Total Supply Chain Cost Model

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ABSTRACT

Sourcing and outsourcing decisions have taken on increased importance within Teradyne to improve efficiency and competitiveness. This project delivered a conceptual framework and a software tool to analyze supply chain costs associated with a specified supply chain design.

Determining total supply chain cost is a complex challenge. This work developed the concept of a hierarchical, inter-related, multi-level supply chain cost architecture. Within this architecture, supply chain costs can be expressed as a sum of only 5 supply chain cost factors (material, labor, logistics, inventory holding, and overhead costs). The reduction of a large number of potential cost factors eases communication about total supply chain costs within an organization. An interactive Excel VBA software was developed which allows the user to experimentally model changes to a specific supply chain design. The VBA program automatically recalculates the supply chain costs based on the changes made. The output of the program is a comparison of costs associated with different supply chain designs. In a case study, the total supply chain cost model was applied to evaluate different supply chain node locations in Southeast Asia for one of Teradyne's testers.

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TABLE OF CONTENTS

ABSTRACT......2

ACKNOWLEDGEMENTS......3

TABLE OF CONTENTS......4

LIST OF FIGURES......6

LIST OF TABLES......6

1 Introduction......7
- 1.1 Teradyne overview......8
- 1.2 Semiconductor test industry......12
- 1.3 Outsourcing......14
- 1.4 Project overview......15

2 VOC and Literature Summary......18
- 2.1 Voice of the customer (VOC) interviews......18
- 2.2 Literature summary......19
  - 2.2.1 The total cost concept......19
  - 2.2.2 Cost structure analysis......21
  - 2.2.3 "Hidden" costs......24

3 Supply Chain Cost Architecture......26
- 3.1 Analysis of Teradyne cost factors......26
- 3.2 "Cost architecture"......28
- 3.3 Total supply chain cost function......30

4 Interactive Excel VBA Software......32
- 4.1 Overview of software......32
- 4.2 Software architecture......33
  - 4.2.1 Data input......34
  - 4.2.2 Supply chain node map......35
  - 4.2.3 Data Output......37
- 4.3 Databases......38
- 4.4 Calculation of main supply chain costs......39
  - 4.4.1 Material cost......39
  - 4.4.2 Labor cost......39
  - 4.4.3 Logistics cost......40
  - 4.4.4 Inventory holding cost......42
  - 4.4.5 Overhead cost......43
- 4.5 Cost effects of higher-level costs......47
- 4.6 Software capabilities and limitations......48
- 4.7 Potential software enhancements......50

5 Application of Model..51
5.1 Case study: Choosing node locations for J750....................................51
5.1.1 Business case...51
5.1.2 Analysis...53
5.1.3 Conclusions and recommendation...............................56
5.2 Comparison of model and professional software output........................58

6 Organizational and Leadership Learnings..62
6.1 Organizational structural design...62
6.2 Implementing a new tool...63
6.3 Leadership learnings...65

7 Conclusions...66
8.1 Key findings...66

APPENDIX A: Voice of the customer interviews..67

APPENDIX B: Language processing (LP) diagrams.......................................69

BIBLIOGRAPHY...71

NOTE: Throughout the thesis actual numbers have been disguised to protect the company's confidentiality.

LIST OF FIGURES

Figure 1.1.1: Breakdown of revenues from Teradyne's 5 major business lines........................9
Figure 1.1.2: Electronic applications for which Teradyne testers are used............................11
Figure 1.2.1: Breakdown of market share for the semiconductor test industry........................12
Figure 1.2.2: Teradyne's annual total sales from 1970-2003 in $M....................................13
Figure 1.2.3: Teradyne's quarterly shipments from 1Q1995 – 4Q2003.................................14
Figure 3.2.1 Total supply chain cost framework: The cost architecture..............................29
Figure 4.2.1.1: Data input worksheet..35
Figure 4.2.2.1: Interactive software user-interface. 36
Figure 4.2.3.1: Tabular data output..37
Figure 4.4.4.1: Comparison of total ATEOPS expense 47
Figure 5.1.1.1: Schematic of current supply chain node design for J750................................51
Figure 5.1.2.1: Comparison of total logistics costs calculated by the software..........................53
Figure 5.1.2.2: Comparison of break-up of logistics costs into different shipping categories.........55
Figure 5.1.2.3: Comparison of supplier shipping costs sorted by supplier countries...................55
Figure 5.2.1.1 Comparison of total logistics costs 60
Figure 5.2.1.2 Comparison of inbound logistics cost to E/M 60
Figure 5.2.1.3 Comparison of inbound logistics cost to FCT 61
Figure 5.2.1.4 Comparison of outbound logistics cost out of FCT 61
Figure 6.1.1 Structural map of intern interaction with groups within ATEOPS.....................63

LIST OF TABLES

Table 2.2.2.1: Supply chain cost factors...22
Table 3.1.1: Cost factors level 1: Quantifiable costs..26
Table 3.1.2: Cost factors level 2: More complex quantifiable costs.................................27
Table 3.1.3 Cost factors level 3: Not directly quantifiable costs....................................27
Table 4.3.1: Rate tables..38
Table 4.4.5.1: Calculation of ATEOPS expense per system...43
Table 4.4.5.2: ATEOPS line items likely to change...44
Table 4.4.5.3 Maximum change in ATEOPS expense due to selected line items....................45
Table 4.6.1: Accuracy level of level 1 costs..49
Table 5.1.1.1: Site combinations to be evaluated in the business case.................................52
Table 5.1.2.1: Total logistics costs associated with the different supply chain scenarios.............54

Chapter 1 Introduction

This thesis describes the results of a joint collaboration between Teradyne, Inc. and the MIT Leaders for Manufacturing (LFM) Program to develop analytical tools that can aid Teradyne to make future sourcing and outsourcing decisions. The outputs of the internship are a theoretical supply chain cost model framework and a software tool capable of estimating supply chain costs for a given supply chain design.

The thesis is organized into several chapters. Chapter 1 starts with a background on the company and gives a brief overview of the semiconductor test industry. A description of the project (motivation, goals, and deliverables) follows. Chapter 2 reports the results of voice of the customer interviews conducted with potential users of the model and summarizes literature on total supply chain cost. Chapter 3 covers an analysis of supply chain costs most relevant to Teradyne's supply chain. The total supply chain cost framework ("Cost Architecture") developed during the internship is introduced. Chapter 4 dives into the specifics of the interactive Excel VBA software tool, which is an important output of the internship. This chapter also discusses software capabilities and limitations and makes suggestions for software improvements. Chapter 5 addresses testing and application of the total cost model in a current business case investigated by Teradyne. Chapter 6 elaborates on organizational and leadership learnings. Chapter 7 finally closes the thesis with a summary of key findings.

1.1 TERADYNE OVERVIEW

Teradyne, Inc. is a world's leading manufacturer of automated test equipment and interconnection systems with sales of $1.8 billion in 2004. It was founded in 1960 by former MIT classmates, Alex D'Arbeloff and Nick DeWolf. [1] In 1966, Teradyne introduced the first integrated circuit tester, in which a minicomputer controlled the test steps. With that invention Teradyne launched and pioneered the automatic test equipment (ATE) industry. Numerous inventions followed and established Teradyne as the technology leader in the industry. Perhaps not surprisingly, the company's motto is: "Technology never stops". The inventions were accompanied with strong business growth. In 1995, Teradyne passed the billion-dollar mark in revenues and entered the S&P 500 in 1999. In 2003, Teradyne opened its first factory in China (Teradyne Shanghai) to serve the growing electronic industry in Asia This move emphasizes a continuing trend of offshoring manufacturing in the semiconductor industry to low-cost regions.

Teradyne's lines of businesses

Today, Teradyne has 5 major business lines:

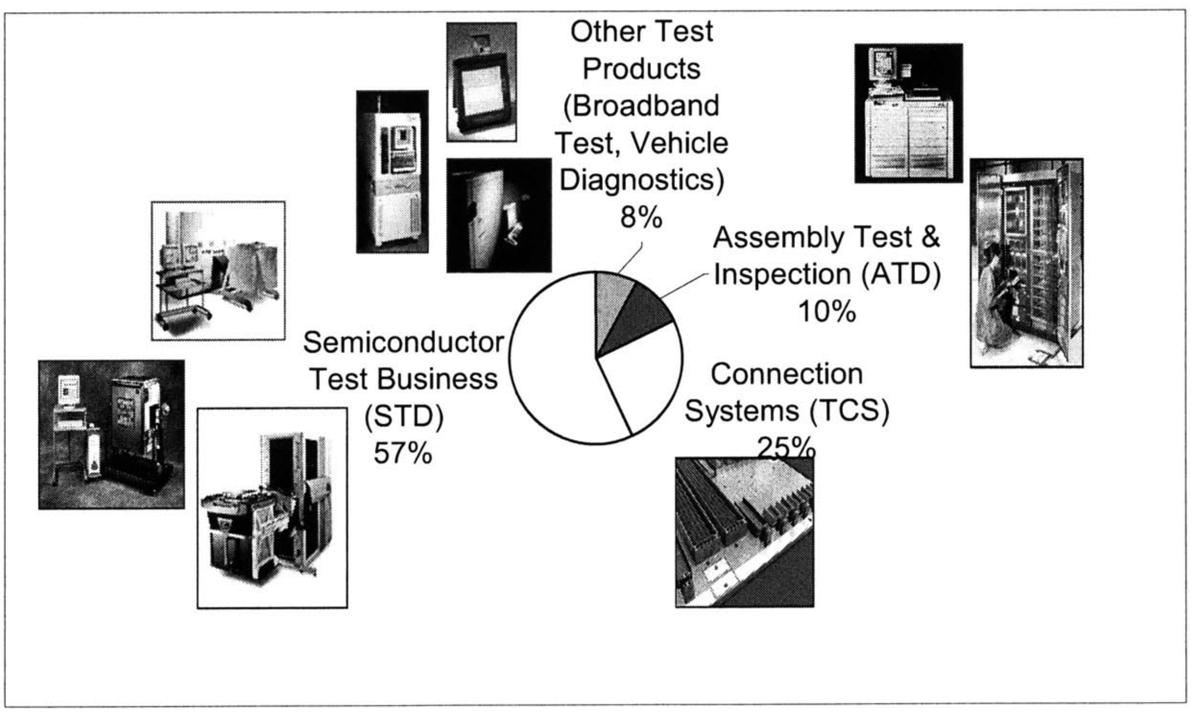
- **Assembly Test Division (ATD)**: ATD manufactures testers for production test of electrical, optical, and x-ray circuit boards and assemblies.
- **Broadband Network Test**: This business unit provides solutions to test broadband, DSL, phone, and cable TV networks.

[1] The company name means a very large force. (Tera = 10^{12} , 1 dyne (dyn) = 10^{-5} Newton (N) (unit of force))

- **Teradyne Connection Systems (TCS)**: TCS is the leader in high-performance connection systems and provides a full line of high-performance connectors, circuit board, and design solutions for OEMs.
- **Vehicle Diagnostic Solutions**: This business unit delivers solutions to test electrical components in the automobile, aerospace, agriculture, and defense industries.
- **Semiconductor Test Division (STD)**: STD is the largest business unit within Teradyne. It produces automated test equipment to test semiconductor microchips for a variety of electronic applications. Teradyne is the global leader with roughly 35% market share.

Figure 1.1.1 depicts an approximate breakdown of the revenues from the different business units.

Figure 1.1.1: Breakdown of revenues from Teradyne's 5 major business lines



The overall name of the business units producing automated test equipment is ATE (Automated Test Equipment). ATE includes all business units except TCS. The project was conducted in ATEOPS (Automated Test Equipment Operations) and was focused on STD. Therefore, the thesis will primarily talk about the semiconductor test business.

The Semiconductor Test Products:

Currently, there are 6 main testers available from semiconductor test:

- **Catalyst**
- **J750**
- **Tiger**
- **Flex**
- **Ultraflex**
- **MicroFlex**

The semiconductor test products find a variety of electronic applications ranging from testing chips for consumer electronics such as cell phones to microprocessors, chipsets in computing applications etc. as depicted in Figure 1.1.2.

