

Inter-Enterprise Cost-Time Profiling

Leonardo Rivera

Dissertation submitted to the faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Industrial and Systems Engineering

F. Frank Chen, Chair
Robert H. Sturges, Jr.
Eileen Van Aken
Patrick Koelling

August 3, 2006
Blacksburg, Virginia

Keywords: Lean Manufacturing, Cost-Time Profile, Leanness, Measurement,
Cost, Investment.

Copyright 2006, Leonardo Rivera.

Inter-Enterprise Cost-Time Profiling

Leonardo Rivera

ABSTRACT

Measuring the use of resources in a production process has been a subject under great scrutiny since more than a hundred years ago. Traditionally, costing systems and cost accounting systems have been in charge of such functions in manufacturing corporations. On the other hand, in recent years Lean Manufacturing has become a powerful and popular force for change. A premier tool for process visualization and understanding is Value Stream Mapping, and it focuses primarily in the time dimension of the processes.

However, it is clear that the interaction of cost and time is very important. This is felt in everyday occurrences, such as paying interests for credit cards, mortgages and other types of loans. It is intuitive that the longer a certain amount of money is held, the more it costs. Also, if a larger amount of money is held for one day, it will obviously cost more than holding a smaller amount of money. Therefore, cost and time, BOTH, determine the real cost of the use of money.

However, this simple perception has not been applied equally to the measurement of manufacturing processes. They usually concentrate on either cost or time, but seldom in both at the same time and their interaction. The Westinghouse corporation formalized the concepts of the Cost-Time Profile in 1993, based on work done there during several decades.

Simply put, the Cost-Time Profile measures *how much money* is invested in the manufacturing process of a product and *for how long*, creating a chart that presents the accumulated cost at every point in time (Cost-Time Profile) and measuring the area under

this curve (Cost-Time Investment), and then using this quantification to measure the bottom line impact.

This research has accomplished two main things: the detailed consideration of the Cost-Time Profile (CTP) and the issues and factors that affect it, and the extension of the concepts to the new reality of Extended Enterprises. In a logical sequence, the basic concepts of CTP are defined and presented. Then, the extension of them to Inter-Enterprise environments follows.

Successive sections present how to build a CTP and the Inter-Enterprise Cost-Time Profile (IE-CTP), as well as discussing the factors that should be taken into account to bring the IE-CTP to practical applications, such as the effect of batching; the interaction with existing accounting systems; the consideration of direct cost, overhead and profit and the relationships between companies in supply networks to build IE-CTPs.

Then the issue of how to improve the results of the Cost-Time Investment (CTI) and CTP is addressed, and schedule optimization models are developed; generic improvement scenarios and lean implementation scenarios are discussed; some simulation studies are presented for cases when this tool has advantages over deterministic tools and an IE-CTP specific software tool is presented.

After learning how to improve the CTP and CTI, a discussion about how to use it and implement it is presented, and finally the summary and conclusions close this research report, identifying the contributions presented and leaving open avenues for future research.

TABLE OF CONTENTS

| | |
|---|-----------|
| 1. INTRODUCTION..... | 1 |
| 1.1. Background and motivation..... | 1 |
| 1.2. Problem Statement and Research Objectives | 3 |
| 1.2.1. Problem Statement..... | 3 |
| 1.2.2. Research Objectives..... | 3 |
| 1.3. Structure of this document..... | 4 |
| 2. LITERATURE REVIEW | 7 |
| 2.1. Lean Manufacturing..... | 7 |
| 2.2. Lean Metrics | 9 |
| 2.3. Project Management | 13 |
| 2.4. Costing Practices..... | 13 |
| 3. BUILDING A CTP – IE-CTP..... | 14 |
| 3.1. Basic concepts of CTP | 14 |
| 3.1.1. Cost-Time Profile..... | 14 |
| 3.1.2. Cost-Time Investment..... | 15 |
| 3.1.3. Direct Cost | 15 |
| 3.2. Introduction to the construction of the CTP and IE-CTP | 16 |
| 3.3. When do things happen: Activity Schedule..... | 16 |
| 3.4. How much do components cost: Activity Cost Rates..... | 17 |
| 3.5. How much cost accumulates at each time unit: Instantaneous Cost Rates..... | 18 |
| 3.6. How much Accumulated Cost is there at each time unit: Cost-Time Profile..... | 19 |
| 3.7. Inter-Enterprise Cost-Time Profile | 20 |
| 3.7.1. Identification of new types of activities..... | 21 |
| 3.7.2. New Actors in the Network: Third Party Logistical Providers..... | 25 |
| 3.8. A Numerical Example..... | 26 |
| 3.8.1. ACME Chairs – Single Enterprise Cost-Time Profile..... | 26 |
| 3.8.2. Inter-Enterprise CTP – Executive Chair | 30 |
| 4. FACTORS THAT AFFECT THE IE-CTP | 36 |
| 4.1. Batching | 36 |
| 4.1.1. Definition of batching..... | 36 |
| 4.1.2. Cases of batching | 36 |
| 4.1.3. Numerical Example | 39 |
| 4.2. Accounting Systems..... | 46 |
| 4.2.1. Standard Costing..... | 47 |
| 4.2.2. Activity Based Costing (ABC) | 48 |
| 4.2.3. Lean Accounting – Lean Costing | 49 |
| 4.2.4. Where does the IE-CTP fit?..... | 49 |
| 4.3. Direct cost, overhead and profit..... | 50 |
| 4.4. Relationship between companies..... | 52 |
| 4.4.1. Power of Negotiation – Role in the Network: | 52 |
| 4.4.2. Topology of the Network (of companies)..... | 53 |
| 4.4.3. Establishment of attractive interest rates | 54 |
| 4.4.4. Sharing of savings..... | 55 |

| | |
|---|------------|
| 4.4.5. Lean collaboration | 55 |
| 5. IMPROVEMENT OF THE IE-CTP..... | 58 |
| 5.1. Schedule Optimization..... | 58 |
| 5.1.1. Minimize completion time..... | 58 |
| 5.1.2. Modified objective function – minimize sum of slacks..... | 60 |
| 5.1.3. Consider resource dependencies..... | 62 |
| 5.1.4. Minimize the Cost-Time Investment | 66 |
| 5.2. Scenarios for direct cost improvement | 69 |
| 5.2.1. Less materials: Reduce the area by spending less money on materials..... | 71 |
| 5.2.2. JIT materials..... | 72 |
| 5.2.3. Wait less: Reduce the area by cutting the waiting times. | 74 |
| 5.2.4. Faster equipment: Use bigger and faster equipment..... | 75 |
| 5.2.5. Cheap activities: Decrease the cost rate of the activities..... | 76 |
| 5.2.6. Late activities: Spend less at the beginning and more at the end..... | 77 |
| 5.2.7. Slower but cheaper (A and B)..... | 78 |
| 5.2.8. Summary | 80 |
| 5.3. Impact of a lean transformation on the Cost-Time Investment | 81 |
| 5.3.1. Lean implementations..... | 81 |
| 5.3.2. Scenario “First Wave”..... | 83 |
| 5.3.3. Scenario “Second Wave”..... | 84 |
| 5.3.4. Scenario “Third Wave”..... | 85 |
| 5.3.5. Scenario “Fourth Wave”..... | 86 |
| 5.4. Simulation Studies | 90 |
| 5.4.1. Model Configuration..... | 90 |
| 5.4.2. Variations of the model..... | 96 |
| 5.4.3. Simulation Results | 98 |
| 5.5. Software Tool: Cost-Time Profiler | 100 |
| 5.5.1. Single-Enterprise Example | 100 |
| 5.5.2. Inter-Enterprise functionality..... | 108 |
| 6. USE AND APPLICATIONS OF THE IE-CTP | 112 |
| 6.1. Analysis of the areas (slice the CTP)..... | 112 |
| 6.1.1. Slice the CTP horizontally | 113 |
| 6.1.2. Slice the CTP vertically | 115 |
| 6.1.3. Analysis of the CTP “slicing”..... | 116 |
| 6.2. How to build the enterprise network for the IE-CTP..... | 117 |
| 6.2.1. Internal assessment | 117 |
| 6.2.2. Assessment of the supply network..... | 118 |
| 6.2.3. Implementation and operation phase | 120 |
| 6.3. Challenges for companies that wish to implement the IE-CTP..... | 121 |
| 7. SUMMARY, CONCLUSIONS AND FUTURE RESEARCH | 123 |
| 7.1. Summary | 123 |
| 7.2. Conclusions and contributions of this research | 126 |
| 7.2.1. The re-examination of the CTP methodology. | 126 |
| 7.2.2. Inter-Enterprise CTP..... | 127 |
| 7.2.3. Optimization models..... | 128 |
| 7.2.4. Scenarios for CTP improvement..... | 128 |

| | |
|--|------------|
| 7.2.5. Framework to implement the IE-CTP on a supply network | 129 |
| 7.2.6. IE-CTP software development..... | 129 |
| 7.3. Future Research Areas | 129 |
| 7.3.1. Application of IE-CTP in non-manufacturing environments | 130 |
| 7.3.2. Application of IE-CTP for analysis of capital investment opportunities..... | 131 |
| 7.3.3. CTP in high-interest (inflation) environments..... | 131 |
| 7.3.4. Integration of IE-CTP with traditional costing systems | 132 |
| 7.3.5. Transfer prices between Business Units of the same company | 132 |
| 7.3.6. Integration with leanness Measurements | 133 |
| REFERENCES..... | 134 |
| APPENDICES..... | 140 |
| Appendix A: Details of the examples of batching..... | 141 |
| Appendix B: SIMAN code of the simulation model. | 150 |
| Vita | 191 |

List of Acronyms

| | |
|--------|---|
| 3PL | Third-Party Logistics Provider |
| ABC | Activity-Based Costing |
| ACR | Activity Cost Rate |
| CHPM | Center for High Performance Manufacturing |
| CTI | Cost-Time Investment |
| CTP | Cost-Time Profile |
| DEA | Data Envelopment Analysis |
| EDI | Electronic Document Interchange |
| EOQ | Economic Order Quantity |
| ERP | Enterprise Resource Planning |
| GUI | Graphical User Interface |
| ICR | Instantaneous Cost Rate |
| IE-CTP | Inter-Enterprise Cost-Time Profile |
| IRR | Internal Rate of Return |
| JIT | Just in Time |
| LP | Linear Programming |
| MARR | Minimum Attractive Rate of Return |
| MIP | Mixed Integer Programming |
| NVA | Non Value Added |
| OCR | Operator Cost Rate |
| OEM | Original Equipment Manufacturer |
| RCR | Resource Cost Rate |
| ROI | Return on Investment |
| SMED | Single Minute Exchange of Dies |
| TCA | Traditional Costing Accounting |
| TPM | Total Productive Maintenance |
| TPS | Toyota Production Systems |
| VA | Value Added |
| VPN | Virtual Private Network |
| VSM | Value Stream Mapping |
| WIP | Work in Process |
| XML | eXtensible Markup Language |

List of Figures

| | | Title | Page |
|---------------|-----------|---|------|
| Figure | 1 | A Cost Time Profile | 15 |
| Figure | 2 | Schedule of Activities(organized by machine) | 16 |
| Figure | 3 | Calculation of the Instantaneous Cost Rates | 18 |
| Figure | 4 | A typical Cost Time Profile | 20 |
| Figure | 5 | Project Net Diagram for the Executive Chair- ACME Chairs | 27 |
| Figure | 6 | Cost Time Profile for the Executive Chair | 29 |
| Figure | 7 | Network Diagram for the IE-CTP | 31 |
| Figure | 8 | Compared CTP and IE CTP for ACME Chairs | 32 |
| Figure | 9 | CTPs per company | 33 |
| Figure | 10 | CTPs when the partner companies are paid JIT | 34 |
| Figure | 11 | Example Production Process | 40 |
| Figure | 12 | CTP and CTI for a single unit | 40 |
| Figure | 13 | CTP and CTI for Case 1 (10 units simultaneously) | 41 |
| Figure | 14 | CTP and CTI for Case 2 JIT Materials | 42 |
| Figure | 15 | CTP and CTI for Case2 Batch Materials | 42 |
| Figure | 16 | Case 3: Batch for equipment requirements (oven) | 43 |
| Figure | 17 | CTP for Case 4: Batch for Material Handling | 44 |
| Figure | 18 | Case 5: Transport between Activities A and B | 44 |
| Figure | 19 | Case 5: Transport between Activities C and D | 45 |
| Figure | 20 | General composition of the cost of a product | 47 |
| Figure | 21 | Levels of cost and overhead | 49 |
| Figure | 22 | Components of the price from a supplier | 50 |
| Figure | 23 | Simplified network topologies | 53 |
| Figure | 24 | Linear sequence of activities | 58 |
| Figure | 25 | Process map for a product with subassemblies | 59 |
| Figure | 26 | Contribution to the area under the curve by an activity | 66 |
| Figure | 27 | Simple production process | 69 |
| Figure | 28 | Cost-Time Profile for the Base Case scenario | 71 |
| Figure | 29 | CTP for the Less Materials scenario | 72 |
| Figure | 30 | CTP for the JIT Materials scenario | 73 |
| Figure | 31 | CTP for the Wait Less scenario | 74 |
| Figure | 32 | CTP for the Faster Equipment scenario | 75 |
| Figure | 33 | CTP for the Cheap Activities scenario | 77 |
| Figure | 34 | CTP for the Late Activities scenario | 78 |
| Figure | 35 | CTPs for the Slower-Cheaper A and B scenarios | 80 |
| Figure | 36 | Waves of a Lean implementation | 82 |
| Figure | 37 | CTP for the First Wave scenario | 84 |
| Figure | 38 | CTP for the Second Wave scenario | 85 |
| Figure | 39 | CTP for the Third Wave scenario | 86 |
| Figure | 40 | CTP for the Fourth Wave scenario | 87 |
| Figure | 41 | Accumulated improvement from the Base Case to the Fourth Wave | 88 |
| Figure | 42 | Structure of the manufacturing process | 91 |

| | Title | Page |
|------------------|---|-------------|
| Figure 43 | Overview image of the simulation model in Arena | 93 |
| Figure 44 | Hold and Assignment modules before Operation J | 94 |
| Figure 45 | Configuration of the HOLD module in Arena | 94 |
| Figure 46 | Transcription of the expression of CTI for each individual entity | 95 |
| Figure 47 | Assignment and Data collection modules at the end of the process | 95 |
| Figure 48 | Run Setup for the Arena models | 96 |
| Figure 49 | Batch for Transportation | 98 |
| Figure 50 | Simple linear production process | 100 |
| Figure 51 | Welcome screen of the Cost-Time Profiler | 101 |
| Figure 52 | Project Selection menu on the Cost-Time Profiler | 101 |
| Figure 53 | Select an existing project | 102 |
| Figure 54 | Project details | 102 |
| Figure 55 | Company details | 103 |
| Figure 56 | Activity details | 104 |
| Figure 57 | Operator details | 104 |
| Figure 58 | Resource details | 105 |
| Figure 59 | CTI Gantt Chart | 106 |
| Figure 60 | CTP chart | 106 |
| Figure 61 | Operator Usage | 107 |
| Figure 62 | Resource Usage | 107 |
| Figure 63 | Main window of a multiple-company project | 108 |
| Figure 64 | CTI Gantt Chart | 109 |
| Figure 65 | CTP chart | 109 |
| Figure 66 | Operator Usage | 110 |
| Figure 67 | Resource Usage | 110 |
| Figure 68 | A Cost-Time Profile | 112 |
| Figure 69 | Horizontal Slices on a CTP | 113 |
| Figure 70 | Slice the CTP vertically | 115 |

List of Tables

| | | Title | Page |
|--------------|-----------|---|------|
| Table | 1 | Brief comment on several literature sources related to Lean Metrics | 10 |
| Table | 2 | Manufacturing Activities for the Executive Chair | 27 |
| Table | 3 | Activity Completion Time | 28 |
| Table | 4 | Per minute cost – rates of the Operators and Resources | 28 |
| Table | 5 | Activities with partner Companies | 30 |
| Table | 6 | Cost rates of Resources and Operators | 31 |
| Table | 7 | Comparative results between CTP and IE CTP | 33 |
| Table | 8 | Numerical comparison between pay-at-the-end and pay JIT | 34 |
| Table | 9 | Example Production Process | 39 |
| Table | 10 | Summary of the 5 cases of batching and their effect on the CTI | 45 |
| Table | 11 | Description of the Base Case | 70 |
| Table | 12 | Results for the Base Case Scenario | 70 |
| Table | 13 | Results for Less Materials Scenario | 71 |
| Table | 14 | Results for JIT Materials Scenario | 73 |
| Table | 15 | Results for Wait Less Scenario | 74 |
| Table | 16 | Results for Faster Equipment Scenario | 75 |
| Table | 17 | Results for Cheap Activities Scenario | 76 |
| Table | 18 | Results for Late Activities Scenario | 77 |
| Table | 19 | Results for Slower Cheaper Scenarios | 79 |
| Table | 20 | Summary of the results of the different Scenarios | 81 |
| Table | 21 | Results for First Wave Scenario | 83 |
| Table | 22 | Results for Second Wave Scenario | 85 |
| Table | 23 | Results for Third Wave Scenario | 86 |
| Table | 24 | Results for Fourth Wave Scenario | 87 |
| Table | 25 | Summary of Lean Implementation Scenarios | 88 |
| Table | 26 | Activity and Resource Data for the numerical example | 91 |
| Table | 27 | Changes in Activities E and D | 96 |
| Table | 28 | Simulation Results | 98 |

List of Equations

| | Page |
|---------------------|-------------|
| Equation 1 | 2 |
| Equation 2 | 15 |
| Equation 3 | 17 |
| Equation 4 | 17 |
| Equation 5 | 60 |
| Equation 6 | 60 |
| Equation 7 | 60 |
| Equation 8 | 61 |
| Equation 9.1 | 63 |
| Equation 9.2 | 63 |
| Equation 9 | 65 |
| Equation 10 | 65 |
| Equation 11 | 67 |
| Equation 12 | 67 |
| Equation 13 | 67 |
| Equation 14 | 67 |
| Equation 15 | 67 |

Acknowledgments

First, I would like to thank my wife Ana M. Valdes and my son Camilo Rivera. They have been my support system during this process; they have graciously lent their husband and father to this program and have always been there for me. This degree is theirs as much as mine, if not more.

To my Advisor and Chair, Dr. F. Frank Chen, who was generous from the beginning with his advice, patience and guidance. His ample knowledge in many of the disciplines of Engineering gave me the ideas I needed to direct my process. To Dr. Robert Sturges (a.k.a. Dr. Bob), who has the sharpest questioning abilities I have ever seen. He asked me questions and never gave me straight answers, more than a couple of “Ah ha!” and “eureka”; that’s what he does best. To Dr. Eileen Van Aken, who gave me valuable organizational and managerial insights and was always supportive of my presentation materials. Finally, to Dr. Pat Koelling, whose calmed and incisive observations called my attention to important issues in my research. His comments were always kind, something that all the students who know him appreciate.

I also wish to express my gratitude to the Center for High Performance Manufacturing, which sponsored me with a Research Assistantship for a year in a project that introduced me to the concepts of the Cost-Time Profile, and gave me the financial support to conduct my studies and my research. Also, the Grado Department of Industrial and Systems Engineering, which sponsored me with several Teaching Assistantships that gave me important learning opportunities and much appreciated financial support.

My Ph.D. studies would not have been possible without the academic and financial support from the Fulbright Scholarship Program, COLCIENCIAS (Instituto Colombiano para el Desarrollo de la Ciencia y la Tecnología, Francisco José de Caldas) and Universidad Icesi (my previous and future employer in Colombia). These institutions have demonstrated their commitment to the development of scholars and researchers for Colombia and they have my heartfelt gratitude and respect for it.

My sincerest acknowledgments to my two families in Colombia (the Rivera Cadavid and the Valdes Duque families), for their love and teachings through all my life, and their continued support during our time in Blacksburg. A special mention goes to Javier for his help and patience with all my software shortcomings. None of this would have been possible without all of you holding me and pushing me forward.

Finally, to my father, who passed away just days after the defense of this Dissertation. You were a great example as father, husband and teacher. I hope to have a life as full and successful as yours.

1. INTRODUCTION

Lean manufacturing has been a powerful philosophy that has dramatically improved the operating processes and results of many companies in diverse industrial, regional and national environments. The basic principles of lean manufacturing include the rationalization and organization of the processes in such a way that waste is minimized, ultimately seeking as one of the main goals the improvement of productivity. It is understood that *productivity* means the ability to obtain a better ratio of output to input, thus improving the use and profit of the company's resources.

The measurement of the “degree of leanness” has been a constant theme of research, with two main avenues: 1). the measurement of the degree of adoption and application of recognized “lean tools, techniques and practices”, which is a measurement of the process and; 2). the measurement of *productivity*, basically related to the capacity to use the resources in an economical fashion, to use them better than in the past or better than other company or business unit (thus making a *lean* process).

This research project focuses on a measurement of the second type, a *productivity* measurement, with two special characteristics: 1). it considers the time-value of money and 2). it is applied beyond the boundaries of a company (or business unit) to encompass all the parties involved in the manufacturing of a product.

1.1. Background and motivation

The word *leanness* can be interpreted as “the quality of being lean”; being lean, however, is open to many different interpretations. This research intends to explore a quantitative measure of leanness, one that is more related to the *results* rather than to the *processes*. This measure will show when a product is being manufactured in a leaner way than with a previous practice, or the level of resources utilized when different companies manufacture similar products.

Traditionally, productivity measures have come from the realm of accounting and financial indicators, where a simple relationship like **Equation 1** has been widely used:

$$productivity = \frac{outputs}{inputs} \quad (Eq. 1)$$

This relationship, simple as it seems, is still in the heart of productivity and leanness measurement. We contend that a more productive process (to manufacture the same product) would be *leaner* than some other. Therefore, productivity measures that concentrate on the results of a process rather than on the steps that happen during the process are of interest for this research.

In the case of the Cost-Time Profile and Cost-Time Investment, the output is supposed to stay constant (one unit of a certain manufactured product), and the measure concentrates in the inputs (how much money is invested for how much time to achieve the production of one unit of finished product).

Of course, the measure of the Cost-Time Investment only reflects the final results of the amount and timing in the use of resources, so it can be regarded as a *final results* measure. However, for industrial engineers it is also extremely important to observe the changes in the system, since it is in the improvement of the processes that this profession thrives. A tool that helps lean practitioners to visualize their processes is *Value Stream Mapping* (VSM). However, VSM considers only the time dimension and ignores the accumulation of cost during the manufacturing process. This fact makes the quantification of savings after a proposed process improvement a difficult proposition.

Also, traditional product costing captures the product-related expenditures in a simple additive manner. One of the biggest teachings of the use of Value Stream Maps has been the discovery that the time it takes a product to flow through the process is usually much longer than it should. This discovery highlights the importance of considering the time dimension and the time-value of money on the costing of a product.

To address these two problems, the Cost-Time Profile is presented here. The basic concepts were developed at Westinghouse Corporation (Fooks, 1993); the discussion, applications, process to construct a CTP, the inter-enterprise application and future research questions are original.

Finally, it is expected that the inter-enterprise extension of the Cost-Time Profile will serve as a collaboration platform for networks of companies that participate in creating and taking a product to the final customer. Discussion of the different issues that need to be considered, the challenges for implementation and the possible benefits to be gained from the implementation of a IE-CTP system are the final subjects of this work.

1.2. Problem Statement and Research Objectives

1.2.1. Problem Statement

As it was discussed above, this research focuses on the development of a quantifiable measurement of leanness, specifically targeted to a single unit of product. A methodology to identify the Cost-Time Investment on a single product (across the different companies that participate in its manufacturing) will be presented. Along this route, the elements that contribute to the Direct Cost and to the final Cost-Time Investment will be identified and characterized. Also, we will discuss the relationships between companies and their effect on the Direct Cost and the Cost-Time Investment.

1.2.2. Research Objectives

We will address a series of steps in order to implement the Inter-Enterprise Cost-Time Profile successfully. These steps are our research objectives, which follow in some detail:

- **Develop a methodology to obtain and present a Cost-Time Profile:**
Tackling this objective involves two main tasks: 1). the development of the algorithm and steps necessary for the construction of the Cost-Time Profile for

a single enterprise (Section 3.2); and 2). the extension of these sequence of steps to build the Inter-Enterprise Cost-Time Profile (Section 3.7).

- **Propose a framework for the application and use of the Inter-Enterprise Cost-Time Profile:** Part of this research is intended to develop concepts and tools that companies can use. As such, an important portion of the work is to determine the possible uses of the products of the research. In order to do this, it is necessary to outline the benefits that would be achieved, the potential for cooperation between the companies involved. Once interest is expressed, it is necessary to identify the needs for infrastructure and information exchange in order to make implementation possible (Chapters 4 and 6).
- **Develop a practical tool to implement the Inter-Enterprise Cost-Time Profile:** All the concepts will not be useful if a tool that implements them is not provided. A software tool will be developed to implement all these concepts in a simple manner, providing basic information about the processes, activities and companies that take part in the manufacturing of a product (Section 5.5).
- **Explore the impact of different system variables and decisions on the Cost-Time Profile and Cost-Time Investment:** We will conduct an exploration of the effects that batching, waits and information exchange mechanisms can have on the results in terms of Cost-Time Profile and Cost-Time Investment (Chapter 4).

1.3. Structure of this document

This document is organized in seven chapters, following a logical sequence of evolution of the subject. At the beginning, the general motivation and structure of the work are presented; then some background literature is discussed. The concepts and construction of the CTP and IE-CTP are next, and then detailed examination of issues that affect them follows. Finally, some suggestions for improvement of the Direct Cost and considerations for the real-life implementation and use of the IE-CTP are presented; and possibilities for expansion and future research are left as open questions.

- a. **Literature Review (Chapter 2):** Includes the review of previous research work on leanness, performance measurement and Cost-Time Profiling.
- b. **Building a CTP – IE-CTP (Chapter 3):** This chapter presents the general methodology for building a Cost-Time Profile in its most simple form, which is a single product being manufactured on a single company. Then, it extends the concepts and methodologies of the previous section to the case where several companies or business units interact in the manufacturing of the product. We identify new elements of cost and also explore the relationships between companies (or business units), the benefits that could be derived from the use of a tool like this one and the requirements of information and infrastructure for the tool to work adequately. Finally, a numerical example of Cost-Time Profile for a single product is presented, and then this example is extended assuming now that several companies or business units participate in its manufacturing.
- c. **Factors that affect the IE-CTP (Chapter 4):** In this chapter some important issues that have an important effect on the Direct Cost and Cost-Time Investment, such as the role of transportation, the impact that batching in the production process has over the CTP, the accounting systems and the relationships between the participating companies will be explored and analyzed.
- d. **Improvement of the IE-CTP (Chapter 5):** Different ways to improve the end result of the Direct Cost and the Cost-Time Investment are explored here, starting with a mathematical model to design the schedule of activities, to simulation studies to understand the effect of critical system variables and the use of a software tool to consider different scenarios and possibilities in a cost-effective manner.
- e. **Use and applications of the IE-CTP (Chapter 6):** Some foreseen applications and uses of this tool are discussed here, along with the challenges that practitioners will face implementing the IE-CTP.
- f. **Summary, Conclusions and Future Research (Chapter 7):** The main takeaways of this research will be presented in a summarized form so the reader can quickly understand what was done in the research. Also, open research

questions are posed here, including future applications to non-manufacturing fields and the use of the CTP for project management and control.

2. LITERATURE REVIEW

Much has been discussed about lean manufacturing, its characteristics and components. This research is not focused on lean manufacturing or its implementation alone, because any company using any manufacturing philosophy can apply the Cost-Time Profile or the Inter-Enterprise Cost-Time Profile. However, there is an interesting relationship between the types of activities that can cause the reduction of the Cost-Time Investment (leading to lower costs) and the types of tools and techniques for improvement suggested by lean manufacturing.

Therefore, a couple of subjects that are of interest for this research are the nature of lean manufacturing and its activities, and also the measurement of “leanness”, because we contend that it is not only important to measure how “compliant” a company is with the tenets and guidelines of lean manufacturing but also how the company is doing in terms of actual monetary results (cost of the products).

2.1. Lean Manufacturing

The term lean manufacturing was coined by a team member in the MIT group that conducted an international study of the manufacturing practices of automakers. The results of this study were published in a book entitled “The Machine that Changed the World” (Womack and Jones, 1990). In it, it surfaced that the Toyota Motor Corporation from Japan had been strengthening its position as a global market leader through the application of many of the principles that have become popular as lean Principles, tools and techniques.

Toyota, under the engineering leadership of Taiichi Ohno, had been faced with the need to recover quickly from World War II, and tend to a small local market that wanted a certain variety of products, all this with very limited resources. This forced

Toyota to learn how to make the best use of its resources, and chase the sources of “waste” (muda) away. The seven types of muda (Ohno, 1988) that are typically discussed in the lean Literature are:

- **Overproduction:** To build more than it is needed.
- **Waste of Time on Hand:** Every form of waiting or downtime due to different factors. Waiting – downtime, part shortages, and long lead time.
- **Waste in Transportation:** Too much motion of the product, wasteful operator traveling.
- **Waste of Processing Itself:** Overprocessing, building more characteristics than the customer wants, redundant or repeated processes.
- **Waste of Stock on Hand:** High levels of inventory of raw materials, WIP or finished products.
- **Waste of Movement:** Too much material handling or disorganized processing paths.
- **Waste of Making Defective Products:** This causes reprocessing, the waste of materials, time and employee effort.

The TPS (Toyota Production System) (Ohno, 1988) appeared as a logical way to attack these types of waste from their roots. The tools and techniques that were gradually identified by the western managerial literature were introduced in different books and publications (Japan Mgmt. Assoc, 1989; Ishikawa, 1985; Richardson, 1996), but it took some more time to present an integrated picture of those tools into what we could call an integrated lean Framework (Womack and Jones, 1996; Liker, 1998).

To implement lean manufacturing, a two-part cultural and operational transformation must be undertaken. We will not go into details here of all the different implementation ideas that are in the literature, but one of the many interesting transformation frameworks (Monden, 1998; Detty and Yuengling, 2000) is presented by Groesbeck (2005), in which the many technical aspects and techniques are organized in a coherent sequence to facilitate a lean implementation. There are more details about a lean implementation in Section 5.3.

Many of the tools and techniques mentioned in the lean Literature will have different impacts in the way companies use their resources. Shah and Ward (2003) identified a set of 22 lean practices, and explored their frequency of appearance in the lean literature. The most commonly mentioned were JIT-continuous flow, pull system-kanban, quick changeover and lot size reduction. The impact of these techniques on the Cost-Time Profile is further discussed in Chapter 5.

2.2. Lean Metrics

There have been many different ways to attempt and measure how lean a system is. One of the most prolific ones has been to observe how many of the different lean tools and techniques, or lean principles a company has implemented. **Table 1** presents a summarized view of 14 different papers related to lean Metrics, with a wide variety of propositions and tools.

