GHz processor and 256 MB memory. A computational time of maximum of 10 minutes has also been noticed in analyzing a few test case analyses. No split demand models take the longest computational time because of more and tighter constraints.

4.5 Scenario 1 – No Split Demand, Single Criterion

Appendix A lists all of the input data for this scenario. The data for all of the scenarios reflect the typical values for all of the parameters of a powertrain engine manufacturing process. They are collected using electronic data collection systems, interview methods and experiential knowledge of the experts. Three time periods of a year each are considered to take into account the cyclical demand variation. The yearly demand for the three customers (vehicle assembly plants) is listed. Two supplier choices are considered at every stage and level of the supply chain. Being a No Split Demand problem, any one of the two suppliers needs to be selected to meet all of the customer demand. The unit production costs, unit inventory costs, production and inventory capacities for each supplier are provided. Two transport options – Economy and Priority are considered. Both options are different in their delivery times and consequently their cost of transportation. Delivery times are not directly captured in these models because the models are meant for use as planning tools and not as operational tools. The unit transportation costs for the two transport options are provided at every level along with transport options capacities. Supplier Quality and On-Time Delivery Risk are not considered in this scenario and will be considered in multi criteria scenario. Only the sum of regular production and transportation costs is considered, as this is a single criterion problem. The following section shows the results of the problem with discussion and conclusions.

4.5.1 Results and Conclusions:

Tables 4.1 through 4.4 show the results of the Supply Chain Design Framework for Supplier Selection for all of the components along with their production quantities, inventory locations and quantities in the supply chain and transport options selection in each year (time period.) As can be seen from the Transport Results Table 4.4, Economy option is selected for shipping parts between Suppliers in the Supply Chain. The Total Supply Chain Costs for the three years is at $ 12.25 Billion with Production Costs at $ 9.07 Billion and Transport Costs at $ 3.18 Billion.

Total Global Supply Chain Costs	**$12,255,150,000**
Total Global Supply Chain Production Costs	$9,073,057,000
Total Global Supply Chain Transportation Costs	$3,182,090,000

Table 4.1: Scenario 1 – Supplier Selection Results

Supplier Selection Per Stage, Level, Time	Supplier Selection		
	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1	Supplier 1 - OH	Supplier 1 - OH	Supplier 1 - OH
Stage 2(Components), Level 1(Blocks)	Supplier 1 - NY	Supplier 1 - NY	Supplier 1 - NY
Stage 2(Components), Level 2(Heads)	Supplier 1 - MI	Supplier 1 - MI	Supplier 1 - MI
Stage 2(Components), Level 3(Cranks)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
Stage 2(Components), Level 4(Cams)	Supplier 2 - CA	Supplier 1 - ON	Supplier 1 - ON
Stage 2(Components), Level 5(Piston/Rod)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
Stage 3(Assembly), Level 1	Supplier 1 - TN	Supplier 1 - TN	Supplier 1 - TN

Table 4.2: Scenario 1 – Production Quantity Results

Production Quantity Per Stage, Level, Supplier, Time	Production Results		
	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	4,898,800	4,632,400	4,468,800
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	991,600	925,000	883,400
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	954,600	928,700	916,700
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	984,200	925,000	890,800
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	925,000	887,100
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	987,900	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	980,500	928,700	890,800
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	954,600	928,700	916,700
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table 4.3: Scenario 1 – Inventory Quantity Results

	Inventory Results		
Inventory Quantity Per Stage, Level, Supplier, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	37,000	33,300	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	29,600	25,900	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	29,600	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	33,300	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	25,900	25,900	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table 4.4: Scenario 1 – Transportation Results

Transport Results								
Transport Quantity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	991,600	925,000	883,400
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	954,600	928,700	916,700
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	984,200	925,000	890,800
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	0	925,000	887,100
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	987,900	0	0
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	980,500	928,700	890,800
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	954,600	928,700	916,700
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	954,600	928,700	916,700
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	954,600	928,700	916,700
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	0	895,400	916,700
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	954,600	33,300	0
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	954,600	928,700	916,700
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	375,000	450,000	525,000
3 (Assembly)	1	1	2 (Vehile Assembly)	1	1 (Economy)	175,000	175,000	175,000
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	375,000	300,000	250,000

Tables 4.5 compares the total customer demand for the three years, and the production quantities from the suppliers at every stage for validation of results.

As can be seen from the above two tables, the total demand for the three years is met, as reflected by the total production quantities between both of the suppliers for the three years.

Table 4.5: Scenario 1 – Production Results Validation

	Total Demand Per Stage Per Year and all Years			
Total Demand for all Customers and for all the Years	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years
Stage 1 - Castings	4,625,000	4,625,000	4,750,000	14,000,000
Stage 2 for Each Level - Components	925,000	925,000	950,000	2,800,000
Stage 3 - Assembly	925,000	925,000	950,000	2,800,000
Stage 4 - Customer 1/2/3	925,000	925,000	950,000	2,800,000

	Production Results			
Total Production by Stage, Level & Suppliers, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years
Stage 1(Castings), Level 1, Supplier 1& 2	4,898,800	4,632,400	4,468,800	14,000,000
Stage 2(Components), Level 1(Blocks), Supplier 1 & 2	991,600	925,000	883,400	2,800,000
Stage 2(Components), Level 2(Heads), Supplier 1 & 2	954,600	928,700	916,700	2,800,000
Stage 2(Components), Level 3(Cranks), Supplier 1 & 2	984,200	925,000	890,800	2,800,000
Stage 2(Components), Level 4(Cams), Supplier 1 & 2	987,900	925,000	887,100	2,800,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1 & 2	980,500	928,700	890,800	2,800,000
Stage 3(Assembly), Level 1, Supplier 1 & 2	954,600	928,700	916,700	2,800,000

This scenario has considered the selection of suppliers with no split constraint for supply chain design and single criterion. Suppliers are selected for every component at every stage and level in the supply chain, such that the global supply chain costs are minimized.

4.6 Scenario 2 – No Split Demand, Multiple Criteria

Appendix B lists all of the input data for this scenario. Being a multi criteria problem, Cost of Quality and Cost of On-Time Delivery Risk are included in this scenario. Collected data is supplied to following variables defined, and shown in the MIP models earlier for inclusion of multiple criteria - First time quality levels of each supplier, Supplier Risk levels for on-time delivery of parts, base penalty rate in case of late delivery and late delivery percentage for each supplier. The rest of the data is similar to Scenario 1 in the previous section.

4.6.1 Results and Conclusion:

Tables 4.6 through 4.9 show the results of Supply Chain Design Framework for Supplier Selection for all of the components along with their production quantities, inventory locations and quantities in the supply chain and transport options selection in each year (time period.) As can be seen from the Transport Results Table 4.9, Economy option is selected for shipping parts between Suppliers in the Supply Chain. Furthermore, this table also lists the transport quantities between different stages during each of the time periods. The Total Supply Chain Costs for the 3 years is at $ 13.49 Billion with Production Costs at $ 10.20 Billion and Transport Costs at $ 3.28 Billion.

Total Global Supply Chain Costs	**$13,492,050,000**
Total Global Supply Chain Production Costs	$10,205,410,000
Total Global Supply Chain Transportation Costs	$3,286,646,000

The additional global supply chain costs as compared to the scenario 1 is due to inclusion of First Time Quality and Supplier On-Time Delivery Risk in this models. This additional cost is the Cost of Quality and Cost of On-Time Delivery.

Table 4.6: Scenario 2 – Supplier Selection Results

	Supplier Selection		
Supplier Selection Per Stage, Level, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1	Supplier 1 - OH	Supplier 1 - OH	Supplier 1 - OH
Stage 2(Components), Level 1(Blocks)	Supplier 1 - NY	Supplier 1 - NY	Supplier 1 - NY
Stage 2(Components), Level 2(Heads)	Supplier 1 - MI	Supplier 1 - MI	Supplier 1 - MI
Stage 2(Components), Level 3(Cranks)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
Stage 2(Components), Level 4(Cams)	Supplier 1 - ON	Supplier 2 - CA	Supplier 1 - ON
Stage 2(Components), Level 5(Piston/Rod)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
Stage 3(Assembly), Level 1	Supplier 1 - TN	Supplier 1 - TN	Supplier 1 - TN

Table 4.7: Scenario 2 – Production Quantity Results

	Production Results		
Production Quantity Per Stage, Level, Supplier, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	5,766,670	5,353,955	5,143,714
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	1,053,210	973,148	930,008
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	1,036,257	1,008,142	995,115
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	1,034,723	946,447	954,498
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	1,024,165	0	914,958
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	957,225	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	1,041,648	987,139	937,637
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	974,082	947,653	935,408
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table 4.8: Scenario 2 – Inventory Quantity Results

Inventory Quantity Per Stage, Level, Supplier, Time	Inventory Results Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	37,000	33,300	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	29,600	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	29,600	29,600	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	25,900	25,900	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table 4.9: Scenario 2 – Transportation Results

Transport Results Transport Quantity Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	Period 1 1st Year	Period 2 2nd Year	Period 3 3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	1,053,210	973,148	930,008
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	1,036,257	1,008,142	995,115
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	1,034,723	946,447	954,498
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	1,024,165	0	914,958
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	0	957,225	0
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	1,041,648	987,139	937,637
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	974,082	947,653	935,408
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	974,082	947,653	935,408
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	974,082	947,653	935,408
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	974,082	0	935,408
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	0	947,653	0
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	974,082	947,653	935,408
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	375,000	450,000	525,000
3 (Assembly)	1	1	2 (Vehile Assembly)	1	1 (Economy)	175,000	175,000	175,000
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	375,000	300,000	250,000

Table 4.10 compares the total customer demand for the three years and the production quantities from the suppliers at every stage for validation of results. The Table also shows the increased production from the suppliers at every stage to

account for First Time Quality and hence also Cost of Quality along with Cost of On-Time Delivery.

Table 4.10: Scenario 2 – Production Results Validation

	Total Demand Per Stage Per Year and all Years			
Total Demand for all Customers and for all the Years	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years
Stage 1 - Castings	4,625,000	4,625,000	4,750,000	14,000,000
Stage 2 for Each Level - Components	925,000	925,000	950,000	2,800,000
Stage 3 - Assembly	925,000	925,000	950,000	2,800,000
Stage 4 - Customer 1/2/3	925,000	925,000	950,000	2,800,000

	Production Results				
Total Production by Stage, Level & Suppliers, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years	% Increase from Demand because of FTQ
Stage 1(Castings), Level 1, Supplier 1& 2	5,766,670	5,353,955	5,143,714	16,264,339	16.2%
Stage 2(Components), Level 1(Blocks), Supplier 1 & 2	1,053,210	973,148	930,008	2,956,366	5.6%
Stage 2(Components), Level 2(Heads), Supplier 1 & 2	1,036,257	1,008,142	995,115	3,039,514	8.6%
Stage 2(Components), Level 3(Cranks), Supplier 1 & 2	1,034,723	946,447	954,498	2,935,668	4.8%
Stage 2(Components), Level 4(Cams), Supplier 1 & 2	1,024,165	957,225	914,958	2,896,348	3.4%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1 & 2	1,041,648	987,139	937,637	2,966,424	5.9%
Stage 3(Assembly), Level 1, Supplier 1 & 2	974,082	947,653	935,408	2,857,143	2.0%

This scenario has considered the selection of suppliers under a no split constraint for supply chain design under multiple criteria, i.e. sum of regular production and transportation costs, cost of quality and cost of on-time delivery. Suppliers are selected for every component at every stage and level in the supply chain such that the global supply chain costs are minimized.

4.7 Scenario 3 – Split Demand, Single Criterion

This scenario allows splitting of demand between more than one supplier if that represents the optimal solution. Two supplier options are considered at each stage and level. Also, this scenario includes capacity restrictions for each supplier, in the sense that no one supplier has enough capacity to single handedly be able to meet all of the customer demand. However, it is assumed that the total capacity of all of the suppliers is greater than the total demand of all of the customers. Again as in earlier scenarios, two supplier choices are considered at every stage and level of the supply chain. Appendix C lists all of the input data for this scenario which include the unit production and inventory costs, production and inventory capacities, number of transport options between stages, unit transportation costs and transportation capacities. Only the sum of regular production and transportation costs are considered for single criterion. Cost of Quality and Cost of On-Time delivery are not considered in this scenario.

4.7.1 Results and Conclusion:

Tables 4.11 through 4.13 show the results of Supply Chain Design Framework for Supplier Selection for all of the components in each year (time period) along with their production quantities, inventory locations and quantities in the supply chain and transport options selection and transport quantities. The Total Supply Chain Costs for the three years is at $ 13.09 Billion with Production Costs at $ 8.55 Billion and Transport Costs at $ 4.54 Billion. The total costs in this scenario are greater than the Scenario 1 (No Split, Single Criteria) due to restricted capacity of all suppliers at every stage and level in single handedly being able to meet the customer demand.

Total Global Supply Chain Costs	**$13,092,190,000**
Total Global Supply Chain Production Costs	$8,551,962,000
Total Global Supply Chain Transportation Costs	$4,540,224,000

Table 4.11: Scenario 3 – Supplier Selection Results

Supplier Selection Per Stage, Level, Time	Supplier Selection		
	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1	Supplier 1 - OH	Supplier 1 - OH	Supplier 1 - OH
	Supplier 2 - Germany	Supplier 2 - Germany	Supplier 2 - Germany
Stage 2(Components), Level 1(Blocks)	Supplier 1 - NY	Supplier 1 - NY	Supplier 1 - NY
	Supplier 2 - China	Supplier 2 - China	Supplier 2 - China
Stage 2(Components), Level 2(Heads)	Supplier 1 - MI	Supplier 1 - MI	Supplier 1 - MI
	Supplier 2 - China	Supplier 2 - China	Supplier 2 - China
Stage 2(Components), Level 3(Cranks)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
	Supplier 2 - Mexico	Supplier 2 - Mexico	Supplier 2 - Mexico
Stage 2(Components), Level 4(Cams)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
	Supplier 2 - CA	Supplier 2 - CA	Supplier 2 - CA
Stage 2(Components), Level 5(Piston/Rod)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
	Supplier 2 - CA	Supplier 2 - CA	Supplier 2 - CA
Stage 3(Assembly), Level 1	Supplier 1 - TN	Supplier 1 - TN	Supplier 1 - TN
	Supplier 2 - Mexico	Supplier 2 - Mexico	Supplier 2 - Mexico

Table 4.12: Scenario 3 – Production Quantity Results

Production Quantity Per Stage, Level, Supplier, Time	Production Results		
	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	3,000,000	3,500,000	3,496,500
Stage 1(Castings), Level 1, Supplier 2(Germany)	2,069,000	1,261,900	672,600
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	500,000	600,000	700,000
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	532,300	369,400	98,300
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	500,000	500,000	600,000
Stage 2(Components), Level 2(Heads), Supplier 2(China)	528,600	436,100	235,300
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	400,000	479,700	500,000
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	624,900	456,400	339,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	491,600	529,600	470,400
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	500,000	432,400	376,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	700,000	800,000	850,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	291,600	158,300	100
Stage 3(Assembly), Level 1, Supplier 1(TN)	500,000	500,000	500,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	491,600	432,400	376,000

Table 4.13: Scenario 3 – Inventory Quantity Results

	Inventory Results		
Inventory Quantity Per Stage, Level, Supplier, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0	33,300	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	40,700	44,400	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	37,000	40,700	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	33,300	37,000	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	29,600	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0	25,900	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	37,000	40,700	0

Table 4.14: Scenario 3 – Transportation Results

Transport Results								
Transport Quantity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	500,000	600,000	700,000
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	500,000	500,000	500,000
1 (Castings)	1	1	2 (Heads)	1	2 (Priority)	0	0	100,000
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	400,000	450,000	500,000
1 (Castings)	1	1	3 (Cranks)	1	2 (Priority)	0	29,700	0
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	108,400	529,600	470,400
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	500,000	432,400	376,000
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	700,000	800,000	850,000
1 (Castings)	1	1	5 (Piston/Rod)	2	1 (Economy)	291,600	158,300	100
1 (Castings)	1	2	1 (Blocks)	2	1 (Economy)	532,300	369,400	98,300
1 (Castings)	1	2	2 (Heads)	2	1 (Economy)	528,600	436,100	235,300
1 (Castings)	1	2	3 (Cranks)	2	1 (Economy)	624,900	456,400	339,000
1 (Castings)	1	2	4 (Cams)	1	1 (Economy)	383,200	0	0
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	500,000	500,000	500,000
2 (Components)	1	1	1 (Assembly)	2	1 (Economy)	0	66,700	233,300
2 (Components)	1	2	1 (Assembly)	2	1 (Economy)	491,600	365,700	142,700
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	400,000	450,000	500,000
2 (Components)	2	1	1 (Assembly)	1	2 (Priority)	100,000	50,000	0
2 (Components)	2	1	1 (Assembly)	2	1 (Economy)	0	0	100,000
2 (Components)	2	2	1 (Assembly)	2	1 (Economy)	491,600	432,400	276,000
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	400,000	479,700	500,000
2 (Components)	3	2	1 (Assembly)	1	1 (Economy)	100,000	20,300	0
2 (Components)	3	2	1 (Assembly)	2	1 (Economy)	491,600	432,400	376,000
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	491,600	500,000	500,000
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	8,400	0	0
2 (Components)	4	2	1 (Assembly)	2	1 (Economy)	491,600	432,400	376,000
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	500,000	500,000	500,000
2 (Components)	5	1	1 (Assembly)	2	1 (Economy)	200,000	274,100	375,900
2 (Components)	5	2	1 (Assembly)	2	1 (Economy)	291,600	158,300	100
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	95,400	196,300	283,300
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	375,000	300,000	250,000
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	1 (Economy)	279,600	253,700	241,700
3 (Assembly)	1	2	2 (Vehile Assembly)	1	1 (Economy)	175,000	175,000	175,000

Tables 4.15 compare the total customer demand for the three years and the production quantities from the suppliers at every stage for validation of results.

Table 4.15: Scenario 3 – Production Results Validation

	Total Demand Per Stage Per Year and all Years			
Total Demand for all Customers and for all the Years	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years
Stage 1 - Castings	4,625,000	4,625,000	4,750,000	14,000,000
Stage 2 for Each Level - Components	925,000	925,000	950,000	2,800,000
Stage 3 - Assembly	925,000	925,000	950,000	2,800,000
Stage 4 - Customer 1/2/3	925,000	925,000	950,000	2,800,000
	Production Results			
Total Production by Stage, Level & Suppliers, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years
Stage 1(Castings), Level 1, Supplier 1& 2	5,069,000	4,761,900	4,169,100	14,000,000
Stage 2(Components), Level 1(Blocks), Supplier 1 & 2	1,032,300	969,400	798,300	2,800,000
Stage 2(Components), Level 2(Heads), Supplier 1 & 2	1,028,600	936,100	835,300	2,800,000
Stage 2(Components), Level 3(Cranks), Supplier 1 & 2	1,024,900	936,100	839,000	2,800,000
Stage 2(Components), Level 4(Cams), Supplier 1 & 2	991,600	962,000	846,400	2,800,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1 & 2	991,600	958,300	850,100	2,800,000
Stage 3(Assembly), Level 1, Supplier 1 & 2	991,600	932,400	876,000	2,800,000

As can be seen from the above two tables, the total demand for the three years is met as reflected by the total production quantities between both of the suppliers for the three years.

This scenario has considered the selection of suppliers for supply chain design with single criterion while allowing splitting of customer demand. Suppliers are selected for every component at every stage and level in the supply chain, such that the global supply chain costs are minimized.

4.8 Scenario 4 – Split Demand, Multiple Criteria

This scenario includes Cost of Quality and Cost of On-Time Delivery as multiple criteria in addition to the sum of regular production and transportation costs. The collected data is supplied to the following variables defined and shown in the MIP models earlier, for inclusion of multiple criteria - First time quality levels of each supplier, Supplier Risk levels for on-time delivery of parts, base penalty rate in case of late delivery and late delivery percentage for each supplier. Splitting of demand between suppliers is allowed, if that represents the optimal solution. Also, this scenario includes capacity restrictions for different suppliers as in the previous scenario. However, it is assumed that the total capacity for all of the suppliers is greater than the total demand of all of the customers. Appendix D lists all of the input data for this scenario.

4.8.1 Results and Conclusion:

Tables 4.16 through 4.19 show the results of Supply Chain Design Framework for Supplier Selection for all of the components, along with their production quantities, inventory locations and quantities in the supply chain and transport options selection and transport quantities. The Total Supply Chain Costs for the 3 years is at $ 14.44 Billion with Production Costs at $ 9.60 Billion and Transport Costs at $ 4.84 Billion.

Total Global Supply Chain Costs	**$14,444,530,000**
Total Global Supply Chain Production Costs	$9,602,914,000
Total Global Supply Chain Transportation Costs	$4,841,618,000

The additional global supply chain costs as compared to scenario 3 is due to the inclusion of First Time Quality and Supplier On-Time Delivery Risk in this model. This additional cost is the Cost of Quality and Cost of On-Time Delivery.

Table 4.16: Scenario 4 – Supplier Selection Results

	Supplier Selection		
Supplier Selection Per Stage, Level, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1	Supplier 1 - OH	Supplier 1 - OH	Supplier 1 - OH
	Supplier 2 - Germany	Supplier 2 - Germany	Supplier 2 - Germany
Stage 2(Components), Level 1(Blocks)	Supplier 1 - NY	Supplier 1 - NY	Supplier 1 - NY
	Supplier 2 - China	Supplier 2 - China	Supplier 2 - China
Stage 2(Components), Level 2(Heads)	Supplier 1 - MI	Supplier 1 - MI	Supplier 1 - MI
	Supplier 2 - China	Supplier 2 - China	Supplier 2 - China
Stage 2(Components), Level 3(Cranks)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
	Supplier 2 - Mexico	Supplier 2 - Mexico	Supplier 2 - Mexico
Stage 2(Components), Level 4(Cams)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
	Supplier 2 - CA	Supplier 2 - CA	Supplier 2 - CA
Stage 2(Components), Level 5(Piston/Rod)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
	Supplier 2 - CA	Supplier 2 - CA	Supplier 2 - CA
Stage 3(Assembly), Level 1	Supplier 1 - TN	Supplier 1 - TN	Supplier 1 - TN
	Supplier 2 - Mexico	Supplier 2 - Mexico	Supplier 2 - Mexico

Table 4.17: Scenario 4 – Production Quantity Results

	Production Results		
Production Quantity Per Stage, Level, Supplier, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	3,000,000	3,500,000	4,000,000
Stage 1(Castings), Level 1, Supplier 2(Germany)	2,900,211	1,429,494	1,374,687
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	500,000	600,000	700,000
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	600,000	278,850	302,487
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	500,000	500,000	531,915
Stage 2(Components), Level 2(Heads), Supplier 2(China)	600,000	407,271	494,092
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	400,000	450,000	500,000
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	675,932	456,116	451,416
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	532,769	392,647	505,051
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	500,000	500,000	474,129
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	700,000	800,000	850,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	359,493	115,251	149,369
Stage 3(Assembly), Level 1, Supplier 1(TN)	500,000	500,000	500,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	517,113	379,794	469,388

Table 4.18: Scenario 4 – Inventory Quantity Results

	Inventory Results		
Inventory Quantity Per Stage, Level, Supplier, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	32,887	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	22,887	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	33,300	37,000	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	0	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	37,000	0	0

Table 4.19: Scenario 4 – Transportation Results

Transport Results								
Transport Quantity Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	Period 1 1st Year	Period 2 2nd Year	Period 3 3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	500,000	600,000	700,000
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	500,000	500,000	500,000
1 (Castings)	1	1	2 (Heads)	1	2 (Priority)	0	0	1,452
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	400,000	450,000	500,000
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	7,769	219,749	505,051
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	500,000	500,000	474,129
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	432,738	800,000	850,000
1 (Castings)	1	1	5 (Piston/Rod)	2	1 (Economy)	359,493	115,251	149,369
1 (Castings)	1	2	1 (Blocks)	2	1 (Economy)	600,000	278,850	302,487
1 (Castings)	1	2	2 (Heads)	1	1 (Economy)	0	0	30,463
1 (Castings)	1	2	2 (Heads)	2	1 (Economy)	600,000	407,271	494,092
1 (Castings)	1	2	3 (Cranks)	2	1 (Economy)	675,932	456,116	451,416
1 (Castings)	1	2	4 (Cams)	1	1 (Economy)	525,000	172,898	0
1 (Castings)	1	2	5 (Piston/Rod)	1	1 (Economy)	267,262	0	0
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	480,000	500,000	500,000
2 (Components)	1	1	1 (Assembly)	2	1 (Economy)	0	82,000	179,000
2 (Components)	1	2	1 (Assembly)	1	1(Economy)	20,000	0	0
2 (Components)	1	2	1 (Assembly)	2	1 (Economy)	517,113	297,794	290,388
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	400,000	450,000	500,000
2 (Components)	2	1	1 (Assembly)	1	2 (Priority)	70,000	20,000	0
2 (Components)	2	2	1 (Assembly)	1	1 (Economy)	30,000	30,000	0
2 (Components)	2	2	1 (Assembly)	2	1 (Economy)	517,113	379,794	469,388
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	388,000	436,500	490,000
2 (Components)	3	2	1 (Assembly)	1	1 (Economy)	112,000	63,500	10,000
2 (Components)	3	2	1 (Assembly)	2	1 (Economy)	517,113	379,794	469,388
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	500,000	384,794	500,000
2 (Components)	4	1	1 (Assembly)	2	1 (Economy)	22,113	115,206	0
2 (Components)	4	2	1 (Assembly)	2	1 (Economy)	495,000	379,794	469,388
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	500,000	500,000	500,000
2 (Components)	5	1	1 (Assembly)	2	1 (Economy)	172,000	268,000	324,500
2 (Components)	5	2	1 (Assembly)	2	1 (Economy)	345,113	111,794	144,888
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	85,400	219,600	240,000
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	375,000	300,000	250,000
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	1 (Economy)	289,600	230,400	285,000
3 (Assembly)	1	2	2 (Vehile Assembly)	1	1 (Economy)	175,000	175,000	175,000

Tables 4.20 compares the total customer demand for the three years and the production quantities from the suppliers at every stage for validation of results. The Table also shows the increased production from the suppliers at every stage to account for First Time Quality and hence the Cost of Quality along with Cost of On-Time Delivery.

Table 4.20: Scenario 4 – Production Results Validation

	Total Demand Per Stage Per Year and all Years			
Total Demand for all Customers and for all the Years	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years
Stage 1 - Castings	4,625,000	4,625,000	4,750,000	14,000,000
Stage 2 for Each Level - Components	925,000	925,000	950,000	2,800,000
Stage 3 - Assembly	925,000	925,000	950,000	2,800,000
Stage 4 - Customer 1/2/3	925,000	925,000	950,000	2,800,000

	Production Results				
Total Production by Stage, Level & Suppliers, Time	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year	Total for 3 Years	% Increase from Demand because of FTQ
Stage 1(Castings), Level 1, Supplier 1& 2	5,900,211	4,929,494	5,374,687	16,204,392	15.7%
Stage 2(Components), Level 1(Blocks), Supplier 1 & 2	1,100,000	878,850	1,002,487	2,981,337	6.5%
Stage 2(Components), Level 2(Heads), Supplier 1 & 2	1,100,000	907,271	1,026,007	3,033,278	8.3%
Stage 2(Components), Level 3(Cranks), Supplier 1 & 2	1,075,932	906,116	951,416	2,933,464	4.8%
Stage 2(Components), Level 4(Cams), Supplier 1 & 2	1,032,769	892,647	979,180	2,904,595	3.7%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1 & 2	1,059,493	915,251	999,369	2,974,113	6.2%
Stage 3(Assembly), Level 1, Supplier 1 & 2	1,017,113	879,794	969,388	2,866,295	2.4%

This scenario has considered the selection of suppliers for supply chain design with multiple criteria, i.e. sum of regular production and transportation costs, cost of quality and cost of on-time delivery and allowing splitting of customer demand. Suppliers are selected for every component at every stage and level in the supply chain such that the global supply chain costs are minimized.