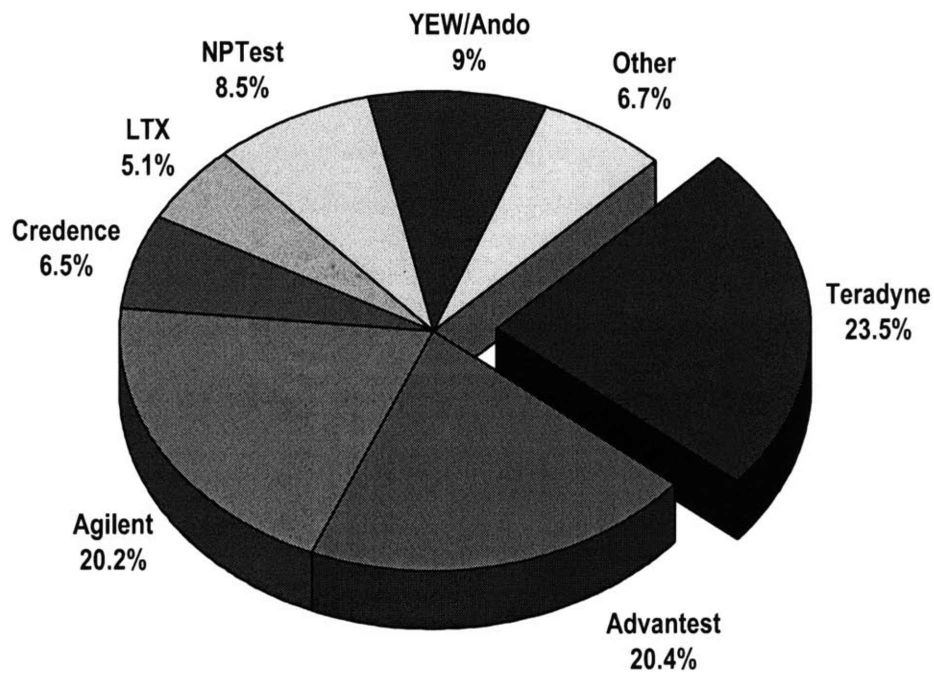
Figure 1.1.2: Electronic applications for which Teradyne testers are used

1.2 The Semiconductor test industry

Overview of the market

The semiconductor test market is a multi-billion dollar market in which Teradyne is the leader with 23.5% of the market. Teradyne's competitors in the semiconductor test market are primarily Agilent (20.2% market share), Advantest (20.4%), Credence (6.5%) and LTX (5.1%). [*Teradyne 1, Teradyne 2*]

Figure 1.2.1: Breakdown of market share for the semiconductor test industry



Teradyne's business challenges

The main business challenge in the semiconductor test industry is volatility. The semiconductor test industry follows the business cycles of the semiconductor chip industry in an extreme fashion (the test industry is exposed to the "bullwhip effect" [*Simchi-Levi et al.*, *Hayes et al.*]). Figure 1.2.2 depicts Teradyne's annual sales from 1970 – 2004. The volatility in sales is especially severe during the "technology bubble" in the late 1990s: Sales more than doubled between 1998 – 2000 and then subsequently dropped by more than 60% between 2000 – 2002. The volatility of the business may be even more pronounced when looking at the quarterly shipments (Figure 1.2.3). The operational difficulties associated with handling suddenly *decreased* demand are actually more severe than the challenges associated with responding to suddenly *increased* demands.

Figure 1.2.2: Teradyne's annual total sales from 1970-2003 in $M

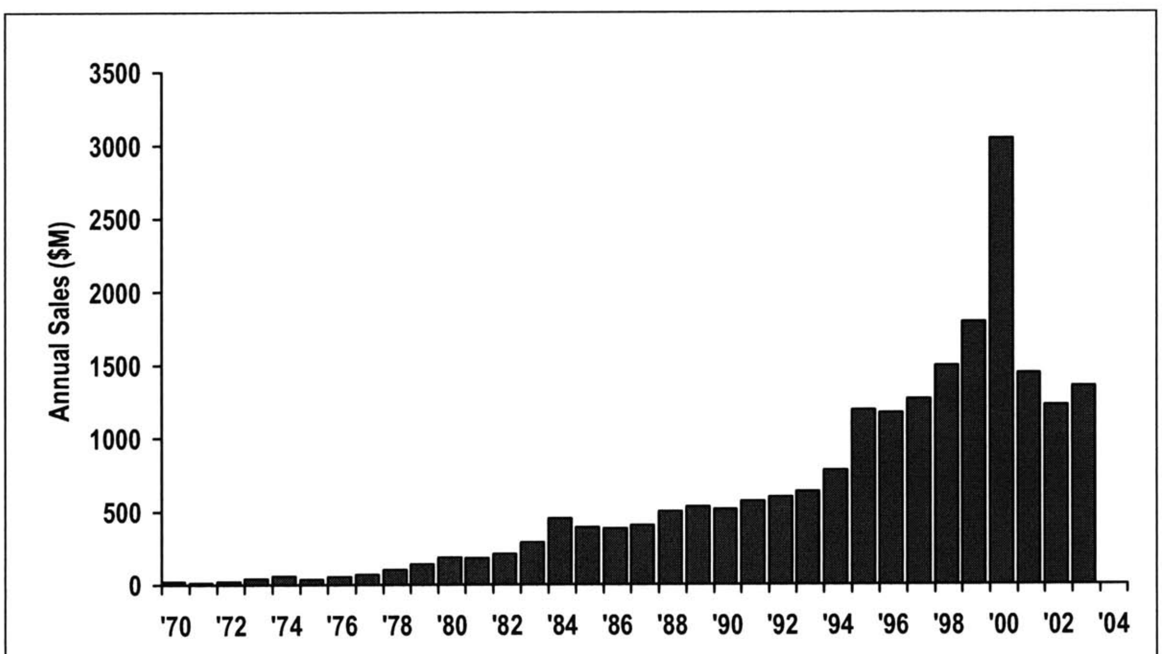
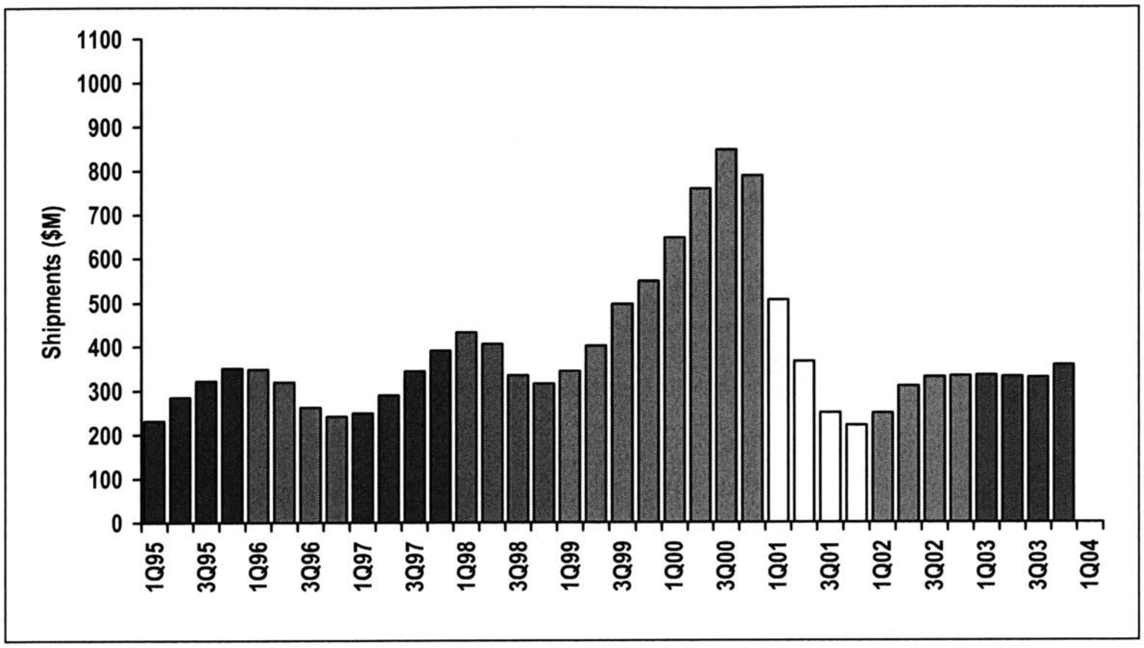


Figure 1.2.3: Teradyne's quarterly shipments from 1Q1995 – 4Q2003



Teradyne is also facing increasing pressure from competitors who are offering lower-priced testers. In order to withstand this pressure and to increase market share, Teradyne's supply chain not only has to be flexible in order to be able to respond to the swings in demand, but also has to be as cost-effective at possible. Overhead costs associated with an infrastructure that can handle large demands in upturns become a large financial burden during downturns.

1.3 Outsourcing

One potential application of the total supply chain cost model is to evaluate supply chain costs associated with outsourcing. Outsourcing offers the *potential* for cost savings in at least 2 ways:

- Lower supply chain costs (primarily material and labor costs)
- Shift fixed to variable costs

Shifting fixed costs to variable costs via outsourcing of some of the operations to outside companies is not advantageous during business upturns (e.g., sub-assemblies purchased from outside are more expensive than assembled in-house). However, during downturns, the savings on fixed costs can be very advantageous as the company that outsources does not have the burden of dealing with the cost of unused machinery and other fixed costs.

In view of the potential cost savings outsourcing offers, not unlike many other manufacturing companies, outsourcing has become a major trend within the automated test equipment industry. A number of competitors are outsourcing manufacturing. Agilent outsources about 70% of total manufacturing to developing countries such as Thailand, Singapore, and Malaysia [*Agilent*]. LTX is the leader in the outsourcing trend in the ATE industry. It outsources 100% of a number of their ATE models [*LTX*].

To remain competitive and to profit from the potential cost benefits of outsourcing (see previous section), Teradyne is increasingly looking at outsourcing and is planning to increase outsourcing over the next few years.

1.4 Project overview

Overall goals

Increasing interest in outsourcing as well as sourcing from low-cost regions was the main driver for the internship project. A first goal of the total supply chain cost model project was to provide a framework for how to address total supply chain costs. The model should be able to address questions such as: What are the supply chain cost factors to be considered?

Which cost factors are most relevant to Teradyne and should be included in modeling supply chain costs? A second goal was to deliver a software tool using the developed framework that can calculate the total supply chain costs of different supply chain alternatives including alternatives that employ outsourcing. This tool should aid executive management in making sourcing as well as outsourcing decisions. Total cost analysis has been examined in previous LFM thesis' [*Henkle, Gerez*]. These thesis' were a valuable information resource for conducting this internship.

Problem Statement

The project is part of a larger effort within ATEOPS to improve efficiency and competitiveness of Teradyne's supply chain. The primary motivation for this project was to reduce total supply chain costs. In the past, some outsourcing of platforms and subassemblies were done based on simple cost models. However, a concern was that these calculations were insufficient in capturing a more complete picture of the total costs involved in outsourcing and sourcing from low-cost regions. Thus, a more detailed cost analysis/model was needed. Included in the project was the development of a software tool that calculated a selection of quantitative and qualitative supply chain cost factors. The project also included the evaluation of several supply chain alternatives and the development of supply chain design recommendations for executive management. Specifically, the internship deliverables agreed upon by Teradyne and LFM are summarized below.

Deliverables

1) A written document outlining a framework how to think about total supply chain costs (i.e., which cost factors to include, why, and how.)
2) A software calculation tool
3) Written documentation of how to use the software and software training sessions
4) Application of the model to an actual business case and development of recommendations

Approach

The project was conducted in a team with members from supply chain design, business process engineering, operations finance, and logistics. The project was performed in 4 phases:

Phase 1: Analysis of current supply chain and its total cost.

Phase 2: Determination of model input and output requirements via analysis of voice of customer and benchmarking surveys.

Phase 3: Development of the total cost model.

Phase 4: Application of the model and development of recommendations.

Chapter 2 Voice of the customer interviews and literature summary

2.1 Voice of the customer interviews

Prior to development of the total cost model voice of the customer (VOC) interviews were conducted with potential users of a total supply chain cost model. The interviewees were mainly higher-level managers and senior executives across ATEOPS, including the VP of operations. The interviews were conducted adhering to the Total Quality Management (TQM) guidelines for VOC interviews practiced at Teradyne [*Teradyne 3*]. The main purpose of these interviews was to understand how a total cost model would be used at Teradyne and associated with it, what the requirements for such a model were. *Appendix A* contains the questionnaire that was used for the VOC interviews. *Appendix B* shows language processing (LP) diagrams of the VOC results for high-level questions addressing desired characteristics of a total supply chain cost model.

Due to confidentiality reasons, the VOC results that describe Teradyne's outsourcing strategy are omitted here. Below is a summary of the top-level results of only the LP specifically related to supply chain cost factors and model requirements. The high-level LP results are written in capitalized letters.

Summary of LP results:

Question: How do you think about total supply chain costs?

- **MAIN SC COSTS ARE ONLY A FEW COST ELEMENTS**
    - Main supply chain costs are material, labor, logistics
- **SC COSTS ARE COMPLEX**
    - Some cost elements are not easily definable
    - Supply chain costs are complex due to geographical differences
    - Supply chain costs are complex due to the high number of parts and suppliers

- Freight and transportation estimates are lacking
    - Total supply chain costs needs to be thought of as an aggregate

- **MAIN TRADE-OFFS ARE AROUND RESPONSIVENESS AND INVENTORY**
    - The supply chain needs to be responsive
    - To effectively manage inventory we need to trade-off supply chain costs
    - Teradyne needs to be engaged in supplier management to gain responsiveness

How do you picture a total supply chain cost model?

- **THE INPUTS TO THE SUPPLY CHAIN DESIGN MODEL SHOULD INCLUDE A LIMITED NUMBER OF QUANTITATIVE AND QUALITATIVE FACTORS THAT CAN BE MANAGED AND STILL PROVIDE OUTPUT NEEDED.**

- **THE OUTPUT OF THE MODEL SHOULD INCLUDE A SUPPLY CHAIN MAP, COMPARATIVE AND SUMMARY METRICS THAT CAN AID DECISION MAKING.**

- **A PROCESS TO USE THE FEATURES OF THE MODEL NEEDS TO DEFINE WHEN, HOW, AND WHO WILL USE THE MODEL FOR DECISION MAKING.**

The results of the VOC interviews suggested that the model should be simple, yet functional. In addition, the output should include a supply chain map and tabular/graphic comparisons of different supply chain designs.

2.2 Literature summary

Calculation of total supply chain cost has been covered in the literature previously. The following provides a summary of some of the results found in literature.

2.2.1 The Total Cost concept

The concept of total cost is a core concept in logistics and procurement. In procurement, total cost takes on a long-term perspective considering costs beyond the purchase price. It involves all costs associated with the true cost of a part/product over its entire lifetime, including servicing and maintenance. Extending the total cost concept to the total cost of a supply chain includes "all costs and factors that create value to achieve customer satisfaction." [*Cavinato, 1992*] Elements of supply chain total costs are discussed under section 2.2.2 (*Cost structure analysis)*.