Table 1: Brief comments on several literature sources related to lean Metrics

| Authors and Year | Strengths | Weaknesses |
|---|---|--|
| Barker, R.C. (1994). | Recognizes the importance of time. It is analogous to Value Stream Mapping, and the format is very compact. Also, it can incorporate several companies or business units. | Does not measure leanness <i>per se</i> . Fails to recognize the concept of investment through time value of money. |
| Shah, R., Ward, P.T. (2003). | Their instrument could be used as a lean assessment tool, although it is used primarily to uncover the relationships between the lean practices and the context variables proposed by the authors. The grouping of the practices in bundles adds an element of consistency and logic to it. | Again, their instrument was not meant to measure leanness, although the adoption of lean practices is related to the performance of the factory, and it is shown that a statistic correlation exists. It would be interesting to examine more closely the impact of the adoption of different lean techniques on the performance of the company. |
| Karlsson, C., Ahlstrom, P. (1996). | It is a very comprehensive compendium of lean principles and practices, very useful for assessing changes in leanness through a transformation process. It is a seminal work in the field of lean assessment and measurement. | Does not propose a score or dimension of leanness. |
| Boyer, K.K. (1996). | Relates the commitment to lean with the actions required to prepare the workforce for the lean transformation. In this way, the degree of readiness for a lean transformation (from the human perspective) can be assessed. | Does not measure leanness directly, however it is clear in its purpose of measuring one of the support factors for lean transformations. |
| Soriano-Meier, H., Forrester, P.L. (2002). | Ties together the two previous papers, recognizing that for a successful lean implementation both managerial commitment and changes to the production and logistics system are required. | Does not specify the possibility of comparing different companies or including suppliers and business partners in the measurement of leanness. |
| Diekmann, J.E., Balonick, J., Krewedl, M., Troendle, L. (2003). | Interesting adaptation of lean thinking to an industry other than traditional manufacturing. The approach is simple and understandable. | The only disadvantage of the document is that being a conference paper, it does not contain details about the questions of the instrument. |

| Authors and Year | Strengths | Weaknesses |
|---|---|---|
| Kirby, K.E., Greene, B.M. (2003). | Adapts the scale from a recognized maturity level such as the CMM for the assessment of the maturity in the utilization of lean tools and techniques. | Does not present a theoretical justification of the attributes chosen to characterize a Value Stream. |
| Li, S., Rao, S., Ragu-Nathan, T.S., Ragu-Nathan, B. (2005). | An excellent article to articulate the concepts of lean thinking with Supply Chain Management. It almost offers a measurement of supply chain leanness. | It delves into great detail about supply chain specific measures (only natural given the objectives and title of the paper). To utilize some of its concepts and constructs for lean measurement will require a closer investigation. |
| Kojima, S., Kaplinsky, R. (2004). | Proposes a single lean Production Index, which would facilitate comparisons between companies or between different moments in time of the same company. | Proposes a single lean Production Index, which will undoubtedly leave unexplained questions related to the causes of improvement and the lean changes that are happening through different practices and policies. |
| Martinez, A., Perez, M. (2001). | Their survey could be used as a lean assessment tools. It shares some elements from Karlsson and Ahlstrom (1996). | They do not argue very convincingly the fulfillment of the objectives of the paper. A better explanation would be very useful for the reader. |
| Rentes, A. F., Van Aken, E. (2003). | The paper presents an adaptable framework for the design of lean performance measurement systems. | It does not suggest a standardized methodology for the measurement of leanness (it was clearly not in its objectives). |
| Tapping, D., Shuker, T., Luyster, T. (2002). | Great tool, very simple and easy to understand. The representation of the “Gap analysis” (Or “lean Profile”) is very visual and informative. | It might be a little long, but most of the comprehensive assessment tools are. |
| Feld, W.M. (2000). | Condensed tool, very compact and simple to understand. Good for demonstration purposes and awareness-raising | Too high level, leaves out many details. |
| Jordan, J.A., Michel, F.J. (2001). | Takes into account the different groups of stakeholders to gather their perceptions of leanness. | Extensive, and the re-formulation of the questions for each stakeholder group may end up asking different things. |

However, the main focus of this research is closer to the measurement of results, and not the measurement of means (or adoption of practices). Therefore some other resources must be consulted.

One of the papers cited in the previous table (Barker, 1994) presents an interesting idea, separating Value Added from Non-Value Added time and graphing the accumulation of value during the processing of a product. However, it did not consider the way in which costs accumulated during this process, only Value.

Also, Rother and Shook (1998) propose a very valuable tool to measure the leanness of the manufacturing of a product: The *Value Stream Map (VSM)*. The VSM follows the process of manufacturing a product through all the production cycle, from the triggering of the order to the delivery of the customer. The most important variable that is presented is *time*, showing a very revealing perspective of all the time products spend in the manufacturing system and how much of all this time is devoted to the addition of value. It is also a useful tool to plan lean transformations, because it highlights how much impact can be gained when improving or reorganizing a certain part of the process. One big difference with the Cost-Time Profile is that the VSM does not consider the amount of costs. However, it focuses on time, which is a very critical element not only when looking for *muda* but also when studying the factors that affect the Cost-Time Investment and the Direct Cost of the product.

One important source that contains seminal ideas is the work done in the Westinghouse Corporation, in a manual called *Operating Profit Through Time and Inventory Management, OPTIM*. These concepts were later published by Jack Fooks in a book titled "Profiles for Performance" (Fooks, 1993). In it, the concept of Cost-Time Profile is first presented. The ideas were developed over a long period (1960s to 1980s, to be finally published in 1993), and the innovative concept was the notion that "*cycle time reduction is a driver of radical change, both in the office and the factory. They also developed the macro profile technique for viewing the total business from a Cost-Time perspective*" (Fooks, 1993). However, the concepts of *Direct Cost, Inter-Enterprise Cost-*

Time Profile and many other aspects of this research work have been developed independently.

2.3. Project Management

In Chapter 5 we will present the procedure to build an activity schedule optimizing the resulting Cost-Time Investment. This procedure includes the organization of the manufacturing activities of a product in a network, and the use of linear programming (LP) and mixed integer programming (MIP) models. Many textbooks present the way to model these project-type structures of activities to obtain the shortest completion time possible. In particular, Hillier and Liebermann (1995) detail the construction of the LP models to treat projects analytically (Model 1 in Section 5.1.1.). Models 2 and 3, with the modified objective function and the consideration for resource and operator sharing were developed for this research.

2.4. Costing Practices

Another important point that will be discussed in the development of this research is the way costs are determined. Many important theories are built around this subject, particularly Activity Based Costing (ABC) that concentrates the cost-assigning effort in the activity as a unit of study (Kaplan and Cooper, 1997). Also, there is Throughput Accounting, (Corbett, 2000) which has different variations but has been closely related to the Theory of Constraints. Some proponents of throughput accounting insist in not assigning the overhead to individual products, but to consider it separately. This literature related to costing practices will be important to answer some of the questions that are still open such as a procedure to quantify the cost of the activities, resources and operators, as well as the study of the way to assign overhead in the CTP and IE-CTP.

3. BUILDING A CTP – IE-CTP

3.1. Basic concepts of CTP

Some of the main concepts mentioned when building and interpreting the Cost-Time Profile and Cost-Time Investment are explained in the following subsections.

3.1.1. Cost-Time Profile

It's a graph that presents how much money is spent on the manufacture of a product and for how much time it remains spent before being recovered via sales. Refer to **Figure 1** for an example of a Cost-Time Profile.

The Cost-Time Profile (CTP) has several components. They are:

- **Activities:** The activities are represented as ascending lines (positive slope), since each unit of time adds to the total accumulated cost that has been generated.
- **Materials:** The addition of materials to the process is presented as a vertical line, assuming that a portion of the materials is received “instantaneously”. This materials cost will continue being spent until the end of the process.
- **Waits:** At certain points in the process, no activity is being performed. Therefore, there is no active addition of cost to the total accumulated cost and for this reason waits are represented as horizontal lines (or “zero slope” lines).
- **Total Cost:** This is the height of the graph at its ending. It represents the dollar amount that has been spent as cost in the manufacture of the product.

Figure 1 presents an example of a Cost-Time Profile with its component parts highlighted.

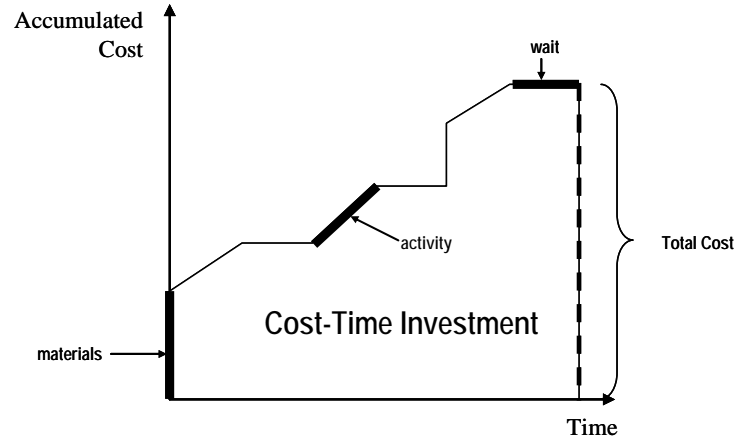


Figure 1: A Cost-Time Profile

3.1.2. Cost-Time Investment

This is the total area under the curve. It represents the amount of cost spent in the manufacture of the product multiplied by the time this cost has been present before being recovered via sales. It is also a measure of the time value of money, since it is evidently better to spend \$10 and recover them in 2 days than spending the same \$10 and recovering them in one month. It is the figure that will ultimately have an impact on the bottom line of the company and its financial management.

3.1.3. Direct Cost

The Cost-Time Investment is analogous to any investment made by a company; the company is expecting a return on this investment. When we apply the Minimum Attractive Rate of Return (MARR) or Internal Rate of Return (IRR) of the company to the Cost-Time Investment, we obtain this return. If we add it to the dollar amount that has actually been spent on the manufacture of the product (total cost), we will have the Direct Cost, which is a measure of the minimum amount that the company should recover when selling the product in order to cover costs caused both by the expenditures of money and the way those expenditures incurred in time. See **Equation 2**.

$$Direct\ Cost = Total\ Cost + (Cost-Time\ Investment * IRR) \quad (Eq. 2)$$

3.2. Introduction to the construction of the CTP and IE-CTP

To properly build a Cost-Time Profile, several intermediate steps need to be accomplished. We need to know *when* the different components of the CTP happen. We also need to know *how much* does each of the components cost. Combining the knowledge of the previous two points we figure out *how much* does *every time unit* of the manufacturing process cost. Finally, with the information from the previous findings, we calculate the *accumulated cost* at every time unit, chart it to obtain the *Cost-Time Profile* and calculate the Cost-Time Investment.

3.3. When do things happen: Activity Schedule

For this section it is required to know the sequence of process steps that occur, as well as the moment on which each component of the CTP happens. This information will be used to determine how much cost is being accumulated at each moment in time. Depictions such as the Gantt chart presented in **Figure 2** help to understand which activities are happening at each point in time, as well as visualize simultaneous occurrences.

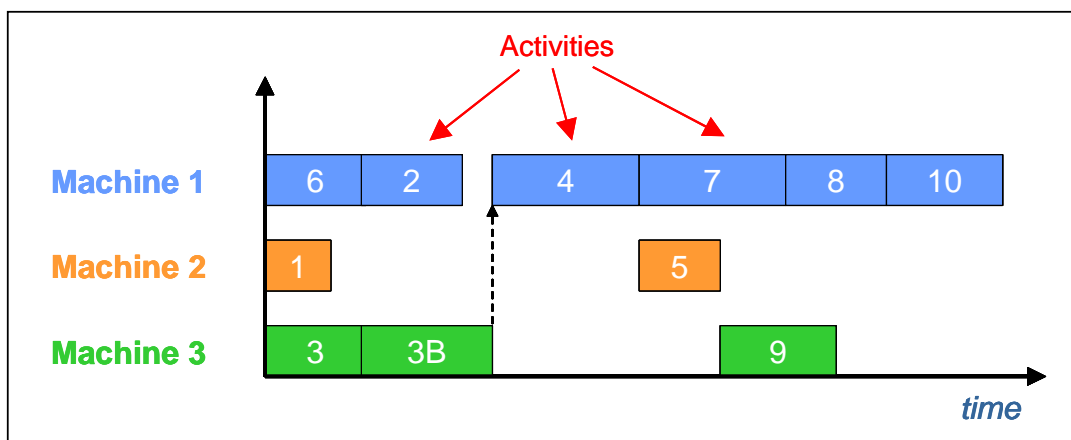


Figure 2: Schedule of Activities (organized by Machine)

For more complex project structures, it is always possible to use a Project Management Network, with its structure of activity dependencies and even resource sharing. This information can be employed in the schedule optimization, which will be discussed in Chapter 5.

3.4. How much do components cost: Activity Cost Rates

The *Activity Cost Rate* (ACR) is the amount of dollars an activity is costing per unit of time. The construction of the ACR is accomplished by adding the operator cost rate of all the operators an activity uses and the resource cost rate of all the resources employed by the specific activity.

The *Operator Cost Rate* is the hourly pay rate of the employee divided by the time units being employed in the project (minutes, seconds or hours). It is simply the amount of money the operator costs per project unit time.

The *Resource Cost Rate* is composed of the depreciation charge and the maintenance charge. The depreciation charge is simply the amount of money lost to depreciation by the machine in service per time unit. The calculation for the depreciation charge is presented in Equation 3.

$$Depr. Charge = \frac{Price_of_equipment}{Years_of_life \times Time_Units_it_is_used_in_a_year} \quad (Eq. 3)$$

The maintenance charge is the amount of maintenance cost that must be charged to each time-unit of activity in a particular resource. Equation 4 presents the formula for the maintenance charge.

$$Maint. Charge = \frac{Maintenance_Cost_per_year}{Time_Units_it_is_used_in_a_year} \quad (Eq. 4)$$

All these calculations for the activity cost rates can be performed before, after or concurrently with all the project structure calculations, because they do not depend on each other's results.

3.5. How much cost accumulates at each time unit: Instantaneous Cost Rates

At this point we know when each activity is happening and how much is each activity costing per time unit. The next step is the determination of the Instantaneous Cost Rates, which is how much is being spent in the manufacturing of the product in each discrete time unit. **Figure 3** presents graphically the determination of the instantaneous cost rates.

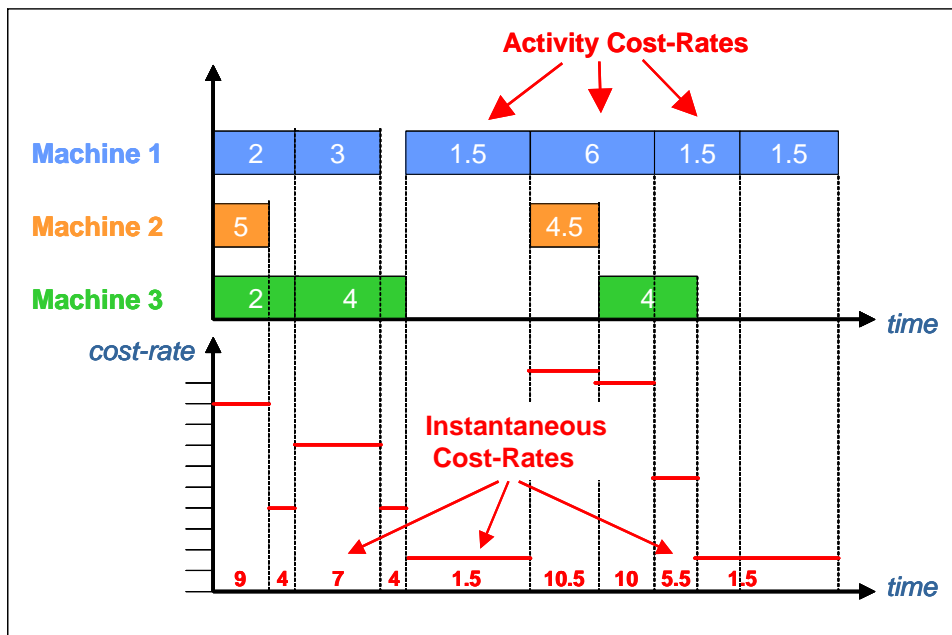


Figure 3: Calculation of the Instantaneous Cost Rates.

After finding the instantaneous cost rates, we know how much money we are spending as cost in each individual time unit. We will use this information to build the Cost Time Profile.

3.6. How much Accumulated Cost is there at each time unit: Cost-Time Profile

The next thing to do is to build a graph with the accumulated cost for each discrete time unit. In **Figure 3** presented above, the first interval has an instantaneous cost rate of \$9/time-unit. This means that the accumulated cost for time 1 is 9, for time 2 will be 18, time 3 will be 27 and so on. Now, let's assume that the second time range begins at time-unit 4 with an instantaneous cost rate of 4. Therefore, for time unit 4 the accumulated cost will be 27 from the previous interval plus 4, and so on.

If at any point the release of materials occurs, these are incorporated all at once at the beginning of the activity that uses the release (or, if the materials for the whole project are released prior to the beginning of work in the unit, the release will occur all together at the beginning of the project). The materials are incorporated in the accumulated cost instantaneously, which means they will cause a vertical increase in the graph. A typical Cost-Time Profile is presented in **Figure 4**.

Finally, at some points during the process there could be waits, which are simply activities that do not use resources, operators or materials. For example, if before a certain machine there is always a two-day inventory of parts, a single unit will have to wait idly or two days before being processed. Waits conserve the accumulated cost that came before them constant; they do not add to it. Therefore, in the Cost-Time Profile graph they look like flat zones, with zero slopes.

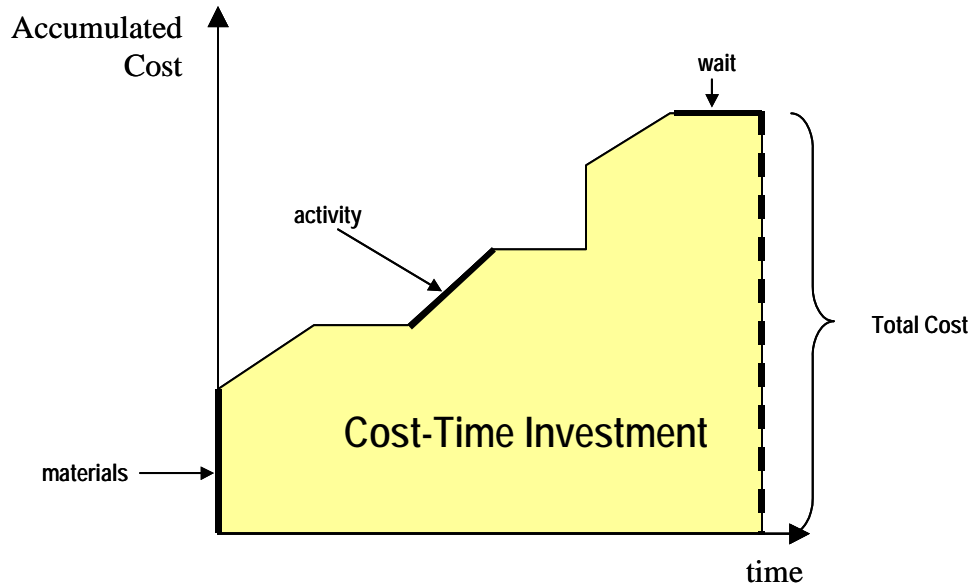


Figure 4: A typical Cost-Time Profile.

3.7. Inter-Enterprise Cost-Time Profile

After learning the steps that are required to build a Cost-Time Profile for a single enterprise, it is necessary to explore what we call the “Inter-Enterprise Cost-Time Profile (IE-CTP)”. The IE-CTP is interested in those products that are manufactured with the intervention that more than one company or business unit. And, when we say “Business Unit” we refer to those belonging to the same parent organization but with enough operational differentiation and separate financial reporting as to be considered two different entities involved in the manufacturing of the product.

In today’s competitive world, the intervention of different companies in the manufacturing of one product is not uncommon at all. Subcontracting, outsourcing, the use of suppliers with different levels of “trust”, maquila operations and other variations and partnerships are all possible operation modes that involve more than one company participating in the creation of a product. This multi-company involvement translates in the need for examination of the Cost-Time Profile of the product and also the CTP for the individual companies that take part in the manufacturing of a given product.

For the IE-CTP, we will consider that there is one main manufacturer, what in some industries is called the Original Equipment Manufacturer (OEM). This is the company that conceives, probably designs (in its majority) the product and that gives it its brand name. It is the company that makes itself “responsible” for the product. The other enterprises that participate in the manufacturing must do some processing on it or on certain subassemblies, with the characteristic that they provide OEM-specific parts or subassemblies and not generic parts or raw materials. In the case of providing only materials or generic parts that are freely sold to whomever wants to acquire them, the other enterprise does not have a relationship that is product-specific enough to be considered part of the IE-CTP; it will only appear as a purchased material or part. Therefore, we will be interested in companies that are “partners” to the OEM and not “suppliers” for the purposes of considering them as participants in the construction of the IE-CTP.

The motivation for the proposition of an Inter-Enterprise Cost-Time Profile is to serve as a coordination and analysis tool that helps on the improvement of the relationships between companies. The underlying hope is that with the advancement of trust and the building of long-lasting partnership relationships, companies exchange and disclose information more openly. This openness is one of the factors required in the construction of the extended enterprises, and the IE-CTP as a tool will be useful in monitoring the results of lean efforts, therefore it can be a very useful tool for the establishment of extended lean enterprises.

3.7.1. Identification of new types of activities

The expansion of the scope of the CTP to encompass several enterprises creates the need to examine new types of activities that appear in the interfaces between companies or business units. These activities will have different characteristics, depending upon the type of relationships and business agreements that are in place between the participants. Business units from the same organization (we would assume) will have a better level of trust and coordination, as well as a joint forecast and some degree of concerted planning amongst them. On the other hand, a strictly buyer-supplier

relationship (i.e., when acquiring a commodity product) might be less recurrent, requiring less trust and joint planning, as well as less information exchange. These different levels will be discussed in subsequent sections of this document.

Assuming that the OEM (Original Equipment Manufacturer, the core company) has continuous and recurring relationships with its partners, there are certain things that will need to be done in order to make operations work. At the simplest level these are:

- *Order-triggering mechanisms:* The partner company needs to know when to start working in an order that the OEM needs. There must be some sort of information interchange system to make this possible and such information systems come in different degrees of technological complexity and system-wide integration.
- *Transportation of materials:* If the partner company needs to receive materials from the OEM, there must be a transportation system that takes those materials there. Physical transportation systems will be considered to analyze what is their role in the IE-CTP.

These new activities will be considered in the IE-CTP, and in the following sections we will discuss some relevant aspects of them that need consideration when building an IE-CTP.

Order-triggering mechanisms: These are the information exchange systems that make a partner company aware that it is time to initiate the operation on an order for the OEM. These systems might be considered as regular activities, because they consume resources at the OEM and at the partner company, take a certain time to be completed and if they are not completed the next activity (start the processing of the subassemblies or components for the order) can not start. They can be considered as happening both on the OEM and the partner company, or just one of them, depending on the kind of technologies used by each party and their degree of integration with production scheduling information systems. Some types of order-triggering and information mechanisms are:

- *Phone call:* At the lowest degree of technological sophistication, orders can be placed via a phone call. This medium will require a human at either side of the line, as well as some small communication costs. If it is used, it should also include what the person receiving the call does afterwards with its information, and how does he incorporate that information to the regular production information systems of the partner company to make that order happen (does he type the information on a computerized information system, does he release a certain type of kanban into the shop floor, does he go and personally tell the production scheduler/manager about this order to make it happen?).
- *Fax:* This medium forces companies at both ends to use some resources. At the ordering company, somebody needs to sit down at a computer, compose the fax, print it and fax it. At the receiving side, somebody needs to collect it from the fax machine (assuming it is a traditional system, not a computerized and automated one that routes the document to the right computer screen automatically), put it in somebody else's inbox (generating a waiting period) and then the right person incorporates it to the company's system, either typing it or releasing a kanban or some other information mechanism. Both faxes and phone calls are plagued with the risk of misunderstandings, incorrect information and missed or misplaced messages. They are not very reliable systems and require too much human intervention.
- *EDI and VPN systems:* Electronic Document Interchange (EDI) and Virtual Private Networks (VPN) are two different types of systems used for the exchange of information between companies. EDI consists on a series of standardized transaction-based messages that convey information between companies using an intermediary or service provider. This intermediary sustains a common mailbox platform, in such a manner that if one company is exchanging EDI messages with many other associate companies, the EDI provider manages a central "post office" in which messages can be left and retrieved. It has been used for many years, and today many companies are migrating to doing EDI using XML (eXtensible Markup Language) for further customization of the exchanged messages. VPNs are private networks established and managed by companies for their use and

interchange with associate companies. They can have proprietary protocols and applications. The main difference with EDI is that they can provide as many or as few services as the owners decide to have, while EDI is an international standard. Both VPNs and EDI are simply an electronic platform for the exchange of information, and their impact on the IE-CTP depends on the degree of integration and coupling these systems have with the company's ERP (Enterprise Resource Planning) systems, or whatever is doing their role. For example, if both enterprises have fully integrated ERP systems and they are thoroughly mapped to EDI, the information exchange will be fast and very cheap. In this case, the delay between the arrival of an order and the beginning of processing operations consists in how long it takes the receiving company to adjust their schedule to include the new order and begin operations on it. Some companies do not have ERP or Production Planning computerized systems, or they do not have an automatic EDI interface, so when an order comes via EDI or VPN it needs to be printed and incorporated to the production scheduling system, basically treated as a fax message would be. Therefore, the presence of an EDI or VPN link does not guarantee that the exchange of electronic information will be smooth and seamless; it also depends on the type of information systems that interact with EDI at both ends of the exchange.

Transportation of Materials: If an associate company is manufacturing a component or subassembly for the OEM, there must be a way to take the parts from the supplier to the buyer. Also, in some cases the supplier company receives parts, components or materials from the OEM to process them and return them when the processing is complete. These transportation activities will appear in the IE-CTP in different forms, depending on who's doing them and how they are being paid for.

- *OEM does the transportation:* In this case, the transportation is just a regular activity that uses resources (trucks) and operators (drivers) and takes a certain amount of time.
- *Supplier does the transportation:* We can apply the same logic that in the previous point to this case. It will be just a regular activity.

- *A third-party logistics provider will transport the materials:* In this case, no resources from the OEM or the supplier are tied in performing the transportation activity. However, it does take time and somebody is going to pay for it at a certain point, all together. Therefore, it presents characteristics of two CTP components that are already known: A wait (takes time but uses no resources nor generates cost) and a materials release (it costs a certain amount and it is paid all at once). A 3PL-performed transformation can be decomposed in a wait (for how long the transportation takes) and a disbursement (similar to a materials release, depending on the amount).

3.7.2. New Actors in the Network: Third Party Logistical Providers

As it was previously mentioned, one of the new important activities that appears when considering the IE-CTP is the transportation of materials. Nowadays it is becoming a widely used practice to contract Third Party Logistics Providers (3PL) to perform these transportations, and even some more activities like storage, labeling, packaging and some other value added services. However, even if the 3PL serves an important role in the manufacturing of a product, they are not viewed as involved in “the manufacturing” of the product, rather their role is limited to perform a service for hire. The more sophisticated of the 3PL are now participating in the joint planning and forecasting efforts of the supply chain.

Also, the type of relationship they have towards the product and the way to generate cost is somewhat different than the one a manufacturer has. For a manufacturer, some materials are released into the process and activities (that generate cost) are performed upon them, creating an accumulation of cost. For a 3PL, the generation of cost does not depend on the materials present on the product or subassembly; rather in the characteristics that affect the performance of the transportation service (like dimensions, weight, fragility, stackability, perishability, temperature requirements and other aspects). These characteristics are disconnected from the cost accumulation that is happening to the part or product. This is the reason why the transportation activities will be added to

the IE-CTP as a wait and a disbursement (like a materials release), because the only way in which they add cost to the product is through the transportation rates, not through processing. The wait will occur when the transportation happens; the disbursement will be scheduled when the payment of the service occurs.

All the considerations given in the previous paragraphs explain why 3PLs will not be considered as partner companies for the construction of the IE-CTP; in this case they will be seen as service performers that collect their fees at a certain point, but do not take part in the transformation of the product.

3.8. A Numerical Example

We will illustrate the construction of the CTP and the IE-CTP with a relatively simple example. It is the ACME Chair Company, and the product in question is the Executive Chair. First, the CTP will be built step by step assuming all the work is done by ACME Chairs, and then for a second case two other companies will manufacture subassemblies of the product. The Excel details for this section are in **Appendix A**.

3.8.1. ACME Chairs – Single Enterprise Cost-Time Profile

The information related to the different activities involved in the manufacturing of the Executive Chair is presented in **Table 2**.

Table 2: Manufacturing Activities for the Executive Chair.

| Activity | Description | Duration (min) | Predecessors | Operators | Resources |
|----------|---|----------------|--------------|-----------|-----------|
| A | Arms Molding | 20 | | OP1 | RS1 |
| B | Back Forming | 15 | | OP2 | RS2 |
| C | Legs Painting | 20 | | OP3 | RS3 |
| D | Arms Polishing | 360 | A | OP1 | RS1 |
| E | Wait_E | 480 | B | | RS4 |
| F | Arms Painting | 30 | D | OP1 | RS1 |
| G | Back Painting | 45 | E | OP2 | RS2 |
| H | Wait_H | 600 | C | | RS4 |
| I | Prepare Upholstery | 50 | F, G | OP1 | RS1 |
| J | Assemble Arms and Back | 30 | F, G | OP2 | RS2 |
| K | Assemble Legs with Upper Part | 20 | H, J | OP4 | RS4 |
| L | Prepare Hydraulics | 45 | H, J | OP2 | RS2 |
| M | Wait_M | 540 | K | | |
| N | Install Cushion | 25 | I | OP1 | RS1 |
| O | Test Hydraulics | 50 | L | OP2 | RS2 |
| P | Assemble Upholstery. Chair and Hydraulics | 45 | M, N, O | OP3 | RS3 |

And the corresponding network diagram is presented in **Figure 5**.

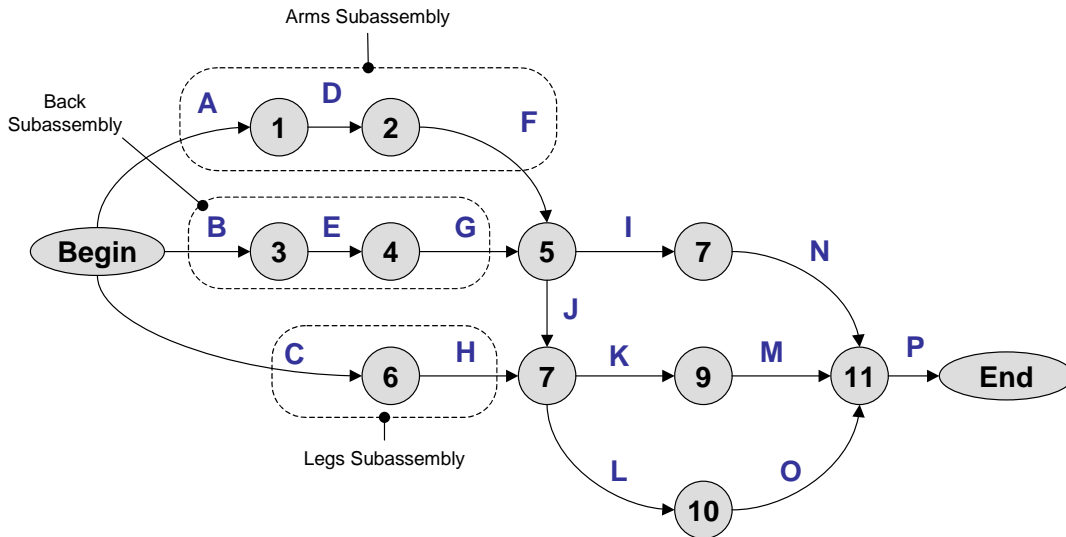


Figure 5: Project Network Diagram for the Executive Chair – ACME Chairs.