CHAPTER 5

SUPPLY CHAIN ANALYSIS

5.1 An Overview

This chapter focuses on aspects relating to design and performance of the supply chain. The following five scenarios are investigated for supply chain analysis:

1. **Splitting Demand Analysis** – The question that will be investigated in this analysis is - Is allowing splitting the demand between two suppliers desirable, even when one supplier has enough capacity to single handedly meet all of the customer demand and under what conditions would it be desirable?
2. **Supplier Selection Analysis -** Supplier selections should be done taking into consideration both production and transportation costs in an increasingly global economy. Two kinds of suppliers are categorized:
   - Domestic Suppliers – to mean suppliers that are closer to home (for example US suppliers) and generally have higher production costs but will have lower transportation costs.
   - Non-Domestic / Overseas Suppliers – to mean suppliers that are relatively far away (for example Mexico, China etc.) and generally have lower production costs but will have higher transportation costs in comparison to domestic suppliers.

This scenario investigates when should a non-domestic supplier be selected versus a domestic supplier taking into consideration varying production costs between the two kinds of suppliers and transportation costs.

3. **Supply Chain Inventory Analysis** - Where should the inventories be located in the supply chain (casting/machining/assembly) such that the global supply chain costs are minimized. Also investigate some factors that influence the location of inventories like inventory carrying costs, production costs and transportation costs.
4. **Supplier Quality Analysis** - Investigate the impact of Supplier Quality i.e. First Time Quality on Supply Chain Costs and Production Quantities in the Supply Chain.
5. **Supplier Risk Analysis** - Investigate the impact of overall Supplier On-Time Delivery reliability on Supplier Costs and Supplier Selection.

Finally, this chapter closes with an evaluation of importance of the different factors considered in the design framework from a data collection perspective.

5.2 Splitting Demand Analysis

In this scenario, Single & Multiple criteria models are used to analyze the impact of splitting the customer demand against having one single supplier meet all of the demand. Total Supply Chain Cost is used as the performance criterion for comparison. While capacity restrictions are considered in this analysis, it is however assumed that there is enough capacity with each supplier to single handedly meet all of the customer demand if necessary. This assumption is made because in cases where one supplier does not have enough capacity to meet all of the customer demand, there is no choice but to split the demand between the two suppliers. However in the real world, even when there is enough capacity with each supplier, the complete production contract is often given to one supplier even though intuition would suggest doing the split.

Cases are set up for study by using the baseline data and varying the different input data like the production costs, inventory costs and transportation costs one at a time across the board. The following two graphs in Figures 5.1 and 5.2 show the results in case of single criterion (sum of regular production and transportation costs only) and multiple criteria (sum of production and transportation costs along with cost of quality and cost of on-time delivery risk.) The results in Table 5.1 and 5.2 respectively lists the Total Supply Chain costs in both of the scenarios and also tracks the difference between the two (i.e. Cost of No Split Demand – Cost of Split Demand.)

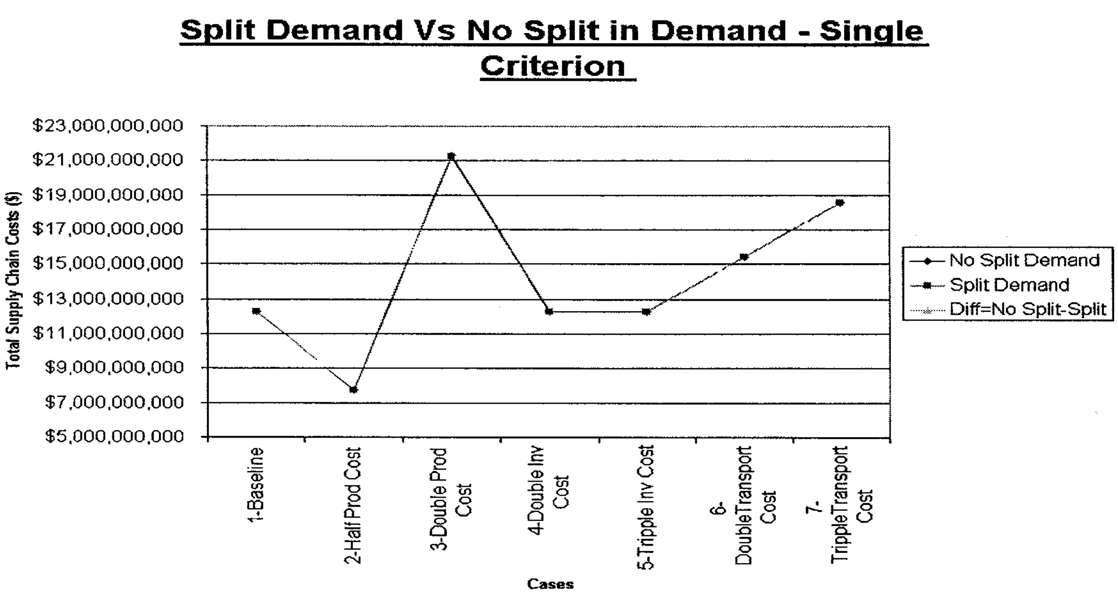


Figure 5.1: Split Demand Vs No Split Demand – Single Criterion

Table 5.1: Split Demand Vs No Split Demand – Single Criterion Results

Single Criteria	No Split Demand	Split Demand	Diff=No Split-Split
1-Baseline	$12,255,150,000	$12,254,520,000	$630,000
2-Half Prod Cost	$7,716,371,000	$7,716,134,000	$237,000
3-Double Prod Cost	$21,313,500,000	$21,259,140,000	$54,360,000
4-Double Inv Cost	$12,260,030,000	$12,259,860,000	$170,000
5-Tripple Inv Cost	$12,263,210,000	$12,263,180,000	$30,000
6-DoubleTransport Cost	$15,427,360,000	$15,426,330,000	$1,030,000
7-TrippleTransport Cost	$18,598,430,000	$18,597,110,000	$1,320,000

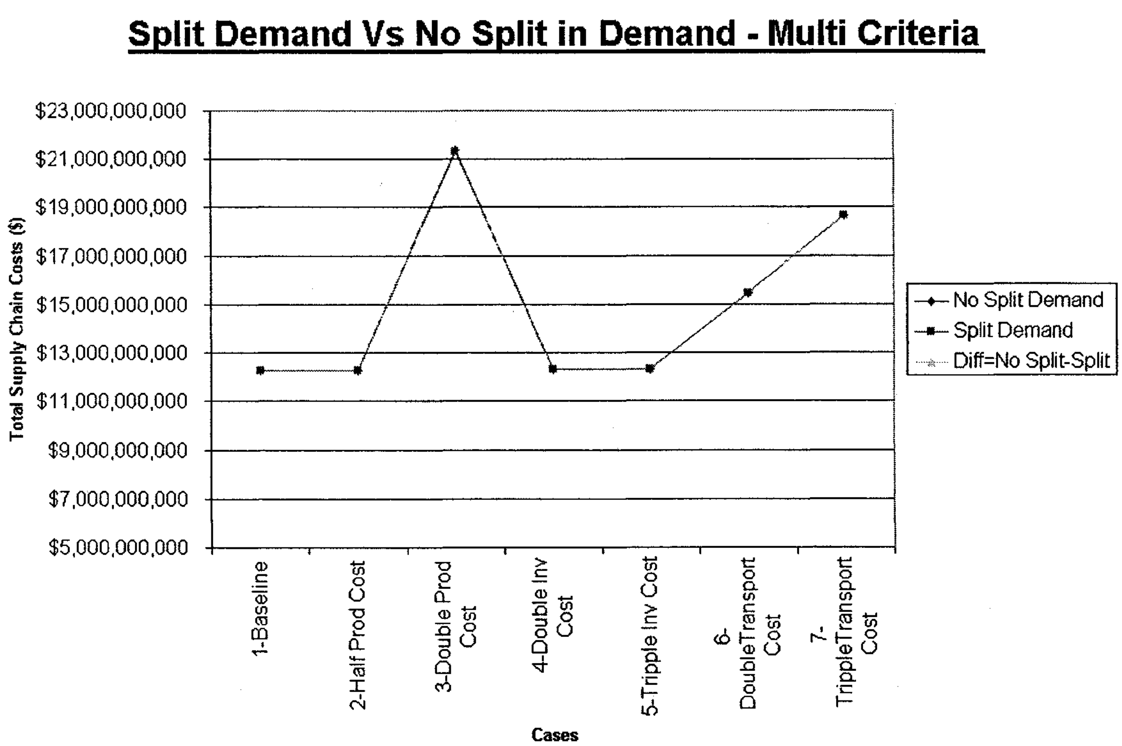


Figure 5.2: Split Demand Vs No Split Demand – Multi Criteria

Table 5.2: Split Demand Vs No Split Demand – Multi Criteria Results

Mutiple Criteria	No Split Demand	Split Demand	Diff=No Split-Split
1-Baseline	$12,295,890,000	$12,295,700,000	$190,000
2-Half Prod Cost	$12,295,890,000	$12,295,700,000	$190,000
3-Double Prod Cost	$21,353,420,000	$21,305,090,000	$48,330,000
4-Double Inv Cost	$12,300,720,000	$12,300,720,000	$0
5-Tripple Inv Cost	$12,304,030,000	$12,304,030,000	$0
6-DoubleTransport Cost	$15,478,280,000	$15,477,260,000	$1,020,000
7-TrippleTransport Cost	$18,649,350,000	$18,648,050,000	$1,300,000

As can be seen from the results of both the graphs and the results tables, the Total Supply Chain costs for No Split in Demand case even though seemingly identical to Split Demand is actually a little higher or equal to the Split Demand case (better seen in the data table of the graph) for both single and multiple criteria in the ranges of the different input datasets. This leads to the following **insights and generalized conclusions for the dataset used in this analysis**:

1. Splitting the customer demand between two suppliers is a better choice from the total supply chain costs perspective for both single and multiple criteria models. Splitting is unavoidable when there is not a sufficient capacity with any one supplier to meet all of the customer demand. However, as the results show, it may be desirable even if there is enough capacity for one supplier to meet all of the demand
2. While Supplier Delivery Risk is considered in the framework model and solutions, the data supplied is typically long-term averages for the suppliers. Such data often does not include catastrophic events like massive equipment failures, union strikes, fatalities, natural disasters etc. Such catastrophic

events, though less frequent, can have a devastating impact on the supply chain performance, often working in Just In Time mode. Therefore, it is highly recommended that the customer demand always be split between more suppliers to mitigate the impact of some of the above-mentioned risks.

5.2.1 Real World Perspective

The value of the above very important conclusions were observed in the automotive industry in the post September 11, 2001, environment when factories often operating in a Just-In-Time mode had to adjust their production schedules because of a lack of adequate supply of components coming from single suppliers while their deliveries were stuck in lengthy time-consuming customs and border inspections. Also from time to time, companies dealing with just one supplier for the entire production contract for a component often have found themselves hostage to more serious quality and delivery problems which they cannot easily break out of until the next contract renewal period.

A single supplier company normally does not specialize in all the parts that may be required for the operation of a customer department. So the supplier company produces their specialty parts in-house while they buy the non-specialty parts (which may be just a minor variant of the specialty part) on the outside from a third party. They can however sell them back to the customer and thus provide a one-stop service. But from the customer department's perspective, buying these parts from the supplier company may be more expensive than directly going to the third party that specializes it. This thus becomes a case where splitting the order between the supplier company and the third party may be better than handing the entire contract to one supplier company that does have the capacity to meet all of the customer's demand.

Using the developed supply chain design tool allows the calculation of the cost of supplier diversification.

5.3 Supplier Selection Analysis

This scenario focuses on Supplier Selection factors and decisions. Some of the questions that will be investigated are: - When should an overseas supplier be chosen or is it a good idea to always outsource to an overseas supplier if that translates into large cost savings for that component? Two factors are chosen in this scenario that could potentially influence the choice for selection of suppliers:

1. Ratio of Production Costs between the two suppliers (Non-Domestic to Domestic) by changing the Non Domestic production costs while keeping the same transportation costs. This is done by varying one stage/level at a time
2. Ratio of Production Costs to Transportation Costs

The following analysis investigates the first factor, i.e. impact of varying the production costs between non-domestic and domestic suppliers. Split Demand, Multiple Criteria models and data are taken as baseline for the analysis and the data for the non-domestic supplier unit production costs varied relative to the domestic supplier unit production costs. However, it is assumed that there is enough capacity with each supplier to meet the customer demand single handedly or in a combination of suppliers. Such an assumption does not violate the representation of the real world and at the same time allows observing the impact on supplier selection more clearly. Figures 5.3 through 5.9 show the results of this analysis on Supplier Selection (Supplier Choice & Production

Quantity) and Total Global Supply Chain Costs as the percent ratio of unit production costs of non-domestic to domestic supplier decreases (from 90% to 40%.)

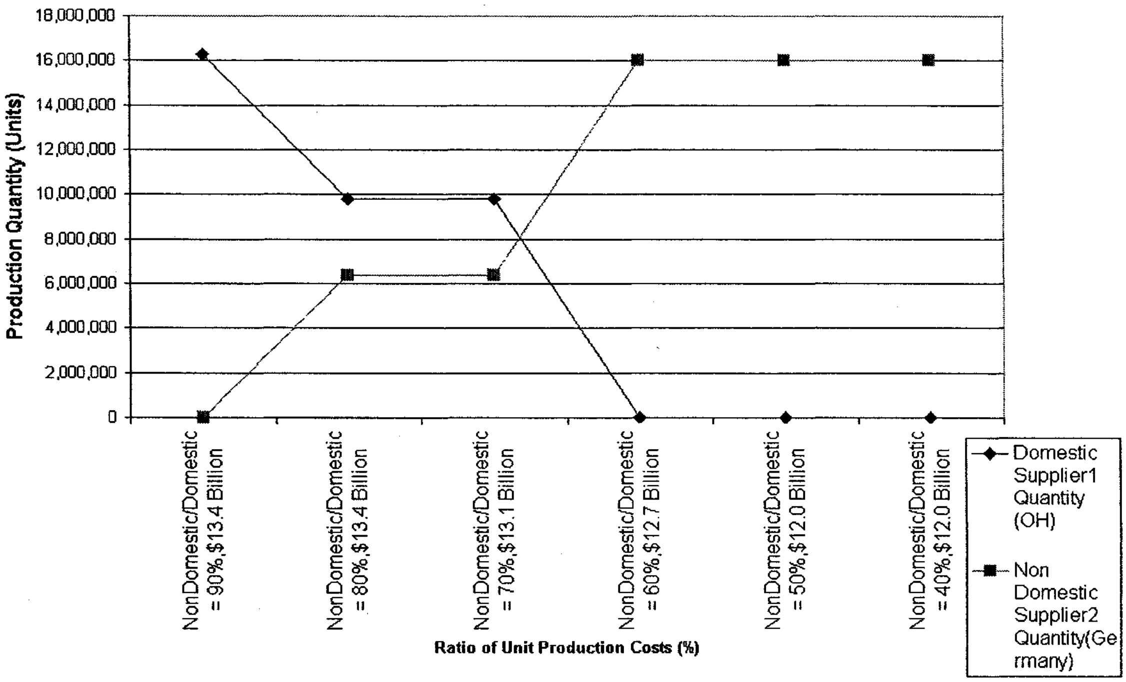


Figure 5.3: Impact of Supplier Costs on Supplier Selection - Castings

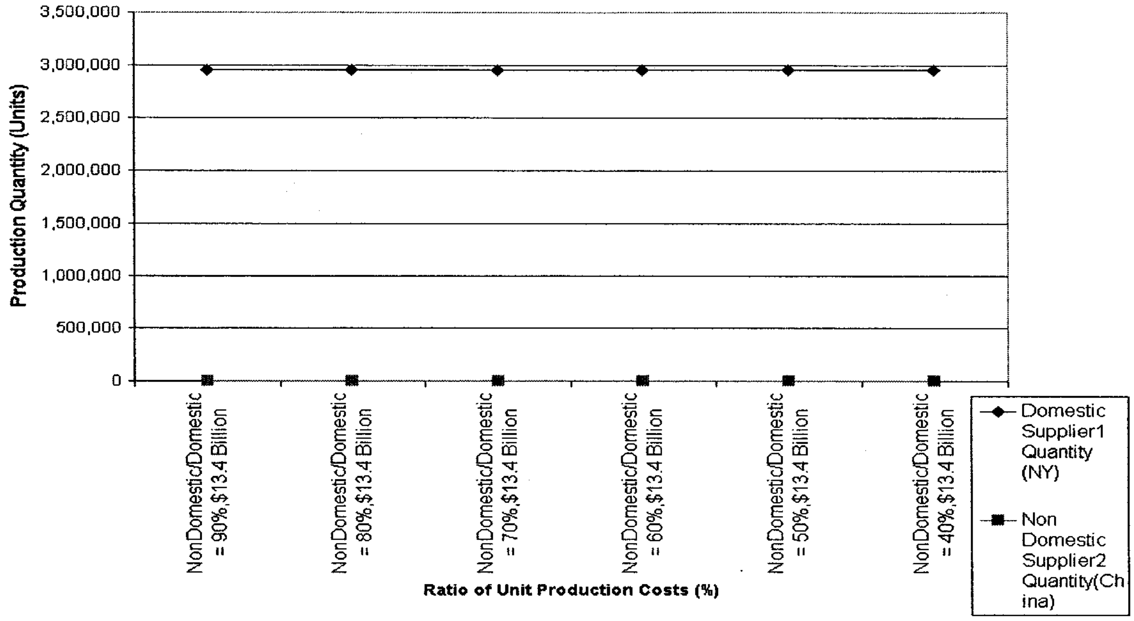


Figure 5.4: Impact of Supplier Costs on Supplier Selection - Blocks

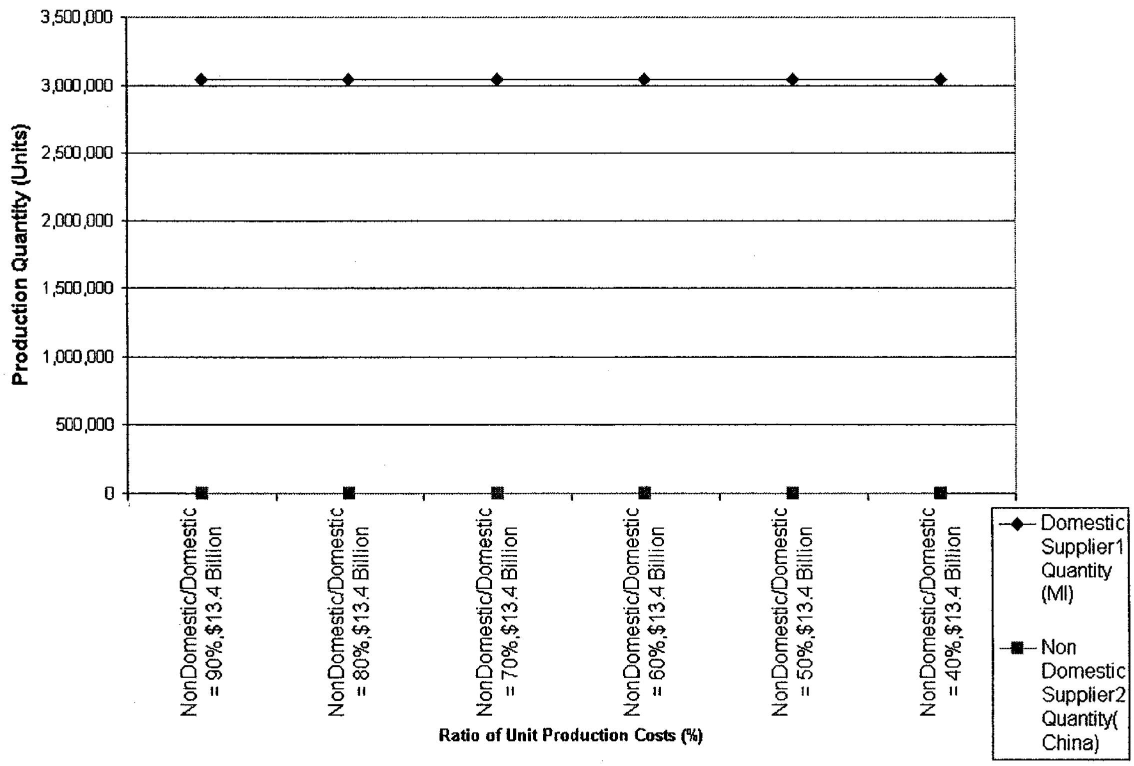


Figure 5.5: Impact of Supplier Costs on Supplier Selection - Heads

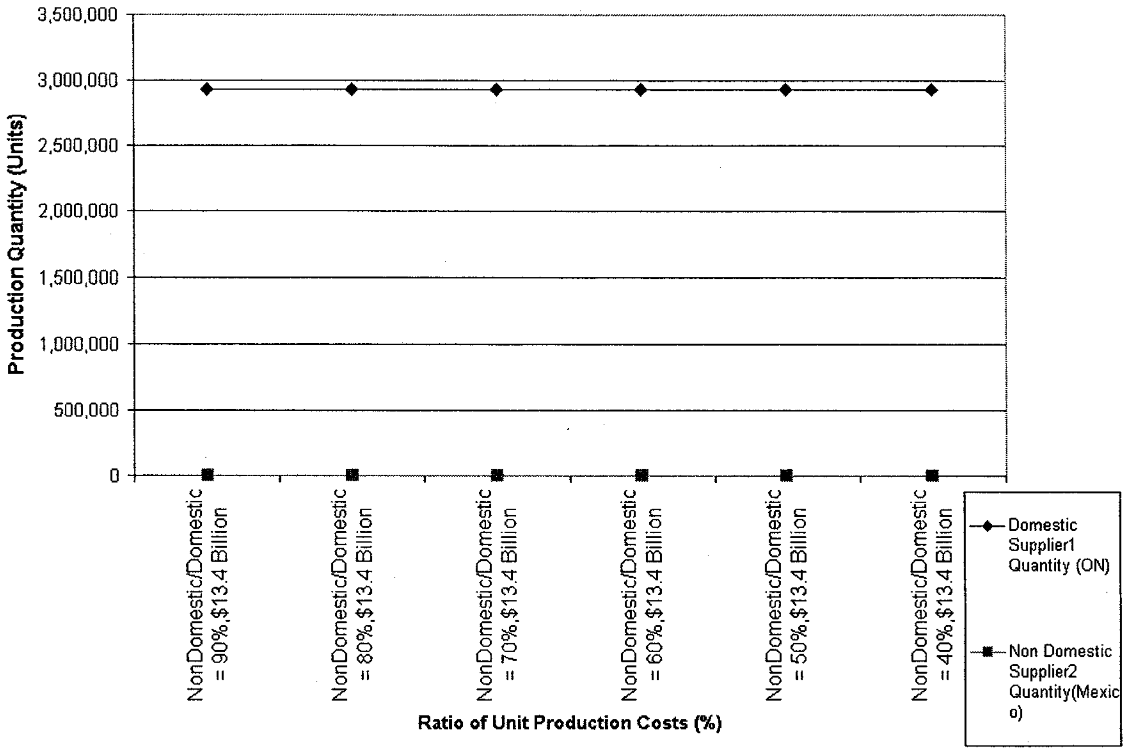


Figure 5.6: Impact of Supplier Costs on Supplier Selection - Cranks

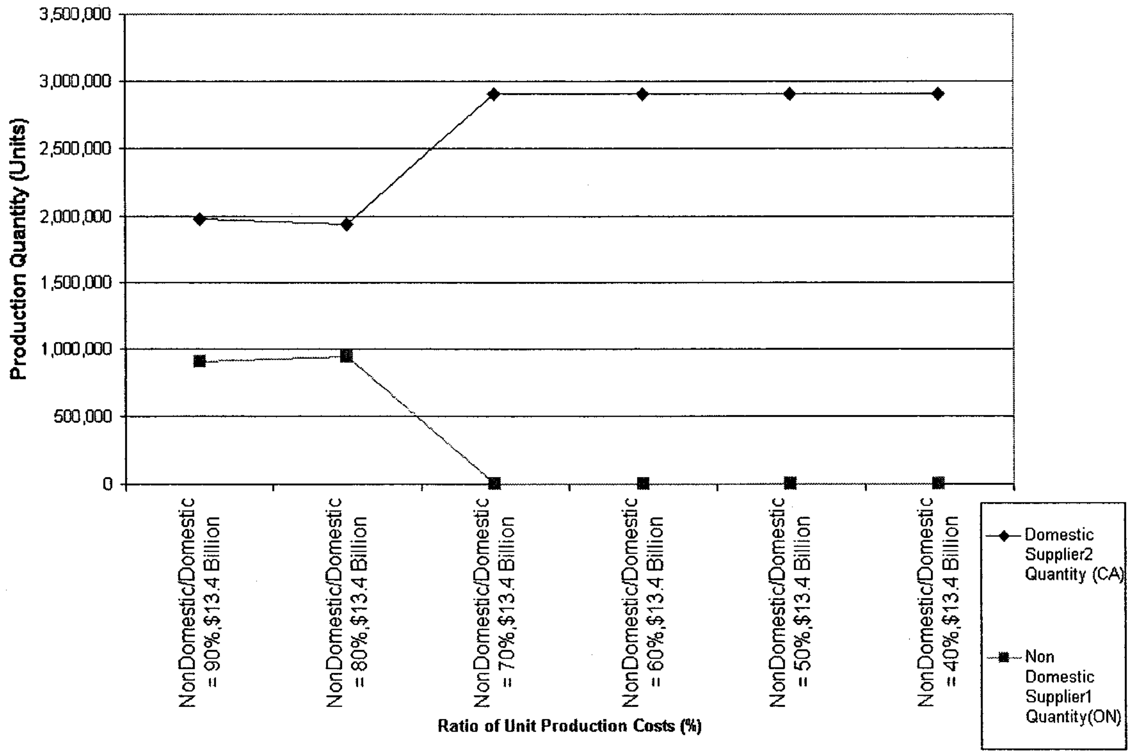


Figure 5.7: Impact of Supplier Costs on Supplier Selection - Cams

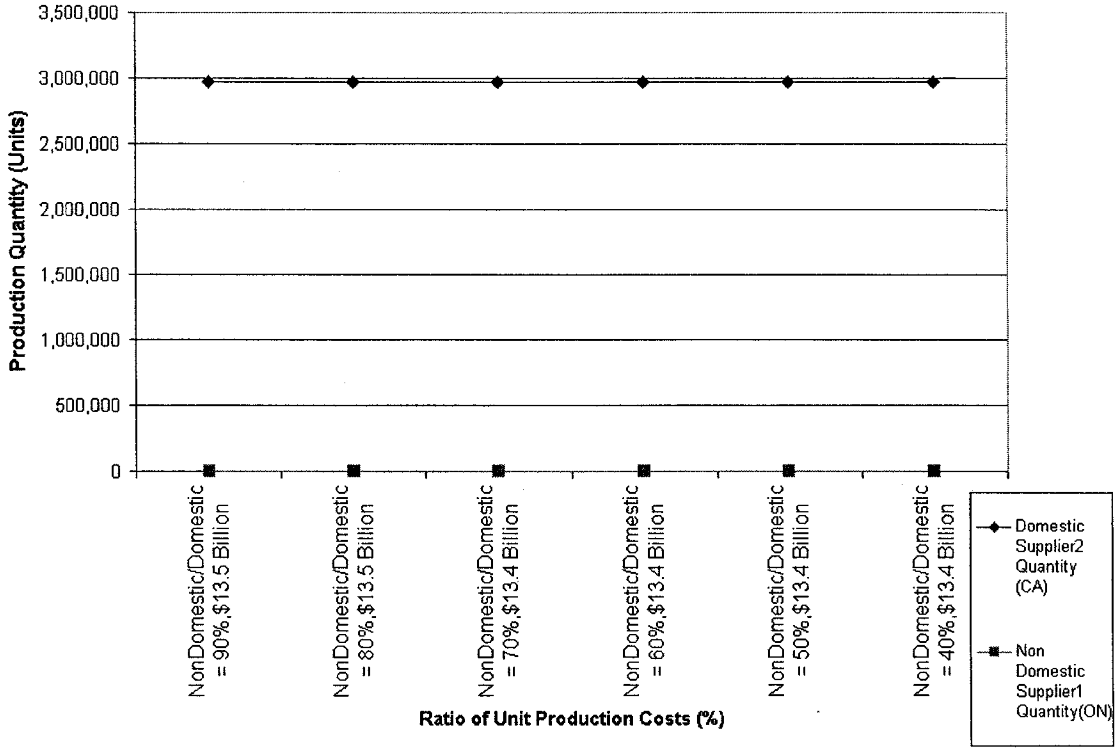


Figure 5.8: Impact of Supplier Costs on Supplier Selection – Piston/Rod

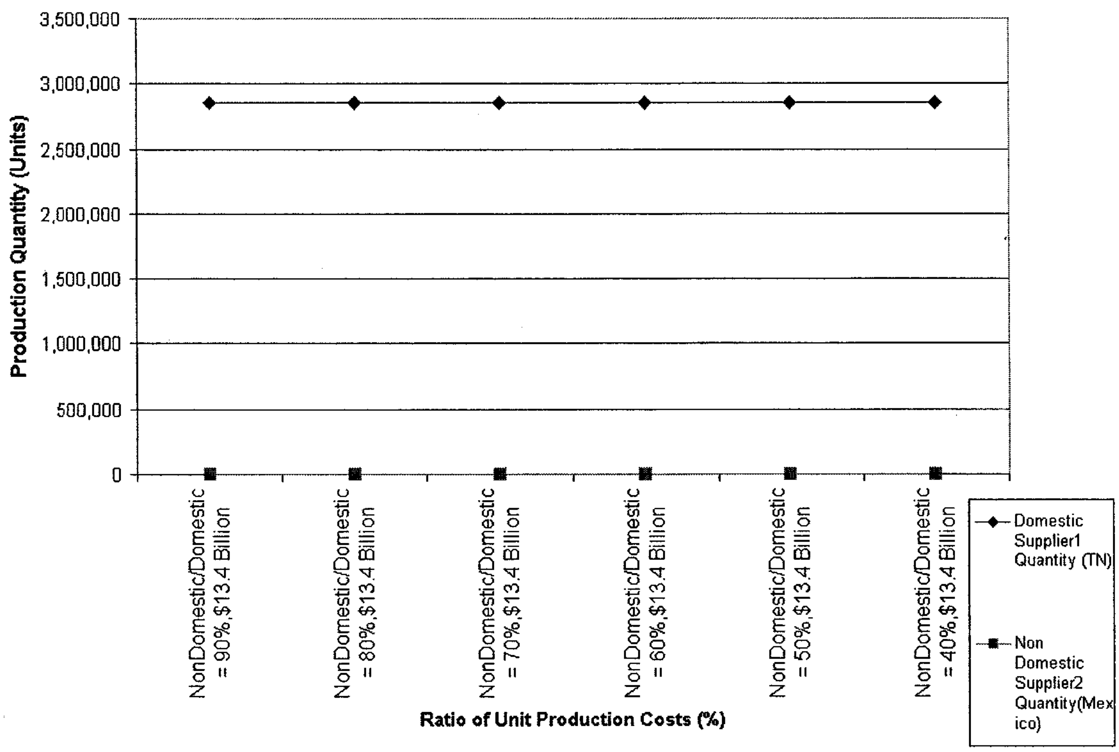


Figure 5.9: Impact of Supplier Costs on Supplier Selection - Assembly

The following observations can be made from the above results:

- For the Castings stage, as the non-domestic supplier production costs decrease, there is a shift in production volume from all domestic at 90% cost ratio to a combination of production volumes between the domestic and non-domestic suppliers at 80% and 70% cost ratio and finally to all of the volumes outsourced to non-domestic supplier at a cost ratio of 60% and below.
- For the rest of the stages, decreasing the cost of non-domestic production costs has virtually no positive impact on supply chain in shifting the production volumes from domestic to non-domestic suppliers. That's an interesting result because the purchasing analyst working in the Purchasing Department at the Block machining stage (Stage 2, Level 1) who always focuses on cost cutting opportunities, without this analysis, is likely to think and conclude that their Production Costs will reduce by 60% if they were to source the Blocks from the non-domestic supplier in China as against a domestic supplier in New York. Furthermore, if one were to consider the Block machining department alone, sourcing from China may be a good decision. But when the complete Supply Chain is considered, Souring from China will actually turn out to be a wrong decision, since it will only increase the global supply chain costs, not decrease it.

The next analysis investigates the second factor, i.e. the ratio of production costs to transportation costs by taking an example where unit production costs of all of the suppliers (domestic & non-domestic) is three times the baseline production costs. This would mean like a different product where the production costs are significantly higher than transportation costs, unlike the baseline case where the magnitude of the difference is smaller. Again in this case, running the models for the two extreme end points, i.e. at 90% and 40% as in the previous case varies the ratio of non-domestic to domestic unit production costs. Also the cost reductions in non-domestic suppliers are done globally across the board, unlike locally, one at a time in the previous case. Figure 5.10 shows the results of the supplier selection and the production quantities.

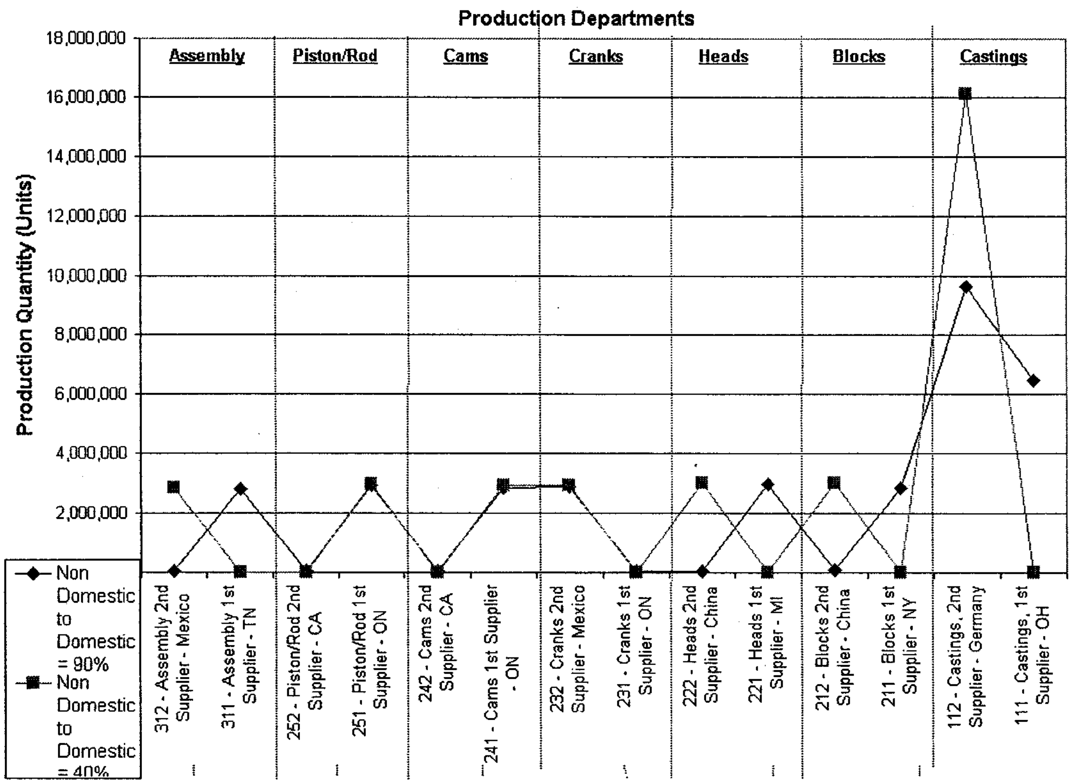


Figure 5.10: Impact of Supplier Costs on Supplier Selection

The following observations can be made from the results:

- Assembly, Heads and Blocks are primarily sourced from domestic suppliers when the ratio of non-domestic to domestic unit production cost is at 90%. However, when the ratio of non-domestic to domestic unit production cost is at 40%, the majority of the production volumes are sourced from a non-domestic supplier. This is an interesting opposite result from the previous case where cost improvements from 90% to 40% made no difference to the supplier selection decision. One can relate this result to three reasons:
    - A different product is considered in this case where the production costs are significantly higher than the transportation costs and so, cost reductions in outsourcing to a farther non-domestic supplier far outweigh any increase in transportation costs.
    - Across the board, global cost reductions in the supply chain can lead to different supplier selection decisions than just local (one component at a stage/level) change.
- Castings are sourced from a combination of non-domestic and domestic suppliers at 90% cost benefit ratio and completely sourced from a non-domestic supplier at a 40% ratio.

The above results lead to the following very important **generalized insights and conclusions that is independent of the data used in this analysis**:

1. Outsourcing to a non-domestic less expensive supplier is not always the best decision for every product when selecting suppliers. This is an important

realization in the current business climate where there is an out-sourcing binge to source suppliers overseas as a way of cost savings.

2. Supplier selection decisions should be made by using a global integrated approach of considering both production and transportation costs for the complete supply chain. Any local decision (looking for the cheapest part from the lowest bidding supplier) in the supply chain of selecting a non-domestic supplier may offer some local benefits (60% improvements as seen in some levels/stages) but may not always necessarily translate into global supply chain benefits. They could in some cases increase the global supply chain costs and shift the cost base to elsewhere in the supply chains. This is extremely important to keep in mind for practicing purchasing analysts or buyers for two reasons:

    - Companies have different departments responsible for purchasing and logistics functions and the two do not necessarily communicate as much as they should.
    - When a supply chain transcends across multiple companies, each company adopts an attitude of improving their bottom line with little regard to shifting the cost base to a different company in the supply chain. This approach, though tempting, should be highly resisted and an approach of mutual negotiation, compromise and benefit should be pursued for global improvement of the supply chain and consequently each of its individual members.

5.3.1 Real World Perspective

The importance of the above conclusions is best seen in this one of these example car powertrain transmission component supply chains in the automotive industry. The automotive transmission component goes through ten process steps. The first five steps called the rough machining is done in St. Catharines, Ontario from where they are sent on truck shipments for five hours to metropolitan Detroit area in Michigan where two additional processing steps are done and again shipped back on trucks to St. Catharines for the final three finish processing steps. In this particular case, the purchasing/supply chain analyst in the initial design phase was doing supplier selections by taking into consideration production costs only and not taking an integrated approach of both production and transportation costs as proposed in the supply chain design framework in this dissertation. It was generally recognized by the St. Catharines personnel that even outsourcing to a local supplier in St. Catharines for those two intermediate processing would have proved to be cheaper than trucking all of the parts to Michigan and back. Part of the reason supply chains like the above get designed is due to the way companies are organized based on the functions and not necessarily based on the integrated supply chain approach.

5.4 Supplier Inventory Analysis

One of the important questions asked in Supply Chain Design is – Where should the inventories be located in the supply chain and what should be their size? This question needs to be answered to design sufficient warehousing space at the identified locations in either green field and/or brown field sites. The developed framework answers those questions and identifies inventory locations and sizes that minimize the total global supply chain costs. In this scenario, sensitivity of inventory locations and sizes to the different cost drivers is analyzed. The Split Demand Multi Criteria model is used for this purpose because allowing splitting in demand has been determined to be desirable and multiple criteria comes closest to representing the real world. The charts in Figures 5.11 through 5.13 show the results for sensitivity to unit inventory costs, unit production costs and unit transportation costs. The chart is in a grid format where locations (identified on the extreme left) chosen for inventory carrying are shaded (on the right side) along with displaying the size of the inventory at that location:

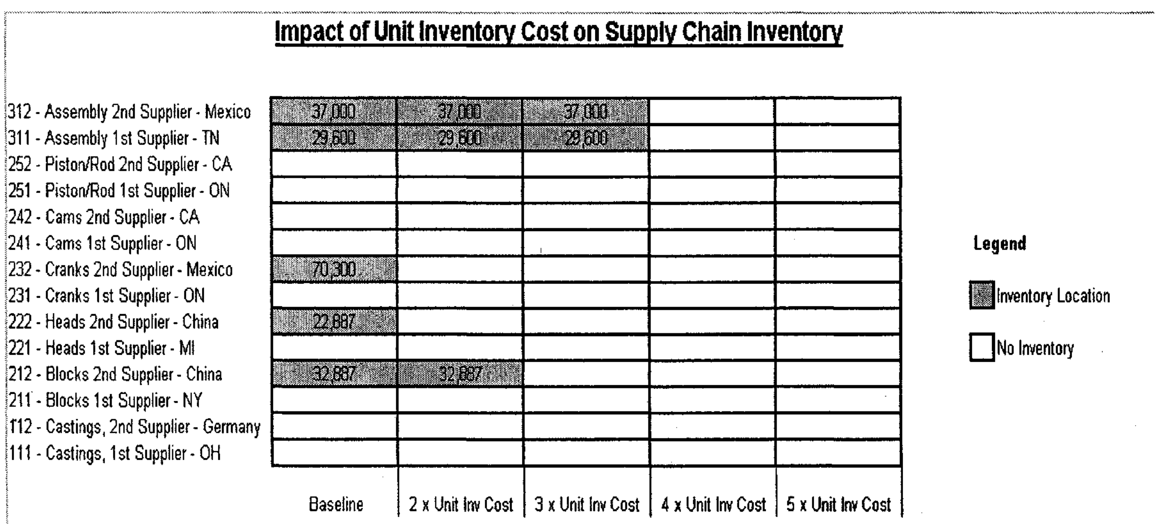


Figure 5.11: Impact of Unit Inventory Cost on Supply Chain Inventory

Impact of Unit Production Cost on Supply Chain Inventory

	Baseline	2 x Unit Prod Cost	3 x Unit Prod Cost	4 x Unit Prod Cost	5 x Unit Prod Cost
312 - Assembly 2nd Supplier - Mexico	37,000	70,121	40,700		
311 - Assembly 1st Supplier - TN	29,600	62,900	56,431		
252 - Piston/Rod 2nd Supplier - CA			66,600		
251 - Piston/Rod 1st Supplier - ON		20,878	51,800		
242 - Cams 2nd Supplier - CA		31,104	66,600		
241 - Cams 1st Supplier - ON		29,600	59,200		
232 - Cranks 2nd Supplier - Mexico	70,300	70,300	70,300	37,000	37,000
231 - Cranks 1st Supplier - ON		29,600	37,475		
222 - Heads 2nd Supplier - China	22,887	40,700	40,700		
221 - Heads 1st Supplier - MI		20,000	29,600		
212 - Blocks 2nd Supplier - China	32,887	85,100	85,100		42,286
211 - Blocks 1st Supplier - NY		33,300	70,300		
112 - Castings, 2nd Supplier - Germany			340,400	177,600	177,600
111 - Castings, 1st Supplier - OH					

Legend
- Inventory Location
- No Inventory

Figure 5.12: Impact of Unit Production Cost on Supply Chain Inventory

Impact of Unit Transportation Cost on Supply Chain Inventory

	Baseline	2 x Unit Tran Cost	3 x Unit Tran Cost	4 x Unit Tran Cost	5 x Unit Tran Cost
312 - Assembly 2nd Supplier - Mexico	37,000	37,000	37,000		
311 - Assembly 1st Supplier - TN	29,600	29,600	29,600		
252 - Piston/Rod 2nd Supplier - CA					
251 - Piston/Rod 1st Supplier - ON					
242 - Cams 2nd Supplier - CA					
241 - Cams 1st Supplier - ON					
232 - Cranks 2nd Supplier - Mexico	70,300	70,300	70,300		
231 - Cranks 1st Supplier - ON		33,587	33,587		
222 - Heads 2nd Supplier - China	22,887	63,587	63,587		
221 - Heads 1st Supplier - MI			17,000		
212 - Blocks 2nd Supplier - China	32,887	32,887	32,887	40,700	40,700
211 - Blocks 1st Supplier - NY					
112 - Castings, 2nd Supplier - Germany					
111 - Castings, 1st Supplier - OH					

Legend
- Inventory Location
- No Inventory

Figure 5.13: Impact of Unit Transportation Cost on Supply Chain Inventory

Figures 5.14 and 5.15 summarize the results for Total Supply Chain Inventory locations:

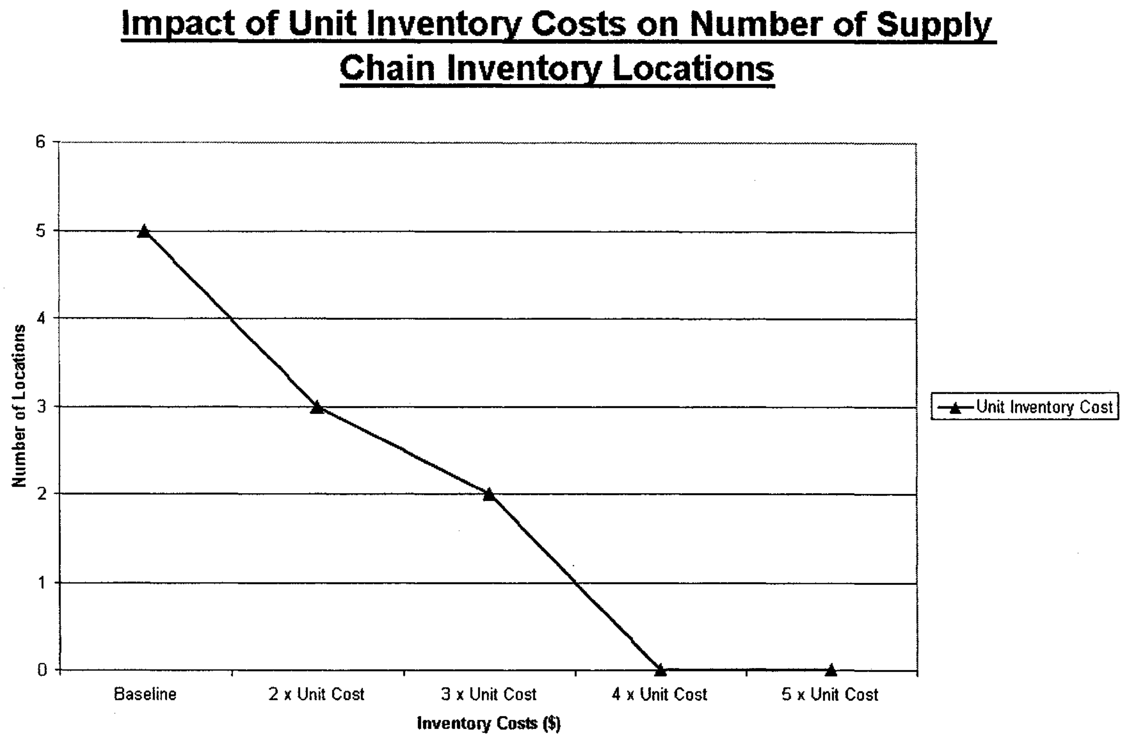


Figure 5.14: Impact of Production/Transport Costs on Supply Chain Inventory Locations

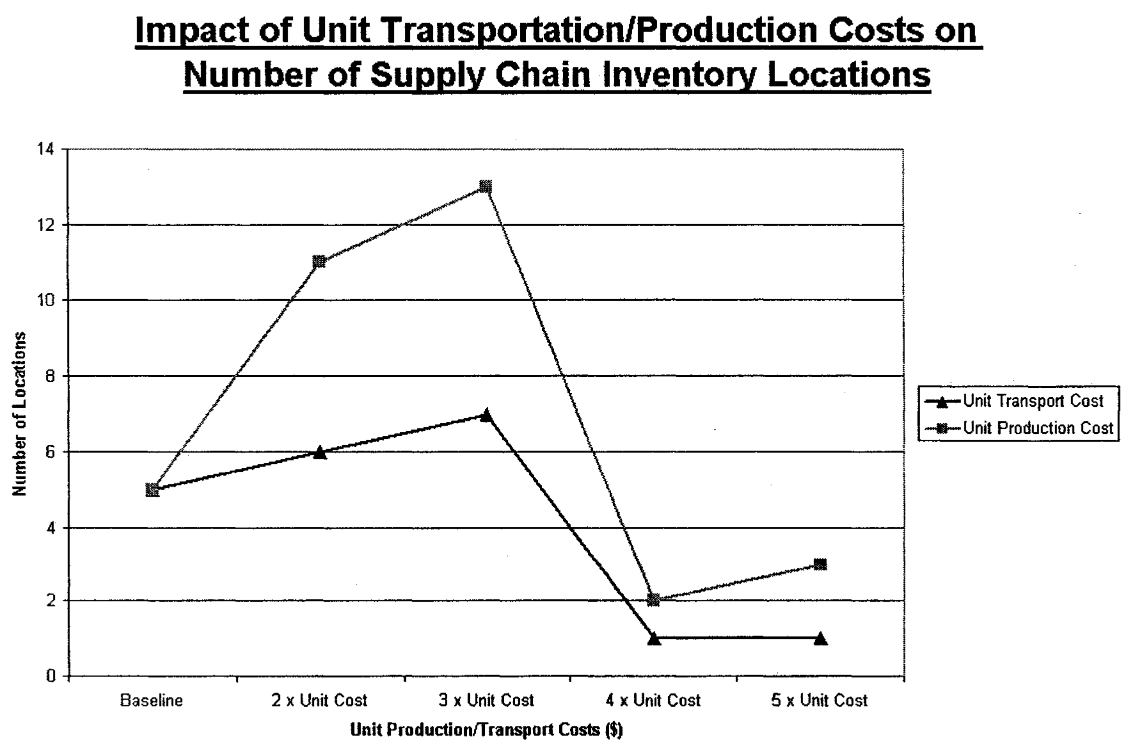


Figure 5.15: Impact of Inventory Unit Costs on Supply Chain Inventory Locations

The following observations can be drawn from the graphs:

- The number of inventory locations in the supply chain decreases with the increasing unit inventory costs.
- The number of Inventory locations in the Supply Chain increase up to three times the Unit Production and Unit Transport costs and then start decreasing as the those costs increase.

The following line graphs in Figures 5.16 and 5.17 summarize the results for Total Supply Chain Inventory Sizes:

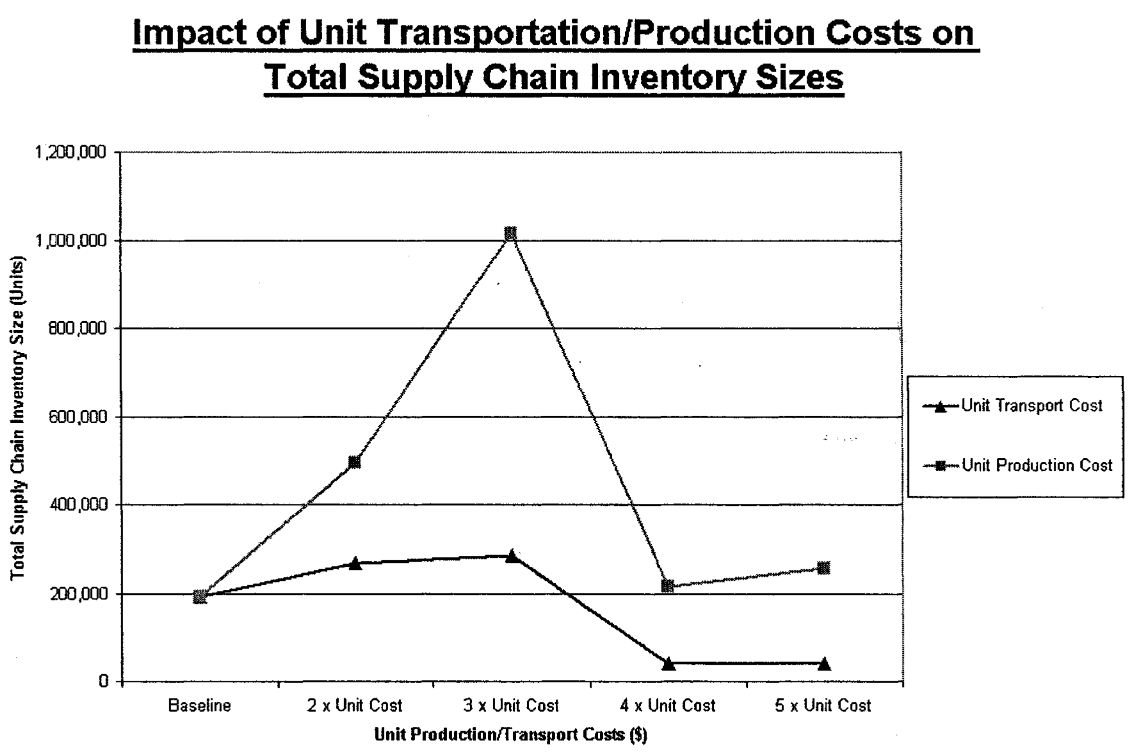


Figure 5.16: Impact of Production/Transport Costs on Supply Chain Inventory Sizes

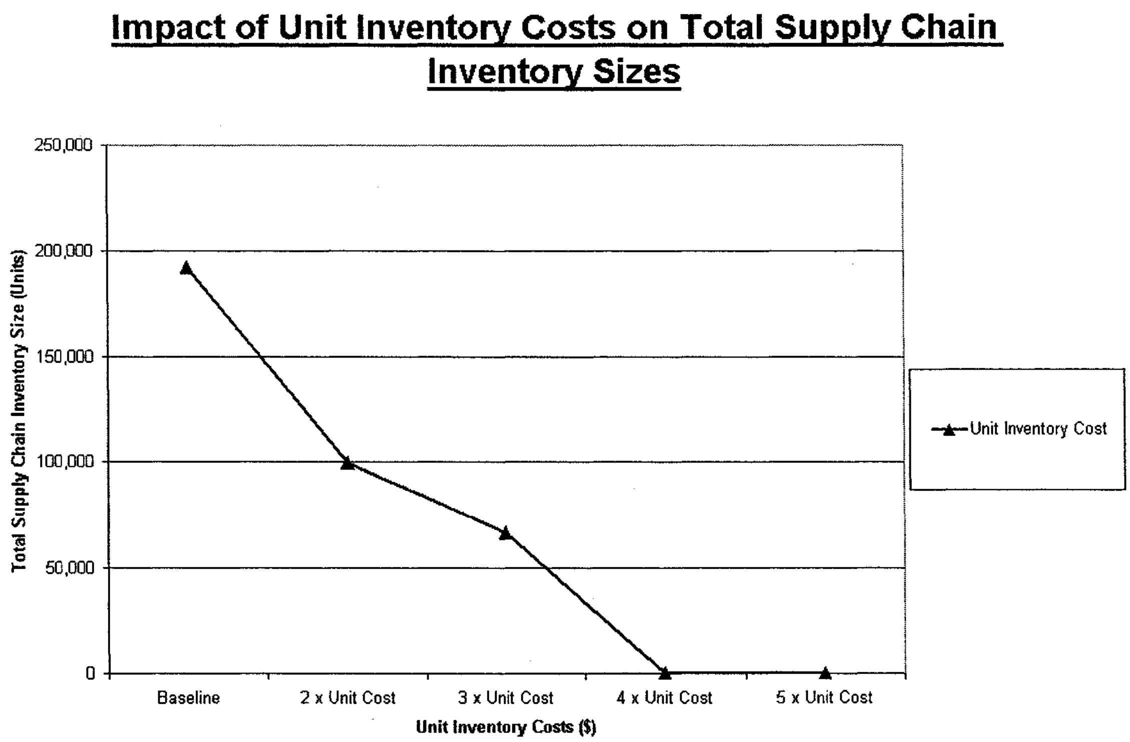


Figure 5.17: Impact of Inventory Unit Costs on Supply Chain Inventory Sizes

The following observations can be drawn from this graph:

- The Total Supply Chain Inventory Sizes rapidly start decreasing as the Unit Inventory cost increases
- The Total Supply Chain Inventory Sizes increase till three times the Unit Production and Transport Costs in this supply chain design problem with the data set in use and any further increase in the unit costs lead to lower Total Supply Chain Inventories.

The above results for inventory locations and sizes can be explained in the following way: Inventory carrying is a production strategy to protect against variation in demand and operational (production and transportation) costs. Thus, carrying higher inventories with increasing production and transportation costs may actually help to reduce the long-term supply chain costs. However on the other hand, carrying excess inventories can result in locking up valuable capital and in storage costs making the supply chain expensive and inefficient. It is for this reason the inventory sizes and locations decrease with increasing carrying costs and increasing production and transportation costs beyond a certain point.