We find the ideas of total cost of procurement and logistics also in the concept of total cost of ownership (TCO). TCO is defined as a way to understand and analyze the true costs of doing business with a particular supplier, of a particular process, or an outsourcing decision. [*Ellram 1*] In TCO, all costs associated with purchased goods and services throughout the entire supply chain are included; that is from the idea inception, as in working with a supplier to develop a new or improved part, through warranty claims associated with that part, once the final product is in use by the customer. [*Ellram 2*] Cost beyond initial purchase price, must be examined from a long-term perspective.[*Ferrin*]

However, the definitions of total supply chain cost can differ. The Supply Chain Council (SCOR) refers to total supply chain cost as

> "Measure of all the costs associated with *managing* a supply chain. Includes costs associated with acquiring and delivering material, planning and order management, but none of the expenditures associated with R&D or sales and marketing."[*SCOR*]

The SCOR metric divides these managing costs into 5 specific cost buckets (material acquisition costs, order management costs, inventory carrying costs, information systems costs, finance and planning costs). These costs are summed and divided by a company's revenue to arrive at a percentage that allows for comparisons.

The ultimate benefit of determining the total supply chain cost is to optimize the costs along the supply chain. This increases bottom-line efficiency and therefore a company enhances its competitive advantage. Competitiveness of the supply chain requires accurate information on the various costs involved. That means, information on where those costs are incurred and whether the costs are rising or falling is required. [*OMR*]

Thus, in order to optimize costs, one has to analyze and understand:

A) Incurrence of costs along the supply chain

B) The underlying cost drivers (what makes the cost fluctuate?)

C) The existence and impact of cost trade-offs

2.2.2 Cost structure analysis

Cost factors

Various resources identified the key cost elements of total supply chain cost. The opinions of AMR research and the Operations Management Roundtable (OMR) as summarized in Table 2.2.2.1 (and further elaborated below the table).

Table 2.2.2.1: Supply chain cost factors

	AMR	*OMR*
Direct purchasing	*X*	*X*
Manufacturing	*X*	*X*
Transportation	*X*	*X*
Warehousing	*X*	*X*
Inventory holding	*X*	
Customer service	*X*	
Transaction and documentation		*X*
Return on investment		
Inter-firm costs:		*X*
Supply chain finance and planning		*X*

According to AMR research, the things one wants to measure depend on the business in which one operates, while the things one can measure depends on a company's accounting systems and internal information flows. Factors to be included are:

- **Purchase costs**
- **Warehouse capital**
- **Total inventory cost**
- **Transport costs**
- **Production costs**
- **Transaction and documentation costs**
- **Return on investment**
- **Personnel costs**

OMR suggests that in order to know where to best optimize along the supply chain, companies must understand the following components of their total costs:

- **Inter-firm costs**: Cost of time, effort, interruptions attributed to managing vendor and customer demands.
- **Procurement:** Cost of purchased materials and services.
- **Order management**: Cost of order capture, validation, sourcing, and distribution.
- **Manufacturing**: Total direct manufacturing costs as a percentage of revenue or cost of sales.
- **Transportation**: Freight cost as a percentage of revenue or cost of sales.
- **Warehousing:** Storage costs of inventory, handling inventory including labor and utility costs, (proportional to flow of material through warehouse).
- **Supply chain finance and planning**: Costs of demand forecasting, general planning within supply chain, technology, inventory financing plus write-offs of excess and obsolete inventory.

Cost drivers

Ferrin et al. conducted a survey with members of the Institute of Supply Chain Management (ISCM). [*Ferrin et al*] The interviewees were asked to identify cost drivers for a purchasing decision. Out of 73 responses, the survey generated a list of 135 different cost drivers relevant to a purchasing decision. Cost drivers need to be distinguished from cost factors. Cost factors are areas where costs occur, whereas cost drivers make these factors change. Examples of cost drivers identified by the survey are:

- Operations costs
  - Machine efficiency
  - Production to Schedule
  - Capacity utilization

- Quality
  - Durability
  - Inspection
  - Cost of quality
  - Rejection cost

- Customer-related
  - User satisfaction
  - Customer perceptions

- Logistics
  - Freight and instability in freight rates
  - Tariffs
  - Leadtime
  - On-time delivery
  - Entry-and harbor maintenance fees
  - Supplier-managed inventory
  - Area of the country customer must order from

- Supplier reliability and capability
  - Partnering costs
  - Trust
  - Service by supplier
  - Payment terms
  - Familiarity with supplier
  - Supplier capabilities

2.2.3 "Hidden costs"

In addition to the cost factors and cost drivers discussed in the literature, one also finds articles that point out "hidden costs", especially associated with outsourcing. As outlined below, Overby identifies a number of costs not usually considered in outsourcing. [*Overby*] The percentages in parentheses indicate by how much the cost of outsourcing per year can be underestimated. Overby suggests that the total of hidden costs can amount to 15.2% - 57% of the total cost of offshoring. (In my discussion with several Teradyne employees involved in international outsourcing, a number of the cost factors listed below were indeed not included in the outsourcing calculations, yet represented a non-neglibile portion of the total cost associated with outsourcing.)

- **Cost of selecting a vendor**: (+**0.2 to 2%**) in addition to annual cost of deal.
    - Documenting requirements
    - Negotiate a contract
    - People required (or outsourcing advisor)
    - Travel expenses

- **Cost of transition (+2 to 3%)**
    - 3 months to 1 year to hand the work over completely to an offshore partner
        - bring people to America or bring people over there for knowledge transfer and ironing out cultural differences
        - In US need to pay US hourly rate to offshore employees (go over specs etc.)

- **Cost of layoffs (+3 to 5%)**
    - Severance and retention bonus

- **Cultural costs (+3 to 27%)**
    - Productivity lags: work takes longer, communication problems, cultural differences

- **Costs of Ramping up (+1 to 10%)**
    - Improving development process

- **Costs of Managing an Offshore Contract (+6% to 10%)**
    - Auditing, invoicing
    - Pay individual to make sure project moves forward, develops and analyzes vendor proposals

Chapter 3 Teradyne Cost factors and "cost architecture"

3.1 Analysis of Teradyne Cost Factors

Given the wealth of potential cost factors and the varying opinions as to what constitutes supply chain costs as found in the literature, the project team compiled its own list of cost factors most relevant to Teradyne. The following cost factors were identified as being potentially important to Teradyne (Table 3.1.1). Initially, these cost factors were sorted into different levels according to their feasibility of quantification.

Table 3.1.1
Cost factors level 1: Quantifiable costs

Cost factors	Details
Material	• Direct material cost • Value-added cost
Direct labor	• Direct labor cost
Transportation	• Freight (including cost of containers, tariffs, and overhead) • Freight Time (transportation/customs clearance etc.)
Warehouse	• Fixed costs (facilities) • Handling costs (labor and utility) • Warehouse storage sq.ft.
Inventory holding	• State taxes, property taxes, insurance on inventory • Maintenance costs • Obsolescence cost (derives from risk an item will lose some of its value because of changes in the market) • Opportunity costs • Safety stock
Purchase costs	• Transaction and documentation (order, set-up, paying the bill etc.) • Discounts (e.g., favorable discounts provided by suppliers given early payment performance, volume discounts) • Vendor policies (min/multiple requirements etc.) • Start Up production costs (jigs /special equipment etc)
Planning	• General planning including demand forecasting (personnel costs, technology costs such as software purchase, training and maintenance)

Table 3.1.2
Cost factors level 2: More complex quantifiable costs

Cost factors	Details
Lead time	• Opportunity costs of capital tied up earlier with longer lead time • Flexibility to respond to unexpected demand
Quality	• Defects (yields) • Rejection, repair/return
Delays	• Caused by vendor or subcontractor not being on time
Stockouts	• Lost sales • Overstock: Inventory costs
Service/cost of managing customers and suppliers	• Costs driven or originated by customers and suppliers (cost of time, effort, interruptions attributed to managing these demands)
New vendor/sub-contractor selection	• Documenting requirements • Analyze vendor proposals • Negotiation • Travel
Lay-offs	• Early retirement, severance packages
Transition	• Time until fully efficient • Transfer of knowledge (e.g., send people offshore and bring people into U.S.) • Pay offshore employees U.S. hourly rate to come over to go over specs etc.

Table 3.1.3
Cost factors level 3: Not directly quantifiable costs

Cost factors	Details
Exchange rate risk	• Currency fluctuations
Supplier relationship	• Trust, personal relationships
Customer relationship	• Customer satisfaction (Short ARO LT, on-time delivery etc.) • Customer perception
Cultural differences	• Communication issues • Cultural issues (e.g., how to deal with defects, reporting, expressing improvement ideas etc.)
Political instability	

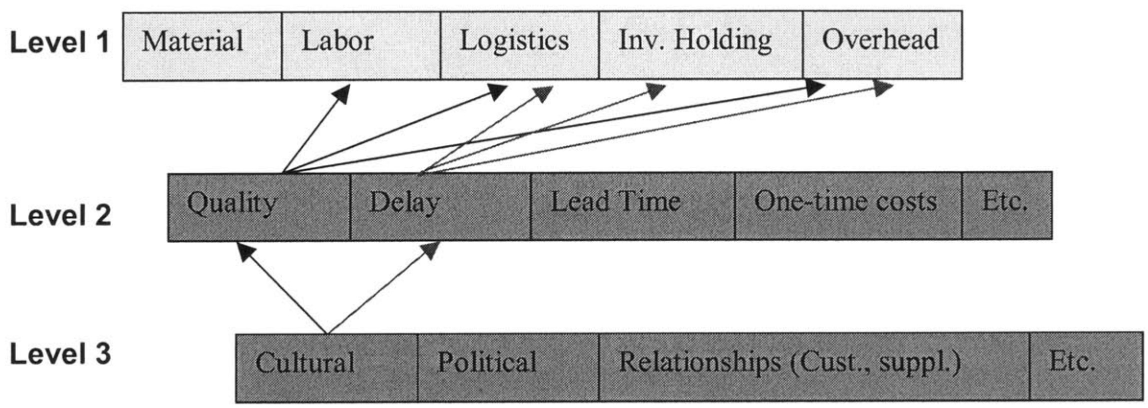
When making a supply chain design decision, all of these factors need to be considered up to a certain degree. However, the total cost function, which is the sum of all of these costs, would therefore not only be hard to calculate, but also hard to grasp because of its complexity.

3.2 "Cost architecture"

The organization into different cost levels as presented in the previous section sparked the idea of a "cost architecture" as a concept for how to think about supply chain costs. In this cost architecture, costs are organized into hierarchical levels of increasing complexity. More importantly, the different levels in this architecture are *inter-related.* Each cost level impacts higher-level costs. As a result, the total cost function, which is a sum of all the costs comprising total supply chain costs, can be expressed as a function of only the costs of the first level in the architecture.

Specifically, in level 1 of our cost architecture we put the "basic" supply chain costs: Material, labor, logistics, inventory holding, and overhead costs. In level 2 we put those costs that are more difficult to quantify. Examples of those costs are: Delay, quality, lead time, stock-outs, one-time costs (e.g., vendor selection, set-up costs, transitioning costs, etc.). In level 3 we have highly-complex costs of mainly qualitative nature: Cultural differences, political unrest, vendor and supplier relationships etc. The beauty of the architecture lies in the fact that the different levels roll-up into another. To illustrate these relationships, we can for example look at how the effects of the costs of cultural differences can be expressed as a function of level 1 costs. Increased costs of cultural differences can for example lead to increased costs of quality and delay. Increased cost of quality in turn can lead to increased labor cost (e.g., through rework), increase cost of logistics (e.g., via return shipments), increased overhead costs (e.g., through handling paperwork). Increased cost of delay can lead to increased cost of logistics (expedited shipment costs), increased inventory holding costs (increased duration of holding material), and increased cost of overhead (increased handling of paperwork). Thus, the total effect of cultural differences can be expressed as increases in labor, logistics, inventory holding, and overhead costs. Figure 3.2.1 depicts the cost architecture and the discussed effects of lower-level costs on higher-level costs in this example.[2]

Figure 3.2.1 Total supply chain cost framework: The cost architecture



[2] One may question how political factors can be expressed as level 1 costs. Political unrest can increase delay, lead time, and/or upfront costs. In the extreme event where political unrest wipes out an entire facility (e.g., through a political revolution), fixed costs (loss of property, plant & equipment) are incurred.

3.3 Total supply chain cost function

Mathematically, the total supply chain cost function can be written as:

Total Supply Chain Cost = Material + Labor + Logistics + Inventory + OVH

$$=\sum_{1}^{5} F_i\left[g_1(x_1,x_2..),g_2(x_1,x_2..),g_3(x_1,x_2..),g_4(x_1,x_2..),g_5(x_1,x_2..)\right]$$

where F_i denotes level 1 costs (i=1,2,3,4,5), g_k denotes level 2 costs (k = 1,2,3…) and x_l denotes level 3 costs (l = 1,2,3…).

The main advantage of the cost architecture is a simplified presentation of the total cost function. An expression of total cost as a function of 5 elements eases communication and discussion of the costs with senior executives. However, it certainly doesn't simplify the problem of quantifying the more complex costs. Thus, one needs to keep in mind that the main purpose of the cost architecture is to provide a framework with which supply chain costs can be thought of and addressed in the company, rather than being a simplified way of calculating total supply chain costs.