The schedule of activities was created minimizing the completion time for the whole process. The results are presented in **Table 3**.

Table 3: Activity Completion Times

| Activity | Duration (min) | Start | Finish |
|----------|----------------|-------|--------|
| A | 20 | 655 | 675 |
| B | 15 | 0 | 15 |
| C | 20 | 475 | 495 |
| D | 360 | 675 | 1035 |
| E | 480 | 15 | 495 |
| F | 30 | 1035 | 1065 |
| G | 45 | 1020 | 1065 |
| H | 600 | 495 | 1095 |
| I | 50 | 1580 | 1630 |
| J | 30 | 1065 | 1095 |
| K | 20 | 1095 | 1115 |
| L | 45 | 1560 | 1605 |
| M | 540 | 1115 | 1655 |
| N | 25 | 1630 | 1655 |
| O | 50 | 1605 | 1655 |
| P | 45 | 1655 | 1700 |

Some other information is required, namely the per-minute cost rates of the four operators and four resources. These are shown in **Table 4**.

Table 4: Per-minute cost-rates of the operators and resources

| Operator or Resource Id | Cost Rate (\$ per minute) |
|-------------------------|---------------------------|
| OP1 | 0.4 |
| OP2 | 0.5 |
| OP3 | 0.3 |
| OP4 | 0.35 |
| RES1 | 0.0998 |
| RES2 | 0.3689 |
| RES3 | 0.5425 |
| RES4 | 0.2821 |

And the Cost-Time Profile for this example is presented in **Figure 6**.

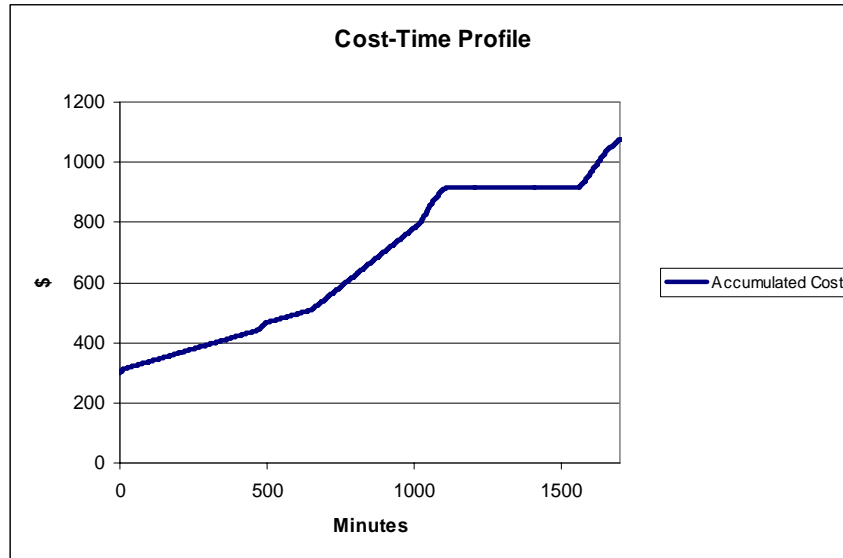


Figure 6: Cost-Time Profile for the ACME Executive Chair

The total cost for this product is **\$1,076.10**. The Cost-Time Investment for this CTP is **1,135,979.40 dollars-minute**. Using a 15% per year as the attractive interest rate for this company, we obtain a direct cost of **\$ 1,077.43**. This might seem a small increase over the total cost (about \$1.33), but it must be taken into account the length of the process in this case (1700 minutes in total, 28 hours and 20 minutes). This is three and a half 8-hour shifts, which is very fast for some industries. When the value stream map is developed, it has been observed that in many cases the total time in the system is larger than two weeks. If the executive chair spent two weeks in the system (10 8-hour shifts), assuming that the product only had to wait after the 1700th minute, the direct cost would be **\$1,081.31**. This is an over cost of \$ 5 per chair. If the company manufactures 100,000 of these chairs per year, there are **\$500,000** in time-related costs that are not being budgeted or considered.

3.8.2. Inter-Enterprise CTP – Executive Chair

Now we will assume that there are two partner companies participating in the manufacturing of the executive chair. ARMS Inc. will manufacture the Arms Assembly, and LEGS Inc. will manufacture the Legs Assembly. The new chart of activities is presented in **Table 5**.

Table 5: Activities with partner companies

| Activity | Description | Company | Duration (min) | Pred. | Oper. | Res. | Materials (or Transp. Cost) |
|----------|---|---------|----------------|---------|-------|------|-----------------------------|
| A | Arms Molding | Arms | 20 | Q | OP5 | RS5 | 50 |
| B | Back Forming | Acme | 15 | | OP2 | RS2 | 300 |
| C | Legs Painting | Legs | 20 | S, T | OP6 | RS6 | |
| D | Arms Polishing | Arms | 360 | A | OP5 | RS5 | |
| E | Wait_E | Acme | 480 | B | | RS4 | |
| F | Arms Painting | Arms | 30 | D | OP5 | RS5 | |
| G | Back Painting | Acme | 45 | E | OP2 | RS2 | |
| H | Wait_H | Legs | 600 | C | | RS6 | |
| I | Prepare Upholstery | Acme | 50 | R, G | OP1 | RS1 | |
| J | Assemble Arms and Back | Acme | 30 | R, G | OP2 | RS2 | |
| K | Assemble Legs with Upper Part | Acme | 20 | U, J | OP4 | RS4 | |
| L | Prepare Hydraulics | Acme | 45 | U, J | OP2 | RS2 | |
| M | Wait_M | Acme | 540 | K | | | |
| N | Install Cushion | Acme | 25 | I | OP1 | RS1 | |
| O | Test Hydraulics | Acme | 50 | L | OP2 | RS2 | |
| P | Assemble Upholstery, Chair and Hydraulics | Acme | 45 | M, N, O | OP3 | RS3 | |
| Q | Send order to Arms Inc. | Acme | 120 | | OP1 | | |
| R | Transport Arms Subassembly | 3PL | 120 | F | | | 50 |
| S | Send order to Legs Inc. | Acme | 15 | | OP1 | | |
| T | Transport materials to Legs Inc. | Acme | 60 | | OP4 | RS7 | 100 |
| U | Transport Legs Subassembly | 3PL | 120 | H | | | 50 |

And the network diagram for this example is presented in **Figure 7**.

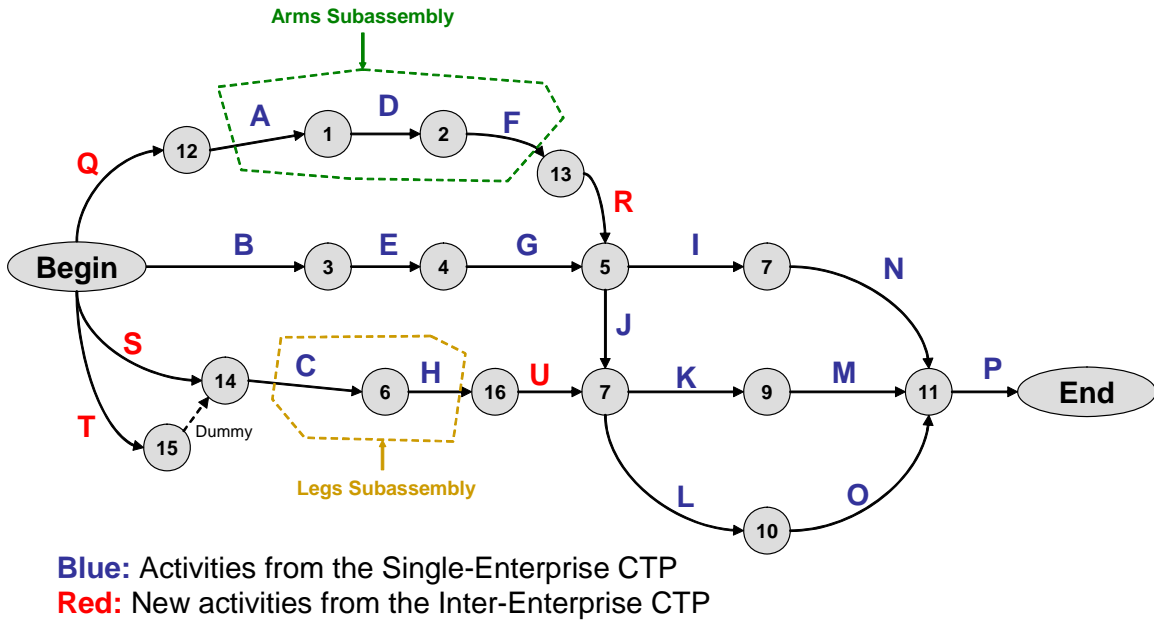


Figure 7: Network diagram for the IE-CTP

Table 6 contains the cost rates for resources and operators given the new assignments.

Table 6: Cost rates of resources and operators

| Operator or Resource Id | Cost Rate (\$ per minute) |
|-------------------------|---------------------------|
| OP1 | 0.4 |
| OP2 | 0.5 |
| OP3 | 0.3 |
| OP4 | 0.35 |
| OP5 | 0.45 |
| OP6 | 0.55 |
| RES1 | 0.0998 |
| RES2 | 0.3689 |
| RES3 | 0.5425 |
| RES4 | 0.2821 |
| RES5 | 0.3689 |
| RES6 | 0.9982 |
| RES7 | 0.45 |

Figure 8 presents a picture comparing the CTP for the ACME company by itself and the IE-CTP when Arms Inc. and Legs Inc. participate in manufacturing the product.

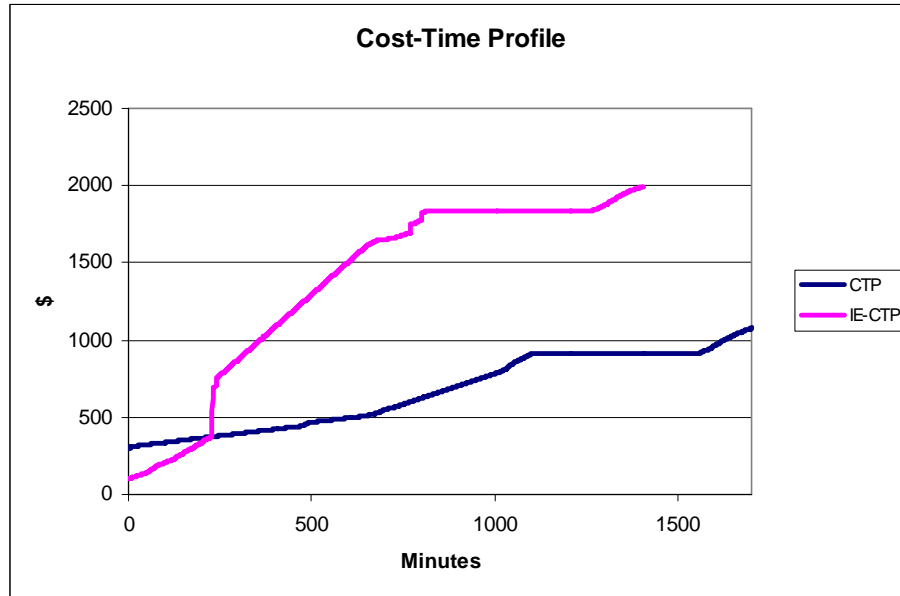


Figure 8: Compared CTP and IE-CTP for ACME Chairs.

From this picture we can notice several things:

- The process is now finishing faster, because when activity H was taken by Legs Inc., a conflict with Activity E for the use of a resource disappeared.
- Since there can be more activities occurring simultaneously, the slope of the curve is steeper at the beginning. The transportation costs are paid JIT and they appear as material releases in the curve.
- The total cost is higher, because now there are transportation costs considered and also new activities for transportation of products and transmission of information.
- In this case, we are assuming that the suppliers are paid when the main manufacturer receives the sales revenue from the product.

Table 7 summarizes the numerical results.

Table 7: Comparative Results between CTP and IE-CTP

| Item | CTP | IE-CTP |
|-----------------------|----------------|----------------|
| Total Cost | 1076.104 | 1994.43 |
| Cost-Time Investment | \$1,135,979.39 | \$1,916,643.24 |
| Direct Cost | 1,077.43 | 1,081.31 |
| Length of the process | 1700 minutes | 1405 minutes |

Figure 9 shows the CTPs decomposed by company.

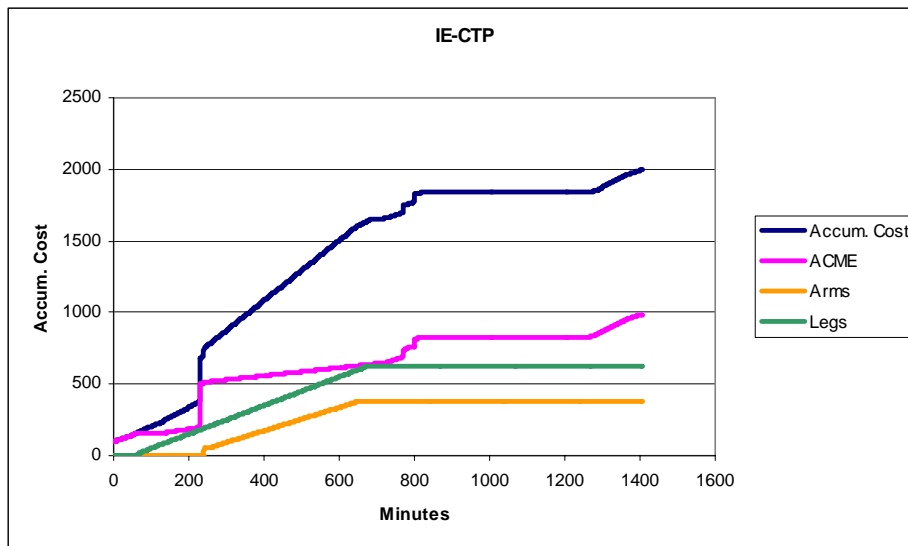


Figure 9: CTPs per company

Now, what would happen if we assumed that the suppliers were paid JIT? In this case, the final result would be the same, except that the CTPs for the partner companies would be smaller and for the main company it would be larger, but the net results would be the same. Figure 10 presents this situation.

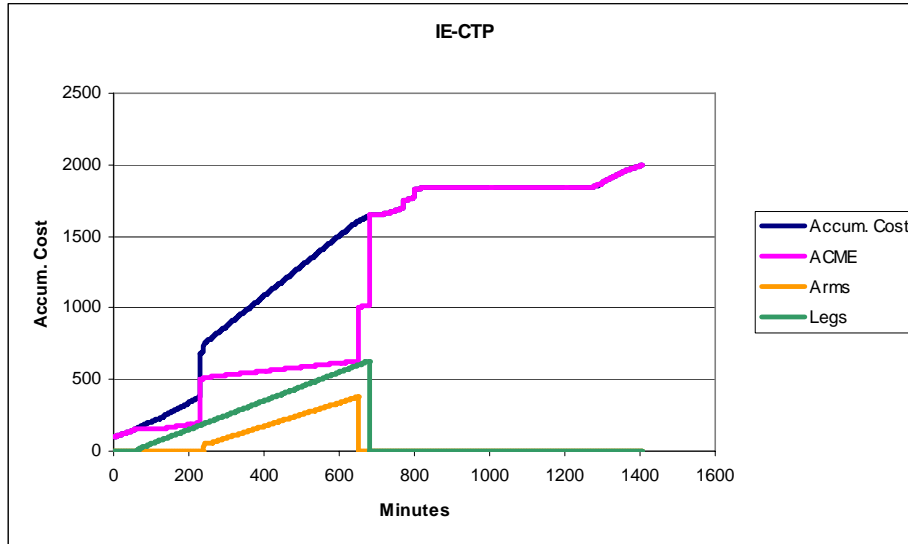


Figure 10: CTPs when the partner companies are paid JIT.

And **Table 8** presents a numerical comparison of these results.

Table 8: Numerical comparison between pay-at-the-end and pay JIT

| | Cost-Time Investment | | Direct Cost | |
|-----------|----------------------|--------------|----------------|----------|
| | Pay at the end | Pay JIT | Pay at the end | Pay JIT |
| ACME | 888,892.07 | 1,631,455.16 | 987.22 | 1,996.65 |
| Arms Inc. | 372,211.64 | 86,541.53 | 378.80 | 0.10 |
| Legs Inc. | 655,539.54 | 198,876.54 | 630.64 | 0.23 |
| Total | 1,916,643.24 | 1,916,873.23 | 1,996.66 | 1,996.98 |

It is important to take into account that this calculations do not take into account the profit margin that the partner companies wish to obtain from the sale of their product and also the profit margin that the main company will obtain from selling to the customers.

As we can see, the matter of the timing of the payment will be an interesting matter for the research work that follows, because even though the numerical net result is quite similar, the parties bearing the load of the Cost-Time Investment are very much

different depending on the payment policies. This will be explored in subsequent stages of this research report.

4. FACTORS THAT AFFECT THE IE-CTP

4.1. Batching

So far, all of the discussion of the CTP and the IE-CTP has been presented for mapping the flow of a single unit of product through the production system. However, it is very common to manufacture products in batches, depending on the size of the order, the availability of material handling equipment and many other factors. It can be argued that until true “extreme” one-piece flow is achieved, there will always be some kind of batching.

4.1.1. Definition of batching

In this document, anything that prevents units of product from flowing individually down the process will be considered batching.

4.1.2. Cases of batching

The IE-CTP has been presented following the progress of unit of product at a time. However, for manufacturers of mass quantities of discrete products (consumer goods, consumer electronics, automotive industry, textiles and many other industrial sectors) it is not practical to consider individual units in isolation because many of their practices treat, move, store, buy and use materials and products in batches.

There are many reasons for the practice of batching, from the classical formula of Economic Order Quantity (EOQ) that balances the costs of ordering and the costs of having inventory finding the right lot size and the right timing to replenish inventories at the optimal total cost, to procurement reasons that specify that certain materials and components come in certain package sizes, to transportation costs and finally machine designs that make costly and impractical to run only one unit at a time. Some of these batching cases will be examined in more detail in the following paragraphs, and in section 4.1.3. a numerical example will be presented.

- *Case 1: Completely simultaneous processing:* A company manufactures product X, and it receives an order for 10 units. It is decided that this order will be treated as a batch, but the company has enough production lines and equipment that each of the 10 units can be manufactured simultaneously by parallel equipment. In this case, production of the 10 units will take the same amount of time that a single unit, because they would be happening in parallel. For such a company, the obvious question would be the balance between agility and quick response (since the size of the order did not affect the lead time) and equipment utilization and ROI (Return on Investment, since it is apparent that there would be a considerable amount of idle time and sub-utilization of the equipment). This is not a very usual case; hardly a company that uses this manufacturing strategy comes to mind. However, service situations come to mind more easily, when checkout lines at stores have fully duplicated functionality and can serve many customers at the same time; a beauty parlor where different servers have “identical” capabilities to serve multiple customers concurrently or a restaurant, where many customers could arguably experience the same service at the same time. Again, it is characteristic of these types of service systems that they have enough installed capacity to fulfill their demand at peak moments (Saturday afternoon for the store, the day before graduation in a college town for the beauty salon and lunch and dinner rush for the restaurant), but for lower occupation periods the infrastructure will be underutilized (only manpower levels are easily varied between high and low demand moments).
- *Case 2: Batch for an order:* If the product offered presents a certain degree of customization, or its cost and specialization prevent it to be manufactured for stock, it is very common to make-to-order the product. On these cases, the common batching occurrence is visible in three instances: 1). The raw materials and components for the batch are usually ordered as a batch themselves; 2). The units that will make up the batch need to be sent down the process one by one, making the last one wait to start being processed at least until all the previous ones have cleared the first workstation, and 3). When the

first unit finishes its processing, it will need to wait until the last one is finished, and then they will be shipped out to the customer. In this case, the Cost-Time Profile of the first unit will look very different than the CTP of the last one, therefore the CTP for such an order should not follow the first, nor the last unit of product (nor any particular unit in between), rather the unit of analysis should shift from being the product unit to the ordered batch.

- *Case 3: Batch for processing equipment requirements:* In many industrial processes there are pieces of equipment that are designed to operate with many more than just one unit, even though in recent years with the widespread application of lean thinking many processes have been right-sized and redesigned for improved material flow. Legacy equipment is still in use and many pieces of it might require very substantial capital investments to be changed, so companies work around them, making the rest of the process flow smoothly and taking special care before and after the batch equipment to make the best use of it. Examples of this type of equipment are ovens, heat treatment enclosures and chemical and surface treatments performed in tanks. The impact on the flow will create two waits: One before the “batch” equipment and another one right after it, waiting for the next process.
- *Case 4: Batch for material handling requirements:* Sometimes the configuration of the process and the capabilities of the material handling equipment in use in a particular situation will have an impact in the way products flow. For example, the size of an order is $5x$; process B is in the second floor and process C is in the first floor, and we will have to use the elevator to move the products from B to C, but the elevator is in constant use and can carry at most x units at a time, a common solution to this material handling problem would be to accumulate units of product (already processed by operation B) close to the elevator until we reach the amount of x units ready to be moved down; it would be considered too slow and costly to move them one at a time if other products are using the elevator also. This would also cause 5 batch moves in the elevator. This interruption in the flow of the process would cause two new waits: 1). The finished product after operation B

needs to wait until $(x-1)$ sister units are finished and get ready to be moved down and 2). Once the batch of x units arrives to operation C, one unit will start processing and the others will have to wait for their turn. The effects of these waits on the total lead time and the CTP will be explored in the numerical example in section 5.1.3.

- *Case 5: Transportation from supplier to buyer:* The situation in Case 5 will be very similar to that in Case 4, except that now the move will take place between two different companies. It is very common that an order is delivered as a single entity; therefore the supplying company would wait until the order was complete to transport it to the buying company. The two waits that appear in Case 4 would also appear here, basically at both ends of the transportation process. This case illustrates the importance of the logistical evolution towards lean operations to improve product flow.

After the presentation of these five cases, a small numerical example will be presented to illustrate the impacts of the batching cases.

4.1.3. Numerical Example

For demonstration purposes, a small case will be presented here (all the detailed calculations are included in the Appendices). It is simple straight line production process, with four operations (A, B, C, D) and two waits (Wait 1 and Wait 2). The relevant information about the process is presented in **Table 9**.

Table 9: Example production process

| Activity | Cost-Rate | Materials | Duration | Begin | End |
|-----------------|------------------|------------------|-----------------|--------------|------------|
| A | 10 | 20 | 3 | 1 | 3 |
| Wait1 | 0 | 0 | 5 | 4 | 8 |
| B | 18 | 30 | 2 | 9 | 10 |
| Wait2 | 0 | 0 | 4 | 11 | 14 |
| C | 15 | 20 | 2 | 15 | 16 |
| D | 22 | 40 | 4 | 17 | 20 |

And a graphical representation of the process is provided in **Figure 11**.

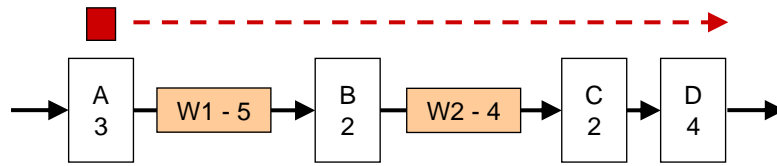


Figure 11: Example production process

If a single unit was followed in its flow down this process, the CTP and CTI would be as presented in **Figure 12**.

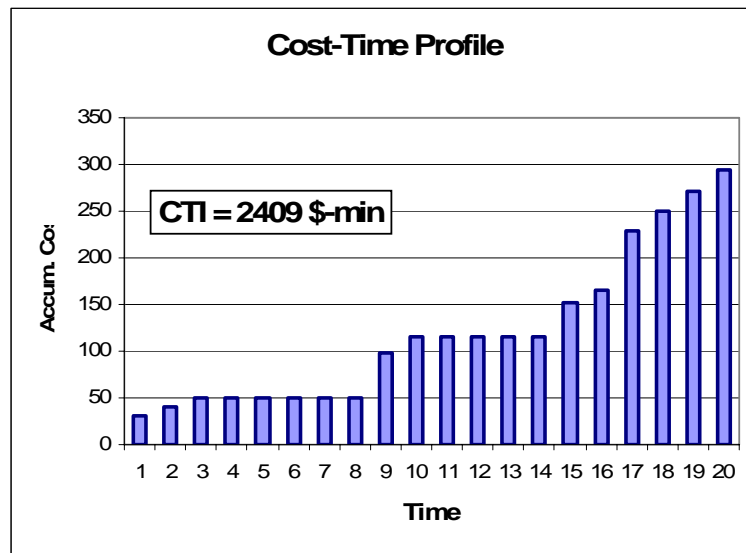


Figure 12: CTP and CTI for a single unit

Using the process for a single unit as a base case for construction of the other cases, we will show the impact these cases have on the CTI and the order lead time. For simplicity and uniformity purposes, we will consider that the size of the batch (or order) is 10 units for all cases.

Case 1: Completely simultaneous processing. In this case, the assumption is that 10 units flow down the process at the same time, being simultaneously processed in parallel equipment. The expected impact would be to have a CTP with the same shape,

only with figures ten times bigger. **Figure 13** shows the CTP and CTI for this case, and it indeed has a CTI 10 times the one for the single unit case.

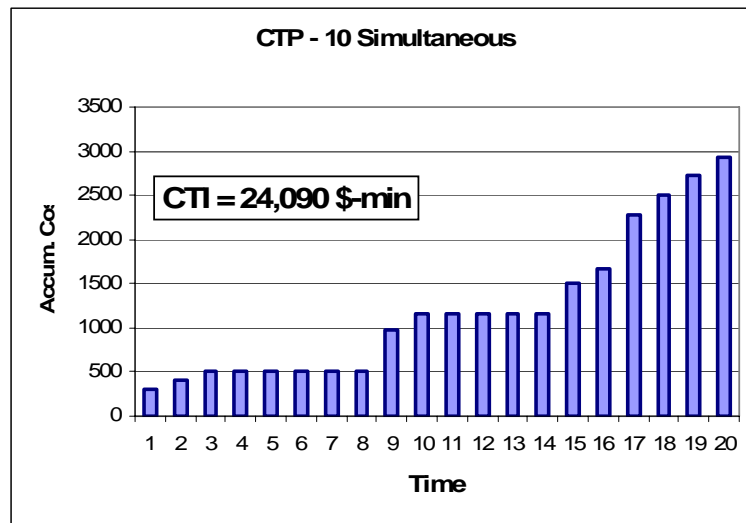


Figure 13: CTP and CTI for Case 1 (10 units simultaneously)

From **Figure 13**, it can be observed that the lead time for the whole batch is still 20 time units, which is the logical consequence of considering all the units processed concurrently.

Case 2: Batch for an order. Two variations will be considered for this case: *JIT materials* and *batched materials*. In JIT materials, the activities that require materials receive them just as each unit of product arrives to be processed. The CTP and CTI for JIT Materials are presented in **Figure 14**.

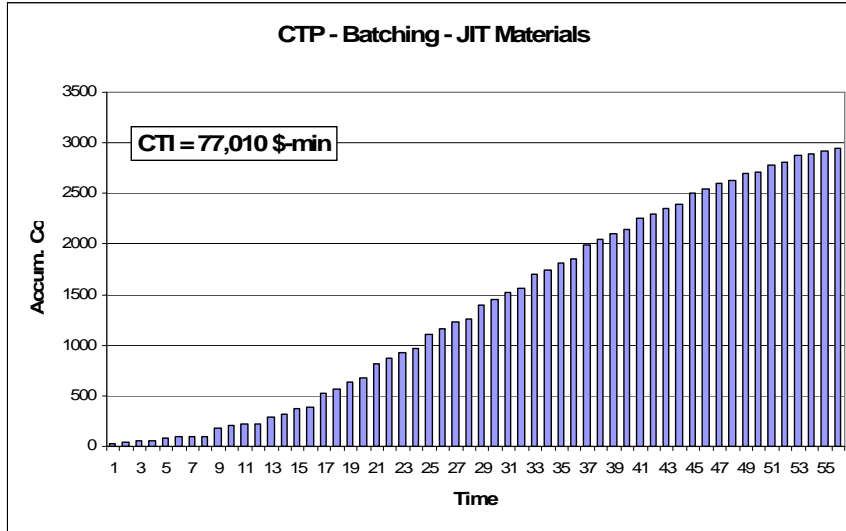


Figure 14: CTP and CTI for Case 2 – JIT Materials

In *Batch Materials*, each activity receives the materials for the full batch right before beginning the processing of the first unit of the batch. The CTP and CTI for these circumstances are presented in **Figure 15**.

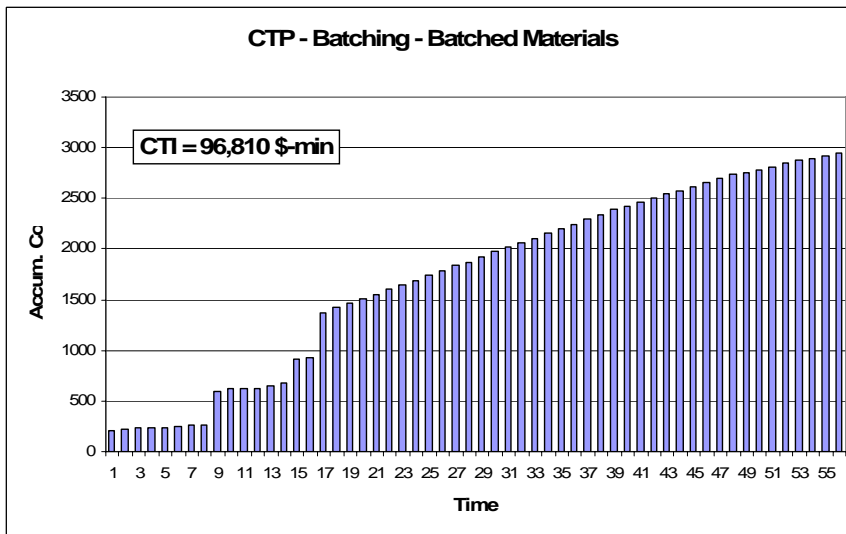


Figure 15: CTP and CTI for Case 2 – Batch Materials

Some observations about Case 2:

- The makespan for the batch has grown from 20 to 55 minutes, a 175% increase.

- The CTI has grown (from the ideal case of 10 simultaneous units) from 24,090 \$-min to 77,010 \$-min for JIT materials and 96,810 \$-min for batch materials, almost four times larger.

Case 3: Batch for processing equipment requirements. For this case, we will consider that activity C is a process that occurs in the oven, and the whole batch will be processed in the oven concurrently. Then, a wait before operation C appears and also simultaneous processing in C for all units of the batch. This situation is presented in **Figure 16**.