The above observations and results from this analysis leads to the following very interesting **insights and generalized conclusions based on the dataset used in this analysis**:

1. Rising Unit Inventory Costs generally have a decreasing effect on Total Supply Chain Inventory Locations and Sizes.
2. As the Unit Production or Transport Costs rise, it may be beneficial to produce or transport shipments resulting in higher inventories but relatively lower global supply chain costs. This result comes in direct contrast to the advice of Lean Engineering community who always advocate low inventories with the extreme being single piece flow. However, increasing inventory sizes is valid only until a certain point with the increasing unit production or transport costs (three times in this example) after which lower inventories are desirable for optimizing the supply chain. This critical point should be determined and kept in mind as supply chains are designed and/or as the supply chains change with time.

5.4.1 Real World Perspective

The importance and relevance of the above conclusions can be seen in this supply chain example in Mexico, where automobile powertrains from the powertrain assembly plant are shipped to the vehicle assembly plant ten hours away by rail cars. Due to high transportation costs involved in shipping by rail cars and also fixed time schedules of the rail cars, shipments are made in full rail car loads as against partial loads. This results in large inventories piled up at the docking yards of the rail car company and also the intermediate companies facilitating the packing and delivery to and from the rail car company, thereby creating inefficient and expensive supply chain. Based on the results of this research, shipments resulting in large inventory sizes would make sense and actually result in lower transportation costs and hence lower the supply chain costs. However, shipments causing an increase in the size of those inventories is only valid to a certain point. Clearly in this case, the supply chain analysts did not determine appropriate inventory sizes to maintain to optimize supply chain costs. In their overzealous effort to reduce transportation costs, they were carried away, resulting in high inventories and an inefficient and expensive supply chain. Having the results of this research in advance could have helped the supply chain designer see the impact of high transportation costs on supply chain inventory and thus focus on determining the appropriate inventory size that would optimize the total supply costs.

5.5 Supplier Quality Analysis

One key question that is asked when talking about performance of a supply chain is – What impact does First Time Quality of Supply Chain members have on the rest of the Supply Chain? Also, how should the Supply Chain members adjust their production plans and quantities to account for their own quality problems and also those of the rest of the Supply Chain members downstream in the Supply Chain? This scenario tries to answer those questions by investigating the impact of Supplier Quality on Total Supply Chain Costs and Production Quantities. Depending on the stage, the "First Time Quality" is varied between different ranges (90% – 20% for castings, 97% - 76% for machining and 99% - 92% for assembly) based on real world experience of castings, machining and assembly processes. The low end of the range of "First Time Quality" (FTQ) values at the different stages represents typical performance during production ramp-up and the high end of the range represents typical performance during steady state. In other words, low FTQ values are transient in nature and get increasingly better as the production system ramps up to a steady state. However, even at a steady state, production systems and consequently suppliers owning those production system rarely reach 100% FTQ for a consistent time period. Therefore, the impact of FTQ on the supply chain design is an important consideration, which needs to be studied and understood. Split Demand models are chosen for this analysis and it is assumed that there is enough capacity with each supplier to be able to meet all of the customer demand, if necessary. The generalized conclusions are not likely to be any different even if takes two suppliers to have enough capacity to meet the customer demand. Regular Production and Transportation costs, along with the impact of First Time Quality are considered. Supplier Delivery Risk is not included so as to study the impact of Quality alone. Figures 5.18 through 5.20 show the impact of First Time Quality of Suppliers on Total Supply Chain Costs, Production Quantities within a stage and Production Quantities across stages:

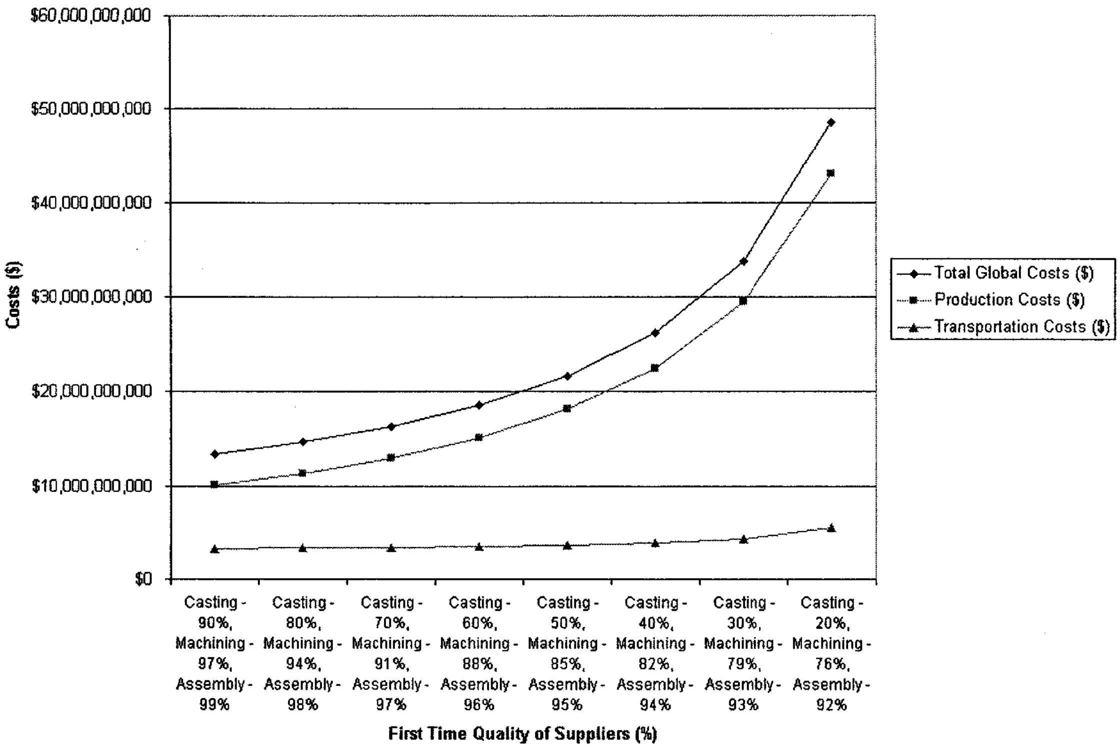


Figure 5.18: Impact of Supplier Quality on Supply Chain Costs

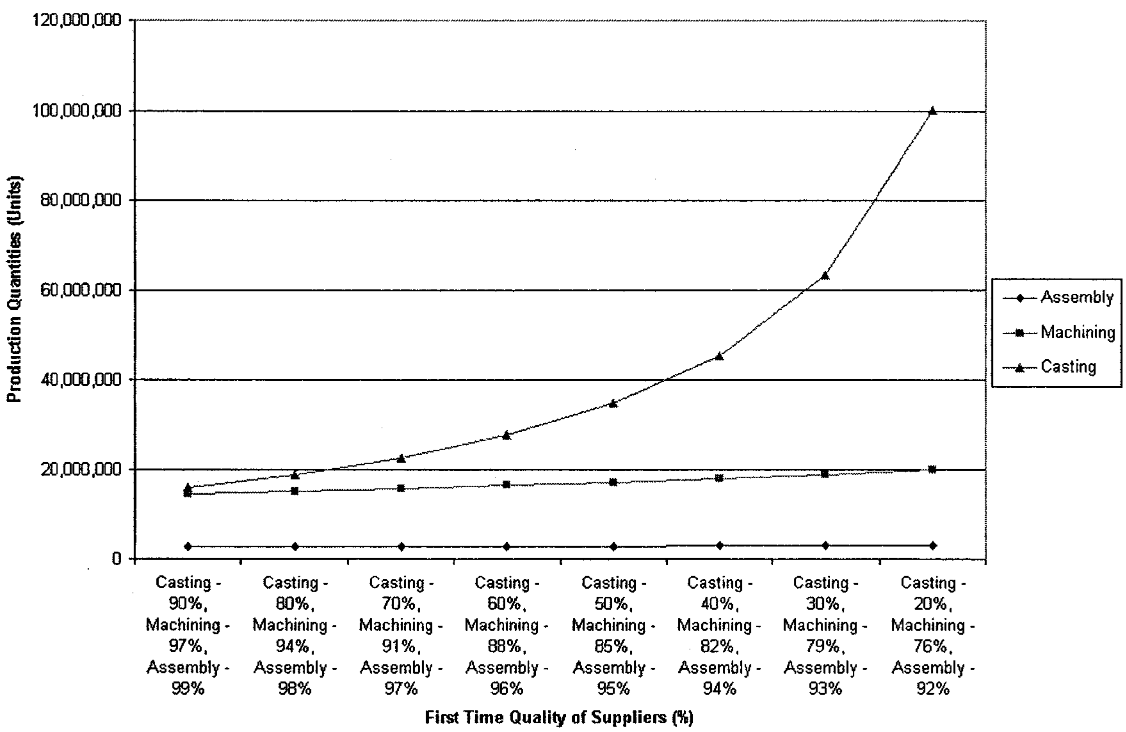


Figure 5.19: Impact of Supplier Quality on Production at Every Stage

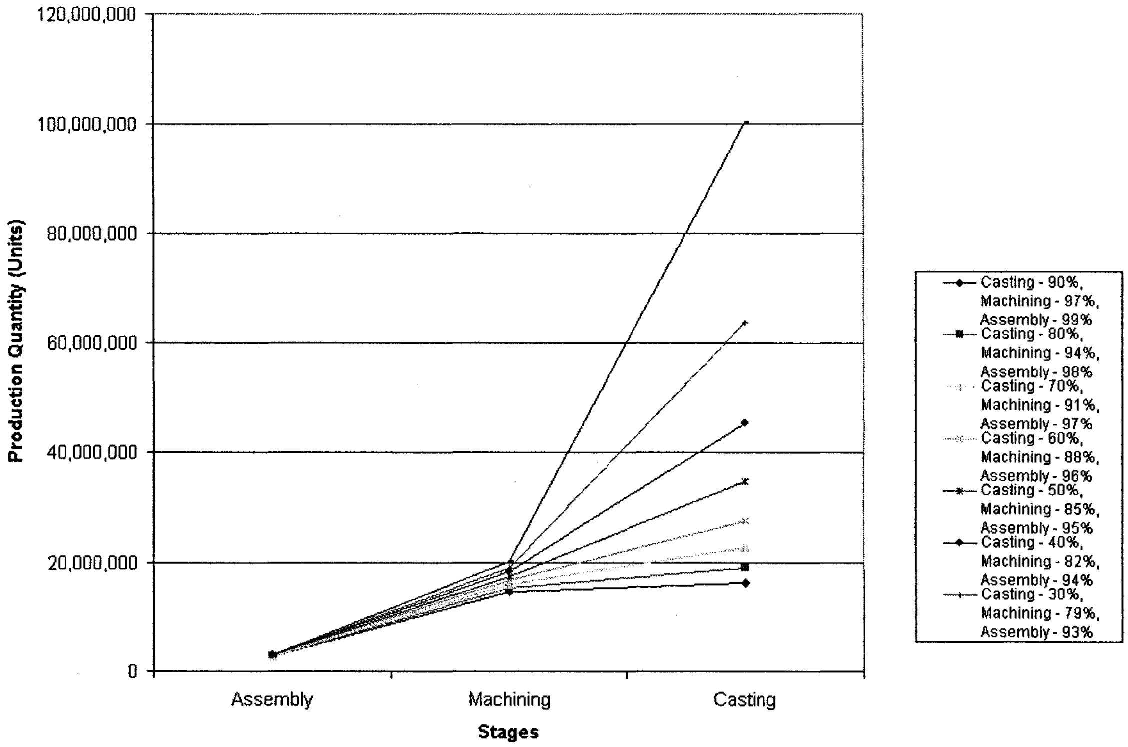


Figure 5.20: Impact of Supplier Quality on Production Across Stages

The following powerful **generalzied insights are drawn from this analysis that is idependent of the data used in this analysis**:

1. The Total Supply Chain Costs, Production Costs and Transportation Costs all increase exponentially (non-linearly) with worsening First Time Quality of the Supply Chain members.
2. The supplier Production Quantities at any stage increase exponentially (non-linearly) with worsening Supplier First Time Quality (FTQ) at that stage.
3. Supplier First Time Quality has the most severe impact on the stage farthest from the demand consumption stage with the impact severity being higher at lower FTQ rates.

5.5.1 Real World Perspective

The importance of the above conclusions can be best seen in this real world supply chain where a powertrain castings plant at Stage 1 is feeding the machining plants at Stage 2, which in turn are feeding the engine assembly plants at Stage 3. All of the plants at the three stages were ramping up on their production plans and volumes, and as is very common during start up and ramp up modes, the plants had very low first time quality with the worst quality levels being at the castings facility. They being farthest from the consumption of demand were experiencing the most severe impact of low first time quality amongst the rest of the stages. The extent of the severity was such that the final vehicle assembly plants had to adjust their production schedules because of a lack of enough number of castings from the casting supplier. This basically meant a loss of valuable, high profit vehicle sales for the company. The results of this research could help and point out a couple of insights into their experience:

- Being the farthest from the consumption of demand, the castings stage will always be hit the hardest to produce additional quantities to account for their own first time quality as well as the rest of the supply chain.
- The additional production will generally have some derivation of the shape and form of an exponential curve. They will still have to determine the actual production quantity to produce depending on the circumstances. However knowing this severity in impact at the castings stage in advance could have resulted in different production plans, for this facility like starting ramp-up a little earlier then the rest of the supply chain members so that all of the quality problems in the supply chain do not hit at the same time. Also, providing

additional short-term capacities during a ramp up phase, like having another supplier on stand-by to provide castings in case of a dire need, will help to meet the vehicle assembly requirements.

5.6 Supplier Risk Analysis

The final scenario that will be investigated in this chapter is the impact of Supplier On Time Delivery Risk. Two questions are investigated in relation to this – What is the impact on Total Supply Chain Costs? And, How does that influence the selection of suppliers? Split Demand models are chosen for this analysis and it is assumed that there is enough capacity with each supplier to be able to meet all of the customer demand if necessary. While making such an assumption helps to better observe and understand the impact of risk, the generalized conclusions again are not likely to be any different even if takes two suppliers to have enough capacity to meet the customer demand. Regular Production and Transportation costs along with the impact of Supplier Delivery Risk are considered. Supplier Quality is not included so as to study the impact of Delivery Risk alone. Figure 5.21 shows the impact of Supplier Delivery Risk (in terms of Low/Medium/High and Percent Late Delivery) on Total Supply Chain Costs:

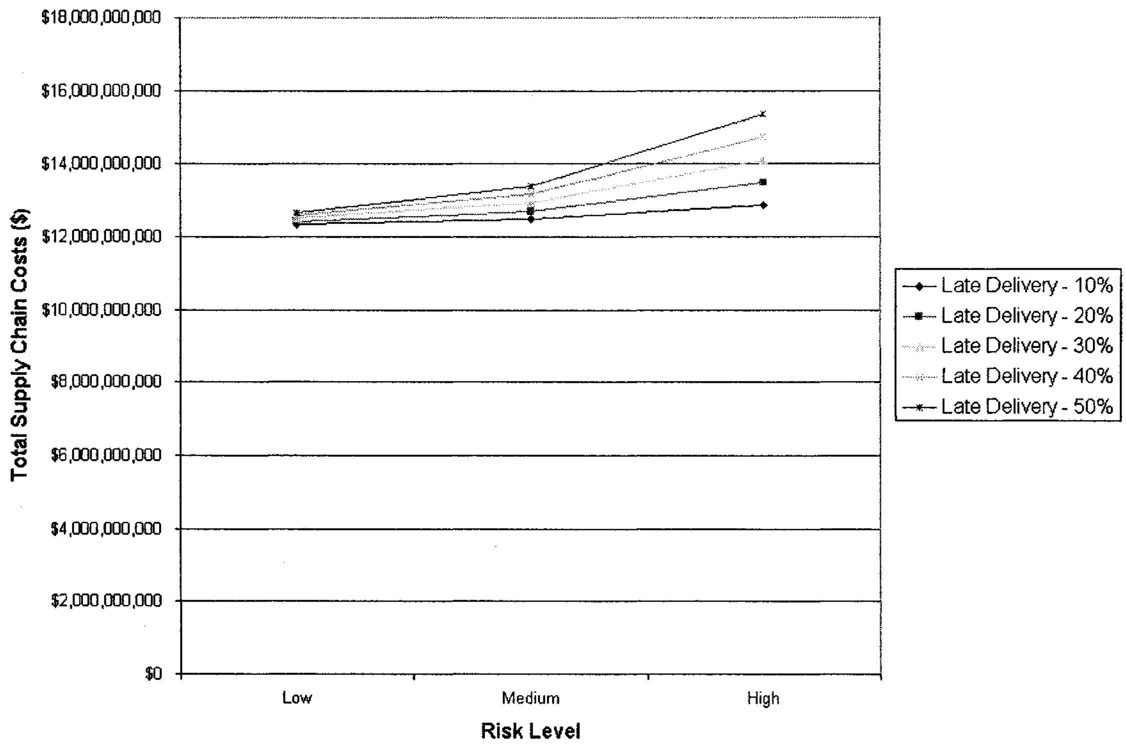


Figure 5.21: Impact of Supplier Delivery Risk Level on Total Supply Chain Costs

As can be expectedly seen from the results, the Total Supply Costs increase exponentially with the increase in level of delivery risk of the suppliers and percentage of late delivery with the worst being at 50% late delivery and at High value of Risk.

The other question that is investigated is-What impact does Supplier On Time Delivery Risk have on Supplier Selection? One of the scenarios developed earlier in Supplier Selection Analysis for products with production costs three times the baseline, i.e. production costs significantly higher than transportation costs is taken and the risk level of the non-domestic supplier is varied from Low to High across the board with keeping the risk level of the domestic supplier at Low along with Supplier Late Delivery Percentage at 10% and 50% for all suppliers. The Split Demand model is used for the analysis. This example is taken because it was seen earlier that there is more likely-hood of outsourcing to a non-domestic supplier for products with higher production costs than transportation costs. Figures 5.22 and 5.23 show the results for the analysis.

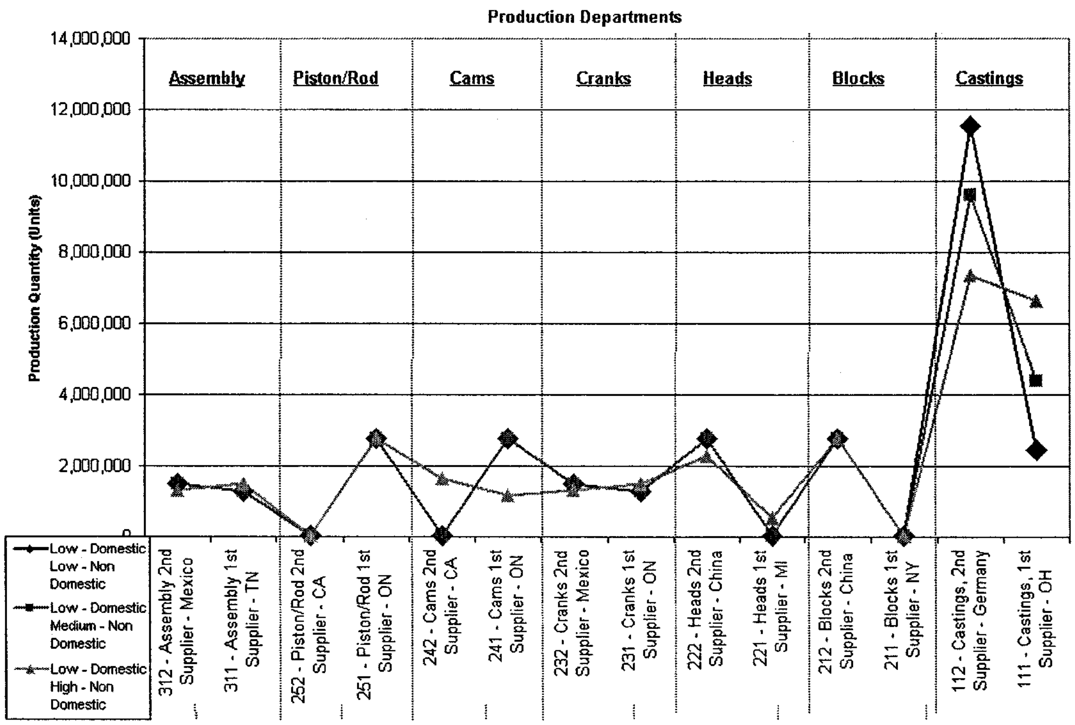


Figure 5.22: Impact of Supplier Risk on Supplier Selection at 10% Late

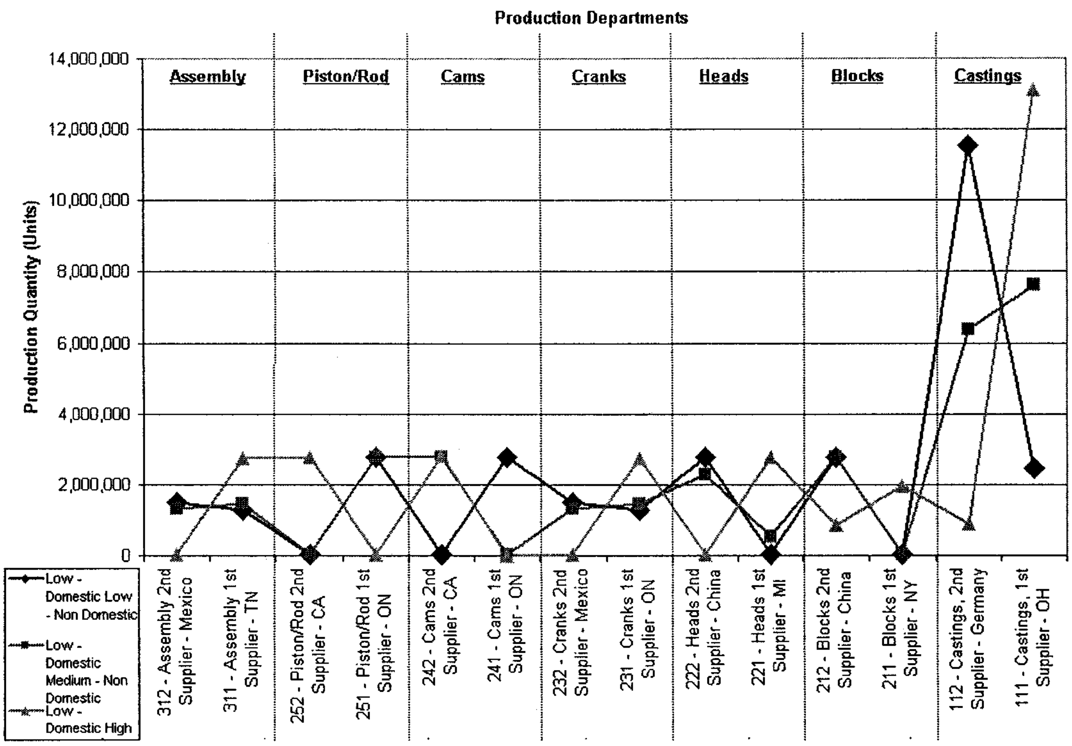


Figure 5.23: Impact of Supplier Risk on Supplier Selection at 50% Late

The following observations can be made looking at the results:

- At 10% Supplier Late Delivery Risk, as the risk level of the non-domestic supplier to be able to deliver parts on time increases from Low (= 1) to High (= 3), there is some impact on supplier selection in camshaft and casting suppliers in the form of slightly increased sourcing from domestic suppliers. In the other components, there is very little impact on supplier selection.
- At 50% Supplier Late Delivery Risk, as the risk level of the non-domestic supplier to be able to deliver parts on time increases from Low (= 1) to High (= 3), there is a huge impact on supplier selection decisions in the form of sourcing majority or all of the production quantities from domestic suppliers as against the cheaper producing non-domestic supplier.

The following important **generalized insights can be drawn from this analysis that is independent of the data used in this analysis**:

1. The Total Supply Chain Costs increase exponentially with decreasing Supplier overall reliability to deliver product in time.
2. Supplier selection decisions need to be made taking into consideration the overall supplier reliability in delivering parts on time. This is very important because the automotive industry increasingly operates in a Just-in-Time mode. Any delays in arrival of shipments can very quickly have a devastating effect on the supply chain performance. Therefore, for products that are more likely to be outsourced to cheaper, non-domestic suppliers, decreasing overall supplier reliability to deliver on time has the effect of splitting the production quantities between non-domestic and domestic suppliers, with the extreme being completely sourced from domestic suppliers at low levels of overall supplier reliability.

5.6.1 Real World Perspective

The importance of the above conclusions were felt in this extreme real world situation right after September 11th, 2001 when long delays in shipment arrivals due to lengthy customs and border crossings was causing nightmare problems to the manufacturing companies to meet their demand. An aftermath of this event has been for companies to start looking for suppliers at other geographical parts of the nation where they can take advantage of somewhat lower costs and also have reliable shipment delivery of shipments. While September 11th is not an every day event, companies are starting to take supplier reliability for on time delivery into consideration at the time of the supplier selection phase for every part.

5.7 Sensitivity of Design Factors to Data Accuracy

Multiple design factors have been taken into consideration in the development of a Supply Chain Design framework. These factors include Unit Production Costs, Unit Inventory Costs, Unit Transportation Costs, First Time Quality and Percent Late Delivery. When designing supply chains, it is important for designers to know upfront which of the factors are most sensitive or critical to final results from a data sensitivity standpoint. This is important because collecting good quality, reliable data in the real world is always hard irrespective of the number of electronic or manual data collection systems that may be available. Furthermore, no matter how good the available data is, it can never be 100% accurate. So that being a valid issue, designers want to design robust supply chains that are less sensitive to the accuracy of input data. The last thing they would want is to have a supply chain implemented that does not perform to the designed expectations, because there ended up being a slight variation in the predicted values of some of the design parameters. It is in this context that this section investigates the sensitivity of final results measured in terms of Total Global Supply Chain Costs to variations in data inputs of different design parameters. For each of the parameters, the data is varied from the baseline scenario to five times the original values, i.e. representing a 400% increase. This is a sufficiently large increase to represent an extreme scenario for doing the sensitivity analysis. A Split Demand – Multiple Criteria model is utilized, while doing the analysis. Figure 5.24 and Table 5.3 show the results of this analysis.