As for the usage of the architecture, one should start with calculating the change in level 1 costs without contribution from higher-level costs for a particular supply chain design. If this analysis doesn't yield significant cost savings over an existing design, there is no need to go to the next step of including higher-level costs in the total cost calculation. If there is, one has to decide which of the higher-level costs are most probably going to impact total supply chain costs significantly (based on past experience, estimates etc.). Those should then be quantified. Level 3 costs are very hard, if not impossible, to quantify. A suggestion how to include those factors into a supply chain design decision is to give these costs a subjective rating.

In this work only level 1 costs as they occur (i.e., without contributions from higher level costs) are included in the cost calculations performed in the software. Such an analysis is a good starting point. As mentioned, if level 1 costs do not yield significant savings, it's not worth going into analyzing the higher level costs. If level 1 costs do provide savings, one should move on to analyzing the higher-level costs.

Chapter 4 Interactive Excel VBA software tool

4.1 Overview of software

A main part of the internship was the development of a software tool capable of calculating the supply chain costs associated with a particular supply chain design. The tool is to be used as an aid to decide among different supply chain designs. Adhering to the requirements on the model per VOC interviews (see Chapter 2), the model had to be simple, yet functional. Its output should include a supply chain node map, as well as summary and comparative metrics. Very simply put, the steps to use the program are:

1) Insert data for a current supply chain
2) Modify the supply chain (e.g., change node location, suppliers etc.)
3) Obtain data output of supply chain costs

Excel Visual Basic for Applications (VBA) was chosen as the programming language for the following reasons:

- Excel in combination with VBA is a powerful language that allows creating a user-friendly, interactive interface and programming with custom-built functions.
- Its output can be easily understood across different levels within the organization as Excel is widely used within Teradyne.
- It's relatively inexpensive.

As mentioned, at this point, the software only addresses level 1 costs as they occur. It is also important to note that the software does not calculate the net present value (NPV) of total supply chain cost at this stage. It rather looks at the cost of steady-state operations (i.e., not only are costs not discounted at the appropriate company cost of capital rate, but also one-time costs are not included). For a more elaborate discussion on how to use the output of the software see Chapter 4, section 4.5.

4.2 Software architecture

The model has 3 major building blocks:

1. ***Data input:*** This is a worksheet in which baseline data for a specific supply chain design is loaded into the model. Most of the data are available from the company's Enterprise Resource Planning system (Oracle).
2. ***Supply chain node map:*** This is an interactive node map of the supply chain, which shows the flow of material and allows one to make changes with respect to the location of the nodes, the percent revenue allocated to customers, and the expected run rate. The node map also allows viewing information on suppliers and parts.
3. ***Data Output:*** The output of the model consists of a tabular and graphic comparison of supply chain costs for different supply chain design scenarios.

4.2.1 Data input

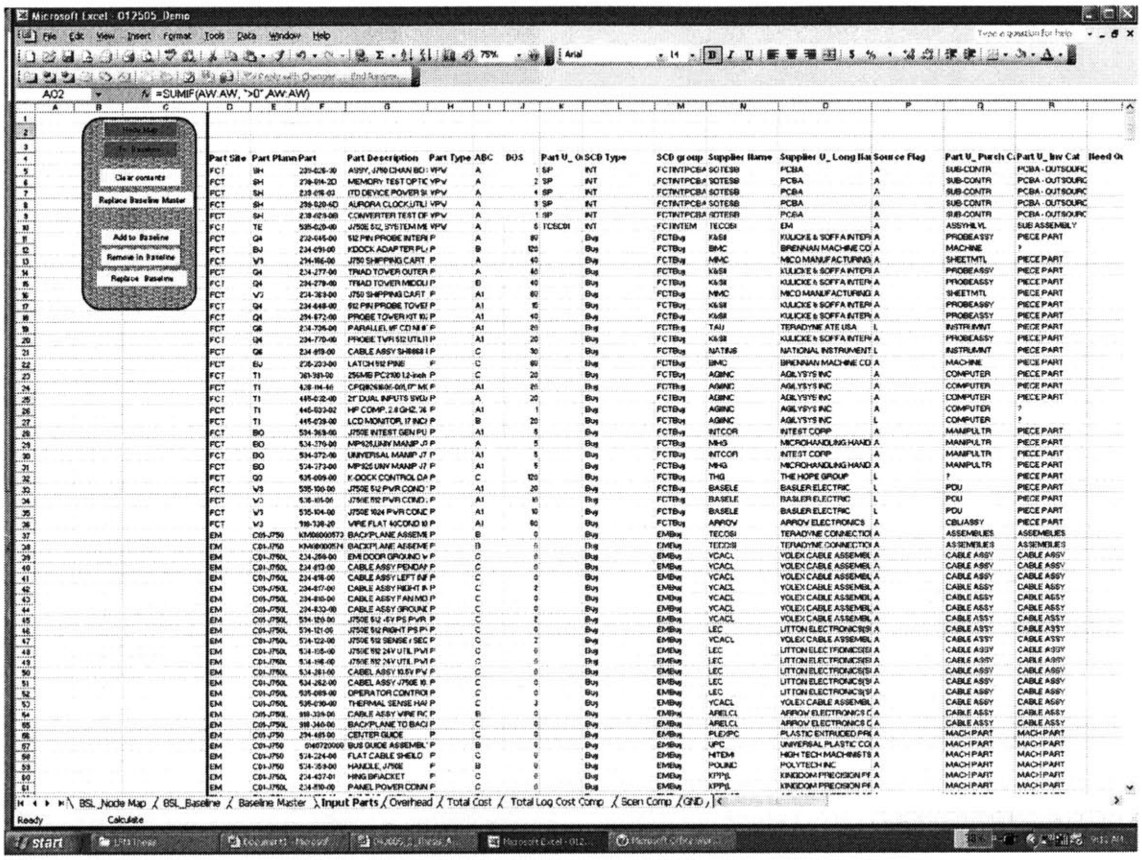
The software models the supply chain as a network of supply chain nodes. The nodes represent different stages of the manufacturing and assembly processes. As the different stages take place at different physical locations, the nodes are associated with different locations. For a map of the supply chain see section 4.2.2.

In order to calculate the supply chain costs, the following data are required as an input in data table form:

- Part Site (the node associated with the part)
- Part Number
- Part Type (buy or internal)
- Supplier name
- Need Quantity (quantity required for 1 system)
- Material cost
- Labor Cost
- Average planned order
- Part Lead time
- Part weight

These data are required for each part. Most of the information is available from Teradyne's ERP system. One important kind of data that is currently not available from ERP is the part weight, needed for calculating the logistics costs. Since it is crucial for calculating logistics costs in general, the company is now thinking of ways to make this data available from the Oracle database. As for the different parts and their position in the BOM (bill of materials), Teradyne employs a software program, that can retrieve the parts in question from the BOM. Figure 4.2.1.1 shows the worksheet where data can be uploaded.

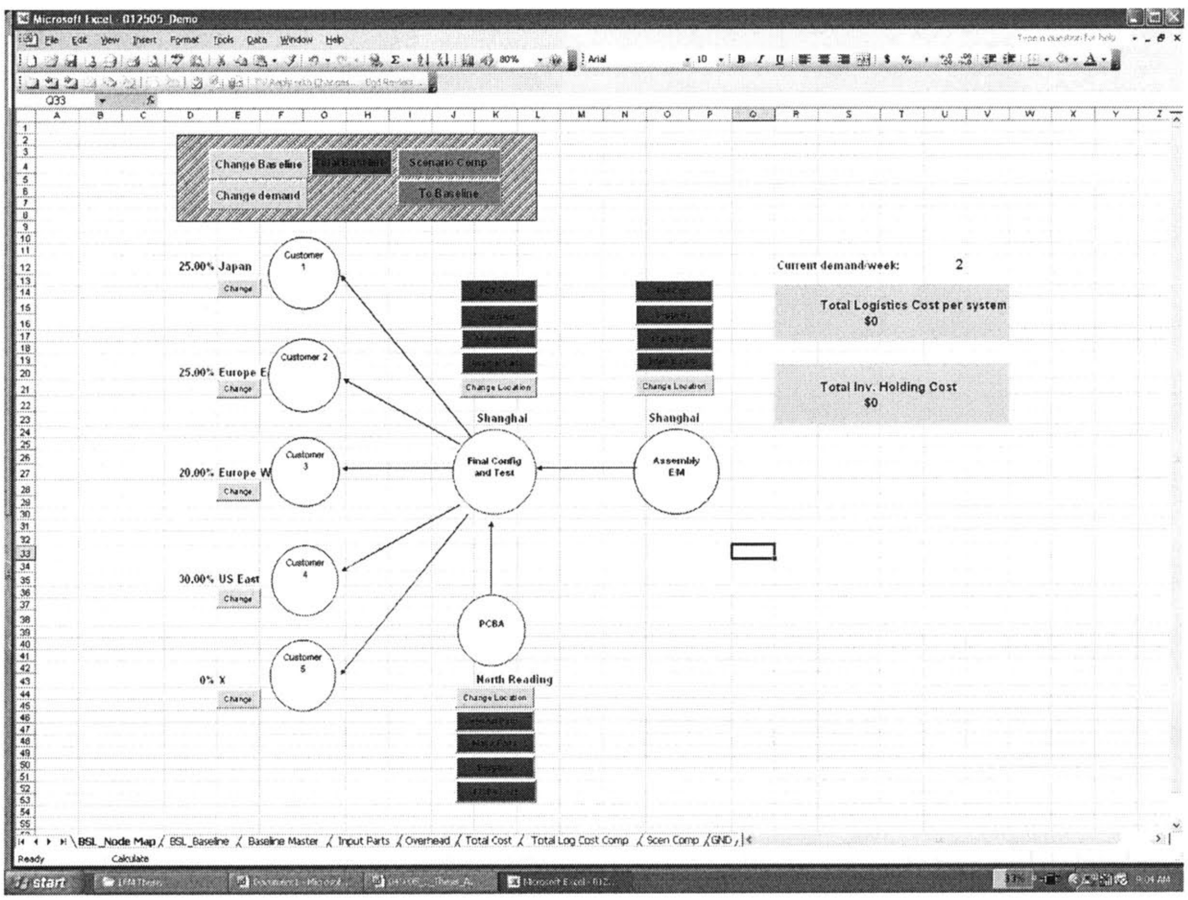
Figure 4.2.1.1: Data input worksheet



4.2.2 Supply chain node map: Interactive user-interface

The software has an interactive user-interface. This interface shows a map of the supply chain nodes with arrows indicating the flow of material. In this interface, the user can make changes to a base supply chain design. Each tester has its own base supply chain design. A typical model interface is shown in figure 4.2.2.1. A number of interactive buttons are present on the interface. Throughout the software, a color code for buttons helps the user distinguish between the different button functions: Yellow buttons are input buttons that allow one to make changes, red buttons are output buttons that contain information on parts, suppliers etc., and green buttons are navigation buttons that toggle between different worksheets of the model. Specifically, in the supply chain node map interface, yellow buttons allow the user to make changes to the supply chain node location, customer node location, the percent of revenue allocated to a customer, and the expected run rate. Red buttons show information regarding a specific node (supplier and part information). The green buttons take the user to worksheets containing comparison data.

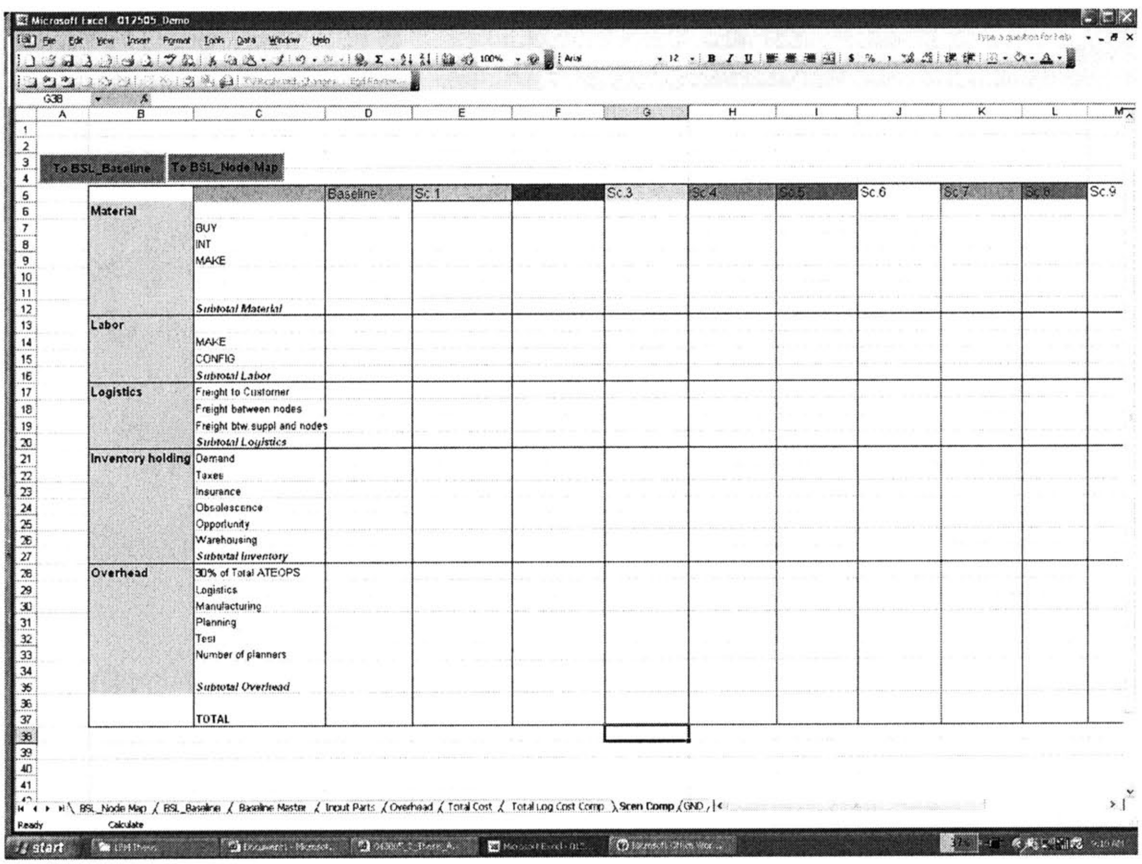
Figure 4.2.2.1: Interactive software user-interface. User-buttons allow one to make changes to the supply chain design, retrieve supplier and parts information, and toggle between different worksheets.