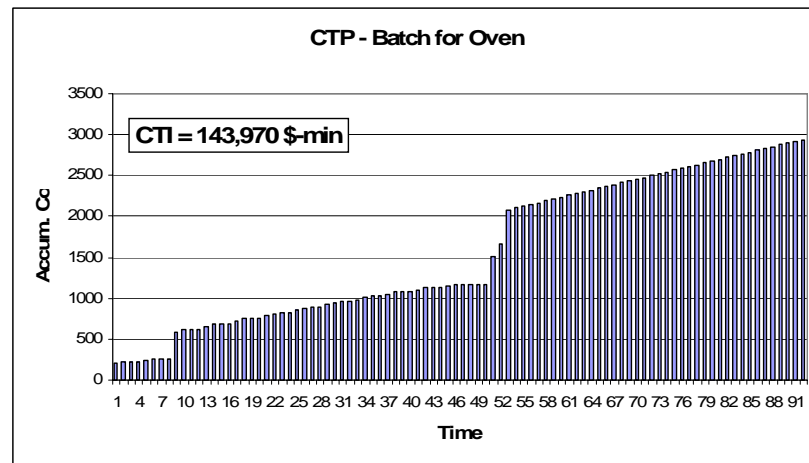


Figure 16: Case 3: Batch for equipment requirements (oven)

- The makespan for the batch has grown from 20 to 92 minutes.
- The CTI has grown (from the ideal case of 10 simultaneous units) from 24,090 \$-min to 143,970 \$-min.

Case 4: Batch for material handling requirements. In this case, half of the units will be moved at a time between process B and C. This is due to the fact that there is only one forklift truck that needs to be shared by many operations, causing the need for grouping units in batches of five before they are moved between process B and C to minimize the number of times that the forklift truck will need to come to operation B. The CTP for this case is presented in **Figure 17**.

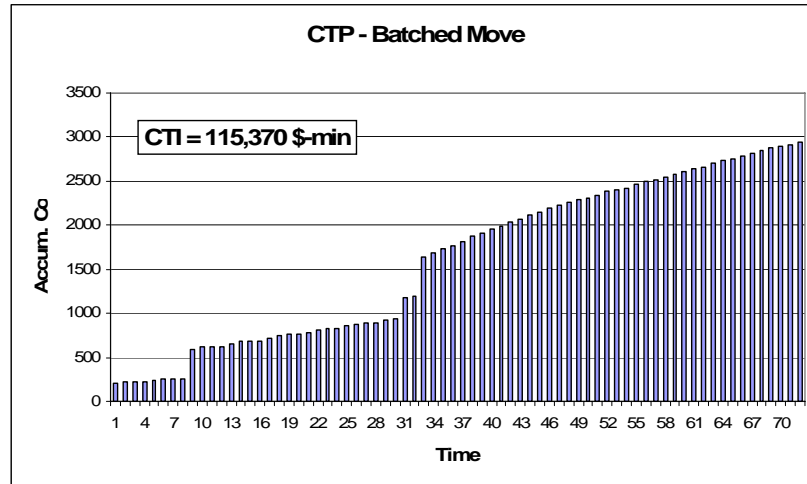


Figure 17: CTP for Case 4: Batch for material handling

The makespan for this Case is 72 minutes, and the CTI is 115,370 \$-min.

Case 5: Transportation from supplier to buyer. In this case, two variations were considered: All the units are transported from a supplier to a buyer between activities A and B, or they are transported between C and D. **Figure 18** presents the first option, and **Figure 19** illustrates the second one. As a special note, it was assumed that Transportation did not take time or create costs, to observe its impact on the process by forcing to group units and making them wait.

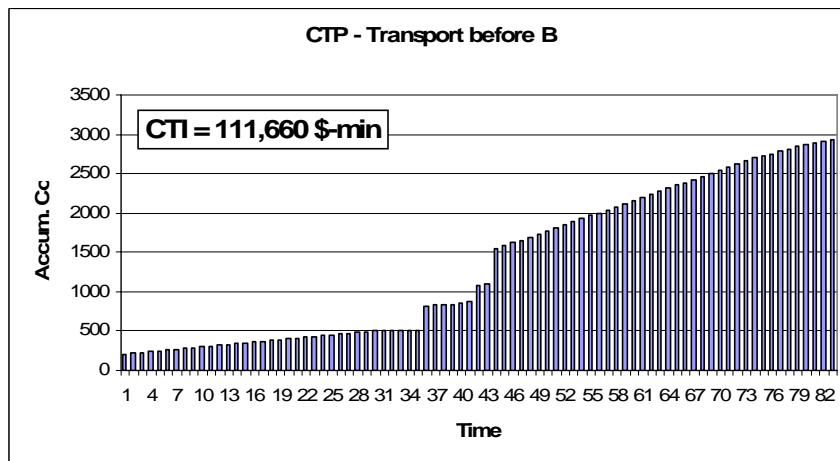


Figure 18: Case 5: Transport between activities A and B.

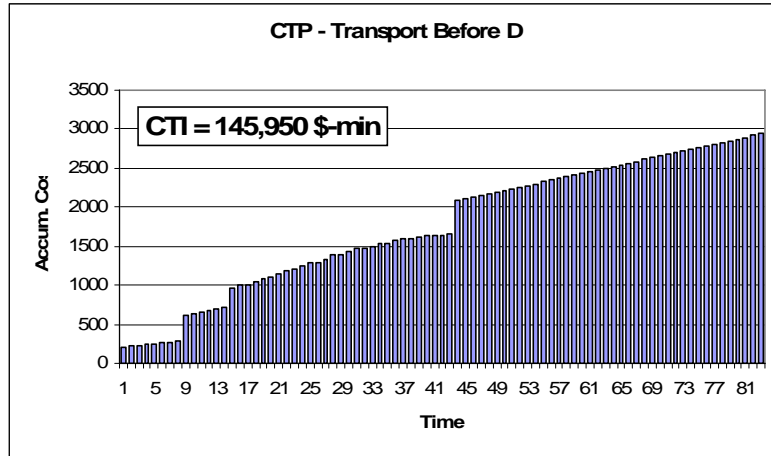


Figure 19: Case 5: Transport between activities C and D.

When the batch is transported early (between A and B), the effect on the CTI (111,670 \$-min) is smaller than when the transportation is performed later (between C and D, 145,950 \$-min). The reason for this is that the completion time in both cases is the same (83 min), but the Accumulated Cost figure at the moment of the transportation-caused waits is much smaller in the early transportation.

A summary of the 5 cases is presented in **Table 10**.

Table 10: Summary of the five cases of batching and their effect on the CTI

| Case | Description | Makespan | CTI |
|------|--|----------|----------------|
| Base | Base Case, one unit | 20 min | 2409 \$-min |
| 1 | Simultaneous processing | 20 min | 24,090 \$-min |
| 2 | Batch for an order – JIT Materials | 56 min | 77,010 \$-min |
| 2 | Batch for an order – Batched Materials | 56 min | 96,810 \$-min |
| 3 | Batch for processing equipment | 92 min | 143,970 \$-min |
| 4 | Batch for material handling | 72 min | 115,370 \$-min |
| 5 | Transportation (between A and B) | 83 min | 111,670 \$-min |
| 5 | Transportation (between C and D) | 83 min | 145,950 \$-min |

As a concluding remark, observing **Table 10** it becomes evident that the impact of batching on the CTP can be very substantial. This is mainly due to the fact that waits are the main change in the CTP of products when batching happens. The main recommendation from this section is that if the CTP of one unit of product is very different from the CTP of the next one due to batching issues, the unit of study for the construction of the CTP and the calculation of the CTI should be the batch (or the order) and not the individual unit. In this way, all the activities that are required to bring the batch to the customer will be taken into account and the CTI will be used to calculate the direct cost of the batch (or order). Besides, when strict one-piece flow is not possible, it has been seen that the CTI for a batch is not the CTI for a single unit multiplied by the size of the batch; the process for the whole batch (with all its waits and moves) needs to be considered to accurately portrait the process and its economic impact.

4.2. Accounting Systems

The CTP and IE-CTP require process information, cost information and activity related information. Traditionally, cost information is designed, collected, controlled and reported by the functional area of accounting. Different companies use different accounting systems, and they gather and handle cost information in different ways.

The calculation of the cost of an activity or the cost of an individual unit of product is a process that depends heavily on the specifications of the costing system and the managerial decisions of the company. Different components of the cost have different levels of traceability to a single unit of product, where some of them are directly and unequivocally due to a particular single unit, while some others will occur regardless of how many units are produced and even some happen just for having the facility open, without any relation to the production or not of a single unit of product. **Figure 20** presents a generic representation of the costs of a company that are related to manufacturing the products.

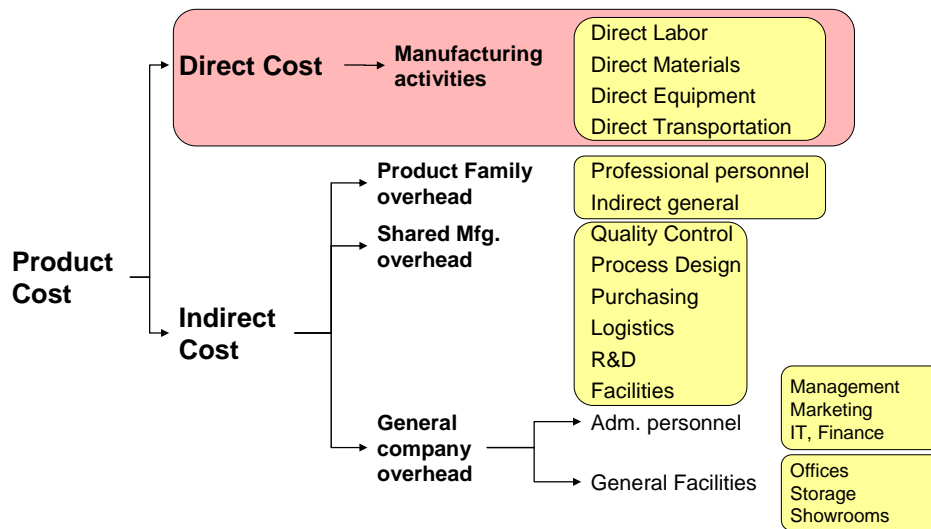


Figure 20: General composition of the cost of a product

We will quickly discuss three costing systems that mark a historical evolution, and identify in which of them the IE-CTP would be a better and more usable tool.

4.2.1. Standard Costing

Standard costing was designed creating a “standard” of the manufacturing process for the product, based on time and motion studies and also the engineering of the product and the process themselves. Processing time, usage of materials and the cost of the materials are some of the basic information outputs that were required. Based on these data, planning and budgeting were prepared and executed. In the control phase, the actual costs and throughput figures were compared with the planning (made based on the standards), and the inconsistencies were labeled “*variations*”. The main managerial activity with this system was the calculation and explanation of the variations: Why was production more costly than the standard, who was responsible and what needs to be done about it.

This system encourages conducts that are contrary to lean thinking, such as running long batches to minimize cycle time (hence improving the piece throughput), buying large amounts of raw materials to obtain volume discounts (hence increasing

inventory costs) and keeping machines and equipment running and busy to increase their utilization (creating overproduction, the most dreaded form of *muda* by the Japanese lean practitioners). Also, very detailed bookkeeping is required, which makes it a rather costly proposition to implement it in full detail.

Finally, indirect costs are assigned to product units based on a prorated scheme, where an “overhead rate” was established (for every dollar in direct costs, 65 cents will be assigned to the product for overhead and indirect expenses). A critique to standard costing has always been that the overhead rate does not discriminate the details of the process of different products, and assumes that all the products will use overhead resources in the same proportion to their use of direct resources.

4.2.2. Activity Based Costing (ABC)

In an effort to make the assignment of costs to product unit more accurate, Activity Based Costing (ABC) was developed. ABC looks at the things that cost, such as resources, and how they are used by different activities. It then decomposes the processes required for the production of the products into activities, and assigns costs to products according to cost drivers and the use the processes make of direct and indirect activities.

“ABC takes a two-stage approach to allocating overhead costs to products based on multiple cost drivers at various levels of activity. In the first stage, overhead costs are assigned to cost pools within an activity center based upon activity-driven cost drivers. There is no equivalent step in traditional costing accounting (TCA). In the second stage, overhead costs are allocated from the cost pools to the products based on the product’s consumption of indirect activities.” (Nachtmann and Al-Rifai, 2004).

All of this sounds very logical, but in reality it creates the need for complicated data collection and management infrastructures, and the levels of detail that are used for the construction of activities, drivers and assignments are quite complicated some times.

4.2.3. Lean Accounting – Lean Costing

Finally, in recent years with the widespread adoption of lean thinking in different industries, another paradigm is starting to be used. It's called lean accounting, and it basically responds to the way the responsibility and management of products are organized. Lean manufacturing proposes that the physical manufacturing be organized according to products and product families, as well as the supporting and non-routine activities (such as product design and development). These “product family teams” make it easier to assign direct costs to products, and the organization of the overhead becomes an exercise in levels, as illustrated by **Figure 21**.

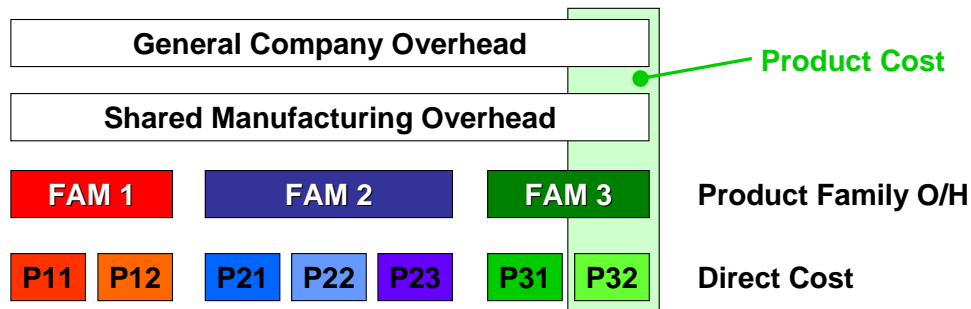


Figure 21: Levels of Cost and Overhead

4.2.4. Where does the IE-CTP fit?

From an idealistic point of view, IE-CTP is more compatible with a lean accounting system, since one of its fundamental reasons for existing is helping companies to become leaner. However, the detailed activity and resource information that ABC systems collect and manage can be efficiently used for the identification of direct costs, which are the ones that are of interest for IE-CTP. IE-CTP is compatible with most accounting systems, as long as there is clear process and costing information available.

As it has been mentioned before, CTP does not deal directly with overhead, precisely because the assignment and reporting of it can be handled in many different ways and there is not yet (and there probably will not be) a unified standard for this assignment. However, when several companies are involved in the manufacturing of a product, it is unavoidable to deal with the allocation of overhead, simply because the

price of a part, component or service that a supplier delivers for a buyer (or a client business unit receives from a sister business unit) contains not only the cost of the product but also the overhead and profit that company charges. This problem and how to conceptually consider it in a IE-CTP is addressed in the following subsection.

4.3. Direct cost, overhead and profit

The IE-CTP is proposed as a tool for the lean collaboration between companies, to increase the visibility and transparency in their progress toward leaner production (Chapter 7). Part of this transparency should be the identification of the components of the price the supplying partner company charges for their product or service. When an IE-CTP is being built, the core company (OEM) will receive parts or components from its suppliers, but the price they quote is not entirely composed of direct cost; it will include the direct cost plus overhead and a percentage of profit, as presented in **Figure 22**.

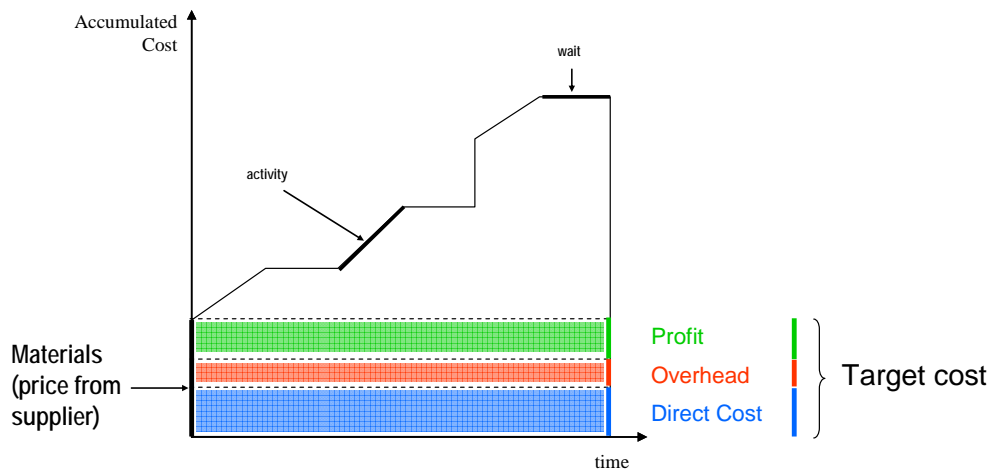


Figure 22: Components of the price from a supplier

The price the supplier charges should be calculated (theoretically) by first finding the direct cost, the costs that are directly related to each unit of product. Then, it is necessary to add the overhead (through an overhead rate or any other type of assignment

mechanism) to make up the product cost. Finally, on top of the product cost goes a certain amount of profit (again, through a proportional rate or any other mechanism decided by management) to finalize the price of the product.

In lean environments, the price of a component supplied by the partner company is usually determined through an agreement between the supplying and the buying company, and sometimes the term *Target Cost* is used to describe the agreed upon figure. In other words, the companies agree about the price beforehand. The decomposition of the price in this manner ($Price = Direct\ Cost + Overhead + Profit$) would allow a better control of the relationship between the two companies. If the supplying company reports a profit margin that is too narrow, it is clear that either the direct cost or the overhead are too large, and therefore the main company should collaborate with the supplying partner with technical assistance for process improvement and cost reduction, because the final aim is to maintain long term relationships, and these are impossible with a non-sustainable profit margin. On the other hand, if the profit margin is too large, a renegotiation of the target cost is what probably follows, as well as technical assistance in the other direction (from the supplier to the buyer), because it would appear that the supplier improved their procedures and technology to achieve better levels of cost and therefore more generous profits. However, the key word here is *sharing*. It would not be fair that learning and improvement by the supplier were not recognized by the buying company; therefore part of the gains should be kept by the supplying partner as an incentive for the continuation of improvement and evolution efforts.

On the other hand, if the price of products and services was reported in this way by the supplying companies, it would be feasible to calculate how much of the CTP areas are caused by direct cost and how much by overheads and profits. This point (which components of the CTP are responsible for which portions of the area under the curve) will be discussed further in section 6.1.

4.4. Relationship between companies

At this point in the discussion of the IE-CTP, it seems apparent that the exchange of information, the technical meetings for monitoring the evolution of the CTPs in the different companies of the network and all other interactions that involve the disclosure of information will only be possible under a specific set of circumstances and partnership agreements. These relationship aspects are important to make the use of tools such as the IE-CTP not only possible but productive.

4.4.1. Power of Negotiation – Role in the Network:

The first issue to discuss is the specific position of the companies that intervene in the manufacturing of the product of interest. For example, if a component is provided exclusively by one company (because of its access to the materials, its technological capabilities or other constraining factors), that company holds a high power of negotiation. On the other hand, if the company provides a widely available commodity, its negotiation power is very low. If a company is the largest customer for a certain component or subassembly, it has high power of negotiation. If, on the other hand, it only buys a handful of units of the product, the supplying companies will pay more attention to bigger companies with more purchasing power.

For the use of the IE-CTP, a willingness to share information is indispensable. Therefore, an agreement of partnership must be in place in such a way that all the companies involved in the manufacturing of a product are informed of the IE-CTP of the product, as well as aspects as pricing and distribution arrangements. This would make any decisions more fair and concerted. Also, this disclosure of information improves the environment for the establishment of trust.

The main company, the one that gives its name to the product and is responsible for it, must establish its position relative to the other companies in the network, and based on that establish strategic long-term relationships that will promote the exchange of information. If a certain supplier is deemed only temporary, or highly volatile, the main

will probably not include it in any strategic agreements and will not share the IE-CTP information with it, making the participation of the supplying company on the IE-CTP appear only as a disbursement (if processing services were performed over materials sent by the main company) or as a materials release (if the supplier delivers a part or component without first receiving any materials from the main company). On the other hand, if a company is deemed as a strategic ally, or if the component supplied or processed by them is critical and central for the product, that company is probably a good choice for the disclosure of CTP information and the technical cooperation that is expected as a result of it.

4.4.2. Topology of the Network (of companies)

Cooper and Slagmulder (1999) propose that the topologies of many networks of companies can be summarized in three main (simplified) denominations, presented in **Figure 23**.

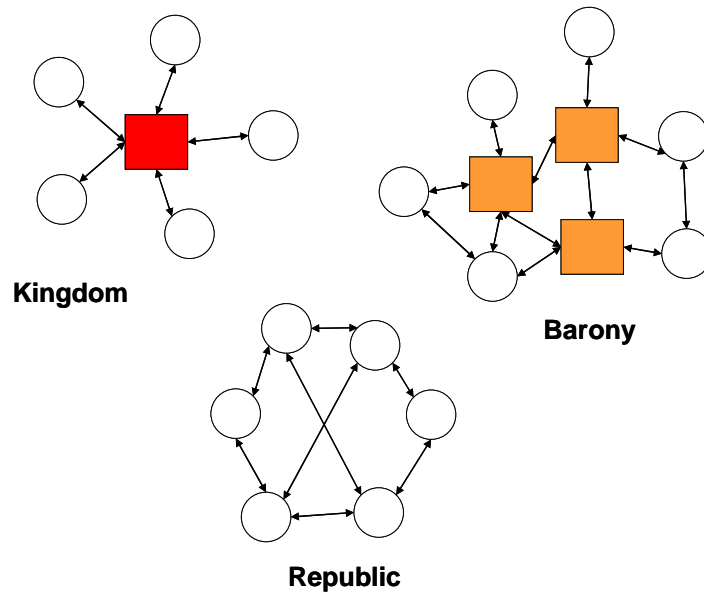


Figure 23: Simplified Network Topologies

In **Figure 23** the shaded squares represent the dominant companies in the network, the ones that control brand names and access to the final consumers. The three main types of networks are:

- *Kingdoms*: There is only one core firm (the “King”), which controls the network. In this case, all the interactions and evolutions of the network are defined by the king, and the enforcement of new rules and protocols is executed “top down”, coming from the dominant company.
- *Baronies*: There are several core firms present. They might belong to similar, synergistic or diverse industrial sectors, but they are probably close together geographically and feed from the same resource pool in terms of supplying companies, human and natural resources. These core firms dominate the network, but there is not one that can dominate the others. In these case protocols of interaction and process management decisions are made in a concerted fashion by the barons and then they are radiated to the other connected companies.
- *Republics*: There are no core firms; therefore many point-to-point loose alliances are formed. All firms have the same level of power. In these networks is hard to establish standardized cooperation systems, because many companies will talk directly to their counterparts and have specific arrangements. Also, legacy systems are common and interactions at different times and under different circumstances mark the possibilities of cooperation between the companies.

Given the need for sharing proprietary activity and cost information for the IE-CTP, the relationships between companies that are desired should be with longer terms in mind, and standards for the exchange of information should be established. Therefore, it seems that for a company to be able to implement the IE-CTP with its network of supplier, the company needs to be in a position of either *King* or *Baron*, as depicted in **Figure 23**.

4.4.3. Establishment of attractive interest rates

Different companies will have different attractive interest rates (the ones applied to the Cost-Time Investment to find the direct cost of the product), due to their type of business and their relationship with the specific customer. If a customer is seen as non-

repeat buyer, the attractive interest rate might be set at a higher level. However, if the customer is a company that has a partnership relationship with the supplier, the establishment of the attractive interest rate might be a negotiated process, aimed at the gain of mutual benefits and the sustainability of the relationship.

4.4.4. Sharing of savings

Once the partnership agreement between companies is established, the dynamic monitoring of the IE-CTP will be an input for the decision of the types of collaborative improvement projects that will be undertaken. When these projects are planned and executed, the CTP can be used to detect cost savings and Cost-Time Investment savings. If these savings are a result of joint efforts, they will need to be shared, and the IE-CTP provides a useful platform to disclose the savings and decide how to assign them.

4.4.5. Lean collaboration

The type of relationships between companies that IE-CTP needs to work fit very well the description of lean collaboration provided by Rivera et. al. (2006c). Some important points about lean Collaboration will be presented here.

Motivation to build lean networks of companies: Companies pursue the generation of reasonable profit. The mean to achieve this is through satisfying customers so they continue buying the products. Therefore, companies should focus not only on money-making considerations but also on what they have to do in order to satisfy customers and make profits. In this case, the establishment of lean collaboration with the other members of the supply chain is done not for friendly and humanitarian reasons, but because it is best for business, and because without it, it is impossible to have a sustainable lean supply chain. This does not mean that the relationships will be fake and hypocritical; on the contrary, legitimate open relationships with mutual benefit and common goals as principles and trust as the quality of the relationships will be what is required to ensure success.

Unity of purpose: In early supply chain literature, supply chains were portrayed as an umbrella of companies that passed product to each other in the direction of the customer, with transportation and warehousing activities buffering the movement of materials between them. Such a limited exchange is not sufficient today. The holistic view of the lean network of companies demands that all the members recognize the need to have unity of purpose and commonality of basic values (at least for the scope of their common activities) in order to interact effectively in the processes to serve the consumers. According to Vitasek et al. (2005), these types of networks are coordinated efforts among partners to eliminate waste across the supply chain, and can only be accomplished through successful collaboration across common processes. Collaboration is the foundation that supports the three building blocks described in the previous sections. It facilitates the implementation of lean logistics, information system integration, and inter-organizational performance measurement systems.

Self-centered vs. process centered: Companies need to look beyond the boundaries of their plants and understand that they are part of a bigger process that brings products and services to end users. The understanding of their role as well as the big picture will make them more effective in their interactions with their partners. The main goal of supply chain integration is to create harmony between partners for horizontal information flows and effective exchange of physical goods. Therefore, the basis of integration can be characterized by not only cooperative partnership, but also collaboration, information sharing, shared technology, and a fundamental shift away from managing individual functional processes, to managing integrated chains of processes (Akkermans, as cited in Power, 2005).

Lean relationships are the glue that holds the network together: Lean collaboration goes beyond contractual obligations and includes a sense of commitment and trust, where companies have decided to work together for the long run. In these situations, if a quality problem arises in a supplier process, the

company buyer company does not run away to find a different supplier, it rather goes in and helps the supplier company to fix them. The extent of this cooperation could go as much as lending equipment and personnel to the partner in need. In return, the supplier should do their best to avoid problems from happening again, and to learn from the experience and move forward.

Elements of Lean relationships: Cooper and Slagmulder (1999), present four major characteristics that should guide lean relationships:

- Reduced Supplier Base: This leads to more mutual knowledge, better control of the process, tighter linkages and richer relationships.
- Level of relationships: It is not necessary to establish the same level of relationships with all suppliers. As the products delivered by the supplier grow in complexity and importance for the final product, the relationship becomes more serious and permanent. Conversely, it is not vital to establish relationships that are that tight with companies that supply easily replaceable commodities, such as standard nuts and bolts, or office supplies.
- Nature of the relationships: Interdependence (buyer depends on the supplier for its technical expertise; supplier depends on the buyer for business and technical support). The outcome of interdependence is that relationships that are stable over time have a higher degree of collaboration and are mutually beneficial. All of this is only possible with Trust. Trust develops through interaction (in time) in a stable relationship.
- Organizational boundaries are blurred as companies dynamically share resources: If relationships are stable, a company might be willing to buy equipment that will be used exclusively for the benefit of the other partner. Also, personnel sharing is not unheard of, sending engineers and experts to provide technical and organizational expertise to the partner companies. These interactions come from the understanding of the common goals and destiny of the members of the lean supply chain.

5. IMPROVEMENT OF THE IE-CTP

Once the IE-CTP has been built, several different strategies can be used to improve the bottom line (Cost-Time Investment and Direct Cost). In this research, four different approaches for the improvement of the Cost-Time Profile will be explored: schedule optimization, scenarios for direct cost improvement, simulation studies and the use of a software tool developed for the Center for High Performance Manufacturing at Virginia Tech.

5.1. Schedule Optimization

The activity schedule that is used to build a Cost-Time Profile reflects the process structure as it is currently executed; however, this does not mean that this project structure is optimal with regards to the Cost-Time Investment or direct cost.

To tackle this problem (the search for a schedule that delivers the product achieving a minimal Cost-Time Investment and direct cost), the manufacturing process will be modeled using the standard project management linear programming model, and then, through a series of progressively more complex elaborations, the model will be extended to incorporate the specific characteristics of the Cost-Time Profile.

5.1.1. Minimize completion time

Products are made in processes that consist on a series of steps. Ideally, these steps would be sequential, performed in a strictly linear sequence as presented in **Figure 24** (in this convention, Activities are labeled on the arcs and the nodes represent milestones in the process).

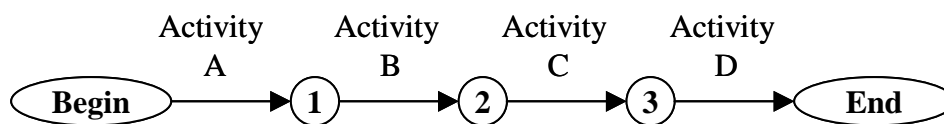


Figure 24: Linear sequence of activities.

However, the most general case is to find process structures that are not perfectly linear. For example, many products require subassemblies prepared by processes that can be undertaken simultaneously. **Figure 25** depicts one such structure.

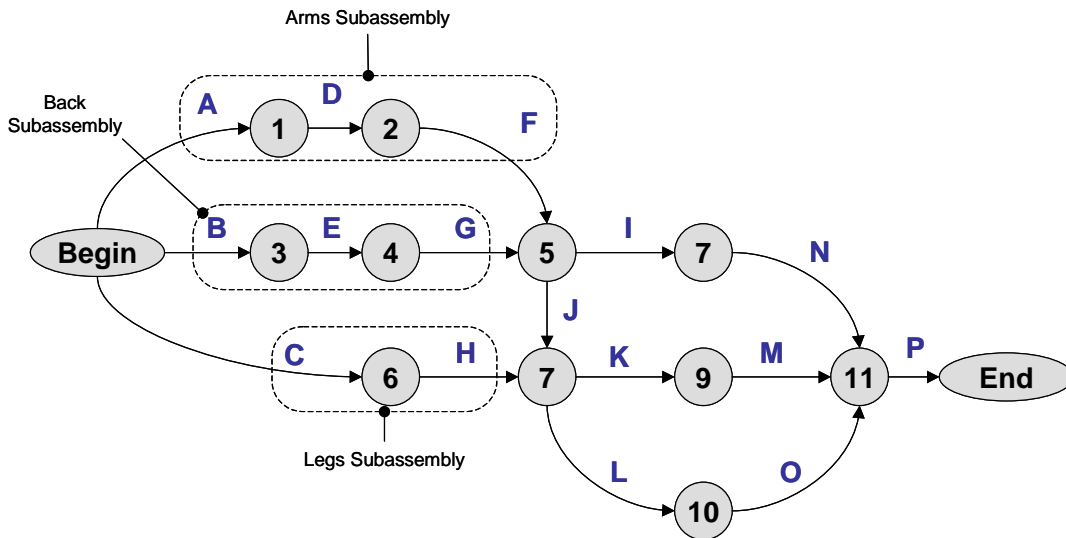


Figure 25: Process map for a product (e.g., a chair) with subassemblies.