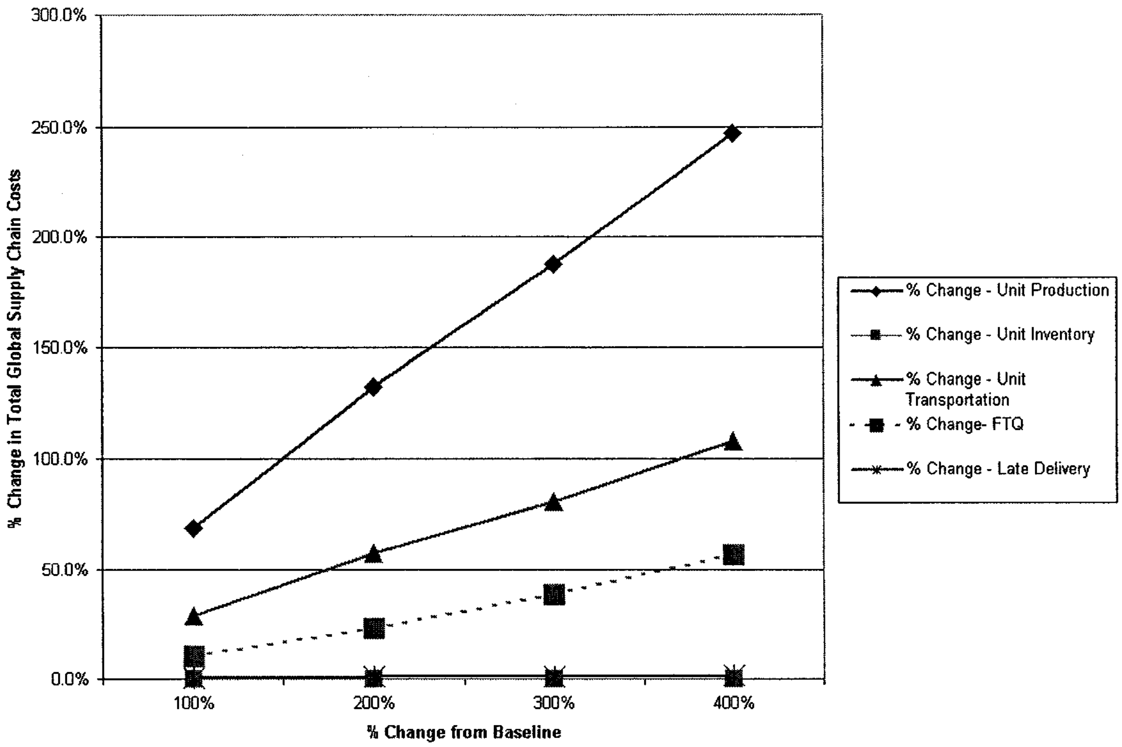


Figure 5.24: Sensitivity of Various Factors in Supply Chain Design Framework

Table 5.3: Sensitivity Results in Supply Chain Design Framework

	% Change from Baseline			
% Change in Total Global Supply Chain Costs	100%	200%	300%	400%
% Change - Unit Production	68.4%	132.2%	187.3%	247.0%
% Change - Unit Inventory	0.1%	0.1%	0.1%	0.1%
% Change - Unit Transportation	28.5%	56.9%	80.7%	107.9%
% Change- FTQ	10.4%	22.9%	38.2%	56.8%
% Change - Late Delivery	0.5%	0.9%	1.3%	1.8%

The results show that there is a substantial increase in Total Global Supply Chain Costs with increases in Unit Production costs, Unit Transportation costs and First Time

Quality. However, the Total Global Supply Chain Costs almost stay flat (or insensitive) to changes in Unit Inventory Costs and Percent Late Delivery. This leads to the following important observations:

- Effort should be focused more on getting good, accurate and reliable data for estimation of Unit Production costs, Unit Transportation costs and First Time Quality during the design phase of the Supply Chain, because the final supply chain performance is likely to be "very sensitive" to changes in these parameters. As far as data for Unit Inventory Costs and Percent Late Delivery, it is acceptable if data estimations are rough-cut, though higher accuracy if obtained easily is not undesirable.
- During the implementation or operational phase of Supply Chain, close attention should be paid to watch for changes in Unit Production costs, Unit Transportation costs and First Time Quality of the supply chain members because small changes in values of these parameters time over time can add up and make the supply chain gradually inefficient. Such small incremental changes from time to time (for example year to year) are often termed as "Creeping."

5.8 Comparing Current Practice to Proposed Framework

Current automotive industry practice in supplier selection is looking for the cheapest from the lowest bidding supplier without regard for long-term quality or on-time delivery reliability. And typically, all the demand is sourced to this lowest bidding supplier. The supply chain framework proposed in this dissertation calls for making supplier selection decisions taking into account production costs, transportation costs, first time quality and on-time delivery. The current industry practice is similar in nature to Scenario 1 of the four classes of problem solved except that at every stage and level, the lowest bidding supplier is selected. The data from Scenario 1 is used to simulate the current industry practice and the results are compared to the results from this dissertation. Comparing Scenario 1 results to Current practice would be most fair comparison. This is because other scenarios include multiple criteria of quality and on-time delivery that are not even considered in decision making in current industrial practice. Tables 5.4 through 5.7 shows the results of current industry practice and the comparison.

Total Global Supply Chain Costs	**$14,425,990,000**
Total Global Supply Chain Production Costs	$7,652,148,000
Total Global Supply Chain Transportation Costs	$6,773,841,000

Table 5.4 – Supplier Selection Results, Current Industry Practice

	Supplier Selection		
Supplier Selection Per Stage, Level, Time	**Period 1 - 1st Year**	**Period 2 - 2nd Year**	**Period 3 - 3rd Year**
Stage 1(Castings), Level 1	Supplier 2 - Germany	Supplier 2 - Germany	Supplier 2 - Germany
Stage 2(Components), Level 1(Blocks)	Supplier 2 - China	Supplier 2 - China	Supplier 2 - China
Stage 2(Components), Level 2(Heads)	Supplier 2 - China	Supplier 2 - China	Supplier 2 - China
Stage 2(Components), Level 3(Cranks)	Supplier 2 - Mexico	Supplier 2 - Mexico	Supplier 2 - Mexico
Stage 2(Components), Level 4(Cams)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
Stage 2(Components), Level 5(Piston/Rod)	Supplier 1 - ON	Supplier 1 - ON	Supplier 1 - ON
Stage 3(Assembly), Level 1	Supplier 2 - Mexico	Supplier 2 - Mexico	Supplier 2 - Mexico

Table 5.5 – Production Results, Current Industry Practice

	Production Results		
Production Quantity Per Stage, Level, Supplier, Time	**Period 1 - 1st Year**	**Period 2 - 2nd Year**	**Period 3 - 3rd Year**
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	4,627,739	4,624,143	4,748,118
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	925,719	924,657	949,624
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	925,685	924,692	949,624
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	925,651	924,726	949,624
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	925,342	925,034	949,624
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	925,342	925,034	949,624
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	925,342	925,034	949,624
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table 5.6 – Inventory Results, Current Industry Practice

	Inventory Results		
Inventory Quantity Per Stage, Level, Supplier, Time	**Period 1 - 1st Year**	**Period 2 - 2nd Year**	**Period 3 - 3rd Year**
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	377	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	343	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	308	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	0	0	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	342	376	0

Table 5.7 –Results Comparison, Current Vs Proposed

	Total Supply Chain Costs ($)		
	Supply Chain Design Framework	Current Industry Practice	Diff = Current - Framework
Scenario 1 - No Split Demand, Single Criteria	$12,255,150,000	$14,425,990,000	$2,170,840,000
Scenario 2 - No Split Demand, Mutiple Criteria	$13,492,050,000	-	
Scenario 3 - Split Demand, Single Criteria	$13,092,190,000	-	
Scenario 4 - Split Demand, Mutiple Criteria	$1,444,530,000	-	

As the comparison from Table shows, the current industry practice in this supply chain example is more expensive than the framework proposed in this dissertation by over two billion dollars. This is a reduction in Total Global Supply Chain Costs by 15%. Even Scenarios 2 and 3 that include multiple criteria and/or splitting in demand (which is not a perfect apples to apples comparison) are cheaper than the current industry practice. The results thus clearly show that there is opportunity for substantial costs savings that can be accrued in a supply chain by implementing the framework proposed in this dissertation.

CHAPTER 6

SYSTEMS DEVELOPMENT PERSPECTIVE

6.1 An Overview

The essence of supply chain management is integrated planning, which has three principal dimensions:

- Functional integration of decisions about purchasing, manufacturing, transportation and warehousing within the company.
- Geographical integration of decisions made by managers in facilities situated in many locations.
- Integration of strategic, tactical and operational decisions.

Supply chains have a profound effect on the way companies are organized. The traditional structure, (which continues in most companies today), divides people according to their functions. Separate departments perform each function. The supply chain in a manufacturing company, for example, has the procurement department, the manufacturing department and the distribution department. Decisions making becomes a functional mission, with a too little overview of the total supply chain. In some situations, this arrangement makes sense, but for the majority this arrangement needs to change. This is driven by increased customer expectation along with a variety of changes in the business environment including a fast product life cycle, just-in-time production, cost leadership and global competition. In recent years, supply chain management has been touted as one of the major strategies to improve organizational performance and generate competitive advantage. However achieving a sustainable competitive advantage through improved supply chain relationships will have to include the flow of information along with all of the activities associated with the flow and transformation of goods from raw materials. The growth in business-to-business commerce has highlighted the role of supply chain management in the modern digital economy. The following sections introduce the Zachman framework for Information Systems architecture and show the potential application of this framework towards development of Supply Chain Design Information Systems.

6.2 Zachman Framework

Zachman introduced a framework for information systems architecture [1992] that has been widely accepted by systems analysts and database designers. It provides taxonomy for relating the concepts that describe the real world to the concepts that describe an information system and implementation. The five rows of the framework are briefly described:

- Scope – Corresponds to an executive summary for a planner or investor who wants an estimate of the scope of the system, what it would cost and how it would perform.
- Business model – Constitutes the design of the business and shows the business entities and processes and how they interact.
- System model – Designed by a systems analyst, it must determine the data elements and functions that represent business entities and processes.
- Technology model – This must adapt the information system model to the details of the programming languages, I/O devices or other technology.

- Detailed representations – Correspond to detailed specifications that are given to the programmers, who code individual modules without being concerned with overall context or structure of the system.

6.3 Applying Zachman Framework to Supply Chain Design

The Figure 6.1 shows the application of Zachman's framework towards potential development of a Supply Chain Design Information System using the Supply Chain Design framework introduced in this dissertation. It shows the vision of relating the planning and business perspective to the detailed technology perspective for supply chain design. It starts from a scope level and goes top down all the way to detailed representation level by answering all of the six questions of what, how, where, who, when and why. The intersecting cell in the grid provides answers each of the six questions corresponding to the business function on the left. Answering all of the questions helps in putting together a business case for creation of supply chain design information system.

	WHAT DATA	HOW FUNCTION	WHERE NETWORK	WHO PEOPLE	WHEN TIME	WHY MOTIVATION
SCOPE **Planner**	**Suppliers** production/inventory costs, quality, reliability of on-time delivery and transportation **costs**	Evaluating each Supplier and Logistics provider by using the **Supply Chain Design Framework** and thus making decisions for supplier selection	**Domestic & Global** Suppliers & Logistics Providers	Product OEM's, **Suppliers**, Logistics Providers (Supply Chain Designers)	**Design Phase** of New Product Program	**Minimize Global Supply Chain Costs** and thereby drive down the product costs
BUSINESS MODEL **Owner**	Entity Relationship Diagram showing the **Business linkage** between the Product OEM's, Component Suppliers and Logistics Providers	Selecting suppliers by inviting them to participate in **Supplier Selection Process** that is developed around the proposed Supply Chain Design Framework	**Supply Chain Department** at the **OEM** and Suppliers	**Cross Functional Teams** from Purchasing/Product/ Manufacturing/Logistics Divisions	Design Phase after the **Approval** of the New Product Program	Minimize Global Supply Chain Costs, Decrease Product Costs, **Increase Company Profitability**
SYSTEM MODEL **Designer**	**Information System Arcitecture** showing the linkage between the different elements of system including data, solution engines and interfaces	Developing **Information systems** that use the **Supply Chain Design Framework**	**Supply Chain Department** at the **OEM** / Information Systems Department	**Supply Chain Design Analysts**/Computer Engineers	Design Phase of a ALL New Programs **prior to Issuing** Purchase Orders for Suppliers	To **analyze** and compare different supply chain designs and **present recommendations** to Management, Increase Company Profitability
TECHNOLOGY MODEL **Builder**	Detailed **Relational Database Design (RDBMS)** showing the organization of Tables & Fields in the Database	Decisions involve around **deciding on Programming environment**, Databases and Networking to start programming code in detailed representation	Central System at **OEM Information Systems site** and potentially networked to Supplier sites	**Computer Engineers**	Design Phase of a ALLNew Programs **prior to Issuing** Purchase Orders for Suppliers	To **analyze** and compare different supply chain designs and **present recommendations** to Management, Increase Company Profitability
DETAILED REPRESENTATION **Subcontractor**	Number of Suppliers & Logistics Providers Unit Production Costs Unit Inventory Costs First Time Quality Risk level of Suppliers Unit Transportation Costs **Similar to Input Data that has been used in the framework**	Writing **detailed Computer Programs**, Databases to develop the Application/System	Setting up **Network Architecture** to link Suppliers / Databases	Computer Specialists, **R&D people**	Design Phase of a ALLNew Programs **prior to Issuing** Purchase Orders for Suppliers	To **analyze** and compare different supply chain designs and **present recommendations** to Management, Increase Company Profitability
FUNCTIONING ENTERPRISE	e.g. DATA	e.g. FUNCTION	e.g. NETWORK	e.g. ORGANIZATION	e.g. SCHEDULE	e.g. STRATEGY

Figure 6.1: Applying Zachman Framework to Supply Chain Design

6.4 Supply Chain Design Information Systems

Figure 6.2 shows a potential Information Systems Architecture for Supply Chain Design. The Mixed LP/NLP models represent the current solvers in the Optimization Engines suite. Future solvers could include discrete event simulation models and other heuristic algorithms.

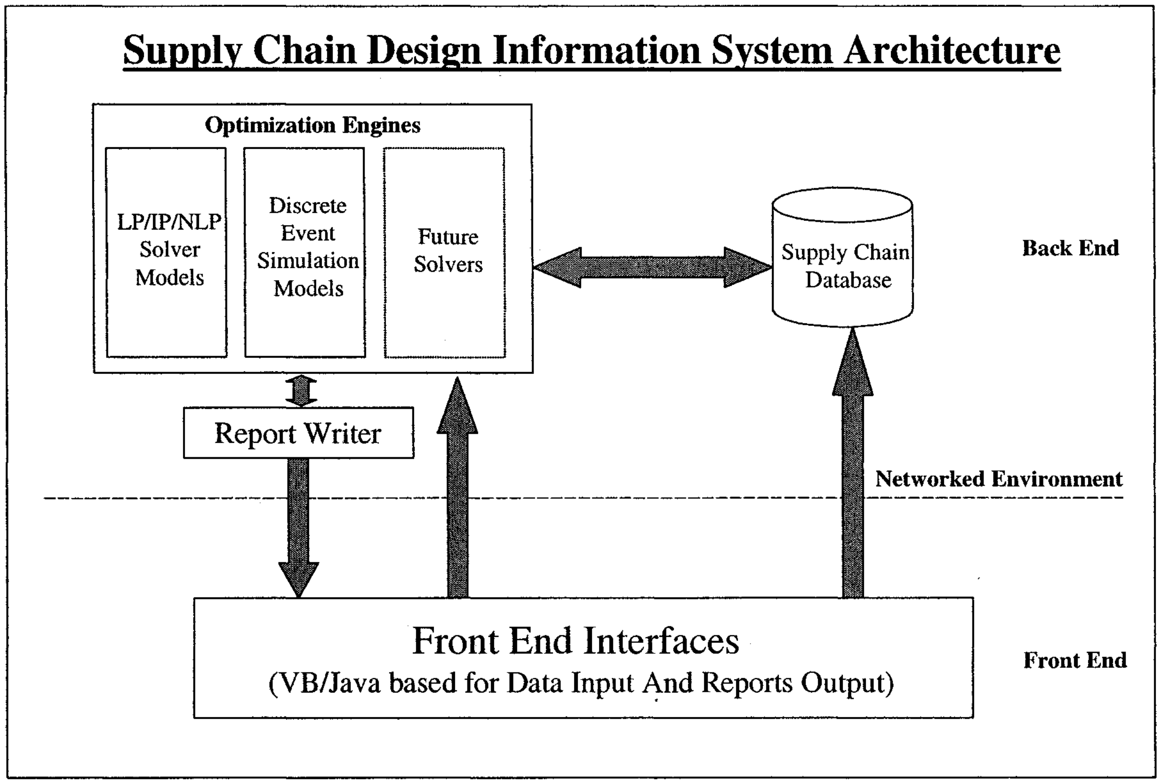


Figure 6.2: Supply Chain Design Information System Architecture

Such a system, when developed, will prove to be extremely useful in creating and automating a business process for supply chain design for new product programs in the design phase. This will also save enormous dollars down the road in the implementation phase by designing it right the first time.

6.5 Supply Chain Software Landscape

Today's Supply Chain Management (SCM) landscape consists of three categories: best-of-breed winners, best-of-breed start-ups and the Enterprise Resource Planning (ERP) players. There is no clear leader in the SCM space. The four best-of-breed winners, i2 Technologies, Manugistics, Ariba and Commerce One are the SCM pioneers and current functional leaders. However, start-ups with superior functionality as well as ERP players (like SAP, Oracle, People Soft and JD Edwards) have been making inroads into their leadership position.

CHAPTER 7

CONCLUSIONS

7.1 An Overview

Supply chain design is recognized as an opportunity for substantial costs savings and improvements that can eventually trickle down to decreased product costs and increased profits. Much of the previous work on Supply Chain design has focused on dealing with supplier selection, production and transportation separately. Only very recently has some work been done on integrating production and logistics costs in a single framework with general conclusions, being that there is a need for more integrated decision making between manufacturers and suppliers in an increasingly global manufacturing system. However none of that work includes the metrics of supplier quality and on-time delivery that are very important to the industry. A variety of solution approaches have been used in previous research, including Discrete Event Simulation, Mathematical Programming and Heuristics.

7.2 Research Summary

This research has focused on the development and solutions of an integrated Supply Chain Design Framework for supplier selection from multiple supplier options that considers supplier production costs, inventory costs, production and inventory capacities, transportation costs and capacities, first time quality and supplier on-time delivery risk. In an increasingly global manufacturing system that is demanded by cost cutting and leveraging global capacities through acquisitions, companies can no longer make supplier selection decisions based on separating production and transportation issues as different functions. An integrated supply chain framework, as proposed in this dissertation, should be used very early on in the design phase of any new product program prior to cutting purchase orders. In fact such a step should be codified as a checklist item in the standard supplier selection business process for every future product program. Real world automobile powertrain processes and data from the automotive industry have been used for demonstrating the application and usefulness of the proposed framework. Four cases were developed and investigated by a combination of single/multiple criteria and allowing the splitting of customer demand or restricting only one supplier for every part. Mixed Integer Programming is used for solving the supply chain design problems. Important real world insights are drawn from this research that can be very useful to some of the problems faced by the industry.

7.3 Conclusions

The following key conclusions relating to Supply Chain Design are developed in this research. They are classified into data dependent (based on the data used in this dissertation) and data independent conclusions.

The following are the data dependent conclusions:

1. Supplier selection decisions at any stage in the supply chain should split total customer demand between at least two suppliers instead of handing the entire contract to one single supplier. Splitting the demand between two suppliers is desirable both from a total supply chain costs perspective and also from partially insulating from

delivery risks relating to catastrophic events. In the Automotive industry, which increasingly operates in Just-In-Time mode, such a move is essential and critical.

2. Rising Unit inventory carrying costs have a decreasing effect on the total number of Supply Chain Inventory Locations and Sizes.
3. As the Unit Production or Transport Costs increase, it may be beneficial to produce or transport shipments resulting in higher inventories but relatively lower global supply chain costs. This result comes in direct contrast to the advise of the Lean Engineering community who always advocate low inventories with the extreme being single piece flow. However, this increasing inventory sizes is valid only till a certain point with the increasing unit production or transport costs after which lower batch size and thereby lower inventories are desirable for optimizing the supply chain. This critical point should be determined and kept in mind as supply chains are designed and/or as the supply chains change with time.
4. Sensitivity analysis of the different factors used in the Supply Chain Design Framework shows that Unit Production Cost, Unit Transportation Cost and First Time Quality are the most critical factors in the Total Global Supply Chain Costs. Any changes in these parameters are likely to have a substantial impact on the supply chain costs. Therefore good accurate and reliable data should be collected for these parameters while designing a new supply chain and attention should be paid to them in existing supply chains to maintain the designed efficiency.

The following are the data independent conclusions:

1. Supplier selection decisions should be made by using a global integrated approach of considering both production and transportation costs for the complete supply chain as

proposed in the Supply Chain Design Framework in this research. Any localized decision in the supply chain of selecting a non-domestic supplier may offer some local benefits (60% improvements as seen in some levels/stages) but may not always necessarily translate into global supply chain benefits. They could in some cases increase the global supply chain costs and shift the cost base to elsewhere in the supply chains.

2. Outsourcing to a non-domestic, less expensive supplier is not always the best decision for every product when selecting suppliers. This is an important realization in the current business climate where there is an out-sourcing binge to contract suppliers overseas as a way of cost savings. Independent analysis and business case should be made for every product based on the case details. Evidence of some of this thinking is starting to emerge very recently in literature with the talk about "best sourcing", where sourcing/setting up new factories in other parts of the nation rather than the traditional industrialized belt is considered as a potential alternative to outsourcing.
3. The Total Global Supply Chain Costs, Production Costs and Transportation Costs all increase exponentially (non linearly) with worsening First Time Quality of the Supply Chain members.
4. The Supplier Production Quantities at any stage increase exponentially (non linearly) with worsening Supplier First Time Quality (FTQ) at that stage
5. Supplier First Time Quality has the most severe impact on the stage farthest from the Demand consumption stage with the impact severity being higher at lower FTQ rates.
6. The Total Supply Chain Costs increases exponentially with decreasing overall supplier reliability to deliver products on time. Supplier selection decisions need to be

made taking into consideration the overall supplier reliability in delivering parts on time. This is very important in the automotive industry, which increasingly operates in a Just-in-Time mode and any delays in arrival of shipments can very quickly have a devastating effect on the supply chain performance.

7.4 Recommendations for Future Research

The following are some recommendations for future work and research directions:

1. The proposed supply chain design framework assumes that one unit of product requires one unit of individual components in the Bill of Material. The framework can be easily extended to a more generic bill of material.
2. The proposed framework is set up to handle only one product with a defined process flow. It can be modified to treat multiple products with their respective process flows while designing supply chains
3. Supplier On Time Delivery Risk is considered as one of the factors in the framework. However, time is not explicitly captured as an additional criterion. This is because the proposed framework is meant for use in designing new supply chains and not for making tactical or operational decisions. Therefore, extending the proposed framework for tactical or operational decisions represents an interesting area for further research.
4. In the proposed framework, all of the multiple criteria are weighted equally in the objective function. Assigning different weights to each criteria and thus indicating their importance can be a further extension to the framework.
5. Mixed Linear programming is used for solving the Supply Chain Design problems in this dissertation. Alternative optimization and heuristic techniques can be explored as

additional solvers for solving the design problems. This may particularly be useful when done in conjunction with the above recommendations and applied to some extremely large supply chains that may result in a very large search space to find an optimal solution.

6. Developing integrated supplier color-coded ratings (Red/Yellow/Green) based on all of the factors considered, represents an interesting extension, from an implementation standpoint.
7. Supply Chain Information System, as proposed in Chapter 6, can be developed to drive creation and implementation of a business process that does supplier selection decisions based on the framework proposed in this dissertation. This will also lead to a more collaborative approach to supply chain design decisions between different functions in one company and between original equipment manufacturers and suppliers in a supply chain. A collaborative model all the way throughout the supply chain is the only way to get systemic on going cost reduction and this is a realization that hasn't really dawned on many of the manufacturers yet.

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APPENDIX A

Scenario 1 – No Split Demand, Single Criterion – Input Data

Table A.1: Scenario 1 - Demand Input Data

Demand (Units/Year)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Customer 1 - Vehicle Asssembly Plant - MI	375,000	450,000	525,000
Customer 2 - Vehicle Asssembly Plant - OH	175,000	175,000	175,000
Customer 3 - Vehicle Asssembly Plant - TN	375,000	300,000	250,000

Table A.2: Scenario 1 – Number of Stages Per Level

	Stage1	Stage2	Stage3	Stage4
Level Number Per Stage	1	5	1	3

Table A.3: Scenario 1 – Number of Suppliers Per Stage Per Level

SupNumPerStgPerLev	Level 1	Level 2	Level 3	Level 4	Level 5
Stage 1 - Castings	2	0	0	0	0
Stage 2 - Components (Blocks, Heads, Cranks, Cams, Piston/Rod)	2	2	2	2	2
Stage3 - Engine Assembly	2	0	0	0	0
Stage 4 - Vehicle Assembly	1	1	1	0	0

Table A.4: Scenario 1 – Unit Production Costs Input Data

Unit Prodn Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$400	$410	$420
Stage 1(Castings), Level 1, Supplier 2(Germany)	$375	$380	$385
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$300	$350	$400
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$200	$225	$240
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$275	$250	$250
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$150	$155	$160
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$100	$105	$110
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$85	$85	$90
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$30	$32	$35
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$40	$40	$40
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$25	$27	$28
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$35	$40	$40
Stage 3(Assembly), Level 1, Supplier 1(TN)	$375	$425	$450
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$300	$310	$320

Table A.5: Scenario 1 – Unit Inventory Costs Input Data

Unit Inv Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$20	$22	$23
Stage 1(Castings), Level 1, Supplier 2(Germany)	$22	$23	$24
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$25	$30	$35
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$20	$22	$23
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$17	$18	$20
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$13	$15	$17
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$15	$14	$13
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$10	$11	$12
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$5	$6	$6
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$8	$9	$10
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$5	$5	$6
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$8	$8	$10
Stage 3(Assembly), Level 1, Supplier 1(TN)	$30	$35	$40
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$30	$30	$35

Table A.6: Scenario 1 – Production Capacity Input Data

Prodn Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	100,000,000	100,000,000	100,000,000
Stage 1(Castings), Level 1, Supplier 2(Germany)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 2(Heads), Supplier 2(China)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	100,000,000	100,000,000	100,000,000
Stage 3(Assembly), Level 1, Supplier 1(TN)	100,000,000	100,000,000	100,000,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	100,000,000	100,000,000	100,000,000

Table A.7: Scenario 1 – Maximum Inventory Capacity Input Data

Max Inv Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	148,000	133,200	106,400
Stage 1(Castings), Level 1, Supplier 2(Germany)	162,800	177,600	152,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	37,000	33,300	26,600
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	40,700	44,400	38,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	25,900	29,600	34,200
Stage 2(Components), Level 2(Heads), Supplier 2(China)	37,000	40,700	45,600
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	29,600	25,900	26,600
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	33,300	37,000	38,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	29,600	29,600	29,600
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	33,300	33,300	34,200
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	25,900	25,900	25,900
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	33,300	33,300	34,200
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	38,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	37,000	40,700	45,600

Table A.8: Scenario 1 – First Time Quality Input Data

FTQ Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	100%	100%	100%
Stage 1(Castings), Level 1, Supplier 2(Germany)	100%	100%	100%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	100%	100%	100%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	100%	100%	100%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	100%	100%	100%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	100%	100%	100%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	100%	100%	100%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	100%	100%	100%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	100%	100%	100%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	100%	100%	100%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	100%	100%	100%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	100%	100%	100%
Stage 3(Assembly), Level 1, Supplier 1(TN)	100%	100%	100%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	100%	100%	100%

Table A.9: Scenario 1 – Late Delivery Input Data

Late Delivery Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0%	0%	0%
Stage 1(Castings), Level 1, Supplier 2(Germany)	0%	0%	0%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0%	0%	0%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0%	0%	0%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0%	0%	0%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0%	0%	0%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0%	0%	0%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0%	0%	0%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0%	0%	0%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0%	0%	0%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0%	0%	0%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0%	0%	0%
Stage 3(Assembly), Level 1, Supplier 1(TN)	0%	0%	0%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0%	0%	0%

Table A.10: Scenario 1 – Penalty Rate Input Data

Penalty Rate Per Period for all Suppliers ($)	0

Table A.11: Scenario 1 – Risk Level Input Data

Risk Per Stage, Level, Supplier, Time (L/M/H - 1/2/3)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	0	0	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table A.12: Scenario 1 – Transport Number Input Data

Transport Number (Between Origin & Destination)				Dest Sup 1	Dest Sup 2
Origin Stage	Org Level	Org Supplier	Dest Level		
1 (Castings)	1	1	1 (Blocks)	2	2
1 (Castings)	1	1	2 (Heads)	2	2
1 (Castings)	1	1	3 (Cranks)	2	2
1 (Castings)	1	1	4 (Cams)	2	2
1 (Castings)	1	1	5 (Piston/Rod)	2	2
1 (Castings)	1	2	1 (Blocks)	2	2
1 (Castings)	1	2	2 (Heads)	2	2
1 (Castings)	1	2	3 (Cranks)	2	2
1 (Castings)	1	2	4 (Cams)	2	2
1 (Castings)	1	2	5 (Piston/Rod)	2	2
2 (Components)	1 (Blocks)	1	1 (Assembly)	2	2
2 (Components)	1 (Blocks)	2	1 (Assembly)	2	2
2 (Components)	2 (Heads)	1	1 (Assembly)	2	2
2 (Components)	2 (Heads)	2	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	1	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	2	1 (Assembly)	2	2
2 (Components)	4 (Cams)	1	1 (Assembly)	2	2
2 (Components)	4 (Cams)	2	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	1	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	2	1 (Assembly)	2	2
3 (Assembly)	1	1	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	3 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	3 (Vehicle Assembly)	2	2