4.2.3 Data output

Once changes have been made to the baseline supply chain design, supply chain costs can be calculated in the software. The output of the software is a comparison of supply chain costs for different supply chain scenarios. The output comparison is in tabular and graphic form The output in tabular form is shown in Figure 4.2.3.1: The level 1 costs (material, labor, logistics, inventory holding, and overhead costs) associated with various supply chain design scenarios are compared. Column D shows the costs associated with the baseline supply chain design, subsequent columns display the costs associated with modifications made to this baseline.

Figure 4.2.3.1: Tabular data output



4.3 Databases

There are several databases that reside within the model from which the model retrieves information to calculate logistics costs. The databases were compiled from Teradyne internal sources

1. **Supplier database**: This database contains information on roughly 9,000 suppliers (supplier country, city, postal code etc.).
2. **Country/City database**: This database contains information on roughly 3,000 cities and assigns countries and airport codes to them.
3. **Rate tables**: The following rate tables are stored in the model:

Table 4.3.1: Rate tables

Worksheet	Rates (origin)
"BOS"	Boston
"MUC"	Muenchen, Germany
"SIN"	Singapore, Singapore
"PEN"	Penang, Malaysia
"SHA"	Shanghai, China
"TPE"	Taipei, Taiwan
"GND"	Average UPS ground transportation rates (origin Boston to UPS region 5)
"Fedex_international"	International Fedex rates to various countries originating from Boston
"Fedex domestic"	Domestic Fedex rates to various Fedex US regions originating in Boston

More rate tables should be added. The model looks up the origin of the shipment and goes to the appropriate rate tables to read in the appropriate rates for shipment to the destination. For a list of assumptions and details on how the different supply chain costs are calculated in the software see the following section.

4.4 Cost calculation of primary supply chain cost factors

The following describes how the main supply chain costs (level 1 costs, i.e., material, labor, logistics, inventory holding, and overhead costs) are determined in the software. Although Teradyne employs Oracle as its ERP system, for most applications, Teradyne uses webplan, which is a software with which data can be pulled from the Oracle databases and further processed. In the following calculations, the data referred to are data available from webplan (which again obtains the data from Oracle). The capitalized names in quotes refer to the nomenclature used in webplan.

4.4.1 Material cost

The baseline material cost is calculated by adding up the material cost of all the parts required to produce 1 system of a particular platform. In webplan, these parts are designated "BUY" parts.

4.4.2 Labor cost

The baseline labor cost is calculated by adding up the labor cost ("EXTENDED RESOURCE COSTS") of the "MAKE" parts required to produce 1 system. (When we examined the labor costs for one particular system, we found that the labor costs were not always accurate depending on whether it was a new product or not. For established platforms the accuracy of the labor cost data is high, while for newer products the data should be treated carefully. For a new platform, the labor cost data should probably be obtained from engineering/finance rather than from webplan.)

4.4.3 Logistics cost

The logistics cost calculation represents the major calculations performed by the software. The baseline logistics cost is calculated by adding up the logistics cost of all the parts required to produce 1 system.

Assumptions and rules for logistics cost calculations

Rates

- International shipments are done via air shipment (Air freight expeditors or FedEx international).
- Domestic shipments are done via surface (UPS ground).
- As domestic shipment rates for international locations were not available at the time of the internship, domestic U.S. UPS rates were used (this is a source of inaccuracy which should be removed as the rates are replaced by actual international inland ship rates).
- For air shipments, only airport-to-airport costs (not door-to-door) are considered
- In calculating shipping rates, contracted rates for Teradyne are used.
- Shipping rates depend only on weights and distance.
- Charges other than shipment included are duties and fuel surcharges.

Lotsize

- The lotsize of the shipments equals the average planned order (how many items are ordered in one ordering process). The average planned order is calculated from past and projected future orders.

Frequency

- No consideration of frequency of shipments is incorporated in the model.

The steps taken in the model to calculate the logistics costs are described below. All tables mentioned reside within the model. All steps are automated in the program.

The logistics cost consists of 2 types of costs:

- External shipping: Shipping costs from suppliers to a supply chain node
- Internal shipping: Shipping of sub-assemblies/parts between Teradyne's supply chain nodes (the shipment to customers is modeled as an internal shipment in the software; customers are modeled as supply chain nodes).

Calculation of shipping costs

From the set of input data, the following 5 entries are used for a particular part number:

- Supplier name
- Need quantity[3]
- Average planned order
- Part weight
- SCD code which identifies the node with which the part is affiliated

From this information, the logistics cost is calculated via the following steps:

1) Calculate: Lotsize weight = Part weight * Average planned order

2) Look up *supplier country* and *city* for a specific supplier from a supplier table

3) Determine *Airport code* (lookup airport code from a city-airport code table

[3] The "Need Quantity" is the number of items needed for one tester (e.g., on average a quantity of 1 manipulator is needed for 1 tester. The need quantity is calculated as an average based on historial and future orders (thus, the need quantity can be less than 1)).

4) Lookup *Node country, city, airport code* in similar fashion

5) Go to rate table for the *supplier airport code* (e.g., if supplier is in Shanghai, China, airport code is SHA. This is the origination airport)

6) Lookup *node airport code* and freight rate for the specific lotsize weight on that rate table

7) Calculate: Lotsize shipping cost = Freight rate * lotsize weight

8) Calculate the final shipping cost per part:

Configuration part ship cost = (Need quantitiy * Lotsize shipping cost)/Average planned order

For internal ("INT") and bought ("BUY") items essentially the same calculations are performed. For internally transferred items, the origin (the "supplier") of the part is a Teradyne node, which needs to be specified. (The locations of the Teradyne nodes are inputs for the user). The distinction between "BUY" and "INT" items becomes important in distinguishing the logistics costs derived from shipping between nodes from those logistics costs derived from shipping from outside vendors supplying to Teradyne.

4.4.4 Inventory holding cost

Inventory holding costs were divided into 3 groups: inventory holding costs for components, work-in-progress (WIP), and assemblies in transit. The inventory holding costs were roughly estimated using the following formulas:

- Components inventory holding costs = 0.5 * lotsize * material costs
- WIP inventory holding costs = Assembly make leadtime * demand * material costs + 0.5 labor costs
- Assembly transit time inventory holding costs = Assembly transit lead time * demand * cost of assembly

4.4.5 Overhead cost

The baseline overhead expense is allocated based on the percent revenue of a platform. A certain portion of the entire ATEOPS expense is allocated as overhead expense to each platform[4]. The average total ATEOPS expense from the first quarter of 2004 to the 4th quarter of 2004 was $40,000,000 and here we are assuming it remains the same in the first quarter of 2005 (1Q05). The baseline overhead expense of a particular platform is allocated based on the expected revenue generated in 1Q05. The expected revenue of this platform is 20% of the total revenue of (0.2 x $40,000,000 = $8,000,000) and the number of system produced is expected to be 50. In a simple approach, an overhead expense of $160,000= $8,000,000/50 can be allocated to 1 system. In summary:

Table 4.4.5.1: Calculation of ATEOPS expense per system

Total ATEOPS expense	Expected rev. %	# of systems	Expense allocated to platform	Expense per system
~$40 MM	20%	50	$8,000,000	$160,000

[4] A platform is a family of testers (i.e., catalyst, Flex, Tiger, Microflex, and J750).

Change in overhead expense as the supply chain design changes

Upon changes to the supply chain, only certain line elements in the total ATEOPS expense are likely to change. Based on discussion with Operations finance, the following line items were identified to change upon supply chain design change:

Table 4.4.5.2: ATEOPS line items likely to change

Line item
Logistics planning costs
Manufacturing: Foundry Board Test
Manufacturing: Electro/Mechanical
Manufacturing: Foundry manufacturing
Manufacturing: Foundry Subcontractor manufacturing
Manufacturing: Administration
Planning: Administration
Planning: Commodity management
Planning: Electro/Mechanical
Planning: Procurement
Planning: Volume PC Board Assembly (PCBA)
Test: Process Labs

Upon changes in the supply chain design, changes in these line items have to be calculated case-by-case. An example for how to quantify the change in a line item expense upon a change in the supply chain design is the change in planning overhead cost when a certain part of the operations is outsourced. The underlying thought here is that as the active number of parts to be managed decreases, the number of planners decreases. In our approach, we tried to find a scaling factor that determines the number of planners as follows:

Number of planners needed = Scaling factor * Number of active part items

In this approach, we estimated the average capacity per planner and determined the planners needed for the different planning functions. However, this analysis was tedious and the question is whether it is worth going into such calculations. We answered this question with the reasoning outlined below.

Analysis of maximum impact of selected overhead items

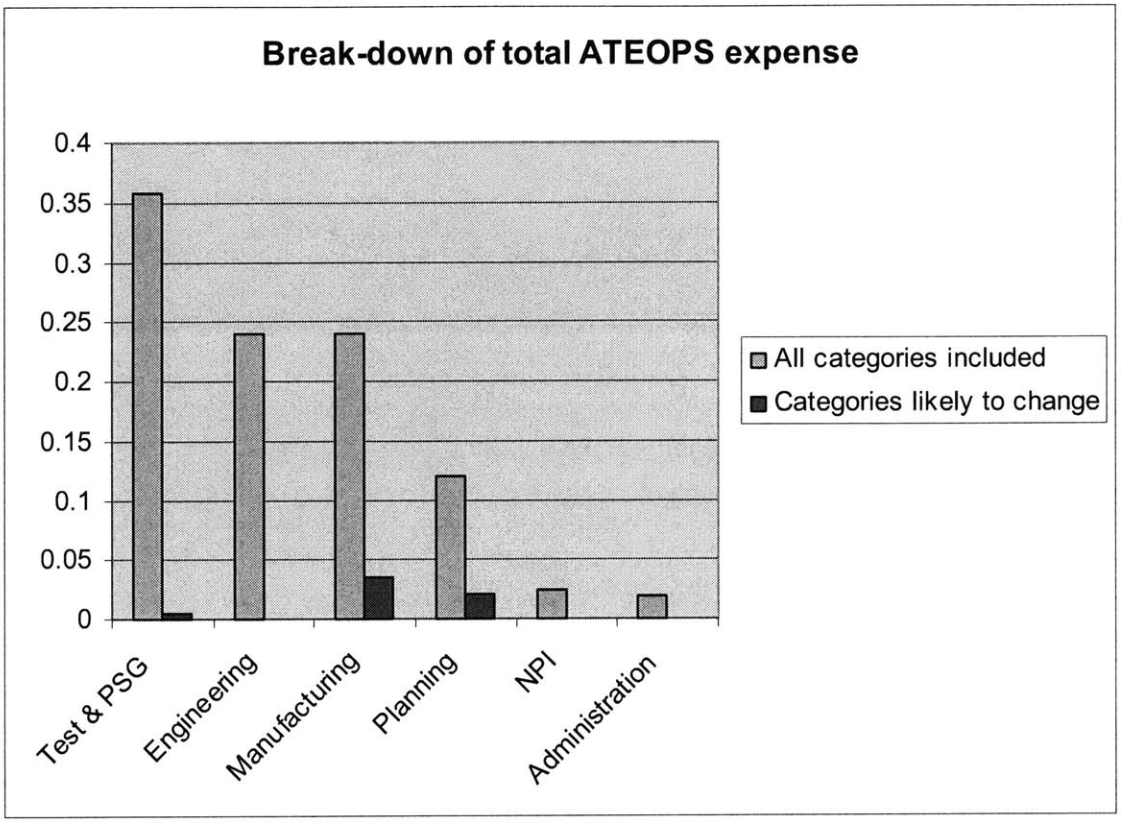
By how much can the overhead cost maximally change maximally if the supply chain changes? If we base expenses on revenue allocation, we can estimate the maximum change by looking at the percentage allocation of the total ATEOPS expense to a particular line item (based on the revenue for a particular platform). The following table summarizes the expenses associated with the selected line items for the particular platform discussed in the previous section.

Table 4.4.5.3: Maximum change in ATEOPS expense due to selected line items

Category	Total Category Spending	% of total ATEOPS Expense	Platform spending (selected line items)	% of total ATEOPS expense	Max. $ impact per system	% of total ATEOPS expense
Test & PSG	$15,000,000	0.358851675	$196,460	0.0047	$3,929	0.000094
Engineering	$10,000,000	0.23923445	$0	0	$0	0
Manufacturing	$10,000,000	0.23923445	$1,442,100	0.0345	$28,842	0.00069
Planning	$5,000,000	0.119617225	$886,160	0.0212	$17,723	0.000424
NPI	$1,000,000	0.023923445	$0	0	$0	0
Administration	$800,000	0.019138756	$0	0	$0	0
Total	**$41,800,000**	**1**	**$2,524,720**	**0.0604**	**$50,494**	**0.001208**

From this analysis we can see that the total of the selected line items allocated to the platform is roughly 6.04%. That means, even if the supply chain design change incurred a complete deletion of the selected overhead line items, at most, it would only change a few percent of the total ATEOPS expense. Manufacturing and Planning overhead are the 2 categories that are most powerful in affecting overhead cost changes. Under the assumptions of this analysis, planning cost can at most affect the total ATEOPS budget by roughly 2%. Currently we have approximately 40 planners. That means that of the selected planning line item expenses, roughly $880,000/40 = $22,000 can be allocated to 1 planner. If a supply chain design change led to a reduction of 10% of the planners (=4 planners here), an overall a reduction of $88,000 (~0.2% of total ATEOPS expense) would occur. The question arises whether overhead costs are worth including in the supply chain design consideration. The graph below depicts a break-down of the total and the line item ATEOPS expenses. Although for a detailed supply chain cost analysis a thorough overhead cost analysis is necessary, for a first-pass analysis, we believe, that the overhead expenses will not change drastically as the supply chain design changes. To get a ballpark figure for overhead, we therefore decided to just allocate the overhead expense based on revenue for a platform in the software. Thus, we did not consider any changes in the overhead cost as supply chain changes are implemented.