This is a commonly accepted way to draw a network of activities, where the directed arcs (arrows) signify that activity C must be finished before activity H can begin. Also, it means that activities A, B and C could begin at the very moment that the project starts. Finally, in this example when activity P finishes, all the project is considered complete.

At this point, we require an algorithm or mathematical model to determine when is each of the activities going to be performed, in such a way that the project is completed in the shortest time possible. There is a way to model and solve these kinds of project networks using linear programming. This is what we will call **Model 1**.

MODEL 1

Set: Activities {A, B, C,...} (n activities).

Indices: i, j on Activities.

Parameters: T_i Execution time for Activity i

$PD_{i,j}$ $\left\{ \begin{array}{l} 1 \text{ if Activity } j \text{ is an immediate predecessor of Activity } i \\ 0 \text{ otherwise} \end{array} \right.$

Variables: X_i Completion time for Activity i .

Y Completion time for the whole project

Objective Function: Minimize the completion time for the project

$$\text{Min } Z = Y \quad (\text{Eq. 5})$$

Constraints: Completion time for the project must be greater than or equal to the completion time for any activity

$$Y \geq X_i ; \text{ for all } i. \quad (\text{Eq. 6})$$

Any activity must only begin after its immediate predecessors have been completed.

$$X_i \geq X_j + PD_{i,j} * T_j ; \text{ for all } i \neq j \quad (\text{Eq. 7})$$

(This constraint is only enforced when the $PD_{i,j}$ is 1, that is, when there exists a relationship of precedence between i and j).

5.1.2. Modified objective function – minimize sum of slacks

In **Model 2**, we will alter the objective function in such a way that the LP algorithm will force the activities that are not in the critical path to occur **as late as possible** without altering the completion date of the project. For this, we modify the objective function (**Equation 5**) and now we try to minimize the sum of all the distances from the completion of each activity to the finishing time of the project. Observe **Equation 8**.

MODEL 2

Set: Activities {A, B, C,...} (n activities).

Indices: i, j on Activities.

Parameters: T_i Execution time for Activity i
 $PD_{i,j}$ 1 if Activity j is an immediate predecessor of Activity i
0 otherwise

Variables: X_i Completion time for Activity i .
 Y Completion time for the whole project

Objective Function: Minimize the sum of times from the finish time of each activity to the finish time for the project

$$\text{Min } Z = \sum_{i=1}^n Y - X_i \quad (\text{Eq. 8})$$

Constraints: Completion time for the project must be greater than or equal to the completion time for any activity

$$Y \geq X_i ; \text{ for all } i. \quad (\text{Eq. 6})$$

Any Activity must only begin after its immediate predecessors have been completed.

$$X_i \geq X_j + PD_{i,j} * T_j ; \text{ for all } i \neq j \quad (\text{Eq. 7})$$

(This constraint is only enforced when the $PD_{i,j}$ is 1, that is, when there exists a relationship of precedence between i and j).

Now, we have the project finishing as soon as possible and the non-critical activities have become critical (since the model will minimize their distances to the end of the project, they will all “eat up” their slacks and will happen as late as possible). There is, however, another major point to be discussed for the assurance of the correct structure of the project, and that is **resource and operator sharing**. Models 1 and 2 are designed under the assumption that there is infinite availability of resources, or better yet, that there is no conflict possible when several activities are happening simultaneously

because the activities do not share resources. This is not always true, therefore in the next section we will discuss how to model and overcome this obstacle.

5.1.3. Consider resource dependencies

In **Model 3**, we will include new constraints that provide the logical structure that we need for the model. What if two activities are scheduled to occur simultaneously by **Model 2** but they happen to use the same machine? The schedule obtained with **Model 2** would become infeasible because it did not consider this possibility.

This new constraint is similar to the one we used to ensure the precedence relationships (“*activity A must be finished before activity B can start*”), however, there is a big difference: In this case, what we need to prevent is the activities from occurring simultaneously, but we do not know which one should go first and which one should go second. The model should also determine this. Therefore, the constraint we need to write becomes something like “*activity A must be finished before activity B can start*” **OR** “*activity B must be finished before activity A can start*”.

The need for this logical construction poses a problem, because in pure linear programs all the constraints present **MUST** be enforced, there is no room for upholding this constraint *OR* this other constraint, *BUT NOT BOTH*. The way to resolve this is to abandon the pure linear programs and to move into the mixed integer programs. Specifically, using binary variables this type of problem can be modeled. Let us explore how we would need to modify **Model 2** to arrive at a **Model 3** that considers the sharing of resources and operators.

First, we will need to build a new parameter for the model, $SR_{i,j}$. It will be 1 if activities i and j share a resource or operator, 0 otherwise. Also, it must be true that $SR_{i,j} = SR_{j,i}$. Finally, in the construction of $SR_{i,j}$ caution must be exercised to ensure that $SR_{i,i} = 0$ for all values of i , because if this is not true, the model could try to schedule an activity before or after itself.

Second, we need to define the binary variable that guarantees the *either-or* structure for the constraints, yI_{ij} . This variable is used for two constraints. The first one will ensure that either yI_{ij} or $yI_{j,i}$ are equal to 1, but not both of them. The constraint is simple enough: $yI_{ij} + yI_{j,i} = 1$; for all $i \neq j$. We do not restrict the $yI_{i,i}$ since these variables do not have practical use and will also be taken care of by the next constraint.

Finally, we use the parameter and binary variables defined above to construct the actual logical constraint. Since this constraint must enforce that either activity i happens before activity j or vice versa, we will construct the two constraints and explain how the *either-or* part happens.

$$X_i \geq T_i + (X_j * SR_{i,j}) - (M * yI_{i,j} * SR_{i,j}) \quad (\text{If } j \text{ needs to happen before } i) \quad (\text{Eq. 9.1.})$$

$$X_j \geq T_j + (X_i * SR_{j,i}) - (M * yI_{j,i} * SR_{j,i}) \quad (\text{If } i \text{ needs to happen before } j) \quad (\text{Eq. 9.2.})$$

M is another parameter, which needs to be a very big number (for example, it can be a multiple of the sum of all the duration of the activities in the project). Let us now examine several scenarios according to the value of the parameters.

No resource dependency between i and j : In this case, both $SR_{i,j}$ and $SR_{j,i}$ will be equal to zero. This would cause Equations 9.1. and 9.2. to look as follows:

$$X_i \geq T_i \quad (\text{Eq. 9.1.})$$

$$X_j \geq T_j \quad (\text{Eq. 9.2.})$$

These, of course, will always remain true, because the completion time of an activity cannot be less than the duration of the activity.

Activities i and j share a resource or operator: In this case, both $SR_{i,j}$ and $SR_{j,i}$ will be equal to one. This would cause Equations 9.1. and 9.2. to look as follows:

$$X_i \geq T_i + X_j - (M * yI_{i,j}) \quad (\text{Eq. 9.1.})$$

$$X_j \geq T_j + X_i - (M * yI_{j,i}) \quad (\text{Eq. 9.2.})$$

Now, adding to this the fact that only one of $y_{I_{i,j}}$ and $y_{I_{j,i}}$ will be equal to one and the other will be forced to be equal to zero, we can see that if, in this example, $y_{I_{j,i}}$ is equal to zero it means that the constraint presented in Equation 9.2. will be enforced, but its sister constraint in Equation 9.1. will be relaxed. These constraints would look as follows:

$$X_i \geq T_i + X_j - (M * y_{I_{i,j}}) \quad (Eq. 9.1.)$$

$$X_j \geq T_j + X_i \quad (Eq. 9.2.)$$

This means that, in this case, activity j must go after activity i is finished.

So, incorporating these new parameters, variables and constraints, **Model 3** will be as follows in the next page.

MODEL 3

Set: Activities {A, B, C,...} (n activities).

Indices: i, j on Activities.

Parameters: T_i Execution time for Activity i

$PD_{i,j} \begin{cases} 1 & \text{if Activity } j \text{ is an immediate predecessor of Activity } i \\ 0 & \text{otherwise} \end{cases}$

$SR_{i,j}$ 1 if Activities i and j share a Resource or an Operator. $SR_{i,j} = SR_{j,i}$ for all i and j . Also, $SR_{i,i} = 0$.

Variables: X_i Completion time for Activity i .

Y Completion time for the whole project

$yI_{i,j}$ Binary Variables to assist in the logical *either-or* construction for Resource and Operator sharing

Objective Function: Minimize the sum of times from the finish time of each activity to the finish time for the project

$$\text{Min } Z = \sum_{i=1}^n Y - X_i \quad (\text{Eq. 8})$$

Constraints: Completion time for the project must be greater than or equal to the completion time for any activity

$$Y \geq X_i ; \text{ for all } i. \quad (\text{Eq. 6})$$

Any Activity must only begin after its immediate predecessors have been completed.

$$X_i \geq X_j + PD_{i,j} * T_j ; \text{ for all } i \neq j \quad (\text{Eq. 7})$$

(This constraint is only enforced when the $PD_{i,j}$ is 1, that is, when there exists a relationship of precedence between i and j).

Logical constraint for the binary variables $yI_{i,j}$ and $yI_{j,i}$, to ensure that exactly one of them is equal to one at a given time.

$$yI_{i,j} + yI_{j,i} = 1 ; \text{ for all } i \neq j \quad (\text{Eq. 10})$$

Either-or constraints to ensure that a pair of Activities that share a Resource or an Operator do not happen simultaneously.

$$X_i \geq T_i + (X_j * SR_{i,j}) - (M * yI_{i,j} * SR_{i,j}) ; \text{ for all } i \neq j \quad (\text{Eq. 9})$$

5.1.4. Minimize the Cost-Time Investment

The last step in the evolutionary sequence of the models is to write an objective function that minimizes the Cost-Time Investment. In this case, it will be seen that minimizing the Cost-Time Investment is equivalent to minimizing the direct cost, since the model will not change the total cost of the process (recall that *Direct Cost = Total Cost + Cost-Time Investment*Interest Rate*, from Equation 2).

For this, the first task is to characterize the contribution to the area under the CTP curve that each activity makes. If we consider that materials are always released at the beginning of an activity, we can see that **Figure 26** presents the typical areas that we would see as a result of a given activity.

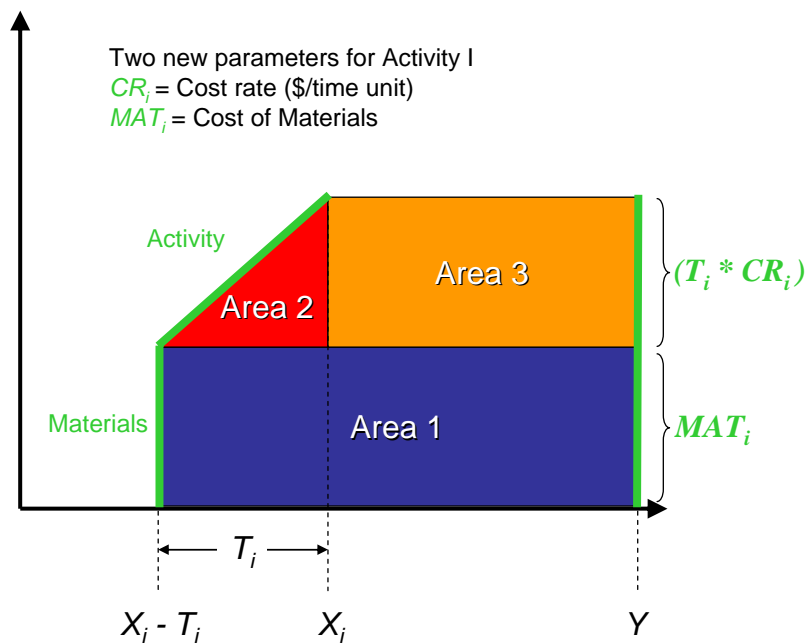


Figure 26: Contribution to the area under the curve by an activity

Area 1 is created if the Activity causes the release of materials to the processes. As it can be seen in **Figure 26**, the materials are released instantaneously at the beginning of the activity and continue invested until the end of the process. Area 1 can be described with **Equation 11**.

$$Area\ 1_i = [Y - (X_i - T_i)] * MAT_i \quad (Eq. 11)$$

Area 2 appears when the activity is happening. This triangular shape is described by **Equation 12**.

$$Area\ 2_i = \frac{(CR_i * T_i) * T_i}{2} = \frac{CR_i * T_i^2}{2} \quad (Eq. 12)$$

Area 3 is caused by the accumulated cost the activity leaves, and then it endures until the end of the process. This rectangular shape is described by **Equation 13**.

$$Area\ 3_i = (CR_i * T_i) * (Y_i - X_i) \quad (Eq. 13)$$

Adding **Area 1**, **2** and **3** we obtain the contribution to the total area by any given activity. Organizing terms we obtain **Equation 14**.

$$AreaContribution_i = (Y - X_i)(CR_i * T_i + MAT_i) + T_i * MAT_i + \frac{CR_i * T_i^2}{2} \quad (Eq. 14)$$

And the new objective function would be to minimize the summation of the area contributions of all the activities. The new objective function is presented in **Equation 15**.

$$\text{Min } Z = \sum_i \left[(Y - X_i)(CR_i * T_i + MAT_i) + T_i * MAT_i + \frac{CR_i * T_i^2}{2} \right] \quad (Eq. 15)$$

Model 4 is presented in the next page. The only change after Model 3 is the new objective function presented in Equation 15.

MODEL 4**Set:** Activities {A, B, C,...} (n activities).**Indices:** i, j on Activities.**Parameters:** T_i Execution time for Activity i

$$PD_{i,j} \begin{cases} 1 & \text{if Activity } j \text{ is an immediate predecessor of Activity } i \\ 0 & \text{otherwise} \end{cases}$$

$$SR_{i,j} \quad 1 \text{ if Activities } i \text{ and } j \text{ share a Resource or an Operator.} \quad SR_{i,j} = SR_{j,i} \text{ for all } i \text{ and } j. \text{ Also, } SR_{i,i} = 0.$$
 CR_i Cost Rate of Activity i MAT_i Materials released at the beginning of Activity i T_i Duration of Activity i **Variables:** X_i Completion time for Activity i . Y Completion time for the whole project $yI_{i,j}$ Binary Variables to assist in the logical *either-or* construction for Resource and Operator sharing**Objective Function:** Minimize the sum of contributions to the total area by the activities

$$\text{Min } Z = \sum_i \left[(Y - X_i)(CR_i * T_i + MAT_i) + T_i * MAT_i + \frac{CR_i * T_i^2}{2} \right] \quad (\text{Eq. 15})$$

$$\text{Constraints:} \quad Y \geq X_i ; \text{ for all } i. \quad (\text{Eq. 6})$$

$$X_i \geq X_j + PD_{i,j} * T_j ; \text{ for all } i \neq j \quad (\text{Eq. 7})$$

$$yI_{i,j} + yI_{j,i} = 1 ; \text{ for all } i \neq j \quad (\text{Eq. 10})$$

$$X_i \geq T_i + (X_j * SR_{i,j}) - (M * yI_{i,j} * SR_{i,j}) ; \text{ for all } i \neq j \quad (\text{Eq. 9})$$

A schedule of activities created using the outputs of Model 4 will respect the precedence constraints of the activities, as well as the constraints imposed by sharing resources or operators amongst activities, and it will minimize the total area under the curve without changing the total cost, which will give us the best possible direct cost result.

5.2. Scenarios for direct cost improvement

In this Section we will investigate different ways that can be devised for the reduction of the area under the curve on a Cost-Time Profile (reduction of the Cost-Time Investment). The objective is to observe their impact through the presentation of the Cost-Time Profile of a base case and an “improved case”, after the application of the tool or technique.

The characteristics of this exercise are the following:

- The manufacturing process is simple and linear (**Figure 27**).
- The materials arrive in certain percentages after the beginning of each activity.
- A base case will be defined, and the derived cases will be characterized. It will be indicated which variables are changed, and it will be assumed that the rest will remain unaffected from the base case.
- In the base case, the total cost of the materials and the total cost of the activities are equal.

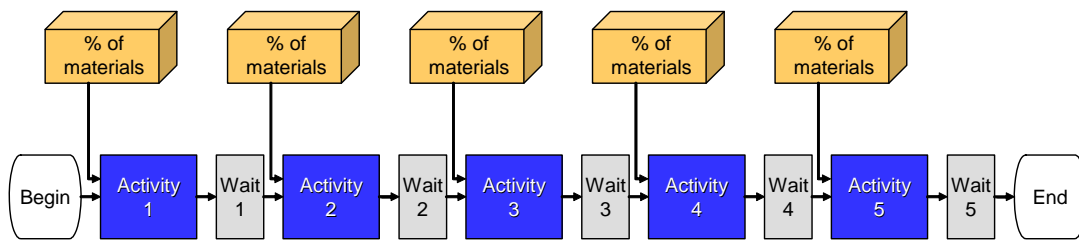


Figure 27: Simple production process.

Base case: In the hypothetical base case, all the materials that are required for the manufacturing of the product arrive together right before the start of the first activity.

Table 11: Description of the base case.

| Activity | Cost Rate | Duration |
|-------------------|------------|------------|
| Materials Arrival | 3000 | 0 minutes |
| Activity 1 | 100 \$/min | 4 minutes |
| Wait 1 | 0 | 11 minutes |
| Activity 2 | 100 \$/min | 5 minutes |
| Wait 2 | 0 | 14 minutes |
| Activity 3 | 100 \$/min | 7 minutes |
| Wait 3 | 0 | 19 minutes |
| Activity 4 | 100 \$/min | 7 minutes |
| Wait 4 | 0 | 21 minutes |
| Activity 5 | 100 \$/min | 7 minutes |
| Wait 5 | 0 | 5 minutes |

In the Value Stream Mapping literature, it is very common to find assertions that products spend more than 90% of their time inside a factory waiting to be moved or operated on. In the base case a 70% of the total time is spent waiting. **Table 12** presents a summary of the results obtained with the base case.

Table 12: Results of the base case scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI |
|-----------|------------|---------------|-----------|------------|----------------|
| Base Case | 100 min | 30 min | 70 min | \$ 6,000 | 457,200 \$-min |

Figure 28 presents the Cost-Time Profile for the base case.

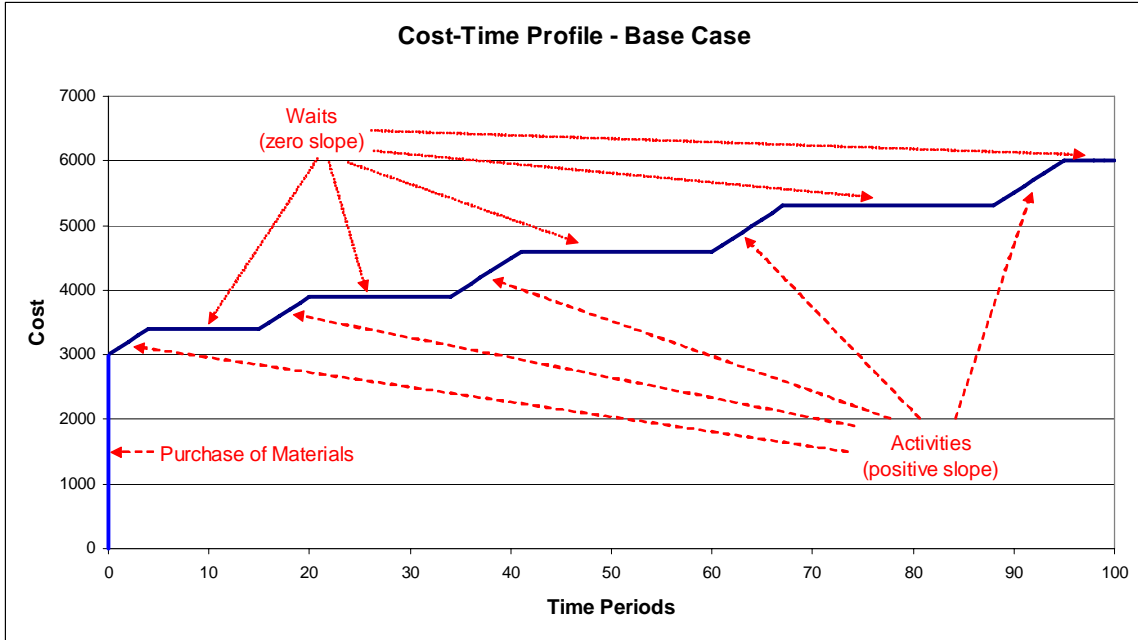


Figure 28: Cost-Time Profile for the base case scenario.

In the following subsections, **seven** different scenarios to reduce the area under the curve in the Cost-Time Profile (Cost-Time Investment) are explained, and their outcomes discussed.

5.2.1. Less materials: Reduce the area by spending less money on materials.

Keeping everything else constant, what would happen if the total cost of the materials used was reduced 20% (from \$3,000 to \$2,400)? The result is presented in **Table 13**.

Table 13: Results for less materials scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings |
|----------------|------------|---------------|-----------|------------|----------------|-------------------------|
| Less Materials | 100 min | 30 min | 70 min | 5,400 min | 397,200 \$-min | 60,000 \$-min 13.12% |

This type of reduction on the use of materials could be the result of different techniques, such as the negotiation with the supplier (or change of supplier) for a lower price, the use of material of a lesser grade or the use of less material because of changes in the design.

The Cost-Time Profile for this scenario is presented in **Figure 29**.

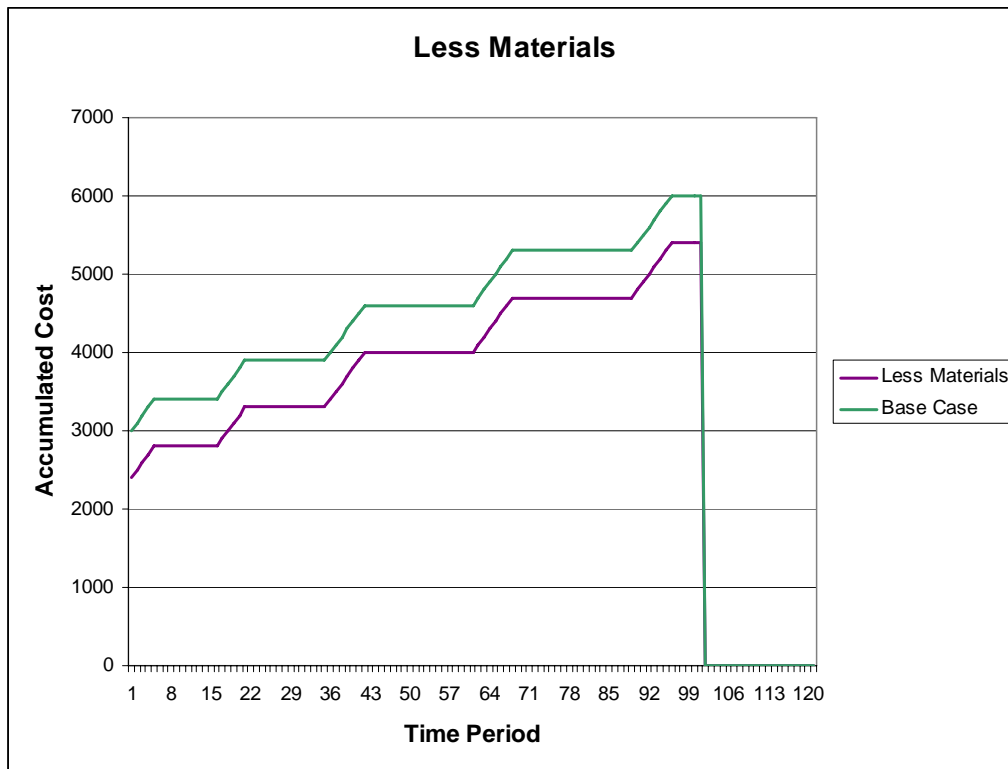


Figure 29: CTP for the less materials scenario.

5.2.2. JIT materials.

For this scenario, the only difference with the base case is that the materials will be delivered exactly before the beginning of each activity, similar to a JIT fashion. The assumption was that each of the five activities uses the same cost of materials, so \$600 will be added to the accumulated cost right before the beginning of each activity. The results are summarized in **Table 14**.

Table 14: Results for JIT materials scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings |
|---------------|------------|---------------|-----------|------------|----------------|--------------------------|
| JIT Materials | 100 min | 30 min | 70 min | \$ 6,000 | 341,400 \$-min | 115,800 \$-min 25.32% |

This scenario is purely speculative; because the assumption is that the base case represents a traditional batch-push manufacturer. If this manufacturer wanted to implement JIT and lean concepts, other steps would be required before it could go operational with JIT supply. However, the scenario was used to work in conjunction with less materials to observe the effect that changing only the materials would have in the CTI.

The CTP for this scenario is shown in **Figure 30**.

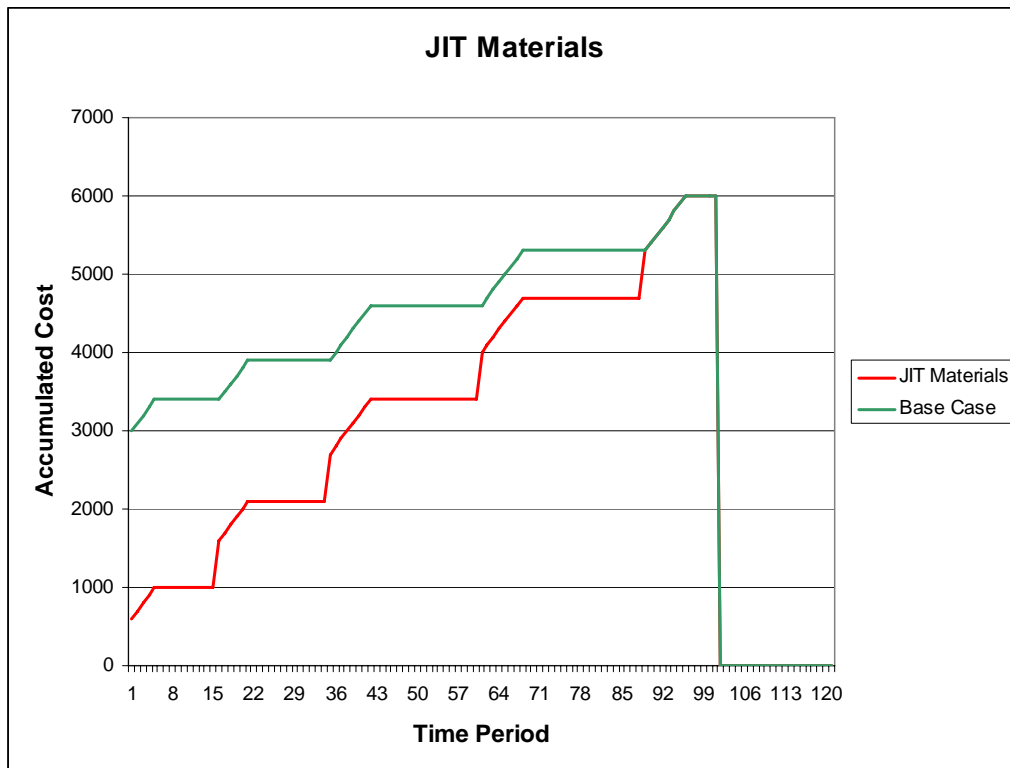


Figure 30: CTP for the JIT materials scenario

5.2.3. Wait less: Reduce the area by cutting the waiting times.

In this scenario, the difference with the base case consists in the amount of waiting time. A reduction of 20% of waiting time is proposed, to observe its effect on the CTI results. **Table 15** presents the results of this scenario.

Table 15: Results for wait less scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings |
|-----------|------------|---------------|-----------|------------|----------------|-------------------------|
| Wait Less | 86 min | 30 min | 56 min | \$ 6,000 | 395,200 \$-min | 62,000 \$-min 13.56% |

Figure 31 presents the CTP for the wait less scenario.



Figure 31: CTP for the wait less scenario.

5.2.4. Faster equipment: Use bigger and faster equipment.

This would increase the processing speed but also the cost rate of the activities. What if the company wanted to gain access to economies of scale by acquiring heavier, bigger and faster equipment? For this situation, we will assume that the processing times are cut in half (from 30 minutes to 15 minutes in total), and the waiting times will be kept constant. The activities will be charged at a higher rate. We then determine which rate would keep the bigger equal to the base case and find that rate to be \$286/minute (more than twice the base rate). **Table 16** summarizes these results.

Table 16: Results for faster equipment scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | Activity Cost Rate |
|------------------|------------|---------------|-----------|------------|----------------|--------------------|
| Faster Equipment | 85 min | 15 min | 70 min | \$ 7,290 | 457,200 \$-min | \$286/minute |

The CTP corresponding to this scenario is presented in **Figure 32**.

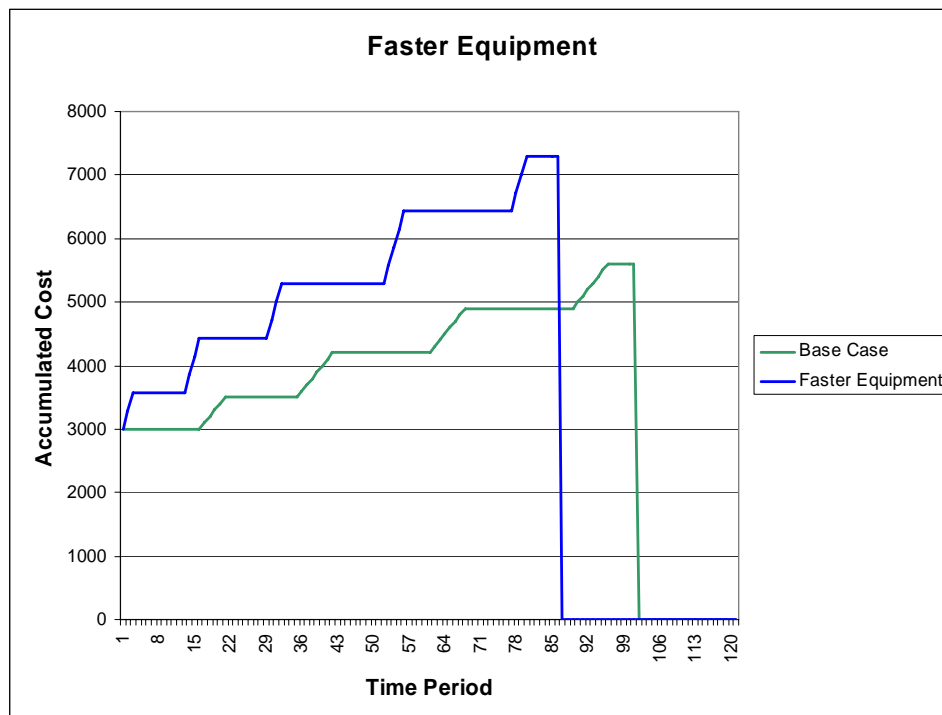


Figure 32: CTP for the faster equipment scenario.