Table A.13: Scenario 1 – Transportation Costs Input Data

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	1 (Blocks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	1 (Blocks)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	1 (Blocks)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	2 (Heads)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	2 (Heads)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	2 (Heads)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	3 (Cranks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	1	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	4 (Cams)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	4 (Cams)	2	2 (Priority)	175	180	190
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	85	90	95
1 (Castings)	1	1	5 (Piston/Rod)	1	2 (Priority)	200	205	210
1 (Castings)	1	1	5 (Piston/Rod)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	5 (Piston/Rod)	2	2 (Priority)	175	180	190
1 (Castings)	1	2	1 (Blocks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	1 (Blocks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	1 (Blocks)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	1 (Blocks)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	2 (Heads)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	2 (Heads)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	2 (Heads)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	2 (Heads)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	3 (Cranks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	3 (Cranks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	2	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	2	4 (Cams)	1	1 (Economy)	170	175	180
1 (Castings)	1	2	4 (Cams)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	4 (Cams)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	4 (Cams)	2	2 (Priority)	215	220	225
1 (Castings)	1	2	5 (Piston/Rod)	1	1 (Economy)	175	180	180
1 (Castings)	1	2	5 (Piston/Rod)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	5 (Piston/Rod)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	5 (Piston/Rod)	2	2 (Priority)	215	220	225
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	127	135	140
2 (Components)	1	1	1 (Assembly)	1	2 (Priority)	273	285	300
2 (Components)	1	1	1 (Assembly)	2	1 (Economy)	223	230	235
2 (Components)	1	1	1 (Assembly)	2	2 (Priority)	276	280	285
2 (Components)	1	2	1 (Assembly)	1	1(Economy)	300	310	320
2 (Components)	1	2	1 (Assembly)	1	2 (Priority)	608	615	620
2 (Components)	1	2	1 (Assembly)	2	1 (Economy)	275	290	300
2 (Components)	1	2	1 (Assembly)	2	2 (Priority)	575	595	604
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	70	75	85
2 (Components)	2	1	1 (Assembly)	1	2 (Priority)	160	165	170
2 (Components)	2	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	2	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	2	2	1 (Assembly)	1	1 (Economy)	269	275	280
2 (Components)	2	2	1 (Assembly)	1	2 (Priority)	353	360	367
2 (Components)	2	2	1 (Assembly)	2	1 (Economy)	245	250	255
2 (Components)	2	2	1 (Assembly)	2	2 (Priority)	325	330	340

Table A.13: Scenario 1 – Transportation Costs Input Data Contd…

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	3	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	3	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	3	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	3	2	1 (Assembly)	1	1 (Economy)	163	165	170
2 (Components)	3	2	1 (Assembly)	1	2 (Priority)	193	200	207
2 (Components)	3	2	1 (Assembly)	2	1 (Economy)	50	55	60
2 (Components)	3	2	1 (Assembly)	2	2 (Priority)	110	115	120
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	4	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	4	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	4	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	4	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	2	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	5	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	5	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	5	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	5	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	2	1 (Assembly)	2	2 (Priority)	143	145	150
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	286	295	305
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	2 (Priority)	558	570	580
3 (Assembly)	1	1	2 (Vehile Assembly)	1	1 (Economy)	286	295	305
3 (Assembly)	1	1	2 (Vehile Assembly)	1	2 (Priority)	558	570	580
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	158	165	170
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	2 (Priority)	315	325	335
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	2 (Vehile Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	2 (Vehile Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	2 (Priority)	625	630	645

Table A.14: Scenario 1 – Transportation Capacity Input Data

Transport Capacity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1	1	1	1	1	1	100,000,000	100,000,000	100,000,000
1	1	1	1	1	2	100,000,000	100,000,000	100,000,000
1	1	1	1	2	1	100,000,000	100,000,000	100,000,000
1	1	1	1	2	2	100,000,000	100,000,000	100,000,000
1	1	1	2	1	1	100,000,000	100,000,000	100,000,000
1	1	1	2	1	2	100,000,000	100,000,000	100,000,000
1	1	1	2	2	1	100,000,000	100,000,000	100,000,000
1	1	1	2	2	2	100,000,000	100,000,000	100,000,000
1	1	1	3	1	1	100,000,000	100,000,000	100,000,000
1	1	1	3	1	2	100,000,000	100,000,000	100,000,000
1	1	1	3	2	1	100,000,000	100,000,000	100,000,000
1	1	1	3	2	2	100,000,000	100,000,000	100,000,000
1	1	1	4	1	1	100,000,000	100,000,000	100,000,000
1	1	1	4	1	2	100,000,000	100,000,000	100,000,000
1	1	1	4	2	1	100,000,000	100,000,000	100,000,000
1	1	1	4	2	2	100,000,000	100,000,000	100,000,000
1	1	1	5	1	1	100,000,000	100,000,000	100,000,000
1	1	1	5	1	2	100,000,000	100,000,000	100,000,000
1	1	1	5	2	1	100,000,000	100,000,000	100,000,000
1	1	1	5	2	2	100,000,000	100,000,000	100,000,000
1	1	2	1	1	1	100,000,000	100,000,000	100,000,000
1	1	2	1	1	2	100,000,000	100,000,000	100,000,000
1	1	2	1	2	1	100,000,000	100,000,000	100,000,000
1	1	2	1	2	2	100,000,000	100,000,000	100,000,000
1	1	2	2	1	1	100,000,000	100,000,000	100,000,000
1	1	2	2	1	2	100,000,000	100,000,000	100,000,000
1	1	2	2	2	1	100,000,000	100,000,000	100,000,000
1	1	2	2	2	2	100,000,000	100,000,000	100,000,000
1	1	2	3	1	1	100,000,000	100,000,000	100,000,000
1	1	2	3	1	2	100,000,000	100,000,000	100,000,000
1	1	2	3	2	1	100,000,000	100,000,000	100,000,000
1	1	2	3	2	2	100,000,000	100,000,000	100,000,000
1	1	2	4	1	1	100,000,000	100,000,000	100,000,000
1	1	2	4	1	2	100,000,000	100,000,000	100,000,000
1	1	2	4	2	1	100,000,000	100,000,000	100,000,000
1	1	2	4	2	2	100,000,000	100,000,000	100,000,000
1	1	2	5	1	1	100,000,000	100,000,000	100,000,000
1	1	2	5	1	2	100,000,000	100,000,000	100,000,000
1	1	2	5	2	1	100,000,000	100,000,000	100,000,000
1	1	2	5	2	2	100,000,000	100,000,000	100,000,000
2	1	1	1	1	1	100,000,000	100,000,000	100,000,000
2	1	1	1	1	2	100,000,000	100,000,000	100,000,000
2	1	1	1	2	1	100,000,000	100,000,000	100,000,000
2	1	1	1	2	2	100,000,000	100,000,000	100,000,000
2	1	2	1	1	1	100,000,000	100,000,000	100,000,000
2	1	2	1	1	2	100,000,000	100,000,000	100,000,000
2	1	2	1	2	1	100,000,000	100,000,000	100,000,000
2	1	2	1	2	2	100,000,000	100,000,000	100,000,000

Table A.14: Scenario 1 – Transportation Capacity Input Data Contd…

Transport Capacity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
2	2	1	1	1	1	100,000,000	100,000,000	100,000,000
2	2	1	1	1	2	100,000,000	100,000,000	100,000,000
2	2	1	1	2	1	100,000,000	100,000,000	100,000,000
2	2	1	1	2	2	100,000,000	100,000,000	100,000,000
2	2	2	1	1	1	100,000,000	100,000,000	100,000,000
2	2	2	1	1	2	100,000,000	100,000,000	100,000,000
2	2	2	1	2	1	100,000,000	100,000,000	100,000,000
2	2	2	1	2	2	100,000,000	100,000,000	100,000,000
2	3	1	1	1	1	100,000,000	100,000,000	100,000,000
2	3	1	1	1	2	100,000,000	100,000,000	100,000,000
2	3	1	1	2	1	100,000,000	100,000,000	100,000,000
2	3	1	1	2	2	100,000,000	100,000,000	100,000,000
2	3	2	1	1	1	100,000,000	100,000,000	100,000,000
2	3	2	1	1	2	100,000,000	100,000,000	100,000,000
2	3	2	1	2	1	100,000,000	100,000,000	100,000,000
2	3	2	1	2	2	100,000,000	100,000,000	100,000,000
2	4	1	1	1	1	100,000,000	100,000,000	100,000,000
2	4	1	1	1	2	100,000,000	100,000,000	100,000,000
2	4	1	1	2	1	100,000,000	100,000,000	100,000,000
2	4	1	1	2	2	100,000,000	100,000,000	100,000,000
2	4	2	1	1	1	100,000,000	100,000,000	100,000,000
2	4	2	1	1	2	100,000,000	100,000,000	100,000,000
2	4	2	1	2	1	100,000,000	100,000,000	100,000,000
2	4	2	1	2	2	100,000,000	100,000,000	100,000,000
2	5	1	1	1	1	100,000,000	100,000,000	100,000,000
2	5	1	1	1	2	100,000,000	100,000,000	100,000,000
2	5	1	1	2	1	100,000,000	100,000,000	100,000,000
2	5	1	1	2	2	100,000,000	100,000,000	100,000,000
2	5	2	1	1	1	100,000,000	100,000,000	100,000,000
2	5	2	1	1	2	100,000,000	100,000,000	100,000,000
2	5	2	1	2	1	100,000,000	100,000,000	100,000,000
2	5	2	1	2	2	100,000,000	100,000,000	100,000,000
3	1	1	1	1	1	100,000,000	100,000,000	100,000,000
3	1	1	1	1	2	100,000,000	100,000,000	100,000,000
3	1	1	2	1	1	100,000,000	100,000,000	100,000,000
3	1	1	2	1	2	100,000,000	100,000,000	100,000,000
3	1	1	3	1	1	100,000,000	100,000,000	100,000,000
3	1	1	3	1	2	100,000,000	100,000,000	100,000,000
3	1	2	1	1	1	100,000,000	100,000,000	100,000,000
3	1	2	1	1	2	100,000,000	100,000,000	100,000,000
3	1	2	2	1	1	100,000,000	100,000,000	100,000,000
3	1	2	2	1	2	100,000,000	100,000,000	100,000,000
3	1	2	3	1	1	100,000,000	100,000,000	100,000,000
3	1	2	3	1	2	100,000,000	100,000,000	100,000,000

APPENDIX B

Scenario 2 – No Split Demand, Multiple Criteria – Input Data

Table B.1: Scenario 2 - Demand Input Data

Demand (Units/Year)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Customer 1 - Vehicle Asssembly Plant - MI	375,000	450,000	525,000
Customer 2 - Vehicle Asssembly Plant - OH	175,000	175,000	175,000
Customer 3 - Vehicle Asssembly Plant - TN	375,000	300,000	250,000

Table B.2: Scenario 2 – Number of Stages Per Level

	Stage 1	Stage 2	Stage 3	Stage 4
Level Number Per Stage	1	5	1	3

Table B.3: Scenario 2 – Number of Suppliers Per Stage Per Level

SupNumPerStgPerLev	Level 1	Level 2	Level 3	Level 4	Level 5
Stage 1 - Castings	2	0	0	0	0
Stage 2 - Components (Blocks, Heads, Cranks, Cams, Piston/Rod)	2	2	2	2	2
Stage 3 - Engine Assembly	2	0	0	0	0
Stage 4 - Vehicle Assembly	1	1	1	0	0

Table B.4: Scenario 2 – Unit Production Costs Input Data

Unit Prodn Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$400	$410	$420
Stage 1(Castings), Level 1, Supplier 2(Germany)	$375	$380	$385
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$300	$350	$400
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$200	$225	$240
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$275	$250	$250
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$150	$155	$160
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$100	$105	$110
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$85	$85	$90
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$30	$32	$35
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$40	$40	$40
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$25	$27	$28
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$35	$40	$40
Stage 3(Assembly), Level 1, Supplier 1(TN)	$375	$425	$450
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$300	$310	$320

Table B.5: Scenario 2 – Unit Inventory Costs Input Data

Unit Inv Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$20	$22	$23
Stage 1(Castings), Level 1, Supplier 2(Germany)	$22	$23	$24
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$25	$30	$35
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$20	$22	$23
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$17	$18	$20
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$13	$15	$17
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$15	$14	$13
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$10	$11	$12
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$5	$6	$6
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$8	$9	$10
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$5	$5	$6
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$8	$8	$10
Stage 3(Assembly), Level 1, Supplier 1(TN)	$30	$35	$40
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$30	$30	$35

Table B.6: Scenario 2 – Production Capacity Input Data

Prodn Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	100,000,000	100,000,000	100,000,000
Stage 1(Castings), Level 1, Supplier 2(Germany)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 2(Heads), Supplier 2(China)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	100,000,000	100,000,000	100,000,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	100,000,000	100,000,000	100,000,000
Stage 3(Assembly), Level 1, Supplier 1(TN)	100,000,000	100,000,000	100,000,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	100,000,000	100,000,000	100,000,000

Table B.7: Scenario 2 – Maximum Inventory Capacity Input Data

Max Inv Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	148,000	133,200	106,400
Stage 1(Castings), Level 1, Supplier 2(Germany)	162,800	177,600	152,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	37,000	33,300	26,600
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	40,700	44,400	38,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	25,900	29,600	34,200
Stage 2(Components), Level 2(Heads), Supplier 2(China)	37,000	40,700	45,600
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	29,600	25,900	26,600
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	33,300	37,000	38,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	29,600	29,600	29,600
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	33,300	33,300	34,200
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	25,900	25,900	25,900
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	33,300	33,300	34,200
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	38,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	37,000	40,700	45,600

Table B.8: Scenario 2 – First Time Quality Input Data

FTQ Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	90%	91%	92%
Stage 1(Castings), Level 1, Supplier 2(Germany)	92%	92%	93%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	96%	97%	97%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	95%	95%	96%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	94%	94%	94%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	95%	95%	95%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	97%	97%	98%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	98%	98%	98%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	98%	98%	99%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	99%	99%	99%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	96%	96%	97%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	96%	97%	97%
Stage 3(Assembly), Level 1, Supplier 1(TN)	98%	98%	98%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	97%	97%	98%

Table B.9: Scenario 2 – Late Delivery Input Data

Late Delivery Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	8%	7%	7%
Stage 1(Castings), Level 1, Supplier 2(Germany)	6%	6%	6%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	4%	4%	4%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	5%	5%	5%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	2%	2%	2%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	4%	3%	3%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	2%	2%	2%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	3%	2%	2%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	3%	3%	3%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	4%	4%	4%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	3%	2%	2%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	3%	3%	3%
Stage 3(Assembly), Level 1, Supplier 1(TN)	3%	2%	2%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	2%	2%	1%

Table B.10: Scenario 2 – Penalty Rate Input Data

Penalty Rate Per Period for all Suppliers ($)	10

Table B.11: Scenario 2 – Risk Level Input Data

Risk Per Stage, Level, Supplier, Time (L/M/H - 1/2/3)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	1	1	1
Stage 1(Castings), Level 1, Supplier 2(Germany)	2	2	2
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	1	1	1
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	3	3	2
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	1	1	1
Stage 2(Components), Level 2(Heads), Supplier 2(China)	3	2	2
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	1	1	1
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	2	2	2
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	1	1	1
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	3	2	2
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	1	1	1
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	2	2	2
Stage 3(Assembly), Level 1, Supplier 1(TN)	1	1	1
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	2	2	2

Table B.12: Scenario 2 – Transport Number Input Data

Transport Number (Between Origin & Destination)					
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Sup 1	Dest Sup 2
1 (Castings)	1	1	1 (Blocks)	2	2
1 (Castings)	1	1	2 (Heads)	2	2
1 (Castings)	1	1	3 (Cranks)	2	2
1 (Castings)	1	1	4 (Cams)	2	2
1 (Castings)	1	1	5 (Piston/Rod)	2	2
1 (Castings)	1	2	1 (Blocks)	2	2
1 (Castings)	1	2	2 (Heads)	2	2
1 (Castings)	1	2	3 (Cranks)	2	2
1 (Castings)	1	2	4 (Cams)	2	2
1 (Castings)	1	2	5 (Piston/Rod)	2	2
2 (Components)	1 (Blocks)	1	1 (Assembly)	2	2
2 (Components)	1 (Blocks)	2	1 (Assembly)	2	2
2 (Components)	2 (Heads)	1	1 (Assembly)	2	2
2 (Components)	2 (Heads)	2	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	1	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	2	1 (Assembly)	2	2
2 (Components)	4 (Cams)	1	1 (Assembly)	2	2
2 (Components)	4 (Cams)	2	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	1	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	2	1 (Assembly)	2	2
3 (Assembly)	1	1	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	3 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	3 (Vehicle Assembly)	2	2

Table B.13: Scenario 2 – Transportation Costs Input Data

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	1 (Blocks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	1 (Blocks)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	1 (Blocks)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	2 (Heads)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	2 (Heads)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	2 (Heads)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	3 (Cranks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	1	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	4 (Cams)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	4 (Cams)	2	2 (Priority)	175	180	190
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	85	90	95
1 (Castings)	1	1	5 (Piston/Rod)	1	2 (Priority)	200	205	210
1 (Castings)	1	1	5 (Piston/Rod)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	5 (Piston/Rod)	2	2 (Priority)	175	180	190
1 (Castings)	1	2	1 (Blocks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	1 (Blocks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	1 (Blocks)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	1 (Blocks)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	2 (Heads)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	2 (Heads)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	2 (Heads)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	2 (Heads)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	3 (Cranks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	3 (Cranks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	2	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	2	4 (Cams)	1	1 (Economy)	170	175	180
1 (Castings)	1	2	4 (Cams)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	4 (Cams)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	4 (Cams)	2	2 (Priority)	215	220	225
1 (Castings)	1	2	5 (Piston/Rod)	1	1 (Economy)	175	180	180
1 (Castings)	1	2	5 (Piston/Rod)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	5 (Piston/Rod)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	5 (Piston/Rod)	2	2 (Priority)	215	220	225
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	127	135	140
2 (Components)	1	1	1 (Assembly)	1	2 (Priority)	273	285	300
2 (Components)	1	1	1 (Assembly)	2	1 (Economy)	223	230	235
2 (Components)	1	1	1 (Assembly)	2	2 (Priority)	276	280	285
2 (Components)	1	2	1 (Assembly)	1	1(Economy)	300	310	320
2 (Components)	1	2	1 (Assembly)	1	2 (Priority)	608	615	620
2 (Components)	1	2	1 (Assembly)	2	1 (Economy)	275	290	300
2 (Components)	1	2	1 (Assembly)	2	2 (Priority)	575	595	604
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	70	75	85
2 (Components)	2	1	1 (Assembly)	1	2 (Priority)	160	165	170
2 (Components)	2	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	2	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	2	2	1 (Assembly)	1	1 (Economy)	269	275	280
2 (Components)	2	2	1 (Assembly)	1	2 (Priority)	353	360	367
2 (Components)	2	2	1 (Assembly)	2	1 (Economy)	245	250	255
2 (Components)	2	2	1 (Assembly)	2	2 (Priority)	325	330	340

Table B.13: Scenario 2 – Transportation Costs Input Data Contd..

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	3	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	3	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	3	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	3	2	1 (Assembly)	1	1 (Economy)	163	165	170
2 (Components)	3	2	1 (Assembly)	1	2 (Priority)	193	200	207
2 (Components)	3	2	1 (Assembly)	2	1 (Economy)	50	55	60
2 (Components)	3	2	1 (Assembly)	2	2 (Priority)	110	115	120
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	4	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	4	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	4	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	4	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	2	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	5	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	5	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	5	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	5	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	2	1 (Assembly)	2	2 (Priority)	143	145	150
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	286	295	305
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	2 (Priority)	558	570	580
3 (Assembly)	1	1	2 (Vehile Assembly)	1	1 (Economy)	286	295	305
3 (Assembly)	1	1	2 (Vehile Assembly)	1	2 (Priority)	558	570	580
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	158	165	170
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	2 (Priority)	315	325	335
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	2 (Vehile Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	2 (Vehile Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	2 (Priority)	625	630	645

Table B.14: Scenario 2 – Transportation Capacity Input Data

Transport Capacity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1	1	1	1	1	1	100,000,000	100,000,000	100,000,000
1	1	1	1	1	2	100,000,000	100,000,000	100,000,000
1	1	1	1	2	1	100,000,000	100,000,000	100,000,000
1	1	1	1	2	2	100,000,000	100,000,000	100,000,000
1	1	1	2	1	1	100,000,000	100,000,000	100,000,000
1	1	1	2	1	2	100,000,000	100,000,000	100,000,000
1	1	1	2	2	1	100,000,000	100,000,000	100,000,000
1	1	1	2	2	2	100,000,000	100,000,000	100,000,000
1	1	1	3	1	1	100,000,000	100,000,000	100,000,000
1	1	1	3	1	2	100,000,000	100,000,000	100,000,000
1	1	1	3	2	1	100,000,000	100,000,000	100,000,000
1	1	1	3	2	2	100,000,000	100,000,000	100,000,000
1	1	1	4	1	1	100,000,000	100,000,000	100,000,000
1	1	1	4	1	2	100,000,000	100,000,000	100,000,000
1	1	1	4	2	1	100,000,000	100,000,000	100,000,000
1	1	1	4	2	2	100,000,000	100,000,000	100,000,000
1	1	1	5	1	1	100,000,000	100,000,000	100,000,000
1	1	1	5	1	2	100,000,000	100,000,000	100,000,000
1	1	1	5	2	1	100,000,000	100,000,000	100,000,000
1	1	1	5	2	2	100,000,000	100,000,000	100,000,000
1	1	2	1	1	1	100,000,000	100,000,000	100,000,000
1	1	2	1	1	2	100,000,000	100,000,000	100,000,000
1	1	2	1	2	1	100,000,000	100,000,000	100,000,000
1	1	2	1	2	2	100,000,000	100,000,000	100,000,000
1	1	2	2	1	1	100,000,000	100,000,000	100,000,000
1	1	2	2	1	2	100,000,000	100,000,000	100,000,000
1	1	2	2	2	1	100,000,000	100,000,000	100,000,000
1	1	2	2	2	2	100,000,000	100,000,000	100,000,000
1	1	2	3	1	1	100,000,000	100,000,000	100,000,000
1	1	2	3	1	2	100,000,000	100,000,000	100,000,000
1	1	2	3	2	1	100,000,000	100,000,000	100,000,000
1	1	2	3	2	2	100,000,000	100,000,000	100,000,000
1	1	2	4	1	1	100,000,000	100,000,000	100,000,000
1	1	2	4	1	2	100,000,000	100,000,000	100,000,000
1	1	2	4	2	1	100,000,000	100,000,000	100,000,000
1	1	2	4	2	2	100,000,000	100,000,000	100,000,000
1	1	2	5	1	1	100,000,000	100,000,000	100,000,000
1	1	2	5	1	2	100,000,000	100,000,000	100,000,000
1	1	2	5	2	1	100,000,000	100,000,000	100,000,000
1	1	2	5	2	2	100,000,000	100,000,000	100,000,000
2	1	1	1	1	1	100,000,000	100,000,000	100,000,000
2	1	1	1	1	2	100,000,000	100,000,000	100,000,000
2	1	1	1	2	1	100,000,000	100,000,000	100,000,000
2	1	1	1	2	2	100,000,000	100,000,000	100,000,000
2	1	2	1	1	1	100,000,000	100,000,000	100,000,000
2	1	2	1	1	2	100,000,000	100,000,000	100,000,000
2	1	2	1	2	1	100,000,000	100,000,000	100,000,000
2	1	2	1	2	2	100,000,000	100,000,000	100,000,000

Table B.14: Scenario 2 – Transportation Capacity Input Data Contd…

Transport Capacity Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	Period 1 1st Year	Period 2 2nd Year	Period 3 3rd Year
2	2	1	1	1	1	100,000,000	100,000,000	100,000,000
2	2	1	1	1	2	100,000,000	100,000,000	100,000,000
2	2	1	1	2	1	100,000,000	100,000,000	100,000,000
2	2	1	1	2	2	100,000,000	100,000,000	100,000,000
2	2	2	1	1	1	100,000,000	100,000,000	100,000,000
2	2	2	1	1	2	100,000,000	100,000,000	100,000,000
2	2	2	1	2	1	100,000,000	100,000,000	100,000,000
2	2	2	1	2	2	100,000,000	100,000,000	100,000,000
2	3	1	1	1	1	100,000,000	100,000,000	100,000,000
2	3	1	1	1	2	100,000,000	100,000,000	100,000,000
2	3	1	1	2	1	100,000,000	100,000,000	100,000,000
2	3	1	1	2	2	100,000,000	100,000,000	100,000,000
2	3	2	1	1	1	100,000,000	100,000,000	100,000,000
2	3	2	1	1	2	100,000,000	100,000,000	100,000,000
2	3	2	1	2	1	100,000,000	100,000,000	100,000,000
2	3	2	1	2	2	100,000,000	100,000,000	100,000,000
2	4	1	1	1	1	100,000,000	100,000,000	100,000,000
2	4	1	1	1	2	100,000,000	100,000,000	100,000,000
2	4	1	1	2	1	100,000,000	100,000,000	100,000,000
2	4	1	1	2	2	100,000,000	100,000,000	100,000,000
2	4	2	1	1	1	100,000,000	100,000,000	100,000,000
2	4	2	1	1	2	100,000,000	100,000,000	100,000,000
2	4	2	1	2	1	100,000,000	100,000,000	100,000,000
2	4	2	1	2	2	100,000,000	100,000,000	100,000,000
2	5	1	1	1	1	100,000,000	100,000,000	100,000,000
2	5	1	1	1	2	100,000,000	100,000,000	100,000,000
2	5	1	1	2	1	100,000,000	100,000,000	100,000,000
2	5	1	1	2	2	100,000,000	100,000,000	100,000,000
2	5	2	1	1	1	100,000,000	100,000,000	100,000,000
2	5	2	1	1	2	100,000,000	100,000,000	100,000,000
2	5	2	1	2	1	100,000,000	100,000,000	100,000,000
2	5	2	1	2	2	100,000,000	100,000,000	100,000,000
3	1	1	1	1	1	100,000,000	100,000,000	100,000,000
3	1	1	1	1	2	100,000,000	100,000,000	100,000,000
3	1	1	2	1	1	100,000,000	100,000,000	100,000,000
3	1	1	2	1	2	100,000,000	100,000,000	100,000,000
3	1	1	3	1	1	100,000,000	100,000,000	100,000,000
3	1	1	3	1	2	100,000,000	100,000,000	100,000,000
3	1	2	1	1	1	100,000,000	100,000,000	100,000,000
3	1	2	1	1	2	100,000,000	100,000,000	100,000,000
3	1	2	2	1	1	100,000,000	100,000,000	100,000,000
3	1	2	2	1	2	100,000,000	100,000,000	100,000,000
3	1	2	3	1	1	100,000,000	100,000,000	100,000,000
3	1	2	3	1	2	100,000,000	100,000,000	100,000,000

APPENDIX C

Scenario 1 – Split Demand, Single Criterion – Input Data

Table C.1: Scenario 3 - Demand Input Data

Demand (Units/Year)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Customer 1 - Vehicle Asssembly Plant - MI	375,000	450,000	525,000
Customer 2 - Vehicle Asssembly Plant - OH	175,000	175,000	175,000
Customer 3 - Vehicle Asssembly Plant - TN	375,000	300,000	250,000

Table C.2: Scenario 3 – Number of Stages Per Level

	Stage 1	Stage 2	Stage 3	Stage 4
Level Number Per Stage	1	5	1	3

Table C.3: Scenario 3 – Number of Suppliers Per Stage Per Level

SupNumPerStgPerLev	Level 1	Level 2	Level 3	Level 4	Level 5
Stage 1 - Castings	2	0	0	0	0
Stage 2 - Components (Blocks, Heads, Cranks, Cams, Piston/Rod)	2	2	2	2	2
Stage 3 - Engine Assembly	2	0	0	0	0
Stage 4 - Vehicle Assembly	1	1	1	0	0