Figure 4.4.4.1: Comparison of total ATEOPS expense and the total expense of only the line items that are expected to change upon a supply chain design change: The sum of the selected overhead expense amount only to about 6% of total operations expense.



4.5 Cost effects of higher-level cost factors

As mentioned earlier, at this point, the software only includes level 1 supply chain costs not considering contributions from higher-level costs. However, these higher-level costs can impact the total supply chain cost significantly. Level 2 costs such as cost of quality, cost of a stock-out, one-time costs etc. can play an important role for total supply chain costs. The same applies to level 3 costs. For example, political factors such as political instability could potentially completely wipe out savings associated with offshoring. Through conversations with Teradyne employees who have been dealing with international vendors, we learned that also cultural differences can lead to substantial delays, quality issues etc. In general, we observed a lot of frustration of these employees stemming from differences in understanding specs, attitude towards deadlines etc. In one conversation, one employee stated, "people at vendor X don't have watches." Furthermore, costs of cultural differences translate into increased cost of travel, international telephone calling charges, inefficiencies due to time differences among others. Therefore it is important to consider and assess the effects of higher-level costs. At this point, these higher-level costs need to enter the total cost analysis via estimates based on business experiences of upper-level management. These estimates could take on the form of a (subjective) rating scheme which could be applied to evaluate a certain supply chain design in addition to the quantitative analysis performed by the software.

4.6 Current software capabilities and limitations

Capabilities

To date, the software is a high-level cost calculation tool. The 5 cost factors included in the model have varying precisions based on the data input available for analysis of the costs. Table 4.6.1 summarizes the cost factors, their main source of information, and the accuracy level.

Table 4.6.1: Accuracy of level 1 costs

Cost factor	Main source of information	Accuracy level
Material	Oracle	High
Labor	Oracle	High- Medium
Logistics	Contracted rate tables, estimates on part weights, Assumptions made on surcharges, avg. planned order and other factors	Medium
Inventory holding	Assumptions made on demand and average lead times	Medium – Low
Overhead	Allocation of overhead expenses based on revenue of platform, estimates on which line items might change upon changes in the supply chain design	Low

Overall, the tool has the capabilities and limitations outlined below.

Capabilities:

- Quickly assess rough cost implications of specified supply chain designs.
- Compare costs with each other through cost comparison table and graphs.
- User-friendly interactive tool.

Limitations:

- The model does not allow exact cost calculations, as assumptions are built into the model.
- At this stage, it doesn't take higher-level costs into account
- It does not perform optimization analysis (i.e., it doesn't suggest how to design a supply chain design).
- The model is not an execution tool to be used on a day-to-day basis, but a design tool.

4.7 Potential software enhancements

A potential improvement of the software would be performing and incorporating the results of a detailed overhead cost analysis, i.e., determine the cost changes of overhead line items that are likely to change upon changes in the supply chain design. So far, an analysis was performed to quantify the changes in number of planners needed as the supply chain changes. Similar analysis is required to estimate a change in the cost of all overhead line items.

An important improvement to the model would be a detailed analysis of how to quantify some of the higher-level costs such as cost of quality, cost of delay, cost of stock-outs etc. which then would roll up into level 1 costs. One-time costs such as set-up costs (level 2 costs) need to be included in a full cost analysis. Once we include such costs, a net present value (NPV) analysis of total costs for a project involving off-shoring would be invaluable for evaluating the feasibility of such projects.

Software development is a time-consuming process in which the software needs to be iteratively refined over time while working with the users of the software. At this point, the software tool can be regarded as a start. When users begin working with the software, they will be able to make suggestions for potential enhancements in the functionality of the tool and the software can be further improved based on these suggestions.

Chapter 5 Application of the model

5.1 Case study: Choosing manufacturing and test sites for J750

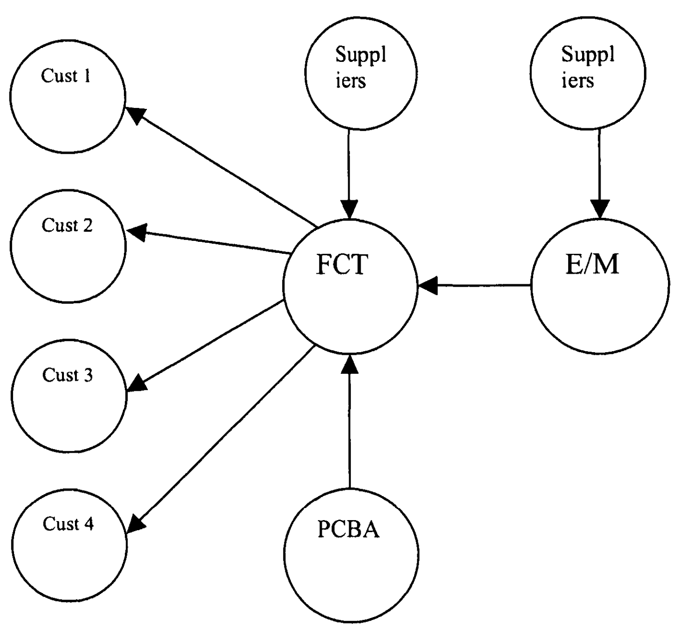
5.1.1 Business Case

The model was applied to a real business case currently being analyzed at Teradyne, in which several manufacturing and test locations of the tester J750 are re-evaluated. J750 is currently being manufactured, configured, and tested in Shanghai. Production steps take place at 2 different sites:

1. *Electro/Mechanical Assembly*, in which electrical and mechanical components are put together (this site is named E/M)
2. *Final configuration and test* (this site is named FCT)

Suppliers deliver material to both sites. In addition, PC board and assembly (PCBA) is sub-contracted and PC boards are delivered to FCT by sub-contractors (from node PCBA). Figure 5.1.1.1 shows the current high-level material flow in the supply chain for J750.

Figure 5.1.1.1: Schematic of current supply chain node design for J750.



The strategic question to be evaluated by Teradyne is whether moving assembly and/or final configuration and test to different locations yields cost savings over the current supply chain configuration. If so, to what locations should these nodes be moved to? So far, most suppliers for J750 are located in Asia, as both FCT and E/M are located in Shanghai. However, logistics cost associated with shipping from US suppliers to the 2 Shanghai production and test sites, and the logistics costs associated with shipping J750 out of Shanghai to customers in different parts of the world constitute a non-negligible portion of the total COGS of J750. Since a large fraction of Teradyne's current customer base for J750 is located in Asia, it is likely most advantageous to keep FCT in Asia. Therefore, the 2 FCT locations currently under consideration are Shanghai in China (the current location) and Penang in Malaysia. For E/M, 4 different locations were examined: Shanghai (current location), Creedmoor, NC in the US, Penang in Malaysia, and Singapore in Singapore. The following table summarizes the 8 scenarios that were analyzed:

Table 5.1.1.1: Site combinations to be evaluated in the business case

Scenario	**E/M Site**	**FCT Site**
1	Shanghai	Shanghai
2	Creedmoor, NC	Shanghai
3	Penang	Shanghai
4	Singapore	Shanghai
5	Shanghai	Penang
6	Creedmoor, NC	Penang
7	Penang	Penang
8	Singapore	Penang

5.1.2 Analysis

Due to the limited scope of the internship only the logistics cost analysis of the 8 scenarios was performed. The total logistics cost is comprised of the freight cost parts shipped from suppliers to either FCT or E/M., the freight cost associated with shipping internal parts and assemblies between nodes as well as the freight cost for shipping the final tester out of FCT to the various customer sites. Figure 5.1.2.1 and table 5.1.2.1 show the output of the model comparing the total logistics cost of the 8 scenarios. As evident from the cost comparison, the node combination Penang/Penang is the cheapest from a logistics point of view (roughly 25% less than the logistics cost associated with the current site locations). The node combination Singapore/Shanghai is the most expensive (roughly 16.5% more expensive than the freight cost associated with the current locations).

Figure 5.1.2.1: Comparison of total logistics costs calculated by the software. The combination Penang/Penang yields the lowest overall logistics cost.

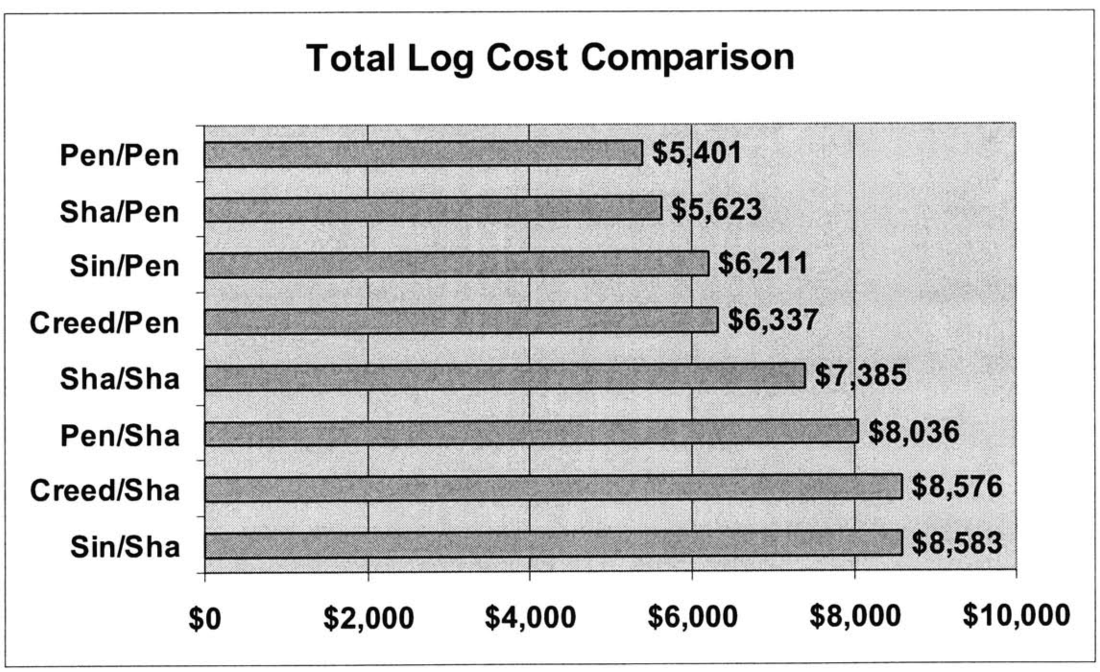


Table 5.1.2.1: Total logistics costs associated with the different supply chain scenarios

Scenario	E/M Site	FCT Site	Total Cost	Comparison to baseline
1	Shanghai	Shanghai	$7,385	100%
2	Creedmoor, NC	Shanghai	$8,576	116.1%
3	Penang	Shanghai	$8,036	108.8%
4	Singapore	Shangahi	$8,583	116.2%
5	Shanghai	Penang	$5,623	76.1%
6	Creedmoor, NC	Penang	$6,337	85.8%
7	Penang	Penang	$5,401	73.1%
8	Singapore	Penang	$6,211	84.1%

Figure 5.1.2.2 shows a break-up of the costs into freight to customers, freight between nodes, and freight from suppliers to nodes. Figure 5.1.2.3 shows the supplier transportation costs sorted by supplier countries.