The main pitfall of this scenario would be that balance between processing speed and activity cost rate needs to be such that the total cost of the new scenario remains constant or is reduced, to achieve real savings over the base case. The effect on the bottom line is not determined by total cost or Cost-Time Investment alone, rather the combined effect that both have on the direct cost calculation. So, a scenario will be attractive only if it improves the direct cost.

5.2.5. Cheap activities: Decrease the cost rate of the activities.

For this scenario the cost of the activities was reduced 20% (from \$100/min to \$80/min). This reduction can be obtained by several means, some nastier than others: Blind downsizing (less people to do the same job as before), implementation of “mistake-proofing” (changing the design of the product or the process) so the work can be done by operators with a lower skill level (and therefore, lower pay grade), use of temporary workers without access to full benefits. Also, cost reduction programs could have this effect (cutting corners in different places) and training programs to make the workforce more flexible would make possible for one operator to handle several machines (and operations) simultaneously instead of keeping the one to one relationship between people and machines. **Table 17** shows the summary of the results for this scenario.

Table 17: Results for cheap activities scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings |
|------------------|------------|---------------|-----------|------------|----------------|------------------------|
| Cheap Activities | 100 min | 30 min | 70 min | \$ 5,400 | 425,760 \$-min | 31,440 \$-min 6.87% |

The CTP corresponding to this scenario is presented in **Figure 33**.

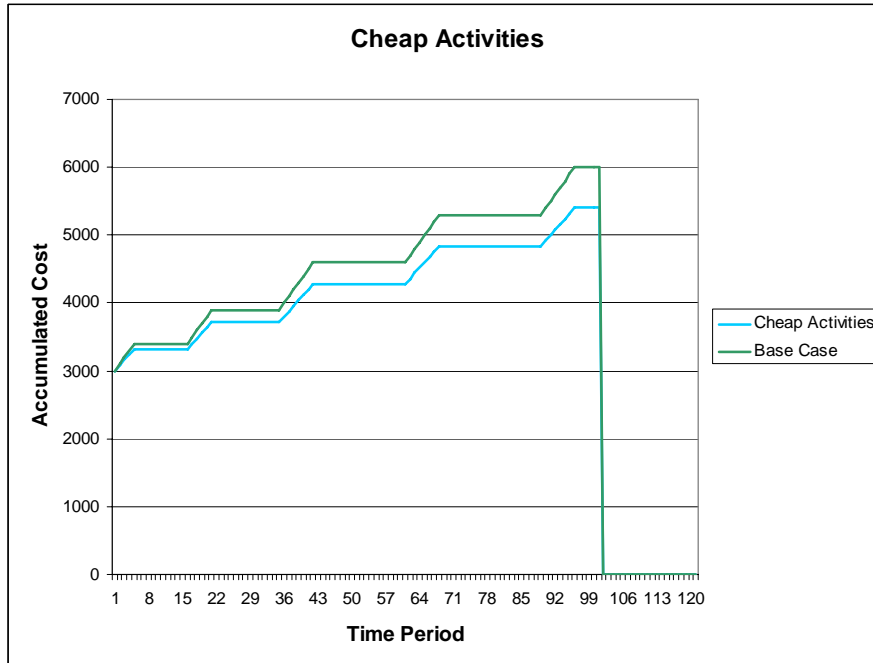


Figure 33: CTP for the cheap activities scenario.

5.2.6. Late activities: Spend less at the beginning and more at the end.

In this scenario, the activities are pushed to the late part of the process, to be made as late as possible. This scenario could correspond to the modularization of assembly operations. The net result over the base case will be that earlier activities cost less and later activities have higher cost rates. In this case, for illustrative purposes, the total amount of money spent was the same as in the base case, only the timing of the expenditures was changed.

Table 18: Results for late activities scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings |
|-----------------|------------|---------------|-----------|------------|----------------|-------------------------|
| Late Activities | 100 min | 30 min | 70 min | \$ 6,000 | 396,563 \$-min | 60,637 \$-min 13,26% |

The Cost Time Profile for this scenario is depicted in **Figure 34**.

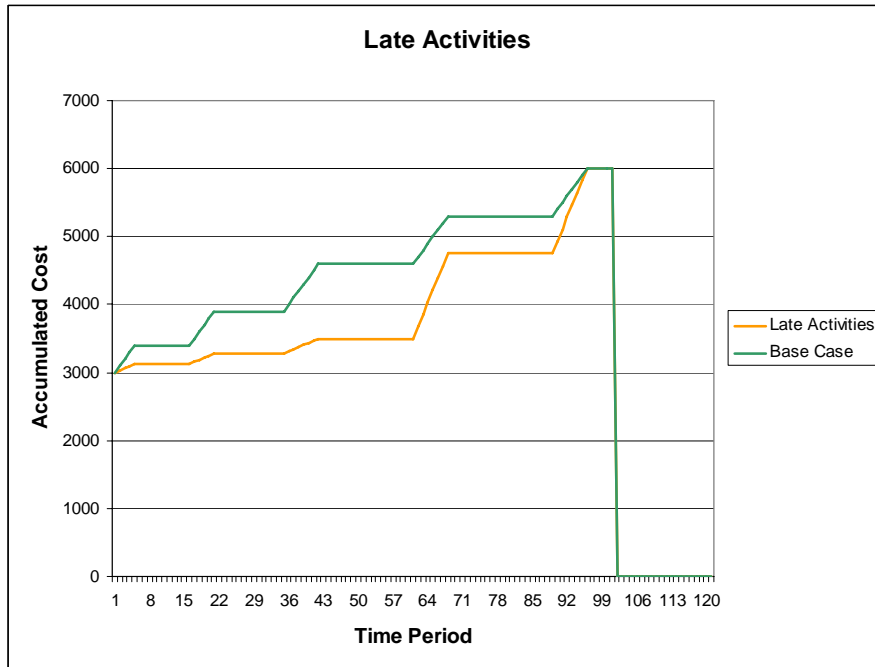


Figure 34: CTP for the late activities scenario

5.2.7. Slower but cheaper (A and B)

This scenario seems counterintuitive, but depending on the parameters of the specific production process, it could make sense. For example, in a die stamping operation increased speed means faster wear and tear of the dice and the machinery in general, bringing more frequent setups and downtime for maintenance and repairs. If the process was slowed down, the associated material and setup costs would also come down.

For experimentation purposes, the base case was modified so the total waiting time is the same (70 min), but the activity time was increased from 30 to 50 minutes. Therefore, the total time horizon is 120 minutes now. With this setup, the activity cost rate would need to go as low as \$30/min (from the original value of \$100/min) to keep the same CTI as in the base case. This scenario (**Slower cheaper A**) has the disadvantage of carrying the full cost of materials since the beginning of the first activity. What if we delivered the materials to each of the activities, just like the scenario JIT materials? How

low would need the activity cost rate to be in that case (to keep the same CTI as in the base case)? We'll call this Scenario **Slower cheaper B**.

As we see in **Table 19**, delivering the materials in this fashion would make an activity cost rate of \$74/min feasible (to keep the CTI at the base level). It does not sound too farfetched to go from \$100/min to \$74/min. This scenario (**Slower cheaper B**) would seem more feasible than **Slower cheaper A**.

Table 19: Results for slower cheaper scenarios

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | Activity Cost Rate |
|------------------|-------------------|----------------------|------------------|-------------------|----------------|---------------------------|
| Slower Cheaper A | 120 min | 50 min | 70 min | \$ 4,517 | 457,200 \$-min | \$30.36/min |
| Slower Cheaper B | 120 min | 50 min | 70 min | \$ 6,700 | 457,200 \$-min | \$74.02/min |

The CTPs for these two scenarios compared to the base case are presented in **Figure 35**.

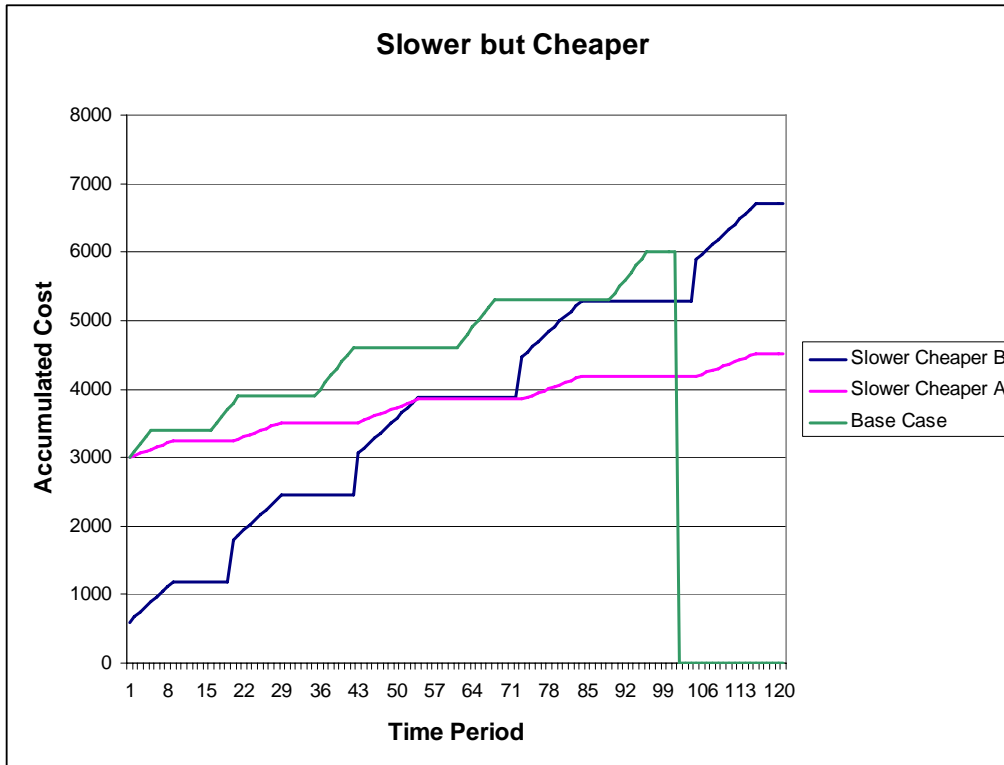


Figure 35: CTPs for the slower cheaper A and B scenarios.

5.2.8. Summary

In this specific case, the scenario with the larger savings was the JIT delivery of materials. However, it is impossible to generalize that this will be always true, because the impact of any change on the CTP depends on many factors. Among these we can mention the following:

- Timing, duration and cost rate of the activities.
- Time of delivery and amount of material expenditures.
- Timing and duration of the waits.
- The ratio of waiting time to activity time.
- The ratio of material cost to activity cost.

Table 20: Summary of the results of the different scenarios.

| Scenario | What was changed? | Results |
|----------------------|--|--|
| Less Materials | Spend 20% less on materials, still together at the beginning of the process. | 13.12% reduction on Total Investment. |
| JIT Materials | Deliver the materials at the beginning of each activity (JIT). | 25.32% reduction on Total Investment. |
| Wait Less | Reduce the waiting time by 20% | 13.52% reduction on Total Investment. |
| Faster Equipment | Use faster equipment, with higher cost rates and the same amount of waiting. | To keep the investment level constant, the activity cost rates needed can go from \$100/timeUnit to \$286/timeUnit. |
| Cheap Activities | Reduce the cost of the activities by 20% | 6.87% savings on Total Investment |
| Late Activities | Perform activities as late as possible, with lower (net) activity rates at the beginning and higher rates towards the end. | 13.26% reduction on Total Investment. |
| Slower But Cheaper A | Reduce the area by taking more time (66% more) but doing the activities cheaper. | To keep the investment level constant, the activity cost rates needed to go from \$100/min to \$30/min (a very steep decrease). |
| Slower But Cheaper B | Reduce the area by taking more time (66% more) but doing the activities cheaper plus deliver the materials JIT. | In this case, the activity cost rate only needed to go from \$100/min to \$74/min in order to keep the same level of Total Investment. |

5.3. Impact of a lean transformation on the Cost-Time Investment

5.3.1. Lean implementations

To discuss the effect of lean implementations and lean approaches, it is useful to consider an implementation framework. In our case, the framework presented in **Figure 36** will be used as a guide, with the observation that there are many feasible and valid approaches to lean implementations.

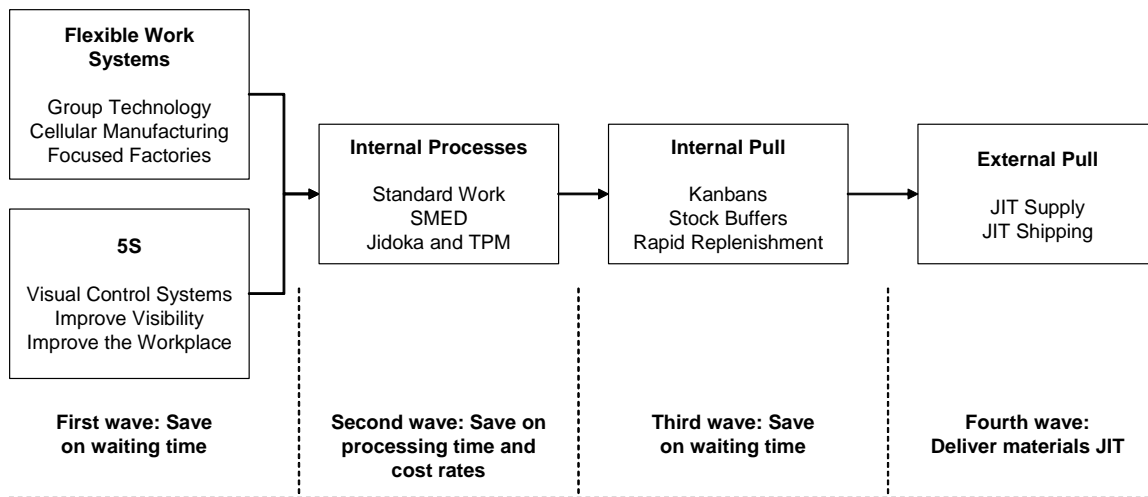


Figure 36: Waves of lean implementation.

This structure presents the logical phases of a lean implementation as “waves”. In these waves an evolutionary process occurs. Flexible work systems organize the manufacturing processes according to product families, while 5S and visual control systems improve on the organization of the workplace. Then the focus of the second wave is in the improvement of internal processes, and once those processes are improved the discipline of pull must be established (third wave). Finally, the company will be ready to establish ties and pull relationships forward and backward, with suppliers and customers (fourth wave).

Some of the more typical lean techniques were extracted, trying to highlight those tools that have a more visible impact on the Investment. These tools are those that reduce the waiting time, the processing time and the cost rates, and deliver the materials JIT at the moment and place where they are needed.

The “waves” are set up according to the type of savings the tools and techniques realize. These waves will also be used to show the improvement scenarios, which in this case will be cumulative (or “evolutionary”). This means that once a company improves

its processes using a set of tools, it creates a new baseline upon which the next wave of improvements will be constructed.

5.3.2. Scenario “First Wave”:

This scenario will be aimed at reducing the waiting time by dedicating groups of equipment to the production of specific families and coupling them more closely together. Ideas such as group technology, cellular manufacturing and focused factories will be applied to achieve this coupling.

Also, the application of 5S will decrease the waiting related to finding the tools for processing, straightening the equipment and supplies and in general being ready for work in a quicker manner, thus reducing the waiting time. In this first wave, we will assume a reduction of the waiting time by about 25%, going from 70 *minutes* to 52 *minutes*. The results are shown in **Table 21**.

Table 21: Results for First Wave Scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings |
|-----------------|-------------------|----------------------|------------------|-------------------|----------------|------------------------|
| First Wave | 82 min | 30 min | 52 min | \$ 6,000 | 370,900 \$-min | 86,300 \$-min 18.9% |

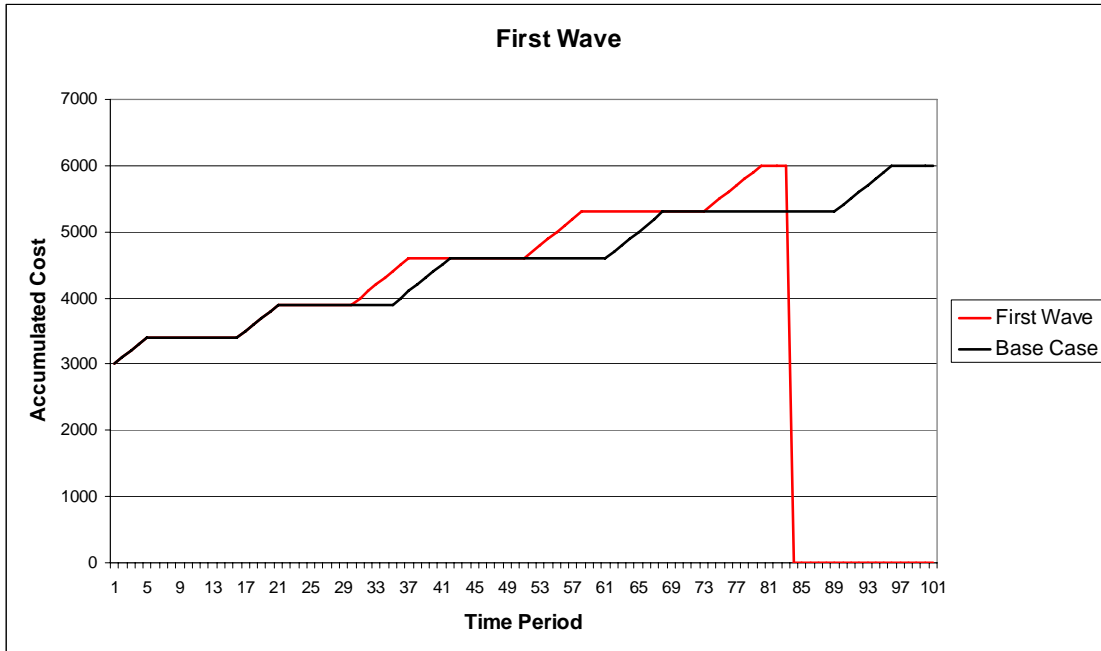


Figure 37: CTP of the First Wave scenario

5.3.3. Scenario “Second Wave”

This scenario will be implemented after First Wave, using it as a base point to improve further. In this case the improvement and standardization of internal processes is the main focus. Tools such as standard work (finding, documenting, disseminating and implementing best practices in the job), SMED (dramatically reducing the time consumed by changeovers and setups), Jidoka (a set of practices including automation and mistake-proofing designed to improve the quality of the process and the resulting products) and TPM (which increases the availability of machines therefore reducing the cost of maintenance) will be used to improve the processing times and practices, therefore reducing processing times and cost rates.

The operating assumptions for this scenario are a reduction of 10% for the activity cost rate and savings of 10% for the processing times. The results are shown in **Table 22**.

Table 22: Results for Second Wave scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings (From Previous Scenario) |
|-------------|------------|---------------|-----------|------------|----------------|---|
| Second Wave | 79 min | 27 min | 52 min | \$ 5,430 | 335,550 \$-min | 35,350 \$-min 9,53% |

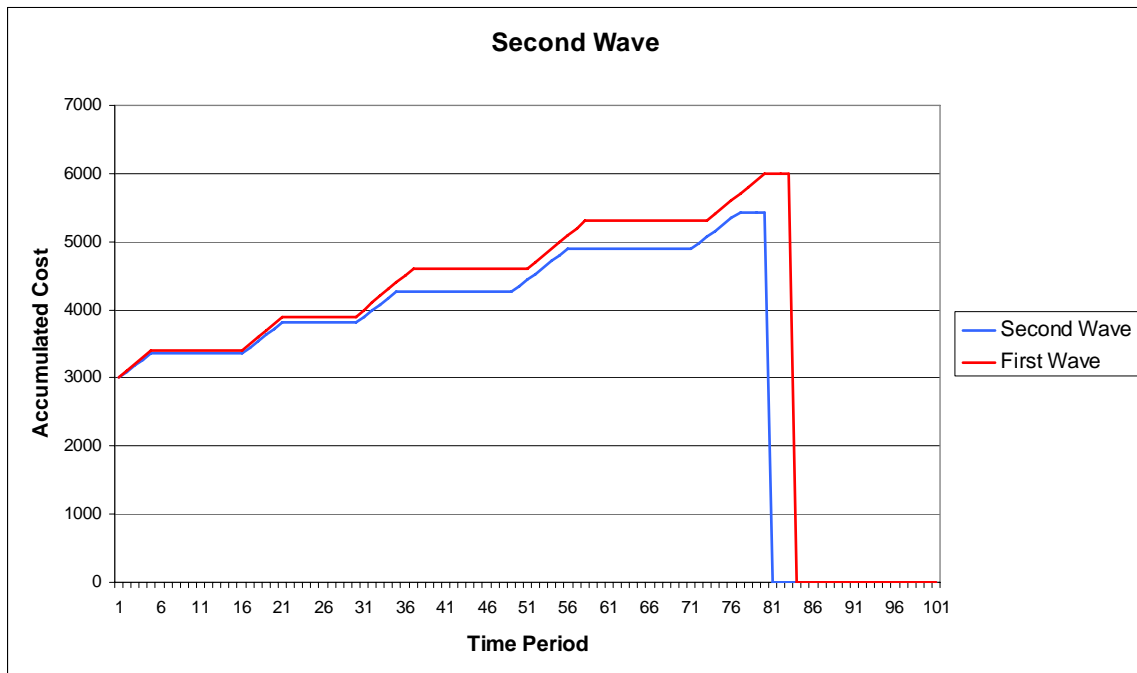


Figure 38: CTP for the Second Wave scenario.

5.3.4. Scenario “Third Wave”

For this scenario, another reduction on the waiting time is realized. The implementation of pull systems in the company should promote a further reduction on the waiting time. Now, there will be much less inventory lying around in the company between operations, and those WIP piles removed are exactly equivalent to the elimination of waiting time. Since the total waiting time is at 52 minutes, it will be decreased by another 18 minutes to drive it down to 34 minutes.

The results for this scenario are presented in **Table 23**.

Table 23: Results for Third Wave scenario

| Scenario | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings (From Previous Scenario) |
|------------|------------|---------------|-----------|------------|----------------|---|
| Third Wave | 61 min | 27 min | 34 min | \$ 5,430 | 255,180 \$-min | 80,370 \$-min 24% |

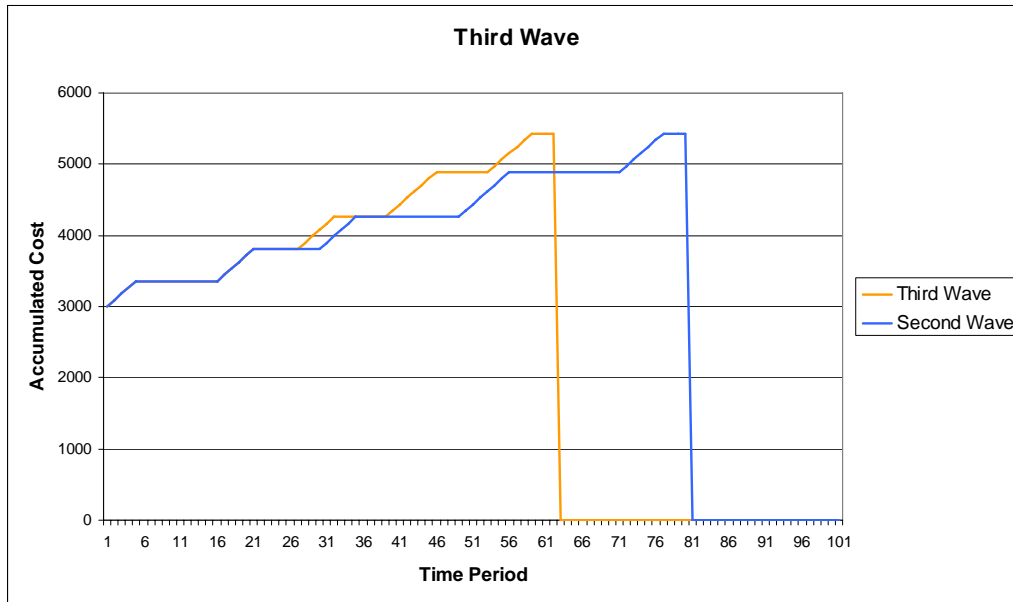


Figure 39: CTP for the Third Wave scenario

5.3.5. Scenario “Fourth Wave”

Once all the previous steps have been applied, the introduction of JIT practices will space better the delivery of materials to the process. Now, instead of receiving (and charging) all the materials together before the beginning of the production process, only the necessary materials are received exactly before the beginning of each activity.

As in the JIT materials scenario, the main assumption is that each of the five activities consumes 20% of all the cost of the materials. **Table 24** shows the results for this scenario.

Table 24: Results for Fourth Wave scenario

| <i>Scenario</i> | Total Time | Activity Time | Wait Time | Total Cost | CTI | CTI Savings (From Previous Scenario) |
|-----------------|------------|---------------|-----------|------------|----------------|---|
| Fourth Wave | 61 min | 27 min | 34 min | \$ 5,430 | 178,980 \$-min | 76,200 \$-min 30% |

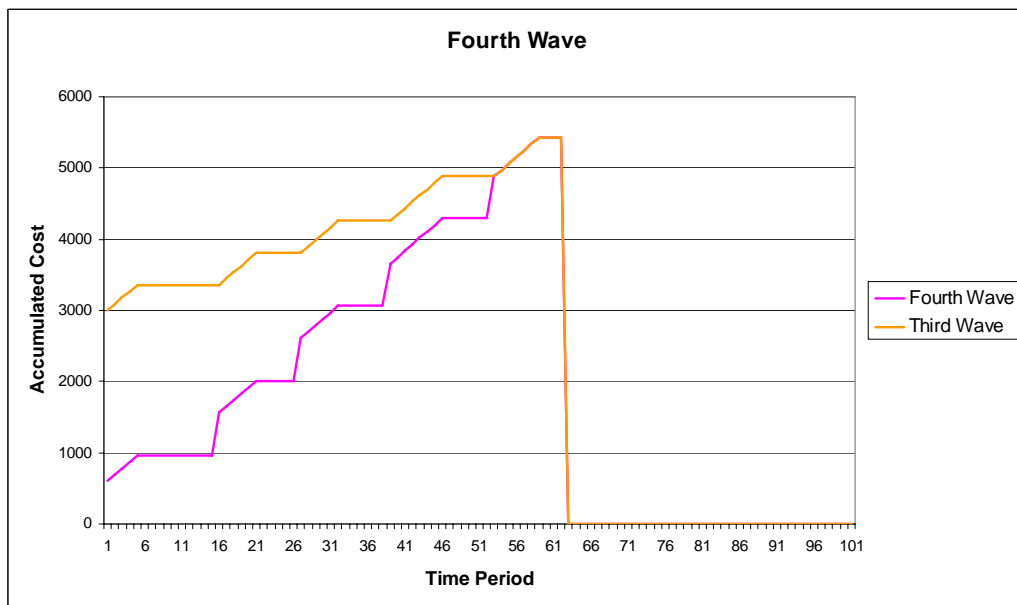


Figure 40: CTP of the Fourth Wave scenario.

In **Figure 41**, a comparative of all the improvement realized between the base case and the Fourth Wave is presented.

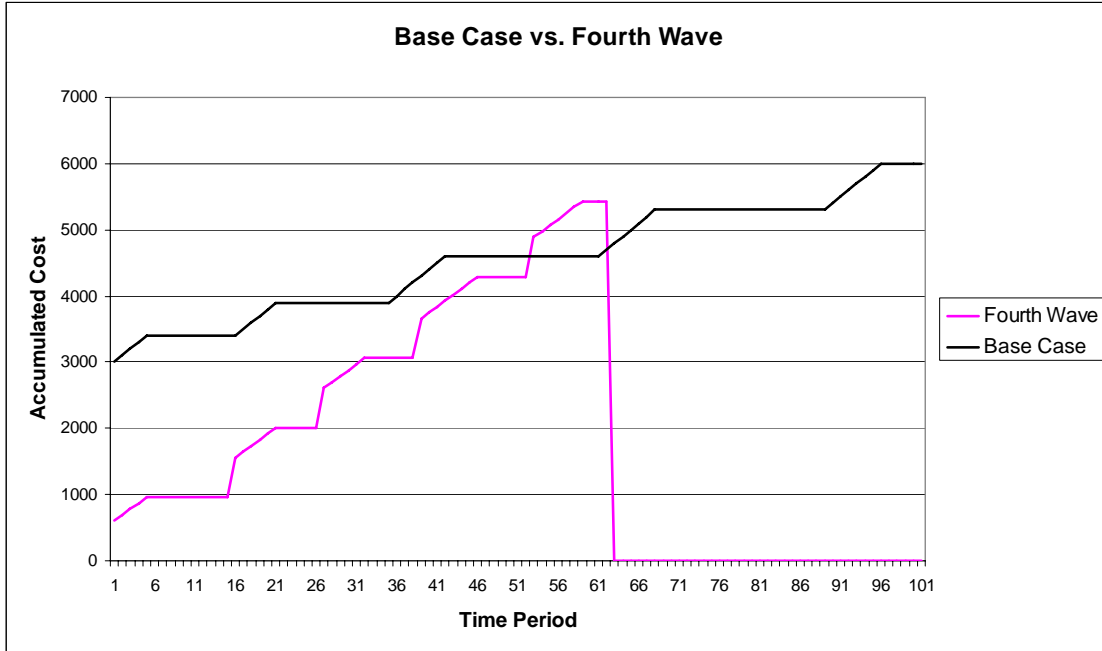


Figure 41: Accumulated improvement from the base case to the Fourth Wave.

Table 25: Summary of lean implementation scenarios

| Scenario | What was done? | Incremental Improvement | Cumulative Improvement |
|-------------|---|--------------------------|------------------------|
| | | (from previous scenario) | (from Base Case) |
| First Wave | Apply 5S and flexible work systems to reduce waiting time. | 18.75% | 18.75% |
| Second Wave | Apply tools for the improvement of internal processes (standard work, SMED, Jidoka and TPM). Reduce processing time and activity cost rates. | 9.45% | 26.43% |
| Third Wave | Apply internal pull mechanisms (kanbans and stock buffers to achieve rapid replenishment). Reduce waiting times further. | 23.74% | 43.90% |
| Fourth Wave | Connect to external entities through pull mechanisms (both with suppliers and customers). Use the customer pull to level the production through Heijunka. | 30.44% | 60.98% |

Table 25 shows that, for this case and with these specific numbers, the systematic and evolutionary application of lean principles would have a dramatic effect on the bottom line of the company. Applying modest improvements in every step (far from the 90% lead time reductions often observed in the documentation of successful cases) it was possible to achieve a 60% reduction on the investment required for manufacturing this hypothetical product.

These results seem to support the assertion that systematic, multi-factor approaches are more effective at reducing the investment than the application of single-factor techniques. Further research in this area should be conducted to learn if these results are of general occurrence or limited to special circumstances.

5.4. Simulation Studies

Arena 7.0 was used to develop and execute a couple of experiments modifying some parameters that have been previously mentioned as having an impact over the CTI. General purpose simulation packages (such as Arena or ProModel) can be used to build models that collect time and cost information (in fact, they have many pre-determined functions for cost and time statistics, although they did not have exactly what was needed to calculate the CTI for a product), and can be configured to track the CTI for each individual unit of product. An example was used to try and confirm some of the assumptions that have been posed about the impact of batching, information exchange mechanisms and waits on the CTI, but now instead of following a single unit of product through the process, the simulation is configured and let run, and CTI values are collected from all the units that flow through the process. In the following subsections we will explain the characteristics of the system that was modeled, the structure of the model itself and the results obtained when different model parameters are changed.