Table C.4: Scenario 3 – Unit Production Costs Input Data

Unit Prodn Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$400	$410	$420
Stage 1(Castings), Level 1, Supplier 2(Germany)	$375	$380	$385
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$300	$350	$400
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$200	$225	$240
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$275	$250	$250
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$150	$155	$160
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$100	$105	$110
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$85	$85	$90
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$30	$32	$35
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$40	$40	$40
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$25	$27	$28
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$35	$40	$40
Stage 3(Assembly), Level 1, Supplier 1(TN)	$375	$425	$450
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$300	$310	$320

Table C.5: Scenario 3 – Unit Inventory Costs Input Data

Unit Inv Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$20	$22	$23
Stage 1(Castings), Level 1, Supplier 2(Germany)	$22	$23	$24
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$25	$30	$35
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$20	$22	$23
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$17	$18	$20
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$13	$15	$17
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$15	$14	$13
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$10	$11	$12
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$5	$6	$6
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$8	$9	$10
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$5	$5	$6
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$8	$8	$10
Stage 3(Assembly), Level 1, Supplier 1(TN)	$30	$35	$40
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$30	$30	$35

Table C.6: Scenario 3 – Production Capacity Input Data

Prodn Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	3,000,000	3,500,000	4,000,000
Stage 1(Castings), Level 1, Supplier 2(Germany)	3,000,000	3,000,000	2,000,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	500,000	600,000	700,000
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	600,000	900,000	700,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	500,000	550,000	600,000
Stage 2(Components), Level 2(Heads), Supplier 2(China)	600,000	800,000	1,000,000
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	500,000	500,000	500,000
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	700,000	1,000,000	1,000,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	700,000	800,000	900,000
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	500,000	500,000	500,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	700,000	800,000	900,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	500,000	500,000	500,000
Stage 3(Assembly), Level 1, Supplier 1(TN)	500,000	500,000	500,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	600,000	900,000	1,000,000

Table C.7: Scenario 3 – Maximum Inventory Capacity Input Data

Max Inv Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	148,000	133,200	106,400
Stage 1(Castings), Level 1, Supplier 2(Germany)	162,800	177,600	152,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	37,000	33,300	26,600
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	40,700	44,400	38,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	25,900	29,600	34,200
Stage 2(Components), Level 2(Heads), Supplier 2(China)	37,000	40,700	45,600
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	29,600	25,900	26,600
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	33,300	37,000	38,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	29,600	29,600	29,600
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	33,300	33,300	34,200
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	25,900	25,900	25,900
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	33,300	33,300	34,200
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	38,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	37,000	40,700	45,600

Table C.8: Scenario 3 – First Time Quality Input Data

FTQ Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	100%	100%	100%
Stage 1(Castings), Level 1, Supplier 2(Germany)	100%	100%	100%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	100%	100%	100%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	100%	100%	100%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	100%	100%	100%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	100%	100%	100%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	100%	100%	100%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	100%	100%	100%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	100%	100%	100%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	100%	100%	100%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	100%	100%	100%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	100%	100%	100%
Stage 3(Assembly), Level 1, Supplier 1(TN)	100%	100%	100%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	100%	100%	100%

Table C.9: Scenario 3 – Late Delivery Input Data

Late Delivery Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0%	0%	0%
Stage 1(Castings), Level 1, Supplier 2(Germany)	0%	0%	0%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0%	0%	0%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0%	0%	0%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0%	0%	0%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0%	0%	0%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0%	0%	0%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0%	0%	0%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0%	0%	0%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0%	0%	0%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0%	0%	0%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0%	0%	0%
Stage 3(Assembly), Level 1, Supplier 1(TN)	0%	0%	0%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0%	0%	0%

Table C.10: Scenario 3 – Penalty Rate Input Data

Penalty Rate Per Period for all Suppliers ($)	0

Table C.11: Scenario 3 – Risk Level Input Data

Risk Per Stage, Level, Supplier, Time (L/M/H - 1/2/3)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	0	0	0
Stage 1(Castings), Level 1, Supplier 2(Germany)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	0	0	0
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	0	0	0
Stage 2(Components), Level 2(Heads), Supplier 2(China)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	0	0	0
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	0	0	0
Stage 3(Assembly), Level 1, Supplier 1(TN)	0	0	0
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	0	0	0

Table C.12: Scenario 3 – Transport Number Input Data

Transport Number (Between Origin & Destination)				Dest Sup 1	Dest Sup 2
Origin Stage	Org Level	Org Supplier	Dest Level		
1 (Castings)	1	1	1 (Blocks)	2	2
1 (Castings)	1	1	2 (Heads)	2	2
1 (Castings)	1	1	3 (Cranks)	2	2
1 (Castings)	1	1	4 (Cams)	2	2
1 (Castings)	1	1	5 (Piston/Rod)	2	2
1 (Castings)	1	2	1 (Blocks)	2	2
1 (Castings)	1	2	2 (Heads)	2	2
1 (Castings)	1	2	3 (Cranks)	2	2
1 (Castings)	1	2	4 (Cams)	2	2
1 (Castings)	1	2	5 (Piston/Rod)	2	2
2 (Components)	1 (Blocks)	1	1 (Assembly)	2	2
2 (Components)	1 (Blocks)	2	1 (Assembly)	2	2
2 (Components)	2 (Heads)	1	1 (Assembly)	2	2
2 (Components)	2 (Heads)	2	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	1	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	2	1 (Assembly)	2	2
2 (Components)	4 (Cams)	1	1 (Assembly)	2	2
2 (Components)	4 (Cams)	2	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	1	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	2	1 (Assembly)	2	2
3 (Assembly)	1	1	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	3 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	3 (Vehicle Assembly)	2	2

Table C.13: Scenario 3 – Transportation Costs Input Data

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	1 (Blocks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	1 (Blocks)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	1 (Blocks)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	2 (Heads)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	2 (Heads)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	2 (Heads)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	3 (Cranks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	1	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	4 (Cams)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	4 (Cams)	2	2 (Priority)	175	180	190
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	85	90	95
1 (Castings)	1	1	5 (Piston/Rod)	1	2 (Priority)	200	205	210
1 (Castings)	1	1	5 (Piston/Rod)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	5 (Piston/Rod)	2	2 (Priority)	175	180	190
1 (Castings)	1	2	1 (Blocks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	1 (Blocks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	1 (Blocks)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	1 (Blocks)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	2 (Heads)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	2 (Heads)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	2 (Heads)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	2 (Heads)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	3 (Cranks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	3 (Cranks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	2	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	2	4 (Cams)	1	1 (Economy)	170	175	180
1 (Castings)	1	2	4 (Cams)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	4 (Cams)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	4 (Cams)	2	2 (Priority)	215	220	225
1 (Castings)	1	2	5 (Piston/Rod)	1	1 (Economy)	175	180	180
1 (Castings)	1	2	5 (Piston/Rod)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	5 (Piston/Rod)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	5 (Piston/Rod)	2	2 (Priority)	215	220	225
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	127	135	140
2 (Components)	1	1	1 (Assembly)	1	2 (Priority)	273	285	300
2 (Components)	1	1	1 (Assembly)	2	1 (Economy)	223	230	235
2 (Components)	1	1	1 (Assembly)	2	2 (Priority)	276	280	285
2 (Components)	1	2	1 (Assembly)	1	1(Economy)	300	310	320
2 (Components)	1	2	1 (Assembly)	1	2 (Priority)	608	615	620
2 (Components)	1	2	1 (Assembly)	2	1 (Economy)	275	290	300
2 (Components)	1	2	1 (Assembly)	2	2 (Priority)	575	595	604
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	70	75	85
2 (Components)	2	1	1 (Assembly)	1	2 (Priority)	160	165	170
2 (Components)	2	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	2	1	1 (Assembly)	2	2 (Priority)	193	198	205

Table C.13: Scenario 3 – Transportation Costs Input Data Contd..

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
2 (Components)	2	2	1 (Assembly)	1	1 (Economy)	269	275	280
2 (Components)	2	2	1 (Assembly)	1	2 (Priority)	353	360	367
2 (Components)	2	2	1 (Assembly)	2	1 (Economy)	245	250	255
2 (Components)	2	2	1 (Assembly)	2	2 (Priority)	325	330	340
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	3	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	3	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	3	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	3	2	1 (Assembly)	1	1 (Economy)	163	165	170
2 (Components)	3	2	1 (Assembly)	1	2 (Priority)	193	200	207
2 (Components)	3	2	1 (Assembly)	2	1 (Economy)	50	55	60
2 (Components)	3	2	1 (Assembly)	2	2 (Priority)	110	115	120
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	4	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	4	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	4	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	4	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	2	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	5	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	5	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	5	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	5	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	2	1 (Assembly)	2	2 (Priority)	143	145	150
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	286	295	305
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	2 (Priority)	558	570	580
3 (Assembly)	[illegible]	1	2 (Vehile Assembly)	1	1 (Economy)	286	295	305
3 (Assembly)	1	1	2 (Vehile Assembly)	1	2 (Priority)	558	570	580
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	158	165	170
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	2 (Priority)	315	325	335
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	2 (Vehile Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	2 (Vehile Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	2 (Priority)	625	630	645

Table C.14: Scenario 3 – Transportation Capacity Input Data

Transport Capacity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1	1	1	1	1	1	500,000	600,000	700,000
1	1	1	1	1	2	600,000	650,000	650,000
1	1	1	1	2	1	1,200,000	1,300,000	1,400,000
1	1	1	1	2	2	900,000	900,000	900,000
1	1	1	2	1	1	500,000	500,000	500,000
1	1	1	2	1	2	600,000	600,000	600,000
1	1	1	2	2	1	1,000,000	1,000,000	1,000,000
1	1	1	2	2	2	900,000	900,000	900,000
1	1	1	3	1	1	400,000	450,000	500,000
1	1	1	3	1	2	600,000	650,000	675,000
1	1	1	3	2	1	975,000	1,000,000	1,100,000
1	1	1	3	2	2	900,000	900,000	900,000
1	1	1	4	1	1	800,000	850,000	850,000
1	1	1	4	1	2	600,000	600,000	600,000
1	1	1	4	2	1	1,400,000	1,450,000	1,470,000
1	1	1	4	2	2	700,000	725,000	730,000
1	1	1	5	1	1	900,000	850,000	850,000
1	1	1	5	1	2	600,000	600,000	600,000
1	1	1	5	2	1	1,300,000	1,450,000	1,470,000
1	1	1	5	2	2	700,000	725,000	730,000
1	1	2	1	1	1	500,000	565,000	600,000
1	1	2	1	1	2	600,000	600,000	600,000
1	1	2	1	2	1	1,100,000	1,100,000	1,100,000
1	1	2	1	2	2	900,000	900,000	900,000
1	1	2	2	1	1	450,000	500,000	550,000
1	1	2	2	1	2	650,000	700,000	750,000
1	1	2	2	2	1	1,250,000	1,250,000	1,250,000
1	1	2	2	2	2	900,000	900,000	900,000
1	1	2	3	1	1	300,000	350,000	375,000
1	1	2	3	1	2	700,000	750,000	775,000
1	1	2	3	2	1	1,000,000	1,100,000	1,200,000
1	1	2	3	2	2	900,000	950,000	950,000
1	1	2	4	1	1	525,000	525,000	525,000
1	1	2	4	1	2	600,000	600,000	600,000
1	1	2	4	2	1	1,000,000	1,000,000	1,000,000
1	1	2	4	2	2	900,000	900,000	900,000
1	1	2	5	1	1	700,000	700,000	700,000
1	1	2	5	1	2	600,000	600,000	600,000
1	1	2	5	2	1	1,200,000	1,200,000	1,200,000
1	1	2	5	2	2	900,000	900,000	900,000
2	1	1	1	1	1	800,000	850,000	850,000
2	1	1	1	1	2	600,000	650,000	650,000
2	1	1	1	2	1	1,100,000	1,100,000	1,100,000
2	1	1	1	2	2	900,000	900,000	900,000
2	1	2	1	1	1	700,000	700,000	700,000
2	1	2	1	1	2	600,000	600,000	600,000
2	1	2	1	2	1	1,000,000	1,000,000	1,000,000
2	1	2	1	2	2	900,000	900,000	900,000
2	2	1	1	1	1	400,000	450,000	500,000
2	2	1	1	1	2	800,000	850,000	900,000
2	2	1	1	2	1	900,000	900,000	900,000
2	2	1	1	2	2	900,000	900,000	900,000

Table C.14: Scenario 3 – Transportation Capacity Input Data Contd…

Transport Capacity Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	Period 1 1st Year	Period 2 2nd Year	Period 3 3rd Year
2	2	2	1	1	1	500,000	500,000	500,000
2	2	2	1	1	2	600,000	600,000	600,000
2	2	2	1	2	1	1,500,000	1,500,000	1,500,000
2	2	2	1	2	2	900,000	900,000	900,000
2	3	1	1	1	1	650,000	650,000	650,000
2	3	1	1	1	2	600,000	600,000	600,000
2	3	1	1	2	1	2,000,000	2,000,000	2,000,000
2	3	1	1	2	2	900,000	900,000	900,000
2	3	2	1	1	1	3,000,000	3,000,000	3,000,000
2	3	2	1	1	2	600,000	600,000	600,000
2	3	2	1	2	1	800,000	800,000	800,000
2	3	2	1	2	2	900,000	900,000	900,000
2	4	1	1	1	1	500,000	500,000	500,000
2	4	1	1	1	2	600,000	600,000	600,000
2	4	1	1	2	1	1,000,000	1,100,000	1,200,000
2	4	1	1	2	2	900,000	900,000	900,000
2	4	2	1	1	1	750,000	750,000	775,000
2	4	2	1	1	2	650,000	650,000	675,000
2	4	2	1	2	1	1,350,000	1,350,000	1,350,000
2	4	2	1	2	2	900,000	900,000	900,000
2	5	1	1	1	1	500,000	700,000	800,000
2	5	1	1	1	2	600,000	600,000	600,000
2	5	1	1	2	1	1,200,000	1,200,000	1,200,000
2	5	1	1	2	2	900,000	900,000	900,000
2	5	2	1	1	1	850,000	850,000	850,000
2	5	2	1	1	2	650,000	650,000	675,000
2	5	2	1	2	1	1,350,000	1,350,000	1,350,000
2	5	2	1	2	2	850,000	900,000	950,000
3	1	1	1	1	1	1,000,000	1,000,000	1,000,000
3	1	1	1	1	2	1,500,000	1,500,000	1,500,000
3	1	1	2	1	1	1,000,000	1,000,000	1,000,000
3	1	1	2	1	2	1,500,000	1,500,000	1,500,000
3	1	1	3	1	1	1,000,000	1,000,000	1,000,000
3	1	1	3	1	2	1,500,000	1,500,000	1,500,000
3	1	2	1	1	1	1,000,000	1,000,000	1,000,000
3	1	2	1	1	2	1,500,000	1,500,000	1,500,000
3	1	2	2	1	1	1,000,000	1,000,000	1,000,000
3	1	2	2	1	2	1,500,000	1,500,000	1,500,000
3	1	2	3	1	1	1,000,000	1,000,000	1,000,000
3	1	2	3	1	2	1,500,000	1,500,000	1,500,000

APPENDIX D

Scenario 1 – Split Demand, Multiple Criteria – Input Data

Table D.1: Scenario 4 - Demand Input Data

Demand (Units/Year)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Customer 1 - Vehicle Assembly Plant - M	375,000	450,000	525,000
Customer 2 - Vehicle Assembly Plant - OH	175,000	175,000	175,000
Customer 3 - Vehicle Assembly Plant - TN	375,000	300,000	250,000

Table D.2: Scenario 4 – Number of Stages Per Level

	Stage 1	Stage 2	Stage 3	Stage 4
Level Number Per Stage	1	5	1	3

Table D.3: Scenario 4 – Number of Suppliers Per Stage Per Level

SupNumPerStgPerLev	Level 1	Level 2	Level 3	Level 4	Level 5
Stage 1 - Castings	2	0	0	0	0
Stage 2 - Components (Blocks, Heads, Cranks, Cams, Piston/Rod)	2	2	2	2	2
Stage 3 - Engine Assembly	2	0	0	0	0
Stage 4 - Vehicle Assembly	1	1	1	0	0

Table D.4: Scenario 4 – Unit Production Costs Input Data

Unit Prodn Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$400	$410	$420
Stage 1(Castings), Level 1, Supplier 2(Germany)	$375	$380	$385
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$300	$350	$400
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$200	$225	$240
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$275	$250	$250
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$150	$155	$160
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$100	$105	$110
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$85	$85	$90
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$30	$32	$35
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$40	$40	$40
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$25	$27	$28
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$35	$40	$40
Stage 3(Assembly), Level 1, Supplier 1(TN)	$375	$425	$450
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$300	$310	$320

Table D.5: Scenario 4 – Unit Inventory Costs Input Data

Unit Inv Cost Per Stage, Level, Supplier, Time ($)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	$20	$22	$23
Stage 1(Castings), Level 1, Supplier 2(Germany)	$22	$23	$24
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	$25	$30	$35
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	$20	$22	$23
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	$17	$18	$20
Stage 2(Components), Level 2(Heads), Supplier 2(China)	$13	$15	$17
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	$15	$14	$13
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	$10	$11	$12
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	$5	$6	$6
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	$8	$9	$10
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	$5	$5	$6
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	$8	$8	$10
Stage 3(Assembly), Level 1, Supplier 1(TN)	$30	$35	$40
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	$30	$30	$35

Table D.6: Scenario 4 – Production Capacity Input Data

Prodn Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	3,000,000	3,500,000	4,000,000
Stage 1(Castings), Level 1, Supplier 2(Germany)	3,000,000	3,000,000	2,000,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	500,000	600,000	700,000
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	600,000	900,000	700,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	500,000	550,000	600,000
Stage 2(Components), Level 2(Heads), Supplier 2(China)	600,000	800,000	1,000,000
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	500,000	500,000	500,000
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	700,000	1,000,000	1,000,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	700,000	800,000	900,000
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	500,000	500,000	500,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	700,000	800,000	900,000
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	500,000	500,000	500,000
Stage 3(Assembly), Level 1, Supplier 1(TN)	500,000	500,000	500,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	600,000	900,000	1,000,000

Table D.7: Scenario 4 – Maximum Inventory Capacity Input Data

Max Inv Capacity Per Stage, Level, Supplier, Time (Units)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	148,000	133,200	106,400
Stage 1(Castings), Level 1, Supplier 2(Germany)	162,800	177,600	152,000
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	37,000	33,300	26,600
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	40,700	44,400	38,000
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	25,900	29,600	34,200
Stage 2(Components), Level 2(Heads), Supplier 2(China)	37,000	40,700	45,600
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	29,600	25,900	26,600
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	33,300	37,000	38,000
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	29,600	29,600	29,600
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	33,300	33,300	34,200
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	25,900	25,900	25,900
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	33,300	33,300	34,200
Stage 3(Assembly), Level 1, Supplier 1(TN)	29,600	33,300	38,000
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	37,000	40,700	45,600

Table D.8: Scenario 4 – First Time Quality Input Data

FTQ Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	90%	91%	92%
Stage 1(Castings), Level 1, Supplier 2(Germany)	92%	92%	93%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	96%	97%	97%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	95%	95%	96%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	94%	94%	94%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	95%	95%	95%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	97%	97%	98%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	98%	98%	98%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	98%	98%	99%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	99%	99%	99%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	96%	96%	97%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	96%	97%	97%
Stage 3(Assembly), Level 1, Supplier 1(TN)	98%	98%	98%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	97%	97%	98%

Table D.9: Scenario 4 – Late Delivery Input Data

Late Delivery Per Stage, Level, Supplier, Time (%)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	8%	7%	7%
Stage 1(Castings), Level 1, Supplier 2(Germany)	6%	6%	6%
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	4%	4%	4%
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	5%	5%	5%
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	2%	2%	2%
Stage 2(Components), Level 2(Heads), Supplier 2(China)	4%	3%	3%
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	2%	2%	2%
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	3%	2%	2%
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	3%	3%	3%
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	4%	4%	4%
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	3%	2%	2%
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	3%	3%	3%
Stage 3(Assembly), Level 1, Supplier 1(TN)	3%	2%	2%
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	2%	2%	1%

Table D.10: Scenario 4 – Penalty Rate Input Data

Penalty Rate Per Period for all Suppliers ($)	10

Table D.11: Scenario 4 – Risk Level Input Data

Risk Per Stage, Level, Supplier, Time (L/M/H - 1/2/3)	Period 1 - 1st Year	Period 2 - 2nd Year	Period 3 - 3rd Year
Stage 1(Castings), Level 1, Supplier 1(OH)	1	1	1
Stage 1(Castings), Level 1, Supplier 2(Germany)	2	2	2
Stage 2(Components), Level 1(Blocks), Supplier 1(NY)	1	1	1
Stage 2(Components), Level 1(Blocks), Supplier 2(China)	3	3	2
Stage 2(Components), Level 2(Heads), Supplier 1(MI)	1	1	1
Stage 2(Components), Level 2(Heads), Supplier 2(China)	3	2	2
Stage 2(Components), Level 3(Cranks), Supplier 1(ON)	1	1	1
Stage 2(Components), Level 3(Cranks), Supplier 2(Mexico)	2	2	2
Stage 2(Components), Level 4(Cams), Supplier 1(ON)	1	1	1
Stage 2(Components), Level 4(Cams), Supplier 2(CA)	3	2	2
Stage 2(Components), Level 5(Piston/Rod), Supplier 1(ON)	1	1	1
Stage 2(Components), Level 5(Piston/Rod), Supplier 2(CA)	2	2	2
Stage 3(Assembly), Level 1, Supplier 1(TN)	1	1	1
Stage 3(Assembly), Level 1, Supplier 2(Mexico)	2	2	2

Table D.12: Scenario 4 – Transport Number Input Data

Transport Number (Between Origin & Destination) Origin Stage	Org Level	Org Supplier	Dest Level	Dest Sup 1	Dest Sup 2
1 (Castings)	1	1	1 (Blocks)	2	2
1 (Castings)	1	1	2 (Heads)	2	2
1 (Castings)	1	1	3 (Cranks)	2	2
1 (Castings)	1	1	4 (Cams)	2	2
1 (Castings)	1	1	5 (Piston/Rod)	2	2
1 (Castings)	1	2	1 (Blocks)	2	2
1 (Castings)	1	2	2 (Heads)	2	2
1 (Castings)	1	2	3 (Cranks)	2	2
1 (Castings)	1	2	4 (Cams)	2	2
1 (Castings)	1	2	5 (Piston/Rod)	2	2
2 (Components)	1 (Blocks)	1	1 (Assembly)	2	2
2 (Components)	1 (Blocks)	2	1 (Assembly)	2	2
2 (Components)	2 (Heads)	1	1 (Assembly)	2	2
2 (Components)	2 (Heads)	2	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	1	1 (Assembly)	2	2
2 (Components)	3 (Cranks)	2	1 (Assembly)	2	2
2 (Components)	4 (Cams)	1	1 (Assembly)	2	2
2 (Components)	4 (Cams)	2	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	1	1 (Assembly)	2	2
2 (Components)	5 (Piston/Rod)	2	1 (Assembly)	2	2
3 (Assembly)	1	1	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	1	3 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	1 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	2 (Vehicle Assembly)	2	2
3 (Assembly)	1	2	3 (Vehicle Assembly)	2	2

Table D.13: Scenario 4 – Transportation Costs Input Data

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1 (Castings)	1	1	1 (Blocks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	1 (Blocks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	1 (Blocks)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	1 (Blocks)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	2 (Heads)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	2 (Heads)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	2 (Heads)	2	1 (Economy)	291	300	310
1 (Castings)	1	1	2 (Heads)	2	2 (Priority)	463	470	480
1 (Castings)	1	1	3 (Cranks)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	3 (Cranks)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	1	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	1	4 (Cams)	1	1 (Economy)	96	100	105
1 (Castings)	1	1	4 (Cams)	1	2 (Priority)	209	215	220
1 (Castings)	1	1	4 (Cams)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	4 (Cams)	2	2 (Priority)	175	180	190
1 (Castings)	1	1	5 (Piston/Rod)	1	1 (Economy)	85	90	95
1 (Castings)	1	1	5 (Piston/Rod)	1	2 (Priority)	200	205	210
1 (Castings)	1	1	5 (Piston/Rod)	2	1 (Economy)	80	85	90
1 (Castings)	1	1	5 (Piston/Rod)	2	2 (Priority)	175	180	190
1 (Castings)	1	2	1 (Blocks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	1 (Blocks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	1 (Blocks)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	1 (Blocks)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	2 (Heads)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	2 (Heads)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	2 (Heads)	2	1 (Economy)	250	265	270
1 (Castings)	1	2	2 (Heads)	2	2 (Priority)	450	465	470
1 (Castings)	1	2	3 (Cranks)	1	1 (Economy)	262	270	275
1 (Castings)	1	2	3 (Cranks)	1	2 (Priority)	341	345	350
1 (Castings)	1	2	3 (Cranks)	2	1 (Economy)	164	170	175
1 (Castings)	1	2	3 (Cranks)	2	2 (Priority)	193	200	210
1 (Castings)	1	2	4 (Cams)	1	1 (Economy)	170	175	180
1 (Castings)	1	2	4 (Cams)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	4 (Cams)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	4 (Cams)	2	2 (Priority)	215	220	225
1 (Castings)	1	2	5 (Piston/Rod)	1	1 (Economy)	175	180	180
1 (Castings)	1	2	5 (Piston/Rod)	1	2 (Priority)	210	215	220
1 (Castings)	1	2	5 (Piston/Rod)	2	1 (Economy)	175	180	185
1 (Castings)	1	2	5 (Piston/Rod)	2	2 (Priority)	215	220	225
2 (Components)	1	1	1 (Assembly)	1	1 (Economy)	127	135	140
2 (Components)	1	1	1 (Assembly)	1	2 (Priority)	273	285	300
2 (Components)	1	1	1 (Assembly)	2	1 (Economy)	223	230	235
2 (Components)	1	1	1 (Assembly)	2	2 (Priority)	276	280	285
2 (Components)	1	2	1 (Assembly)	1	1(Economy)	300	310	320
2 (Components)	1	2	1 (Assembly)	1	2 (Priority)	608	615	620
2 (Components)	1	2	1 (Assembly)	2	1 (Economy)	275	290	300
2 (Components)	1	2	1 (Assembly)	2	2 (Priority)	575	595	604
2 (Components)	2	1	1 (Assembly)	1	1(Economy)	70	75	85
2 (Components)	2	1	1 (Assembly)	1	2 (Priority)	160	165	170
2 (Components)	2	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	2	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	2	2	1 (Assembly)	1	1 (Economy)	269	275	280
2 (Components)	2	2	1 (Assembly)	1	2 (Priority)	353	360	367
2 (Components)	2	2	1 (Assembly)	2	1 (Economy)	245	250	255
2 (Components)	2	2	1 (Assembly)	2	2 (Priority)	325	330	340

Table D.13: Scenario 4 – Transportation Costs Input Data Contd...