Figure 5.1.2.2: Comparison of break-up of logistics costs into different shipping categories

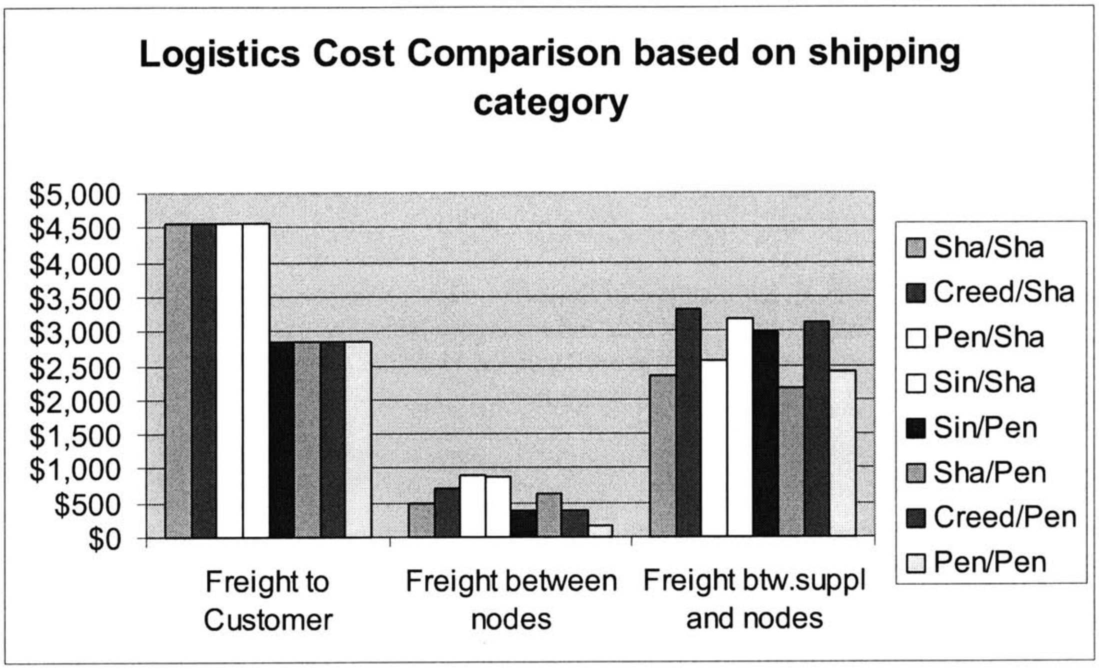
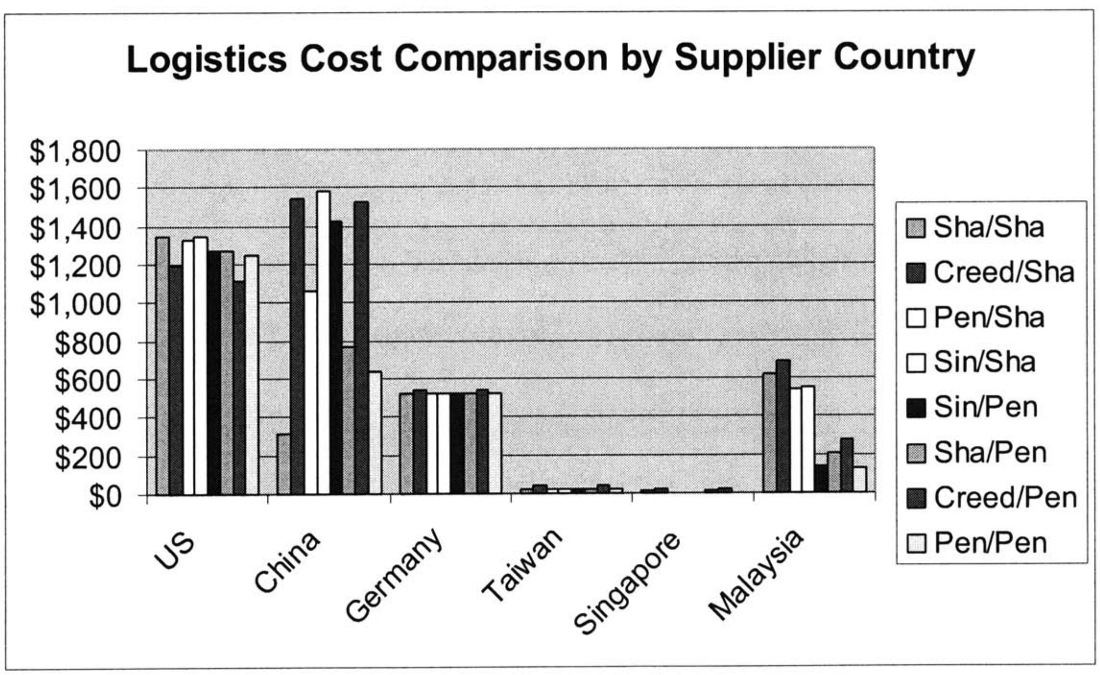


Figure 5.1.2.3: Comparison of supplier shipping costs sorted by supplier countries



What is interesting is that the transportation costs for US and German suppliers are fairly independent of both FCT and E/M locations. In the case of shipments from the US, this is largely due to the fact that US suppliers supply the most expensive items to FCT. The transportation cost of shipments to Shanghai and Penang (the 2 FCT locations under consideration) on the other hand are comparable. Thus, the shipping costs for items from the US are fairly independent of the locations under consideration for both FCT and E/M. As for the German suppliers, a similar reasoning applies: The most expensive items (constituting more than 90% of the cost) are supplied to FCT. As in the case of US suppliers, the transportation cost of German suppliers to Shanghai and Penang are comparable.

The costs associated with 2 supplier countries that vary strongly with E/M sites are China and Malaysia. Most of the Chinese suppliers supply to the assembly site (E/M). The baseline scenario (Shanghai/Shanghai) incurs the least supplier transportation costs from China (which is no surprise as the suppliers were chosen for the current baseline case). The transportation costs from China to Penang are the lowest and the transportation costs from China to the US are the highest. As for suppliers from Malaysia, there is a strong overall decrease in transportation costs as the FCT site is moved to Penang. This can be explained by the cheaper freight to customers (shipping out of China is much more expensive than shipping out of Penang). In addition, we observe a somewhat strong variation of costs with the E/M site as well. The variation stems from Malaysian suppliers supplying to E/M.

5.2.3 Conclusions and recommendation

The model's overall logistics cost comparison shows that the node combination Penang/Penang yields the lowest freight cost. It is lower by roughly 25% than the current total freight cost. Qualitatively, one can also understand this result from the following perspective:

The comparison of logistics cost associated with different supplier countries shows that one should choose the site of the nodes based on what sites give the lowest logistics cost associated with Chinese and/or Malaysian suppliers (because for the other supplier countries, different node locations don't result in a big difference in logistics costs.) This suggests, one should choose the node to be either in Shanghai or Malaysia to increase proximity of suppliers and nodes. Shipping into and out of Malaysia in general is cheaper than shipping into and out of China. Thus, it may not be a surprise that the combination Penang/Penang yields the overall lowest logistics costs. (Certainly, one would have to perform a detailed comparison of the number of parts and total weights shipped into and out of China and Malaysia respectively to quantitatively verify the above statement).

While based on logistics costs alone, the recommendation is to choose the node combination Penang/Penang, one should keep in mind that the comparison of the logistics cost constitutes only one part of a total cost analysis of the 8 different node location scenarios. A number of other cost factors need to be evaluated in order to decide which of the node combinations yields the overall lowest cost savings. In addition to logistics costs, one needs to evaluate material, labor, inventory holding, and overhead costs associated with the 8 designs ("level 1" costs as outlined in Chapter 3).

To perform a full analysis, one also needs to employ the cost architecture described in Chapter 3 and determine which of the higher-level costs would have a non-negligible impact on the total cost. For example, transitioning costs could be substantial and not make moving the FCT site a viable option. A major factor to be considered could also be the cost effects of level 3 costs such as cultural differences and/or political considerations (see Chapter 4, section 4.5).

5.2 Comparison of model and professional software output

Teradyne had the 8 scenarios analyzed by a professional software. The software calculated total landed cost, which included the following costs:

Components of Total Landed Cost [*Solectron*]

- Product Cost
- Raw materials
- E/M Subassemblies
- Finished Goods (J750)
- Air, Truck, or Ocean Freight Costs
- Fuel Surcharges
- Origin Fees (terminal, inland, handling, etc)
- Destination Fees
- Security Surcharges
- Brokerage Fees
- Import fees
- Duty
- MPF or Similar
- Freight Cargo Insurance
- Carrying Costs While In Transit
- Export fees
- Border Fees
- China VAT Holdback
- Peak Season Adjustments
- Expedite Adjustments

Most of these fees and charges (except for duties and fuel surcharges) were not included in the software to keep the model as simple as possible. Nevertheless, comparing the professional software output and the Excel VBA output yielded a very good agreement on relative costs. The absolute costs calculated in the model, however were lower by roughly 40%. Given that a number of costs are not considered in the model, this is not surprising. If those cost factors were known, they could be inserted in the model. The following figures compare the logistics cost calculated with the Excel tool with the logistics cost calculated by a professional software. Figure 5.2.1.1 compares the total logistics cost, figure 5.2.1.2 compares the inbound logistics cost to the E/M site, figure 5.2.1.3 compares the inbound logistics cost to the FCT site, and figures 5.2.1.4 compares the outbound logistics cost out of Shanghai and Penang respectively.

Figure 5.2.1.1 – 5.2.1.4: Comparison of logistics costs calculated by the Excel tool and by a professional software