5.4.1. Model Configuration

Figure 42 presents the configuration of the model. It is a manufacturing process with a core company and two suppliers, where the core company sends information (orders) to Supplier 2 and orders plus materials to Supplier 1. The SIMAN code that underlies the graphical interface of the model is presented in **Appendix B**.

All the information about the activities and resources that is required to build the IE-CTP is presented in **Table 26**. We will use all this information to configure the model in Arena.

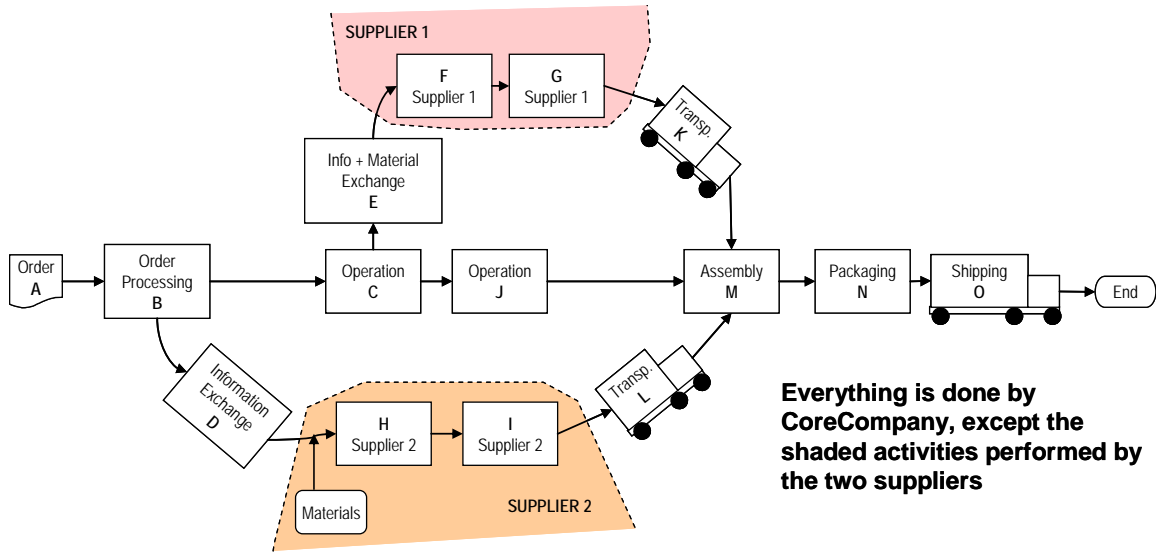


Figure 42: Structure of the manufacturing process

Table 26: Activity and Resource Data for the numerical example

| Activity ID | Activity Description | Predecessors | Company | Materials | Resources | Duration | Cost Rate |
|-------------|--------------------------|--------------|------------|-----------|-----------|----------|-----------|
| A | Reception of an order | - | CORE | | RES1 | 10 | 0.02778 |
| B | Order Processing | A | CORE | | RES2 | 40 | 0.03356 |
| C | Operation C | B | CORE | 2 | RES3 | 50 | 0.38194 |
| D | Information Exchange | B | CORE | | RES4 | 70 | 0.03356 |
| E | Info + Material Exchange | C | CORE | 1 | RES13 | 20 | 0.03356 |
| F | F-Supplier 1 | E | Supplier 1 | | RES9 | 40 | 1.21528 |
| G | G-Supplier 1 | F | Supplier 1 | | RES10 | 80 | 0.97222 |
| H | H-Supplier 2 | D | Supplier 2 | 7 | RES11 | 10 | 0.41667 |
| I | I-Supplier 2 | H | Supplier 2 | | RES12 | 60 | 0.13889 |
| J | Operation J | C | CORE | | RES5 | 30 | 0.22222 |
| K | Transportation K | G | CORE | 10 | | 90 | |
| L | Transportation L | I | CORE | 10 | | 150 | |
| M | Assembly M | J, K, L | CORE | | RES6 | 90 | 0.10417 |
| N | Packaging N | M | CORE | 15 | RES7 | 50 | 0.13889 |
| O | Shipping O | P | CORE | | RES8 | 10 | 0.27778 |
| P | Finished Goods Storage | N | CORE | | | 2400 | |

| Resource ID | Resource Description | Cost Rate |
|-------------|----------------------|-----------|
| RES1 | Computer 1 | 0.02778 |
| RES2 | Computer 2 | 0.03356 |
| RES3 | Milling Machine | 0.38194 |
| RES4 | Computer 3 | 0.03356 |
| RES5 | Lathe | 0.22222 |
| RES6 | Assembly table | 0.10417 |
| RES7 | Pallet Wrapper | 0.13889 |
| RES8 | Shipping equipment | 0.27778 |
| RES9 | CNC Machine - S1 | 1.21528 |
| RES10 | CNC 2 - S2 | 0.97222 |
| RES11 | Turning equipment | 0.41667 |
| RES12 | Welding equipment | 0.13889 |
| RES13 | Computer 4 | 0.03356 |

| Company ID | Description | % Overhead | % Profit | Interest Rate |
|------------|--------------|------------|----------|---------------|
| CORE | Core Company | 0.3 | 0.15 | 0.00001 |
| Supplier1 | Supplier 1 | 0.35 | 0.25 | 0.00001 |
| Supplier2 | Supplier 2 | 0.4 | 0.3 | 0.00001 |

To build a model like this in Arena, it is necessary to use the modules provided by the package. Arena uses very purpose-specific modules, so the sole processing modules are not enough to gather the necessary time information.

For example, the *Process* module can only include information related to the processing of the entity, but not assignment of attributes or variables, so it is necessary to add *Assignment* modules with this purpose. Also, the processing modules do not control divergence and convergence of entities in the flow of the process, so *Batch* and *Separate* modules are used. The image of the basic model is presented in **Figure 43**, although it will probably be too small to be readable, but in the electronic file it can be zoomed in to 500% to read the names of the modules.

The information that is required to build an IE-CTP, and how it was gathered in Arena are presented in the following points:

- ***Activity cost rates and materials:*** At the beginning of the model, there is a module (*After_Arrival*) that assigns values to many important variables (the same for every entity) and attributes (different value for each entity). In this module we assign the values of all the resource cost rates (which, in this model correspond to the activity cost rates since the activities are only using resources and not operators) and the materials that are released to the process by the different activities. This way, every time we use them in the process we only have to reference them by name, and if they ever change, it is only necessary to change them in one place in the model, not every time they appear.
- ***Finishing time for each activity:*** Right after each activity there is an Assignment module that assigns an attribute for the entity with the name “*T_end_Activity*”, in which each entity records the finishing time for each activity in its process.

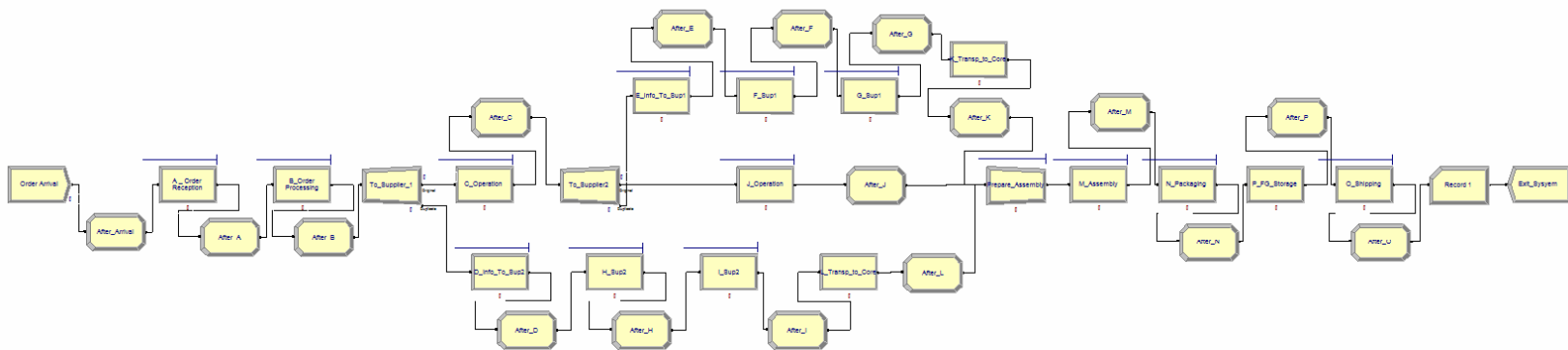


Figure 43: Overview image of the simulation model in Arena (Zoom to 500% for details)

- **Beginning time for each activity:** This was a little more complicated, because if we register the time when the entity enters the Process box of an activity, that would include the time spent in queue, and for us that is not part of the time of the activity, it is a wait. Therefore, a Hold module was placed before the activities, specifying that it would only release entities to the activity when the state of its resource was equal to “idle”. After the entity was released to enter the activity (Process) module, the Assignment module (Before_J) will assign the attribute T_{start_J} to the entity. Some more details of this configuration are shown in **Figures 44** and **45**.

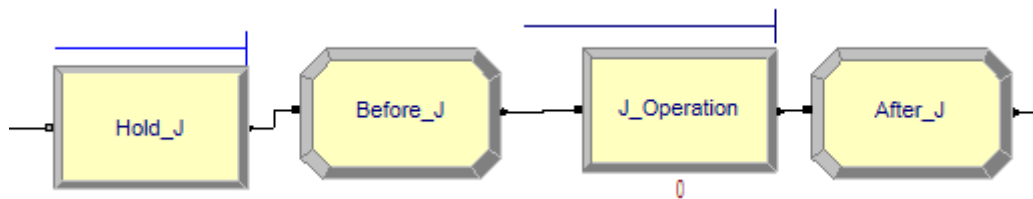


Figure 44: Hold and Assignment modules before operation J

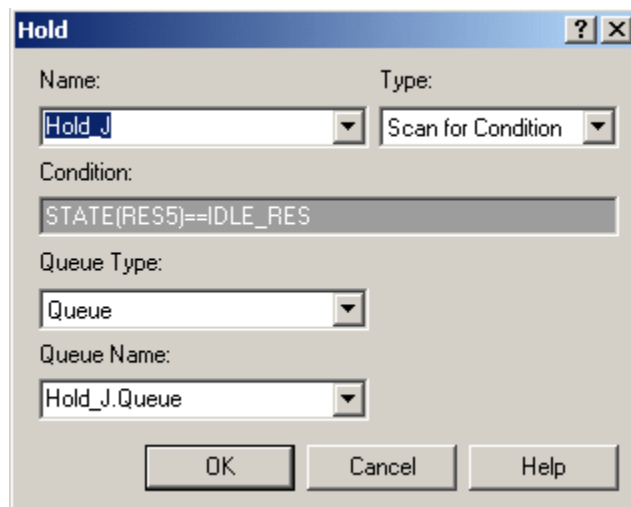


Figure 45: Configuration of the Hold module in Arena

- **CTI calculation for each entity:** For this, an expression had to be built to account for the contribution of each activity to the CTI, and using the variables and attributes calculate the CTI for each entity that passed through the system. Arena has multiple built-in functions to handle cost and time,

however, none of them provided the exact functionality that was required for the CTI, and therefore a very big expression had to be built. **Figure 46** presents a transcription of the CTI expression for each individual entity.

$$\begin{aligned}
 & (T_end_O - T_end_A) * (RES1_CR * (T_end_A - T_start_A)) + (RES1_CR * (T_end_A - \\
 & T_start_A) ** 2) / 2 + (T_end_O - T_end_B) * (RES2_CR * (T_end_B - \\
 & T_start_B)) + (RES2_CR * (T_end_B - T_start_B) ** 2) / 2 + (T_end_O - \\
 & T_end_C) * (RES3_CR * (T_end_C - T_start_C) + MAT_C) + MAT_C * (T_end_C - \\
 & T_start_C) + (RES3_CR * (T_end_C - T_start_C) ** 2) / 2 + (T_end_O - \\
 & T_end_D) * (RES4_CR * (T_end_D - T_start_D)) + (RES4_CR * (T_end_D - \\
 & T_start_D) ** 2) / 2 + (T_end_O - T_end_E) * (RES13_CR * (T_end_E - \\
 & T_start_E) + MAT_E) + MAT_E * (T_end_E - T_start_E) + (RES13_CR * (T_end_E - \\
 & T_start_E) ** 2) / 2 + (T_end_O - T_end_J) * (RES5_CR * (T_end_J - T_start_J)) + \\
 & (RES5_CR * (T_end_J - T_start_J) ** 2) / 2 + (T_end_O - \\
 & T_end_M) * (RES6_CR * (T_end_M - T_start_M)) + (RES6_CR * (T_end_M - \\
 & T_start_M) ** 2) / 2 + (T_end_O - T_end_N) * (RES7_CR * (T_end_N - \\
 & T_start_N) + MAT_N) + MAT_N * (T_end_N - T_start_N) + (RES7_CR * (T_end_N - \\
 & T_start_N) ** 2) / 2 + (RES8_CR * (T_end_O - T_start_O) ** 2) / 2 + (T_end_O - \\
 & T_end_F) * (RES9_CR * (T_end_F - T_start_F)) + ((RES9_CR * (T_end_F - \\
 & T_start_F) ** 2) / 2) + (T_end_O - T_end_G) * (RES10_CR * (T_end_G - \\
 & T_start_G)) + ((RES10_CR * (T_end_G - T_start_G) ** 2) / 2) + (T_end_O - \\
 & T_end_K) * TRANSP_K + (T_end_O - T_end_H) * (RES12_CR * (T_end_H - \\
 & T_start_H) + MAT_H) + MAT_H * (T_end_H - T_start_H) + (RES12_CR * (T_end_H - \\
 & T_start_H) ** 2) / 2 + (T_end_O - T_end_I) * (RES5_CR * (T_end_I - \\
 & T_start_I)) + ((RES5_CR * (T_end_I - T_start_I) ** 2) / 2) + (T_end_O - \\
 & T_end_L) * TRANSP_L
 \end{aligned}$$

Figure 46: Transcription of the expression for CTI for each individual entity.

This expression, along with the finishing time of the project (T_end_O) are both calculated in a module called “After O”, as it is shown in **Figure 47**. The module “Cost_Time_Investment” gathers the value of the CTI for each individual unit..

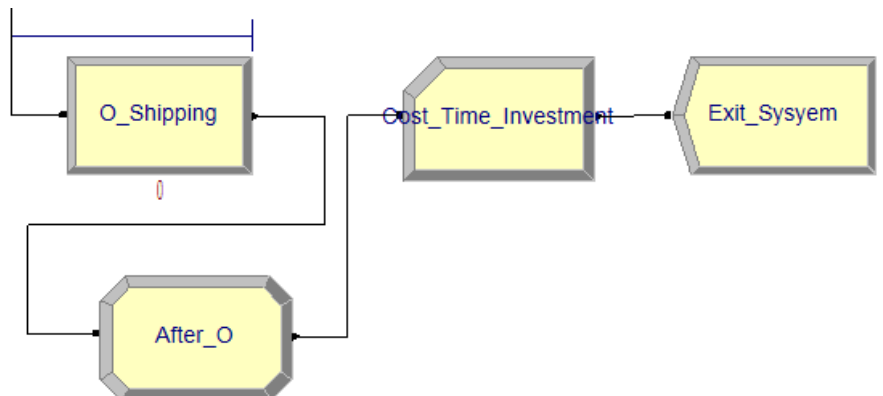


Figure 47: Assignment and Data collection modules at the end of the process

5.4.2. Variations of the model

As it was mentioned above, several variations of the model were used to check for the impact of some system variables on the CTI. The general Run Setup was kept the same for all the configurations, as it can be seen in **Figure 48**.

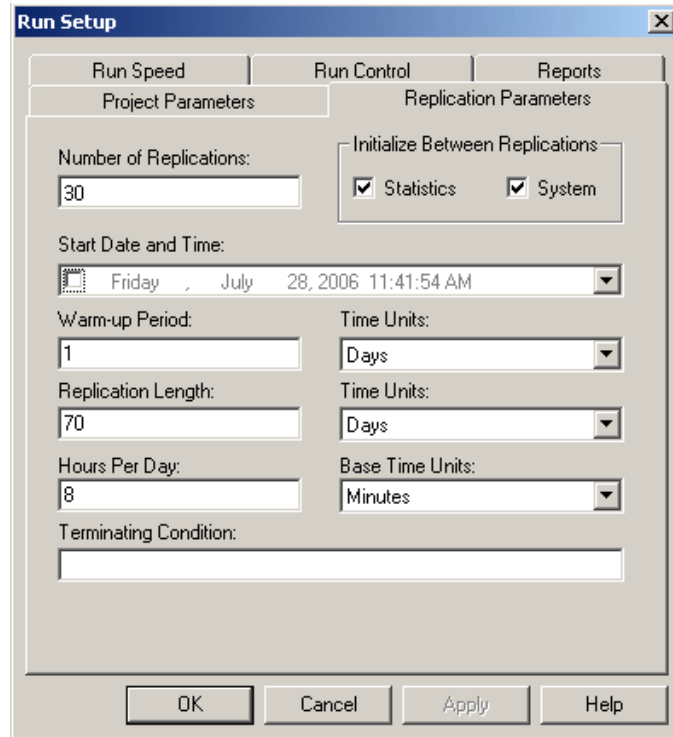


Figure 48: Run Setup for the Arena models

- The first variation was to *change the speed of the information exchange mechanisms*. This will affect activities D and E, and the changes are summarized in **Table 27**.

Table 27: Changes in activities E and D

| Parameter | Activity D | Activity E |
|---------------|------------------|------------------|
| Old Time | Normal (70, 3) | Normal (20, 4) |
| New Time | Normal (5, 0.01) | Normal (5, 0.01) |
| Resource | RES_4 | RES_13 |
| Old Cost Rate | 2.0136 | 2.0136 |
| New Cost Rate | 0.6 | 0.6 |

These changes intend to simulate the difference from a fax-based ordering system to an EDI based system. In the first case, it took 20 and 70 minutes (respectively) to execute the whole ordering operation. In the second case this time went down to five minutes for both operations and the standard deviation is proportionally much smaller, reflecting the fact that an electronic process will probably be more consistent in its execution time than a human-based ordering process. It would be expected that the CTI of the products went down, because there is now an activity being performed faster and at a much smaller cost rate. Results for all the variations of the model will be summarized and discussed after the presentation of all of the variations.

- The second variation was to *change the time the finished goods stay in inventory*. The original model assumed a stay in finished inventory of five days (2400 minutes), and for this variation of the model this time was reduced to one day (40 minutes).
- The third variation was to *batch units before shipping*, to reflect a more realistic way of shipping units when the process has finished. It would not be very practical to ship units one at a time; therefore this variation has practical interest. Two options were explored: Ship out when five units are gathered and ship out when 20 units are ready to go.
- The last variation was to *batch before transportation back to the core company (before K and L)*. In this case we are applying the same logic to the transportation between the suppliers and the core company, transporting units only when there are five or 20 units gathered and ready to be transported. This configuration can be observed in **Figure 49**.

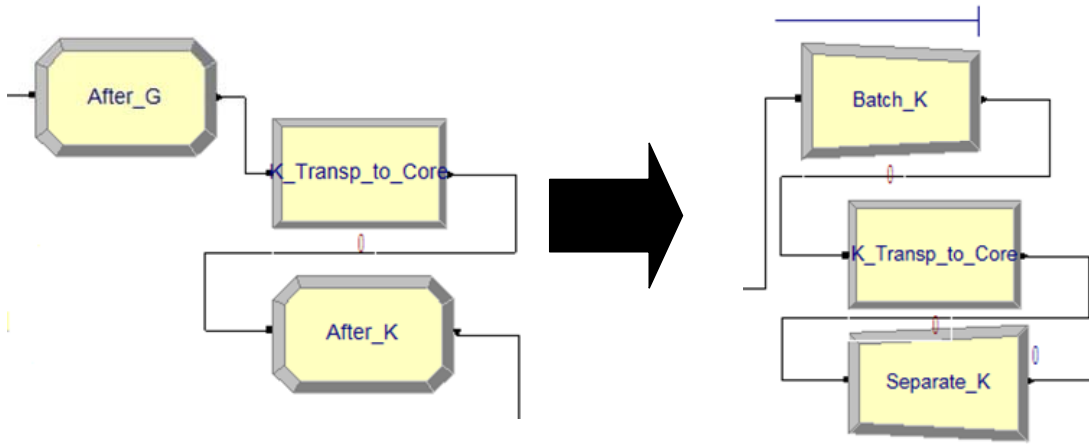


Figure 49: Batch for transportation

5.4.3. Simulation Results

Table 28 presents the results of the simulations for the CTI values.

Table 28: Simulation results

| Replication | Base Model Average CTP | Electronic Info Average CTP | Finished Goods Shorter Average CTP | Batch Before Shipping - 5 Average CTP | Batch Before Shipping - 20 Average CTP | Batch Transportation 05 Average CTP | Batch Transportation 20 Average CTP |
|-------------|---------------------------|--------------------------------|--|---|--|---|---|
| 1 | 50,809,408 | 50,557,753 | 46,824,884 | 60,984,050 | 61,963,570 | 51,100,600 | 52,582,386 |
| 2 | 50,861,341 | 50,659,482 | 46,890,656 | 60,852,220 | 61,677,080 | 51,134,440 | 52,613,948 |
| 3 | 50,902,656 | 50,671,996 | 46,906,820 | 60,729,200 | 61,457,840 | 51,145,703 | 52,643,979 |
| 4 | 50,921,843 | 50,679,506 | 46,912,306 | 60,707,470 | 61,338,280 | 51,232,616 | 52,660,761 |
| 5 | 50,966,589 | 50,696,650 | 46,976,468 | 60,541,210 | 61,264,380 | 51,267,462 | 52,671,202 |
| 6 | 50,990,416 | 50,698,583 | 46,976,984 | 60,491,170 | 61,053,250 | 51,327,728 | 52,686,985 |
| 7 | 51,008,988 | 50,703,169 | 47,038,890 | 60,471,830 | 60,797,410 | 51,327,767 | 52,698,406 |
| 8 | 51,011,425 | 50,705,628 | 47,094,600 | 60,270,490 | 60,698,400 | 51,336,203 | 52,721,841 |
| 9 | 51,029,862 | 50,727,220 | 47,146,708 | 60,125,020 | 60,185,060 | 51,395,158 | 52,730,462 |
| 10 | 51,045,086 | 50,743,732 | 47,167,243 | 60,042,080 | 60,170,460 | 51,396,671 | 52,752,338 |
| 11 | 51,047,943 | 50,746,234 | 47,178,372 | 59,872,280 | 60,073,440 | 51,402,091 | 52,754,089 |
| 12 | 51,050,416 | 50,761,431 | 47,197,844 | 59,785,160 | 60,054,820 | 51,407,211 | 52,760,370 |
| 13 | 51,065,738 | 50,798,943 | 47,203,936 | 59,675,240 | 59,836,290 | 51,428,101 | 52,767,149 |
| 14 | 51,081,534 | 50,804,776 | 47,221,055 | 59,561,400 | 59,616,960 | 51,438,302 | 52,771,273 |
| 15 | 51,093,966 | 50,806,384 | 47,222,439 | 59,295,980 | 59,567,460 | 51,442,936 | 52,786,183 |
| 16 | 51,117,351 | 50,825,393 | 47,223,447 | 59,129,640 | 59,505,330 | 51,444,938 | 52,786,762 |
| 17 | 51,124,800 | 50,842,695 | 47,267,914 | 58,947,640 | 59,370,400 | 51,453,122 | 52,788,091 |
| 18 | 51,136,110 | 50,905,343 | 47,354,188 | 58,846,120 | 59,292,440 | 51,484,207 | 52,788,118 |
| 19 | 51,166,352 | 50,916,591 | 47,375,038 | 58,597,620 | 59,233,600 | 51,487,446 | 52,796,304 |
| 20 | 51,200,481 | 50,920,200 | 47,378,721 | 58,175,710 | 59,137,880 | 51,504,503 | 52,840,336 |
| 21 | 51,246,359 | 50,930,377 | 47,394,125 | 57,984,500 | 58,686,020 | 51,517,459 | 52,858,350 |
| 22 | 51,264,118 | 50,946,563 | 47,415,928 | 57,807,830 | 58,557,360 | 51,527,414 | 52,871,049 |
| 23 | 51,292,574 | 50,968,242 | 47,456,613 | 57,775,870 | 58,452,920 | 51,564,079 | 52,880,635 |
| 24 | 51,320,800 | 50,971,920 | 47,500,336 | 56,894,940 | 57,958,000 | 51,567,269 | 52,884,393 |
| 25 | 51,341,369 | 50,972,576 | 47,532,533 | 56,824,530 | 57,948,980 | 51,623,311 | 52,909,759 |
| 26 | 51,414,130 | 50,973,279 | 47,537,047 | 56,441,600 | 57,701,790 | 51,636,694 | 52,924,702 |
| 27 | 51,434,180 | 50,997,434 | 47,574,416 | 56,324,040 | 57,657,270 | 51,676,237 | 52,935,830 |
| 28 | 51,516,158 | 51,024,041 | 47,602,476 | 55,657,530 | 57,379,870 | 51,714,872 | 52,966,570 |
| 29 | 51,607,435 | 51,056,265 | 47,849,085 | 54,443,270 | 57,281,530 | 51,949,599 | 53,060,659 |
| 30 | 51,945,491 | 51,072,259 | 47,985,222 | 54,115,870 | 56,984,680 | 52,025,417 | 53,079,185 |
| Mean | 51,167,163.97 | 50,836,155.50 | 47,280,209.80 | 58,712,383.67 | 59,496,759.00 | 51,465,318.53 | 52,799,070.50 |
| Max | 51,945,491.00 | 51,072,259.00 | 47,985,222.00 | 60,984,050.00 | 61,963,570.00 | 52,025,417.00 | 53,079,185.00 |
| Min | 50,809,408.00 | 50,557,753.00 | 46,824,884.00 | 54,115,870.00 | 56,984,680.00 | 51,100,600.00 | 52,582,386.00 |
| Std. Dev. | 242,288.29 | 137,589.79 | 278,564.72 | 1,923,129.78 | 1,419,304.86 | 207,705.04 | 121,513.99 |

The results behaved as it would have been expected. The base case has an average CTI (over 30 replications) of 51,167,163 \$-min. When the *electronic information exchange* was used, the average CTI went down to 50,836,155 \$-min, which is not a really big difference. This means that for this example, the time and cost savings realized by changing to an automated information exchange system were very small, almost negligible. This will be commented on the next paragraph.

When the time spent in *finished goods storage* went down from five days to only one day, the impact was more noticeable. This is because the amount of time originally spent in storage is a larger proportion of the total time than the time spent by information exchange mechanisms. This shorter stay brought the CTI down to 47,280,209 \$-min, which represent bigger savings than the previous model variation.

Batching before shipping proved to be the largest increase in the CTI, which was expected also, because any additional waits towards the end of the process cause longer delays with high accumulated costs, therefore incrementing the CTI noticeably. Batching five units before shipping took the average CTI to 58,712,383 \$-min, and batching 20 units brought it to 59,496,759 \$-min. These are the highest average CTI values recorded in the different variations that were tried. In contrast, when *batching before transportation*, the batching occurs at a much earlier stage in the process, so less cost has been accumulated and the forecasted result would be that the impact on the average CTI would be less noticeable, as indeed it was. When five units are batched the average CTI went to 51,465,318 \$-min (which is not very far from the CTI for the base case) and when 20 units are batched the average CTI was 52,799,070 \$-min.

Clearly, simulation models can be used to evaluate the impact that changes in the parameters or configuration of the production process will have over the average CTI of the products. Conditions such as large quantities of products, variability in the production times and the natural behavior of units in the process when batching or congestion occur are more easily evaluated using simulation than other tools. However, it can also be a cumbersome and complex process, given that the general purpose simulation packages

are very flexible and customizable, but they do not include CTI-friendly built in functions. In the following section a CTP-specific software tool is presented.

5.5. Software Tool: Cost-Time Profiler

An IE-CTP specific tool was developed to facilitate data capture, calculations and graphic output of CTP and IE-CTP projects. This software tool was developed in a CHPM (Center for High Performance Manufacturing) center designated project. Originally its scope was only to develop single-enterprise CTPs, but given its relationship with this research and the possibility to extend the concepts and its operation it was extended to include the inter-enterprise situation.

The tool was originally coded in Java, and then for the development of the Graphical User Interface (GUI) it was migrated and completed using the Microsoft .NET Framework 2.0. The author of this Dissertation developed all the logic and basic Java functionality, and external assistance was obtained for the GUI development. In the next two subsections we will present two example projects implemented on the Cost-Time Profiler, especially to present screenshots that illustrate the navigation of the user through the tool.

5.5.1. Single-Enterprise Example

Figure 50 presents a simple production process occurring in a single enterprise.

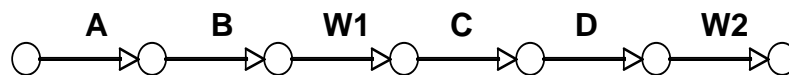


Figure 50: Simple linear production process.

We will now follow its implementation in the Cost-Time Profiler. The first thing that appears when the Cost-Time Profiler is activated is a welcome screen, with information related to CHPM and the project team (**Figure 51**).



Figure 51: Welcome screen of the Cost-Time Profiler

When the “OK” button is hit to continue, the main interface is presented. At this point the user needs to go to the “File” menu to choose between creating a new project or opening an existing one (**Figure 52**)

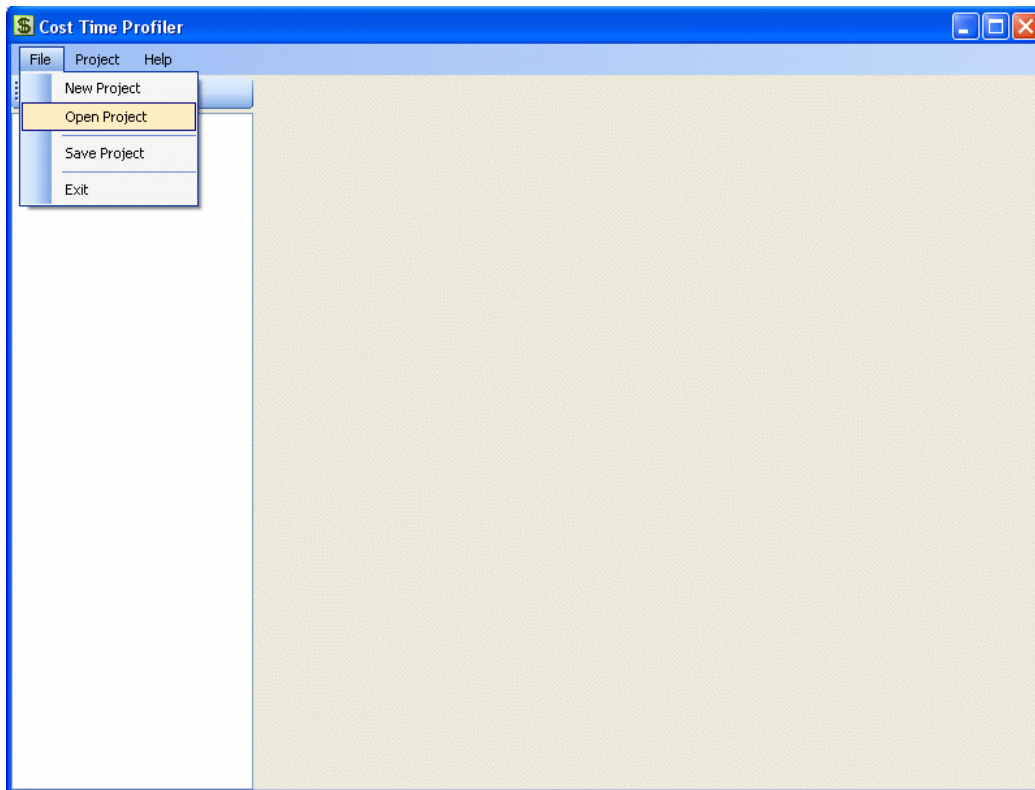


Figure 52: Project selection menu in Cost-Time Profiler

For this example, we will select an existing project (model1.ctp, **Figure 53**).