Unit Transport Cost ($)						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
2 (Components)	3	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	3	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	3	1	1 (Assembly)	2	1 (Economy)	164	170	175
2 (Components)	3	1	1 (Assembly)	2	2 (Priority)	193	198	205
2 (Components)	3	2	1 (Assembly)	1	1 (Economy)	163	165	170
2 (Components)	3	2	1 (Assembly)	1	2 (Priority)	193	200	207
2 (Components)	3	2	1 (Assembly)	2	1 (Economy)	50	55	60
2 (Components)	3	2	1 (Assembly)	2	2 (Priority)	110	115	120
2 (Components)	4	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	4	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	4	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	4	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	4	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	4	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	4	2	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	1	1 (Assembly)	1	1 (Economy)	60	62	65
2 (Components)	5	1	1 (Assembly)	1	2 (Priority)	140	142	145
2 (Components)	5	1	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	1	1 (Assembly)	2	2 (Priority)	143	145	150
2 (Components)	5	2	1 (Assembly)	1	1 (Economy)	65	70	75
2 (Components)	5	2	1 (Assembly)	1	2 (Priority)	150	155	160
2 (Components)	5	2	1 (Assembly)	2	1 (Economy)	131	135	140
2 (Components)	5	2	1 (Assembly)	2	2 (Priority)	143	145	150
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	1(Economy)	286	295	305
3 (Assembly)	1	1	1 (Vehicle Assembly)	1	2 (Priority)	568	570	580
3 (Assembly)	1	1	2 (Vehile Assembly)	1	1 (Economy)	286	295	305
3 (Assembly)	1	1	2 (Vehile Assembly)	1	2 (Priority)	568	570	580
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	1 (Economy)	158	165	170
3 (Assembly)	1	1	3 (Vehicle Assembly)	1	2 (Priority)	315	325	335
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	1 (Vehicle Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	2 (Vehile Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	2 (Vehile Assembly)	1	2 (Priority)	625	630	645
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	1 (Economy)	501	510	514
3 (Assembly)	1	2	3 (Vehicle Assembly)	1	2 (Priority)	625	630	645

Table D.14: Scenario 4 – Transportation Capacity Input Data

Transport Capacity						Period 1	Period 2	Period 3
Origin Stage	Org Level	Org Supplier	Dest Level	Dest Supplier	Trans Mode	1st Year	2nd Year	3rd Year
1	1	1	1	1	1	500,000	600,000	700,000
1	1	1	1	1	2	600,000	650,000	650,000
1	1	1	1	2	1	1,200,000	1,300,000	1,400,000
1	1	1	1	2	2	900,000	900,000	900,000
1	1	1	2	1	1	500,000	500,000	500,000
1	1	1	2	1	2	600,000	600,000	600,000
1	1	1	2	2	1	1,000,000	1,000,000	1,000,000
1	1	1	2	2	2	900,000	900,000	900,000
1	1	1	3	1	1	400,000	450,000	500,000
1	1	1	3	1	2	600,000	650,000	675,000
1	1	1	3	2	1	975,000	1,000,000	1,100,000
1	1	1	3	2	2	900,000	900,000	900,000
1	1	1	4	1	1	800,000	850,000	850,000
1	1	1	4	1	2	600,000	600,000	600,000
1	1	1	4	2	1	1,400,000	1,450,000	1,470,000
1	1	1	4	2	2	700,000	725,000	730,000
1	1	1	5	1	1	900,000	850,000	850,000
1	1	1	5	1	2	600,000	600,000	600,000
1	1	1	5	2	1	1,300,000	1,450,000	1,470,000
1	1	1	5	2	2	700,000	725,000	730,000
1	1	2	1	1	1	500,000	565,000	600,000
1	1	2	1	1	2	600,000	600,000	600,000
1	1	2	1	2	1	1,100,000	1,100,000	1,100,000
1	1	2	1	2	2	900,000	900,000	900,000
1	1	2	2	1	1	450,000	500,000	550,000
1	1	2	2	1	2	650,000	700,000	750,000
1	1	2	2	2	1	1,250,000	1,250,000	1,250,000
1	1	2	2	2	2	900,000	900,000	900,000
1	1	2	3	1	1	300,000	350,000	375,000
1	1	2	3	1	2	700,000	750,000	775,000
1	1	2	3	2	1	1,000,000	1,100,000	1,200,000
1	1	2	3	2	2	900,000	950,000	950,000
1	1	2	4	1	1	525,000	525,000	525,000
1	1	2	4	1	2	600,000	600,000	600,000
1	1	2	4	2	1	1,000,000	1,000,000	1,000,000
1	1	2	4	2	2	900,000	900,000	900,000
1	1	2	5	1	1	700,000	700,000	700,000
1	1	2	5	1	2	600,000	600,000	600,000
1	1	2	5	2	1	1,200,000	1,200,000	1,200,000
1	1	2	5	2	2	900,000	900,000	900,000
2	1	1	1	1	1	800,000	850,000	850,000
2	1	1	1	1	2	600,000	650,000	650,000
2	1	1	1	2	1	1,100,000	1,100,000	1,100,000
2	1	1	1	2	2	900,000	900,000	900,000
2	1	2	1	1	1	700,000	700,000	700,000
2	1	2	1	1	2	600,000	600,000	600,000
2	1	2	1	2	1	1,000,000	1,000,000	1,000,000
2	1	2	1	2	2	900,000	900,000	900,000

Table D.14: Scenario 4 – Transportation Capacity Input Data Contd…

2	2	1	1	1	1	400,000	450,000	500,000
2	2	1	1	1	2	800,000	850,000	900,000
2	2	1	1	2	1	900,000	900,000	900,000
2	2	1	1	2	2	900,000	900,000	900,000
2	2	2	1	1	1	500,000	500,000	500,000
2	2	2	1	1	2	600,000	600,000	600,000
2	2	2	1	2	1	1,500,000	1,500,000	1,500,000
2	2	2	1	2	2	900,000	900,000	900,000
2	3	1	1	1	1	650,000	650,000	650,000
2	3	1	1	1	2	600,000	600,000	600,000
2	3	1	1	2	1	2,000,000	2,000,000	2,000,000
2	3	1	1	2	2	900,000	900,000	900,000
2	3	2	1	1	1	3,000,000	3,000,000	3,000,000
2	3	2	1	1	2	600,000	600,000	600,000
2	3	2	1	2	1	800,000	800,000	800,000
2	3	2	1	2	2	900,000	900,000	900,000
2	4	1	1	1	1	500,000	500,000	500,000
2	4	1	1	1	2	600,000	600,000	600,000
2	4	1	1	2	1	1,000,000	1,100,000	1,200,000
2	4	1	1	2	2	900,000	900,000	900,000
2	4	2	1	1	1	750,000	750,000	775,000
2	4	2	1	1	2	650,000	650,000	675,000
2	4	2	1	2	1	1,350,000	1,350,000	1,350,000
2	4	2	1	2	2	900,000	900,000	900,000
2	5	1	1	1	1	500,000	700,000	800,000
2	5	1	1	1	2	600,000	600,000	600,000
2	5	1	1	2	1	1,200,000	1,200,000	1,200,000
2	5	1	1	2	2	900,000	900,000	900,000
2	5	2	1	1	1	850,000	850,000	850,000
2	5	2	1	1	2	650,000	650,000	675,000
2	5	2	1	2	1	1,350,000	1,350,000	1,350,000
2	5	2	1	2	2	850,000	900,000	950,000
3	1	1	1	1	1	1,000,000	1,000,000	1,000,000
3	1	1	1	1	2	1,500,000	1,500,000	1,500,000
3	1	1	2	1	1	1,000,000	1,000,000	1,000,000
3	1	1	2	1	2	1,500,000	1,500,000	1,500,000
3	1	1	3	1	1	1,000,000	1,000,000	1,000,000
3	1	1	3	1	2	1,500,000	1,500,000	1,500,000
3	1	2	1	1	1	1,000,000	1,000,000	1,000,000
3	1	2	1	1	2	1,500,000	1,500,000	1,500,000
3	1	2	2	1	1	1,000,000	1,000,000	1,000,000
3	1	2	2	1	2	1,500,000	1,500,000	1,500,000
3	1	2	3	1	1	1,000,000	1,000,000	1,000,000
3	1	2	3	1	2	1,500,000	1,500,000	1,500,000

APPENDIX E

This Appendix details the software code for No Split Demand - Single/Multiple Criteria models. The code is written in LINGO software language and requires the LINGO software program to run. Figures 4.10 and 4.11 shown earlier capture the components of the software system and the flow of data.

No Split Demand – Single/Multi Criteria Model Code

```
MODEL:
! NO Split Demand (BINARY VARIABLES), Single/Multi Criteria Formulation
;
! Has Production, Transport Costs, First Time Quality and Risk - All
Input read from InputData7.xls ;

SETS:

Customer/1, 2, 3/;
TimePeriod/1, 2, 3/;
Suppliers /1, 2/;                    ! Maximum number of suppliers at
any level at any stage;
TransModes /1, 2/;                   ! Maximum number of modes of
transport between any origin and destination;
Demand(Customer, TimePeriod): Dem ;
Stage/1, 2, 3, 4/ :LevNumPerStg;
Level/1, 2, 3, 4, 5/;                ! Maximum number of levels in any
stage;
Org_Stage/1, 2, 3/;
LevelsPerStage(Stage,Level): SupNumPerStgPerLev; ! LevStg1;

! Should read supplier data in the order of Stage, Level, Supplier,
TimePeriod;
SupplierData(LevelsPerStage,Suppliers,TimePeriod): C_Stg_Lev_Tim,
h_Stg_Lev_Tim, P_Stg_Lev_Tim, MH_Stg_Lev_Tim, F_Stg_Lev_Tim, X, Inv,
Risk, LateDelv, BX;

! Should read transport data in the order Origin Stage, Level,
Supplier, Destination Level, Supplier, Transport Mode, Timeperiod;
TransportData(Org_Stage,Level,Suppliers,Level,Suppliers,TransModes,Time
period): g_O_st_l_su_D_l_su_m_t, C_V_O_st_l_su_D_l_su_m_t, V, BV;
TransportNum(Org_Stage,Level,Suppliers,Level,Suppliers): TransNum;

EndSets

DATA:

StgNum = 4;
```

```
Dem  = @OLE('InputData7.xls', CustDem);
LevNumPerStg  = @OLE('InputData7.xls', LevNum);
SupNumPerStgPerLev  = @OLE('InputData7.xls', SupNum);
C_Stg_Lev_Tim  = @OLE('InputData7.xls', UnitCost);
h_Stg_Lev_Tim  = @OLE('InputData7.xls', UnitInv);
P_Stg_Lev_Tim  = @OLE('InputData7.xls', ProdCap);
MH_Stg_Lev_Tim  = @OLE('InputData7.xls', InvCap);
F_Stg_Lev_Tim  = @OLE('InputData7.xls', FTQ);
g_O_st_l_su_D_l_su_m_t = @OLE('InputData7.xls', TransCost);
C_V_O_st_l_su_D_l_su_m_t = @OLE('InputData7.xls', TransCap);
TransNum = @OLE('InputData7.xls', TransOpNum);
Risk  = @OLE('InputData7.xls', Risk);
LateDelv  = @OLE('InputData7.xls', Late);
PenaltyRt = @OLE('InputData7.xls', Penalty);

ENDDATA


! Inventory Balance Constraint;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t)| t #EQ# 1:
                        Inv(i, l, j, t) = (X (i, l, j, t) *
F_Stg_Lev_Tim (i, l, j, t)) -
                        @SUM(Level(d_l)| d_l #LE# LevNumPerStg((i +
1)):
                        @SUM(Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((i + 1), d_l):
                        @SUM(Transmodes (m)| m #LE# TransNum(i, l, j,
d_l, d_j):
                        V (i, l, j, d_l, d_j, m, t);)));); 
      ! Zero Starting Inventory ;
                  @FOR (Timeperiod (t)| t #GT# 1:
                        Inv(i, l, j, t) = Inv(i, l, j, (t-1)) + (X (i,
l, j, t) * F_Stg_Lev_Tim (i, l, j, t)) -
                        @SUM(Level(d_l)| d_l #LE# LevNumPerStg((i +
1)):
                        @SUM(Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((i + 1), d_l):
                        @SUM(Transmodes (m)| m #LE# TransNum(i, l, j,
d_l, d_j):
                        V (i, l, j, d_l, d_j, m, t);)));))));
      ! Inventory balance constraint;



! Flow Constraint;
! For every Time Period;
 @FOR (Timeperiod (t):
      ! For Each Origin Stage;
       @FOR( Stage( o_i)| o_i #LE# (StgNum - 2):
            ! For Origin each Level;
```

```
            @FOR( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
                  @FOR( Level( d_l)| d_l #LE# LevNumPerStg(o_i+1):
                        @FOR (Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((o_i+1), d_l):
                              @SUM(Suppliers (o_j)| o_j #LE#
SupNumPerStgPerLev(o_i, o_l):
                              @SUM(Transmodes (m)| m #LE# TransNum(o_i,
o_l, o_j, d_l, d_j):
                                    V (o_i, o_l, o_j, d_l, d_j, m, t)))
=
                                    X ((o_i+1), d_l, d_j, t);)))))); !
Flow Constraint;


! Meeting Customer Demand ;
! For every Time Period;
 @FOR (Timeperiod (t):
      ! For each Customer;
       @FOR (Customer (c):
            @SUM(Level(o_l)| o_l #LE# LevNumPerStg((stgnum - 1)):
            @SUM(Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev((stgnum -
1), o_l):
            @SUM(Transmodes (m)| m #LE# TransNum((stgnum -1), o_l, o_j,
c, 1):
            V ((stgnum -1), o_l, o_j, c, 1, m, t)))) = Dem(c,t););
            ! Meeting Customer Demand ;


! Single Supplier Selection Constraint;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For every Time Period;
            @FOR (Timeperiod (t):
                  ! Summation over every supplier at that stage &
level;
                  @SUM (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                        BX (i, l, j, t)) = 1 ; )));          ! Single
Supplier Selection Constraint ;


! Single Transport Selection Option Constraint;
! For Each Origin Stage;
 @FOR( Stage( o_i)| o_i #LE# (StgNum - 1):
      ! For each Origin Level;
      @FOR( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
            ! For each Origin Supplier;
            @FOR (Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev(o_i,
o_l):
                  ! For each Destination Level;
                  @FOR( Level( d_l)| d_l #LE# LevNumPerStg((o_i + 1)):
                        ! For each Destination Supplier;
```

```
                        @FOR (Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((o_i + 1), d_l):
                              ! For every Time Period;
                              @FOR (Timeperiod (t):
                              ! Summation over every Transport option
between origin and destination;
                              @SUM (Transmodes (m)| m #LE#
TransNum(o_i, o_l, o_j, d_l, d_j):
                                          BV (o_i, o_l, o_j, d_l, d_j,
m, t)) <= 1;       ))))));    ! Single Transport Option Selection
Constraint;



! Non Negativity, Capacity Constraint for each Supplier;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t):
                        X (i, l, j, t) >= 0;
      ! Non Negativity Constraint;
                        X (i, l, j, t) <= P_Stg_Lev_Tim (i, l, j, t) *
BX (i, l, j, t));)));    ! Supplier Capacity Constraint;



! Non Negativity, Inventory Capacity Constraint for each Supplier;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t):
                        Inv (i, l, j, t) >= 0;
      ! Non Negativity Constraint;
                        Inv (i, l, j, t) <= MH_Stg_Lev_Tim (i, l, j, t)
* BX (i, l, j, t));))); ! Supplier Inventory Capacity Constraint;



! Non Negativity, Transport Capacity Constraint for each Transport
Option;
! For Each Origin Stage;
 @FOR( Stage( o_i)| o_i #LE# (StgNum - 1):
      ! For each Origin Level;
      @FOR( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
            ! For each Origin Supplier;
            @FOR (Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev(o_i,
o_l):
                  ! For each Destination Level;
                  @FOR( Level( d_l)| d_l #LE# LevNumPerStg((o_i + 1)):
```

```
                        ! For each Destination Supplier;
                        @FOR (Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((o_i + 1), d_l):
                              ! For each Mode of Transport;
                              @FOR (Transmodes (m)| m #LE#
TransNum(o_i, o_l, o_j, d_l, d_j):
                                    ! For every Time Period;
                                    @FOR (Timeperiod (t):
                                          V (o_i, o_l, o_j, d_l, d_j,
m, t) >= 0;       ! Non Negativity Constraint;
                                          V (o_i, o_l, o_j, d_l, d_j,
m, t) <= C_V_O_st_l_su_D_l_su_m_t (o_i, o_l, o_j, d_l, d_j, m, t) * BV
(o_i, o_l, o_j, d_l, d_j, m, t)  );)))))));      ! Transport Capacity
Constraint;


! Binary Variables Definition for selecting One Supplier;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t):
                        @BIN ( BX (i, l, j, t) );))));      ! Binary
Supplier Variables Definition;



! Binary Variables Definition for selecting One Transport Option;
! For Each Origin Stage;
 @FOR( Stage( o_i)| o_i #LE# (StgNum - 1):
      ! For each Origin Level;
      @FOR( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
            ! For each Origin Supplier;
            @FOR (Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev(o_i,
o_l):
                  ! For each Destination Level;
                  @FOR( Level( d_l)| d_l #LE# LevNumPerStg((o_i + 1)):
                        ! For each Destination Supplier;
                        @FOR (Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((o_i + 1), d_l):
                              ! For each Mode of Transport;
                              @FOR (Transmodes (m)| m #LE#
TransNum(o_i, o_l, o_j, d_l, d_j):
                                    ! For every Time Period;
                                    @FOR (Timeperiod (t):
                                          @BIN ( BV (o_i, o_l, o_j,
d_l, d_j, m, t)  );))))))));   ! Binary Transport Variable Definition;



! Objective Function ;

PRODCOSTS = @SUM (Timeperiod (t):
            @SUM ( Stage( i)| i #LE# (StgNum - 1):
```

```
            @SUM ( Level( l)| l #LE# LevNumPerStg(i):
            @SUM ( Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  C_Stg_Lev_Tim (i, l, j, t) * X (i, l, j, t) +
h_Stg_Lev_Tim (i, l, j, t) * Inv (i, l, j, t) + LateDelv (i, l, j, t) *
X (i, l, j, t) * PenaltyRt * @EXP(Risk(i,l,j,t));))));

TRANSCOSTS = @SUM (Timeperiod (t):
             @SUM ( Stage( o_i)| o_i #LE# (StgNum - 1):
             @SUM ( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
             @SUM ( Level( d_l)| d_l #LE# LevNumPerStg((o_i + 1)):
             @SUM ( Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev(o_i,
o_l):
             @SUM ( Suppliers (d_j)| d_j #LE# SupNumPerStgPerLev((o_i +
1), d_l):
             @SUM ( Transmodes (m)| m #LE# TransNum(o_i, o_l, o_j, d_l,
d_j):
                  g_O_st_l_su_D_l_su_m_t (o_i, o_l, o_j, d_l, d_j, m,
t) * V (o_i, o_l, o_j, d_l, d_j, m, t) ;)))))));

TOTALCOSTS = PRODCOSTS + TRANSCOSTS;

MIN = TOTALCOSTS;


END
```

APPENDIX F

This Appendix details the software code for Split Demand - Single/Multiple Criteria models. The code is written in LINGO software language and requires the LINGO software program to run. Figures 4.10 and 4.11 shown earlier capture the components of the software system and the flow of data.

Split Demand – Single/Multi Criteria Model Code

```
MODEL:
! Split Demand, Single/Multi Criteria Formulation ;
! Has Production, Transport Costs, First Time Quality and Risk - All
Input read from InputData7.xls ;

SETS:

Customer/1, 2, 3/;
TimePeriod/1, 2, 3/;
Suppliers /1, 2/;                    ! Maximum number of suppliers at
any level at any stage;
TransModes /1, 2/;                   ! Maximum number of modes of
transport between any origin and destination;
Demand(Customer, TimePeriod): Dem ;
Stage/1, 2, 3, 4/ :LevNumPerStg;
Level/1, 2, 3, 4, 5/;                ! Maximum number of levels in any
stage;
Org_Stage/1, 2, 3/;
LevelsPerStage(Stage,Level): SupNumPerStgPerLev; ! LevStg1;

! Should read supplier data in the order of Stage, Level, Supplier,
TimePeriod;
SupplierData(LevelsPerStage,Suppliers,TimePeriod): C_Stg_Lev_Tim,
h_Stg_Lev_Tim, P_Stg_Lev_Tim, MH_Stg_Lev_Tim, F_Stg_Lev_Tim, X, Inv,
Risk, LateDelv;

! Should read transport data in the order Origin Stage, Level,
Supplier, Destination Level, Supplier, Transport Mode, Timeperiod;
TransportData(Org_Stage,Level,Suppliers,Level,Suppliers,TransModes,Time
period): g_O_st_l_su_D_l_su_m_t, C_V_O_st_l_su_D_l_su_m_t, V;
TransportNum(Org_Stage,Level,Suppliers,Level,Suppliers): TransNum;

EndSets

DATA:

StgNum = 4;
Dem  = @OLE('InputData7.xls', CustDem);
```

```
LevNumPerStg   = @OLE('InputData7.xls', LevNum);
SupNumPerStgPerLev   = @OLE('InputData7.xls', SupNum);
C_Stg_Lev_Tim   = @OLE('InputData7.xls', UnitCost);
h_Stg_Lev_Tim   = @OLE('InputData7.xls', UnitInv);
P_Stg_Lev_Tim   = @OLE('InputData7.xls', ProdCap);
MH_Stg_Lev_Tim   = @OLE('InputData7.xls', InvCap);
F_Stg_Lev_Tim   = @OLE('InputData7.xls', FTQ);
g_O_st_l_su_D_l_su_m_t = @OLE('InputData7.xls', TransCost);
C_V_O_st_l_su_D_l_su_m_t = @OLE('InputData7.xls', TransCap);
TransNum = @OLE('InputData7.xls', TransOpNum);
Risk   = @OLE('InputData7.xls', Risk);
LateDelv   = @OLE('InputData7.xls', Late);
PenaltyRt = @OLE('InputData7.xls', Penalty);

ENDDATA


! Inventory Balance Constraint;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t)| t #EQ# 1:
                        Inv(i, l, j, t) = (X (i, l, j, t) *
F_Stg_Lev_Tim (i, l, j, t)) -
                        @SUM(Level(d_l)| d_l #LE# LevNumPerStg((i +
1)):
                        @SUM(Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((i + 1), d_l):
                        @SUM(Transmodes (m)| m #LE# TransNum(i, l, j,
d_l, d_j):
                        V (i, l, j, d_l, d_j, m, t);)));););
      ! Zero Starting Inventory ;
                  @FOR (Timeperiod (t)| t #GT# 1:
                        Inv(i, l, j, t) = Inv(i, l, j, (t-1)) + (X (i,
l, j, t) * F_Stg_Lev_Tim (i, l, j, t)) -
                        @SUM(Level(d_l)| d_l #LE# LevNumPerStg((i +
1)):
                        @SUM(Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((i + 1), d_l):
                        @SUM(Transmodes (m)| m #LE# TransNum(i, l, j,
d_l, d_j):
                        V (i, l, j, d_l, d_j, m, t);)));))));
      ! Inventory balance constraint;


! Flow Constraint;
! For every Time Period;
 @FOR (Timeperiod (t):
      ! For Each Origin Stage;
       @FOR( Stage( o_i)| o_i #LE# (StgNum - 2):
            ! For Origin each Level;
            @FOR( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
                  @FOR( Level( d_l)| d_l #LE# LevNumPerStg(o_i+1):
```

```
                        @FOR (Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((o_i+1), d_l):
                              @SUM(Suppliers (o_j)| o_j #LE#
SupNumPerStgPerLev(o_i, o_l):
                              @SUM(Transmodes (m)| m #LE# TransNum(o_i,
o_l, o_j, d_l, d_j):
                                    V (o_i, o_l, o_j, d_l, d_j, m, t)))
=
                                    X ((o_i+1), d_l, d_j, t);)))))); !
Flow Constraint;


! Meeting Customer Demand ;
! For every Time Period;
 @FOR (Timeperiod (t):
      ! For each Customer;
       @FOR (Customer (c):
            @SUM(Level(o_l)| o_l #LE# LevNumPerStg((stgnum - 1)):
            @SUM(Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev((stgnum -
1), o_l):
            @SUM(Transmodes (m)| m #LE# TransNum((stgnum -1), o_l, o_j,
c, 1):
            V ((stgnum -1), o_l, o_j, c, 1, m, t)))) = Dem(c,t);));
            ! Meeting Customer Demand ;


! Non Negativity, Capacity Constraint for each Supplier;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t):
                        X (i, l, j, t) >= 0;
      ! Non Negativity Constraint;
                        X (i, l, j, t) <= P_Stg_Lev_Tim (i, l, j,
t));)));    ! Supplier Capacity Constraint;


! Non Negativity, Inventory Capacity Constraint for each Supplier;
! For Each Stage;
 @FOR( Stage( i)| i #LE# (StgNum - 1):
      ! For each Level;
      @FOR( Level( l)| l #LE# LevNumPerStg(i):
            ! For each Supplier;
            @FOR (Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  ! For every Time Period;
                  @FOR (Timeperiod (t):
                        Inv (i, l, j, t) >= 0;
      ! Non Negativity Constraint;
                        Inv (i, l, j, t) <= MH_Stg_Lev_Tim (i, l, j,
t));)));    ! Supplier Inventory Capacity Constraint;
```

```
! Non Negativity, Transport Capacity Constraint for each Transport
Option;
! For Each Origin Stage;
 @FOR( Stage( o_i)| o_i #LE# (StgNum - 1):
      ! For each Origin Level;
      @FOR( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
            ! For each Origin Supplier;
            @FOR (Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev(o_i,
o_l):
                  ! For each Destination Level;
                  @FOR( Level( d_l)| d_l #LE# LevNumPerStg((o_i + 1)):
                        ! For each Destination Supplier;
                        @FOR (Suppliers (d_j)| d_j #LE#
SupNumPerStgPerLev((o_i + 1), d_l):
                              ! For each Mode of Transport;
                              @FOR (Transmodes (m)| m #LE#
TransNum(o_i, o_l, o_j, d_l, d_j):
                                    ! For every Time Period;
                                    @FOR (Timeperiod (t):
                                          V (o_i, o_l, o_j, d_l, d_j,
m, t) >= 0;       ! Non Negativity Constraint;
                                          V (o_i, o_l, o_j, d_l, d_j,
m, t) <= C_V_O_st_l_su_D_l_su_m_t (o_i, o_l, o_j, d_l, d_j, m, t)
);)))))); ! Transport Capacity Constraint;


! Objective Function ;

PRODCOSTS = @SUM (Timeperiod (t):
            @SUM ( Stage( i)| i #LE# (StgNum - 1):
            @SUM ( Level( l)| l #LE# LevNumPerStg(i):
            @SUM ( Suppliers (j)| j #LE# SupNumPerStgPerLev(i, l):
                  C_Stg_Lev_Tim (i, l, j, t) * X (i, l, j, t) +
h_Stg_Lev_Tim (i, l, j, t) * Inv (i, l, j, t) + LateDelv (i, l, j, t) *
X (i, l, j, t) * PenaltyRt * @EXP(Risk(i,l,j,t));)))));

TRANSCOSTS = @SUM (Timeperiod (t):
             @SUM ( Stage( o_i)| o_i #LE# (StgNum - 1):
             @SUM ( Level( o_l)| o_l #LE# LevNumPerStg(o_i):
             @SUM ( Level( d_l)| d_l #LE# LevNumPerStg((o_i + 1)):
             @SUM ( Suppliers (o_j)| o_j #LE# SupNumPerStgPerLev(o_i,
o_l):
             @SUM ( Suppliers (d_j)| d_j #LE# SupNumPerStgPerLev((o_i +
1), d_l):
             @SUM ( Transmodes (m)| m #LE# TransNum(o_i, o_l, o_j, d_l,
d_j):
                   g_O_st_l_su_D_l_su_m_t (o_i, o_l, o_j, d_l, d_j, m,
t) * V (o_i, o_l, o_j, d_l, d_j, m, t) ;))))))));

TOTALCOSTS = PRODCOSTS + TRANSCOSTS;

MIN = TOTALCOSTS;


END
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VITA AUCTORIS

Ramesh Majety was born in India in 1972. He graduated from Senior Secondary School in 1989 in India. Afterwards, he obtained his Bachelor of Science in Electronics Engineering in 1993 in India. He worked for Hewlett Packard for 1.5 years until January 1995. He pursued his Masters in Industrial Engineering at the University of Windsor, Canada, which he finished in the Fall of 1996. Thereafter, he enrolled full time for his Ph.D. in Industrial and Manufacturing Systems Engineering at the University of Windsor, Canada. In 1998, he transferred his Ph.D. to part-time status and commenced full time employment with General Motors (GM) Powertrain in Michigan as a Team Leader in the Manufacturing Systems Analysis Department. He is a candidate for the Doctoral degree and hopes to graduate in Fall 2004.