Figure 5.2.1.1

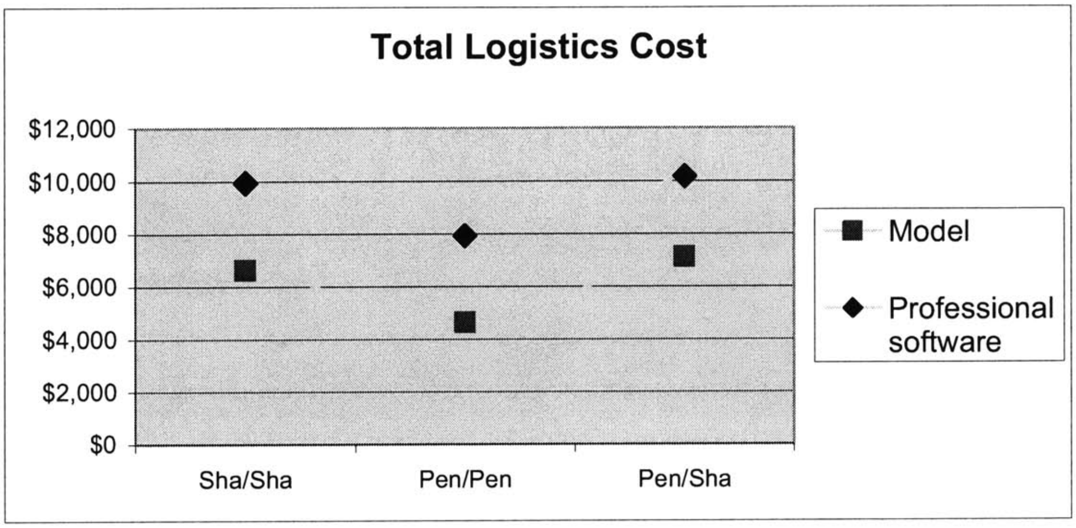


Figure 5.2.1.2

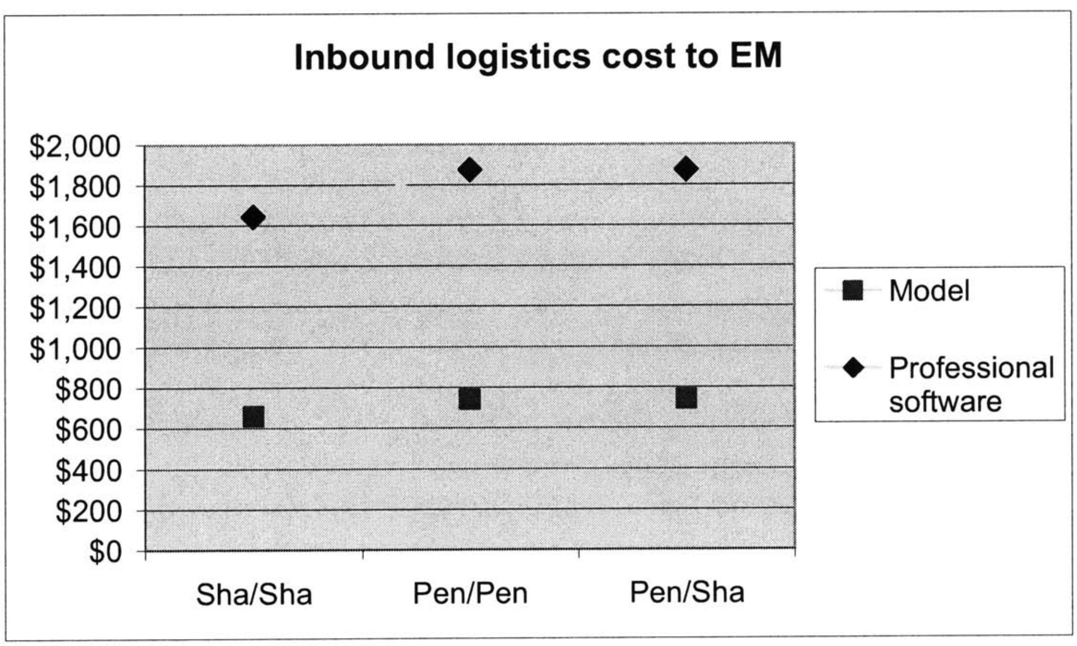


Figure 5.2.1.3

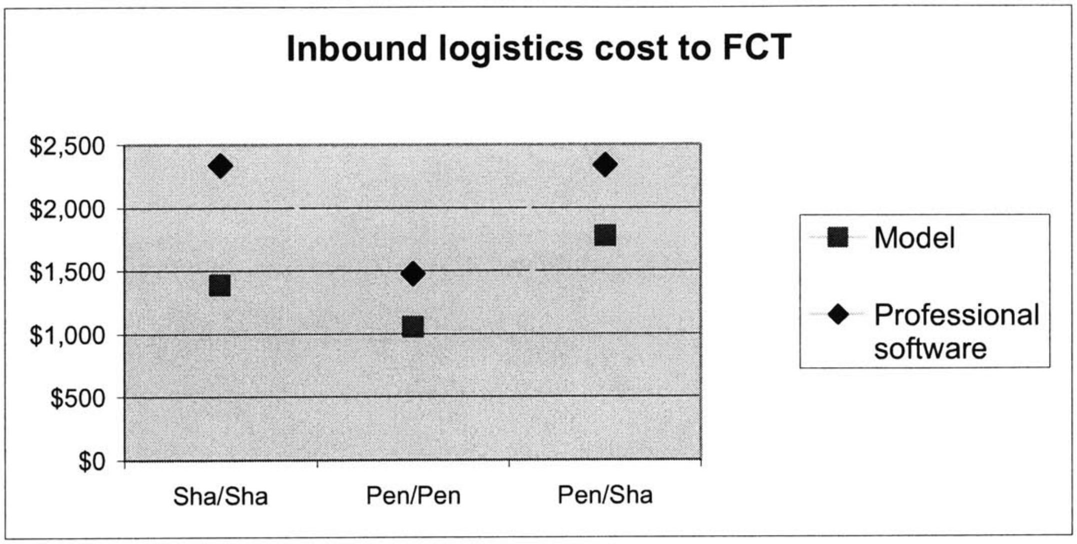
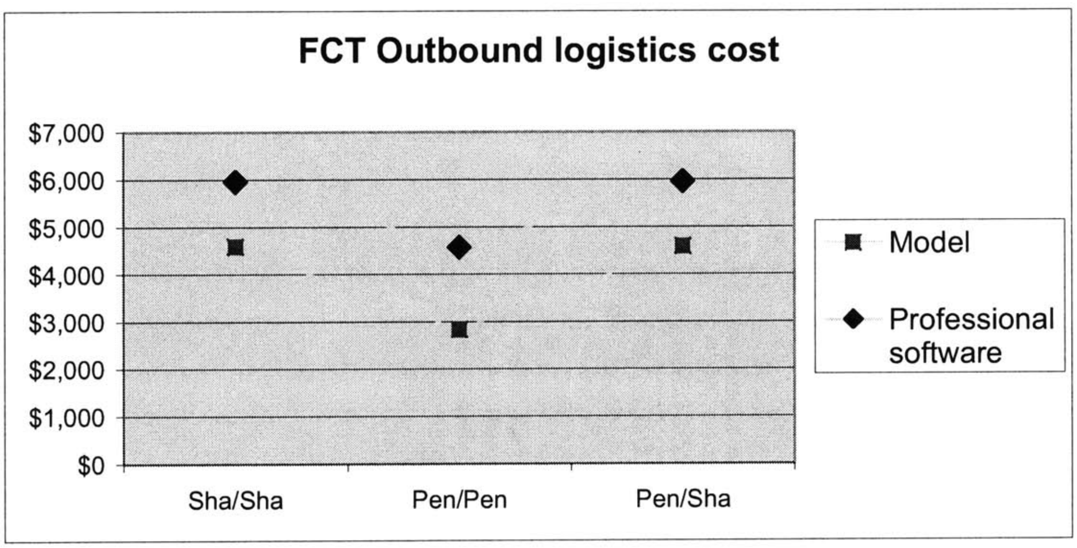


Figure 5.2.1.4



Chapter 6 Organizational and leadership learnings

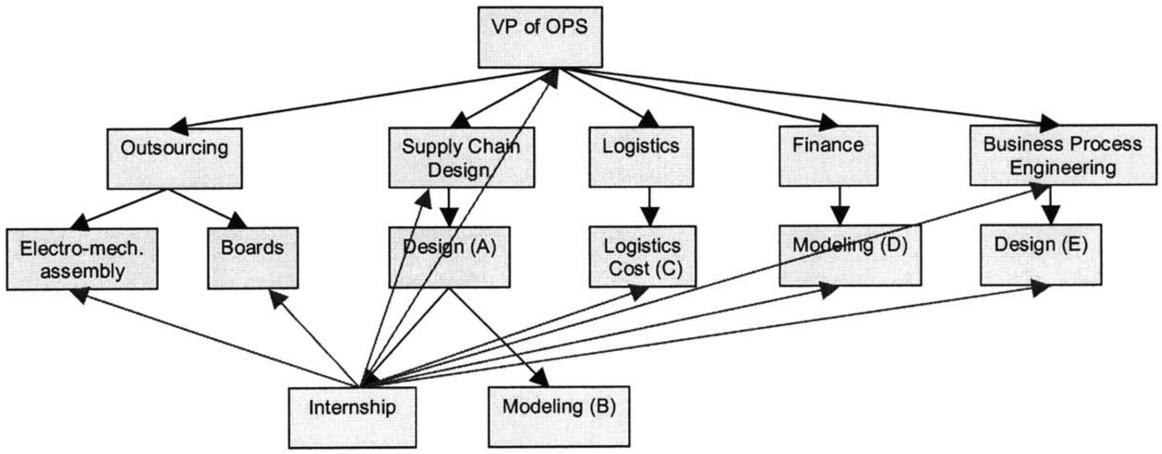
6.1 Organizational structural design

During the internship I learned about how an organization works primarily from the interaction among the groups that influenced the internship. ATEOPS is divided into numerous functional groups. The main groups that impacted the project were:

- Supply chain design (the group in which the project was officially conducted)
- Business process engineering
- Outsourcing
- Operations finance
- Logistics

For a structural map of the business units that influenced the project, see Figure 6.1.1. The red arrows indicate the cross-functional interaction between the group in which the internship was conducted and the groups that affected the project. Although the groups are clearly defined at Teradyne, the separation into groups did not hinder the project. To the contrary, cross-functional communication played an important role to obtain information or data for a particular issue. The fact that the team members came from different functional groups facilitated such data collection and communication between supply chain design and other groups.

Figure 6.1.1: Structural map of intern interaction of intern with different groups within ATEOPS



6.2 Implementing a new tool at Teradyne

One challenge with the outcome of an internship is how to pass on the learnings and to implement and maintain the results within the company. Solving these challenges was strongly associated with organizational tools, methods and customs in place at Teradyne. First of all, passing on the knowledge and learnings of the project was somewhat facilitated by the fact that a project team was established at the start of the internship. Teamwork is an important constituent of the Teradyne culture. Maintaining and upgrading the tool within the company have taken place primarily by 2 means:

- Training sessions with potential users of the tool
- Written documentation of how the model works and how to use it

These methods of introducing new tools in the company are customary. Training sessions are also fairly common in the company. In such sessions, one member, the "owner" of the tool, presents how a software works and trains a group of people on how to the use the tool. Excel is widely used in the company, so that the technical tools are already present. However, VBA expertise within the company is not common generally, which presents a potential challenge for maintaining and further developing the tool.

At Teradyne, TQM influences how jobs are assigned and done. Standardization is an important concept of TQM. Thus, the project was conducted conforming to many project guidelines from the start. For example project planning was conducted using Microsoft Project specifying steps and timeline of the project, a risk and benefit analysis was performed using a Teradyne risk and benefit template, and voice of the customer interviews were conducted strictly following the VOC guidelines of the company.

Overall, the organizational structure, along with the standardization of how things are done in the company, should facilitate implementing the tool. Long approval processes for purchasing expensive tools (such as professional software) helped the internship project in the sense that a number of people were in favor of the project (i.e., develop a software in-house vs. buy a professional software) not at last because of the time it takes to approve the purchase of a software.

6.3 Leadership leanings

The internship represented a rich learning experience. Instrumental was the teamwork that led to the results of this work. During this internship I learned how important planning and execution is to the success of a project. A role model from whom I learned many lessons in leadership was my project supervisor. Primarily thanks to him I learned the following key lessons in leadership:

:

- Pursuing ideas with persistence wins
- Know when to give directions and when to step back
- A team rises and falls with organization and scheduling
- Diplomacy can be used to tackle differences between opinions
- Back up your opinions with data
- Humor helps

Chapter 7 Conclusions

Many cost factors affect total supply chain costs. Trying to assess total supply chain costs is a complex and difficult task. This thesis developed a conceptual framework for total supply chain costs in which different cost factors are sorted into a "cost architecture". The framework gives guidance for how one can think about supply chain costs. In the cost architecture, costs are organized into hierarchical levels of increasing complexity which are *inter-related*. Thus, the total cost function (which is comprised of all costs affecting total supply chain costs) can be expressed as a sum of only 5 basic supply chain costs. This simplifies the total cost function and eases communication and discussion of the costs within an organization. Besides quantitative costs, qualitative costs (such as the costs of political instability or cultural differences) can be substantial and need to be weighted carefully case-by-case in order to make decisions with regards to making changes in supply chain design.

An interactive cost calculation tool was developed using Excel VBA. The software allows the user to experimentally model changes to the supply chain design. The VBA program automatically recalculates the supply chain costs based on the changes made. The output of the program is a comparison of costs associated with different supply chain designs.

In a case study, the model was applied to evaluate the feasibility of different node locations for one of Teradyne's testers. The output of the Excel tool was compared to the output of a professional software. The comparison showed very good agreement on relative logistics costs.

APPENDIX A

VOC questionnaire for Teradyne internal customers

Questions regarding supply chain costs

1. How do you think about supply chain costs? (Elements, drivers, trade-offs)

Questions regarding outsourcing:

1. What is our global outsourcing strategy? What are the specific cost implications of international outsourcing? Reverse logistics?

2. What factors should be considered to make outsourcing decisions?

3. What are your thoughts on outsourcing assembly/manufacturing?

4. Which outsourcing regions do you consider and why? Close to customers? Close to supply base?

Questions regarding supply chain cost model:

Past

5. How was cost modeling done in the past?

Present

6. How is cost modeling done today? What do you like *and* not like about it? Can you give us a copy of what you are using today?

7. How well does Teradyne manage its supply chain costs relative to other companies?

Future

8. How do you picture an ideal supply chain cost model? What capabilities would it have? What are the outputs that will allow decisions to be made?

9. Can you list and rank the top 5 characteristics that you would expect from a good cost model?

10. Can you give examples when and how you would use the total supply chain cost model? Should there be standardization across the company?

11. Who would use the model in your group? What kinds of questions would they want to answer?

12. What inputs would they be able to provide? Data and more subjective thoughts.

Concerns

13. What are your concerns with a model like this?

Appendix B

Voice of the customer interviews language processing (LP) diagrams

SUPPLY CHAIN DESIGN Section 3 VOC responses
(How do you picture a total supply chain cost model?)

A process to use the features of the model needs to define when, how, and who will use the model for decision making.

Ability to simulate supply chain scenarios

- Ability to move a node and see the cost implications **[Bob K]**
- Do what if's on volume and customer location **[Jim F]**
- The model can take you from current state to future state.**[Geo C]**
- Model should be incorporated into a process that discuss supply chain design options **(Jim D)**

Prepare the model to be migrated to a formalized software tool.

- Eventually invest in software to manage global supply chain **[Bob K]**

Model must work in all Platform RPD phases

- Need to build model that enables you to make decisions early in RPD phase so that you can properly influence sourcing decisions **(Ed R)**

Process stakeholders need to add value to the model output to finalize decisions

- Concerns: Won't correlate with our system expenses **[Geo C]**
- Concerns: It becomes the bible ("the model says"), need to distinguish between model output and reality. **[Ira D]**

Model must be balanced between being too simplistic and too cumbersome.

- Concerns with model: complexity, ability to be refreshed **[BobK]**
- Concern: Too complicated so people won't use it **[Jim F]**
- Simplicity: As simple as we can get. **[Geo C]**
- Concerns: Complexity (worried about that with SCE) **[Geo C]**
- Model needs to balance simplicity and complexity **(Rod H)**
- Model needs to be simple (few variables, understood by many, and intuitive) **(Tom F)**

Model owner and users need to be defined by the team

- Model will be used by Kenney's group and planning **[JimF]**
- Concern: Unless JF enforces it, nobody will use the tool **[JimF]**
- Conceptual elements like value-mapping should be standardized. **[Geo C]**
- Who would use the model: I would use for PCBA to validate building boards inside vs. outsource **[Geo C]**
- Model should be used owned by Finance and used by Jim F. and the DQC **(Jim D)**
- Ability of budget analysts to evaluate stability of the forecast on spending, inventory risk, and cost of sales **(Bill M)**
- Need to have right group managing the model such that you get an unbiased selection of suppliers **(Bill M)**

SUPPLY CHAIN DESIGN Section 3 VOC responses
(How do you picture a total supply chain cost model?)

The output of the model should include a Supply Chain Map, comparative and summary metrics that can aid decision making

A summarized map with key nodes and major cost elements for presentation purposes

- A supply chain node map connected by arrows (indicating transportation costs) where you are able to see the major 3-4 cost elements (COGS, transportation, management) **[Bob K]**

Provide a List of Outputs for each Supply Chain scenario including: Total Cost (Unit, Labor, Freight, Overhead), Responsiveness, Inventory, Capability, etc.

- Consider what is the premium for responsiveness **[Jim F]**
- Could the model demonstrate cycle time and show cost differences. **[Geo C]**
- Outputs: Certainly costs, inventory, responsiveness **[Geo C]**
- Need model that enables you to see the triangle of cost, technology and responsiveness **(Bill M)**
- Model needs to identify supply chain cost with outputs being total cost, flexibility, and inventory exposure based on varying service level assumptions (lead-time and stock-out) **(Rod H)**
- Model must be able to measure flexibility, quality, ease of overhead maintenance (ex. Transactions), & responsiveness **(Tom F)**
- Provide a landed cost for each source. **(Mike S.)**

Must be able to compare outputs for different scenarios to help understand differences in design.

- Ability to tell us when the coin (savings) flips without too many dimensions **[Jim F]**
- Create an optimum/balance between the things we are driving the business on (most important thing is flexibility) **[Ira D]**
- Is map and future map: what if you put this over there, could you achieve higher yield? **[Geo C]**
- Model must be able to identify changes in economic advantages of low cost regions to determine best location **(Lou F)**
- Model should help develop supply chain and manage it over time and would justify investments needed to improve supply chain **(Rod H)**

Summary of Qualitative measures to identify "good" (capable, responsive, Engineering Investment) suppliers

- Model must be able to identify suppliers that add value beyond the unit cost **(Tom F)**

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