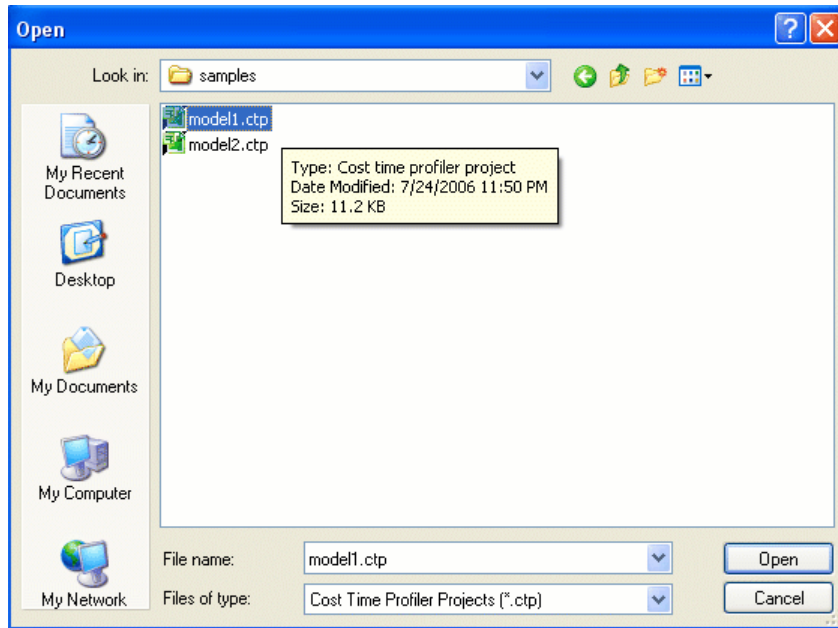


Figure 53: Select an existing project

After opening a project, the user sees the following interface (**Figure 54**).

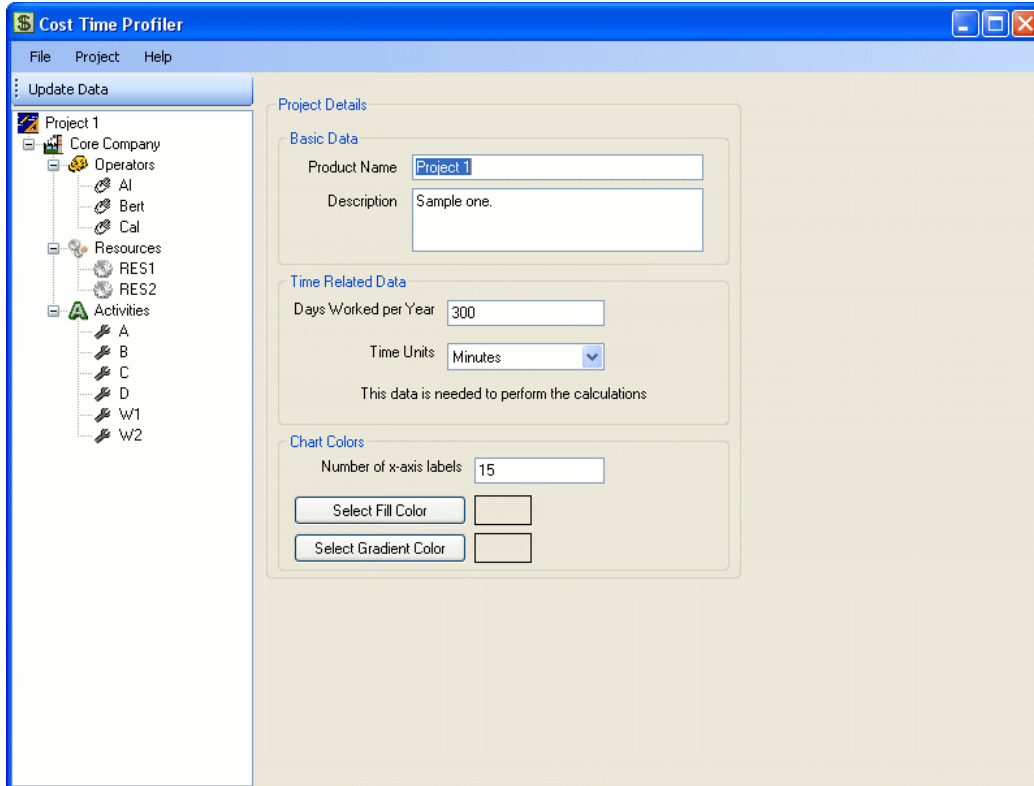


Figure 54: Project details

If the user clicks on Project, he will see the screen presented in the previous figure. In this screen the user will enter general information about the project that will apply to the project as a whole, including all participating companies.

Then, a default company is created. There must be at least one company, and it is created with the templates to enter information about its activities, operators and resources (**Figure 55**).

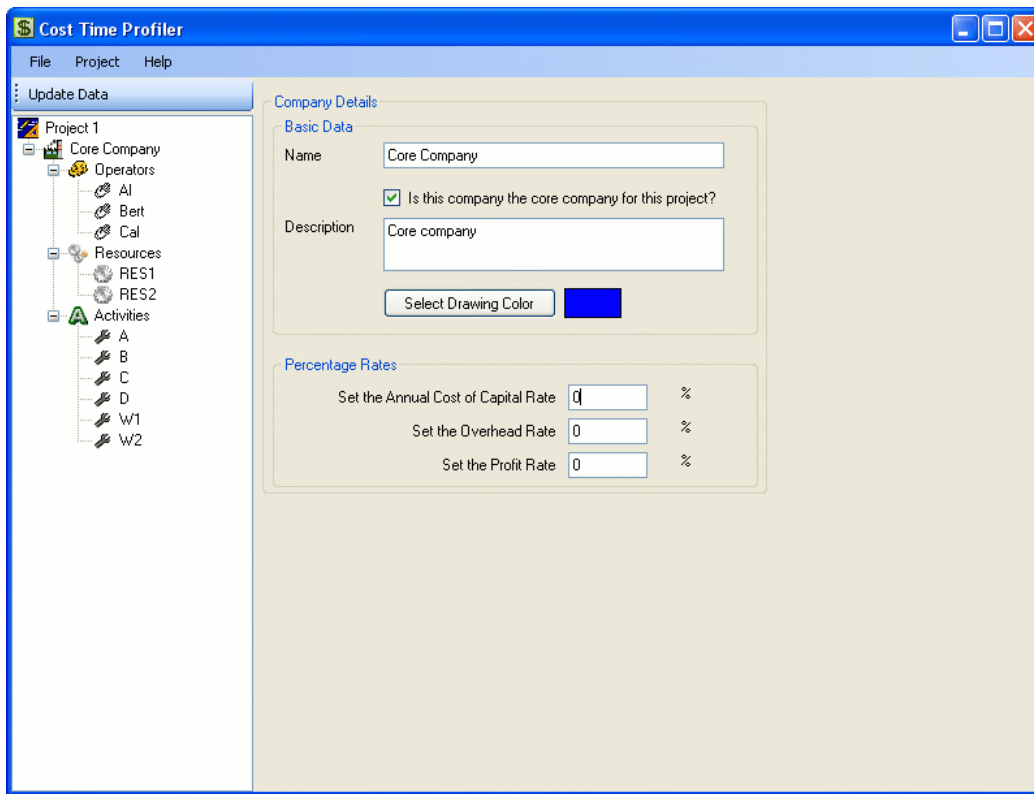


Figure 55: Company details

The existing project, *modell.ctp*, has one company, three operators, two resources and six activities. **Figure 56** presents the information form for activities. It can be observed that in this form we can associate operators, resources and predecessors to the activity in the form.

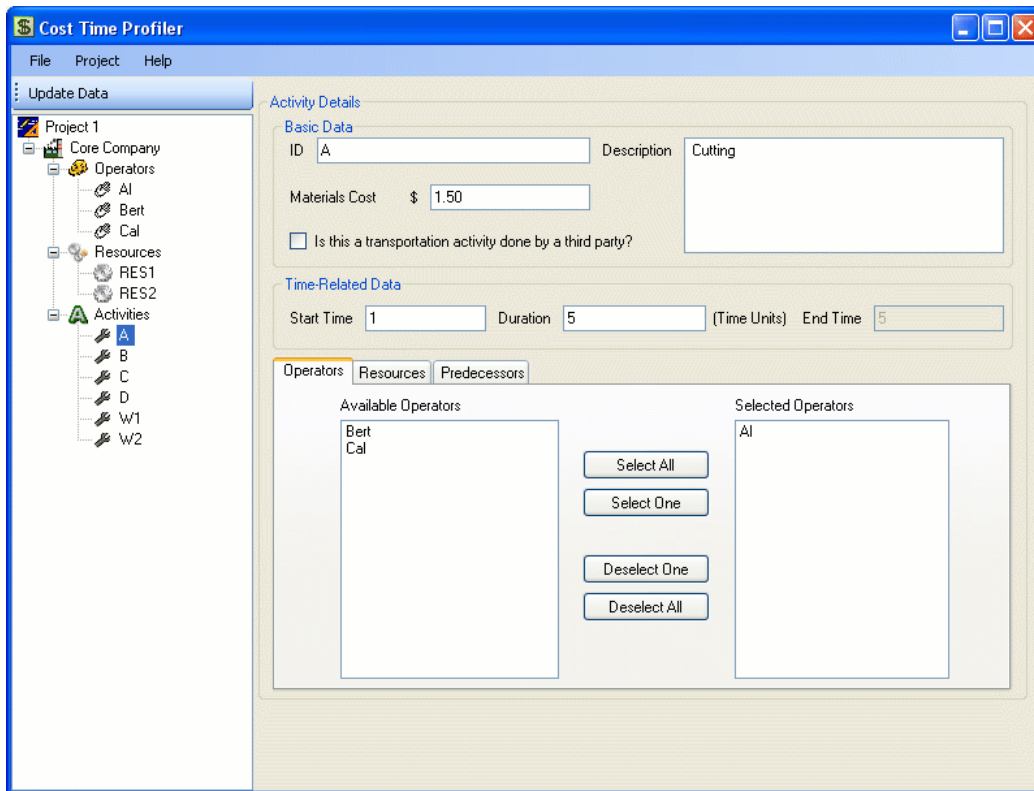


Figure 56: Activity details

Figure 57 presents the details for an operator.

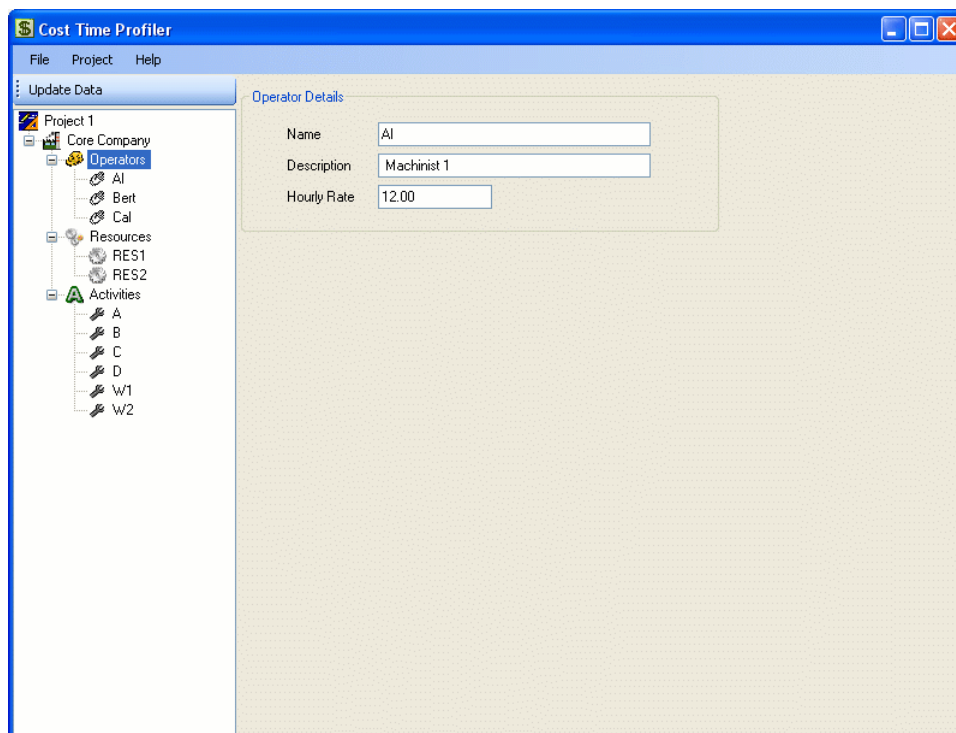


Figure 57: Operator details

And **Figure 58** shows the details for a Resource.

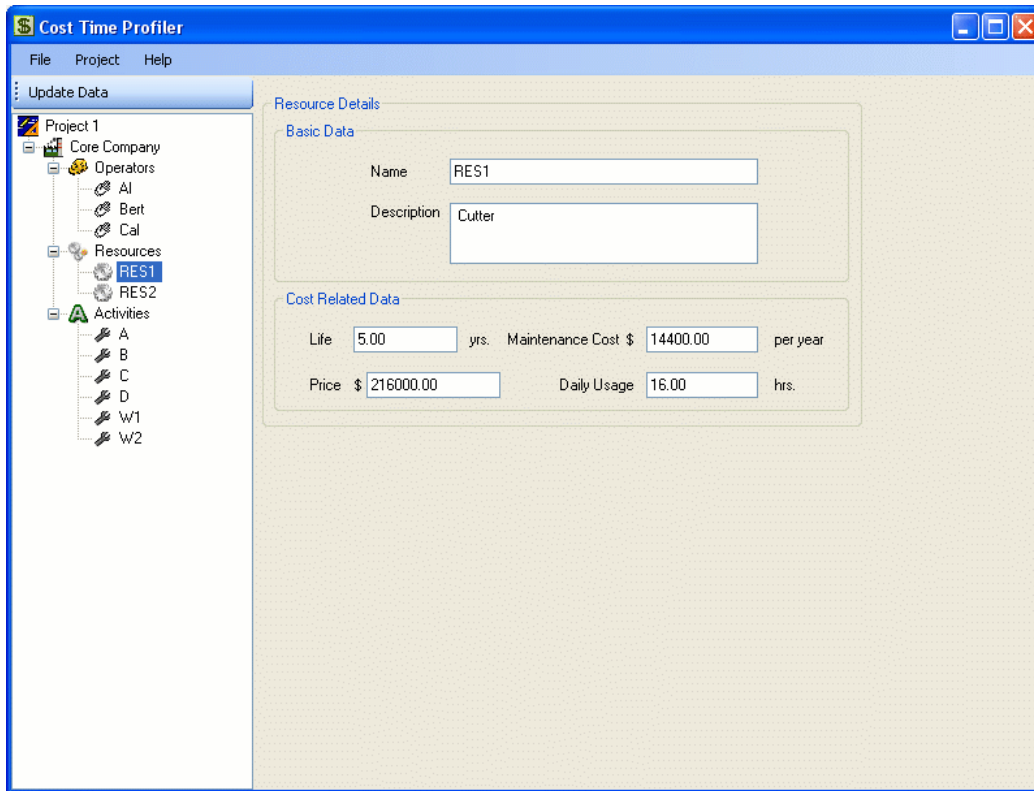


Figure 58: Resource details

When all the information has been entered, two options exist: To perform the CTI calculations and build the CTP chart, or to create the data file for the Schedule Optimization MIP (the logic model does not change, and it is supplied with the Cost-Time Profiler; it is the AMPL coding of Model 4, presented in Chapter 5). **Figure 59** presents the CTI, Gantt Chart; **Figure 60** presents the CTP-Chart; **Figure 61** presents the Operator Usage and **Figure 62** the Resource Usage.

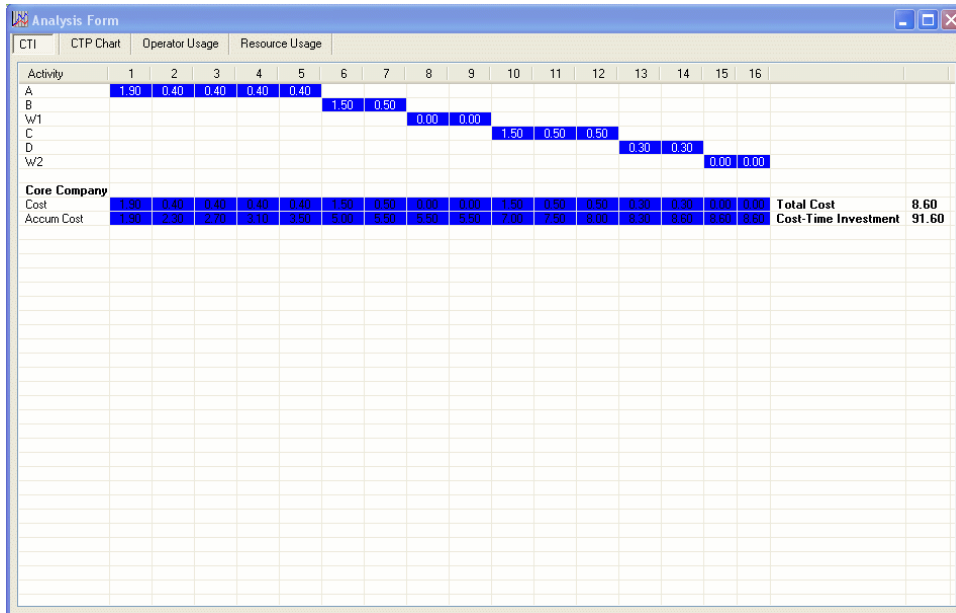


Figure 59: CTI Gantt chart.

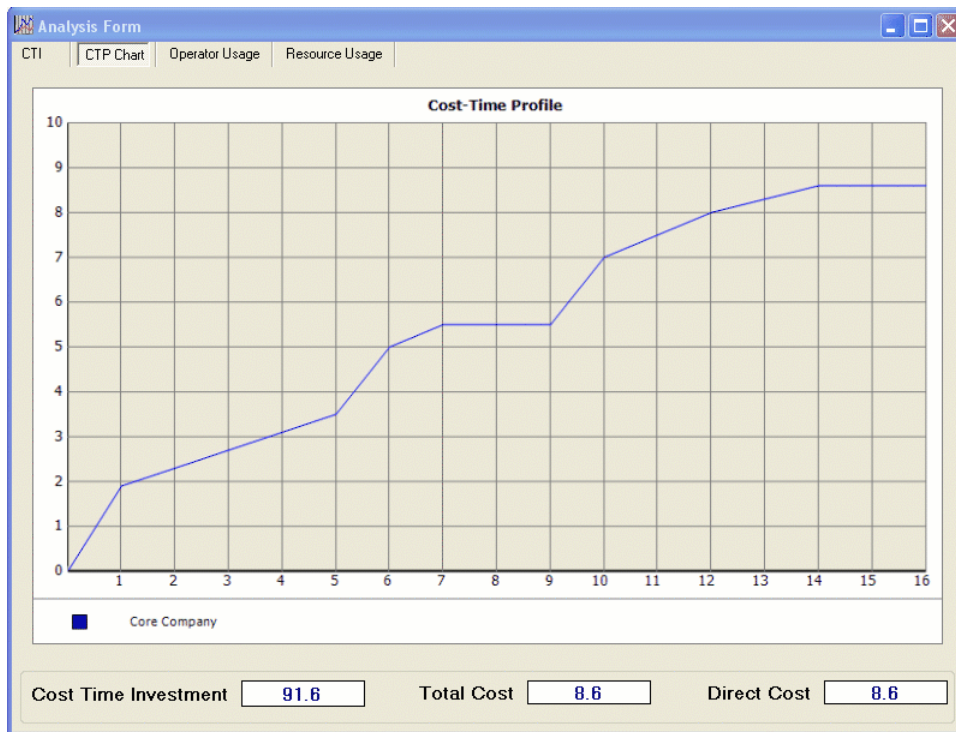


Figure 60: CTP Chart

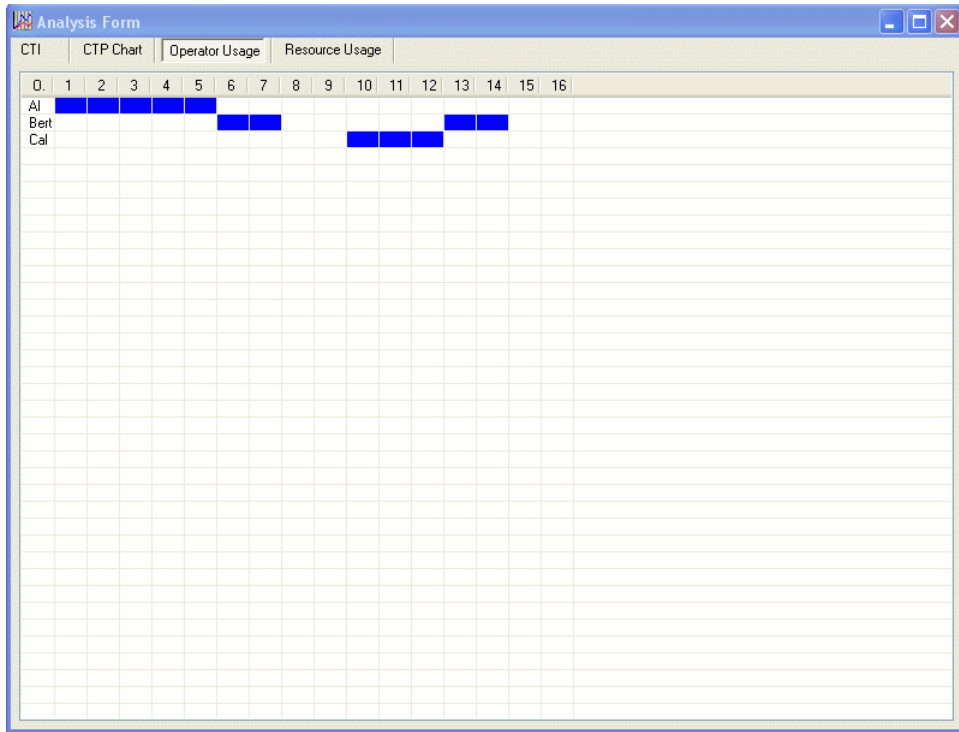


Figure 61: Operator usage

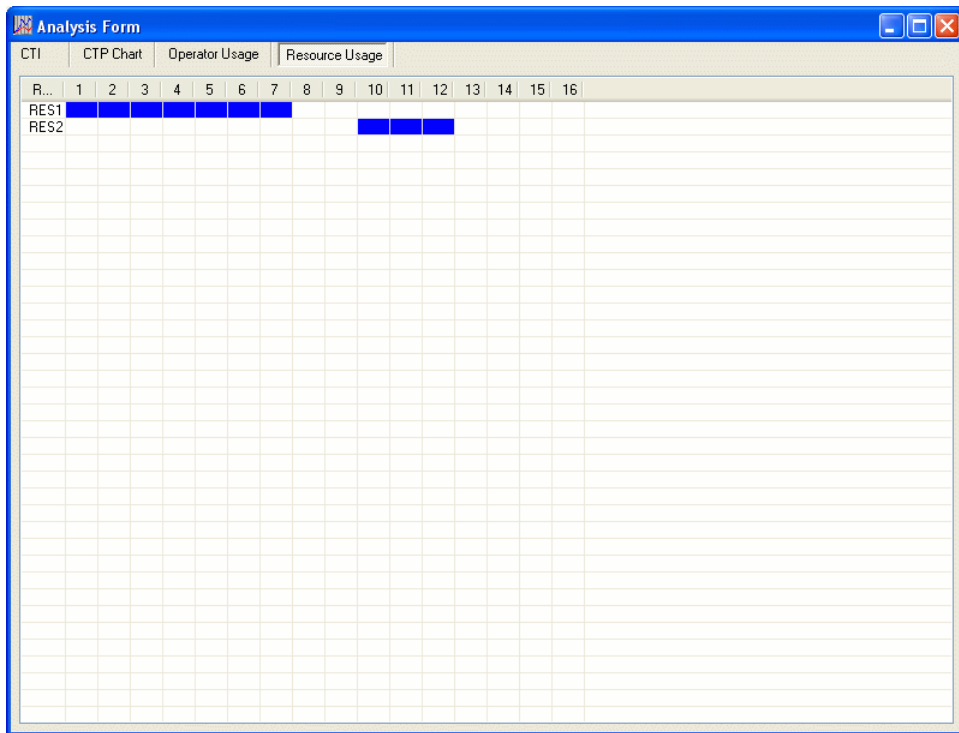


Figure 62: Resource usage

5.5.2. Inter-Enterprise functionality

The main difference when multiple companies are involved has to do with the main window, which separates the information for the different companies as presented in **Figure 63**. Different submenus are available for Suppliers 1 and 2, so it is possible to maintain their operators and resources separated.

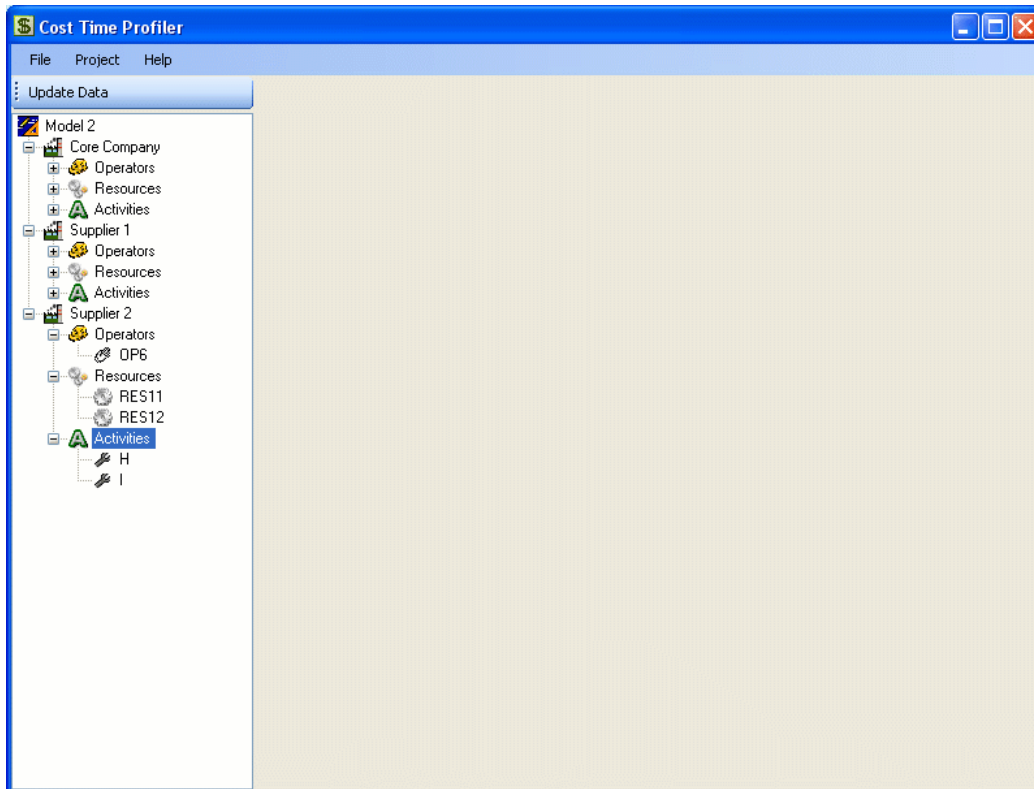


Figure 63: Main window of a multiple-company project.

The CTI Gantt Chart is presented in **Figure 64**, the CTP Chart in **Figure 65**, the Operator Usage in **Figure 66** and the Resource Usage in **Figure 67**. Notice how each company has a distinctive, user selected color that identifies it in all of the charts and screens.

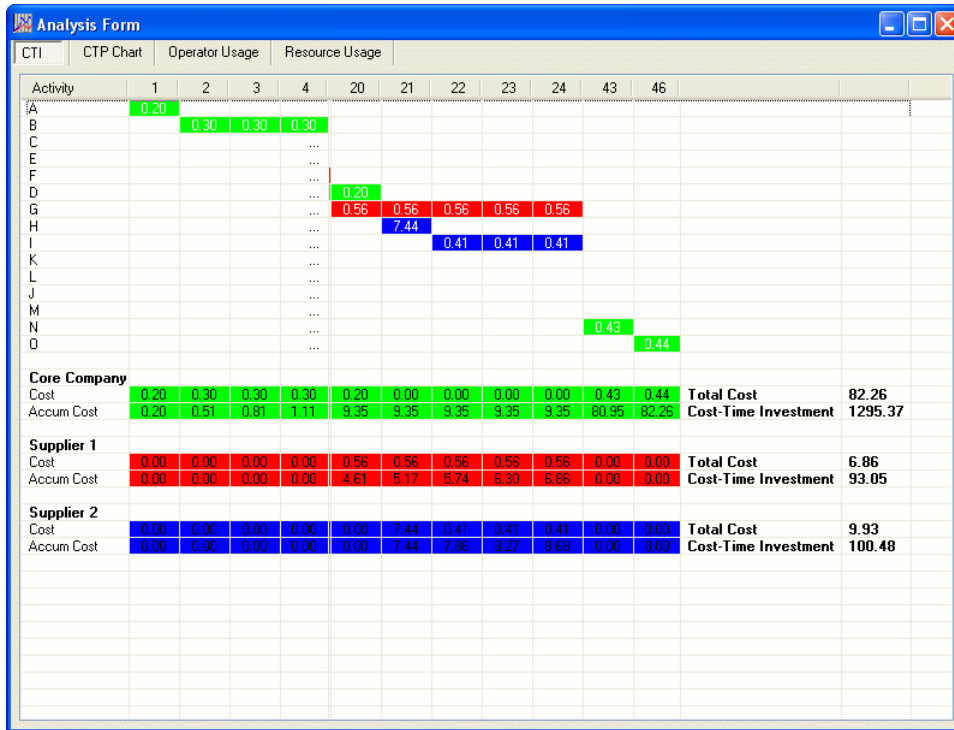


Figure 64: CTI Gantt chart



Figure 65: CTP chart

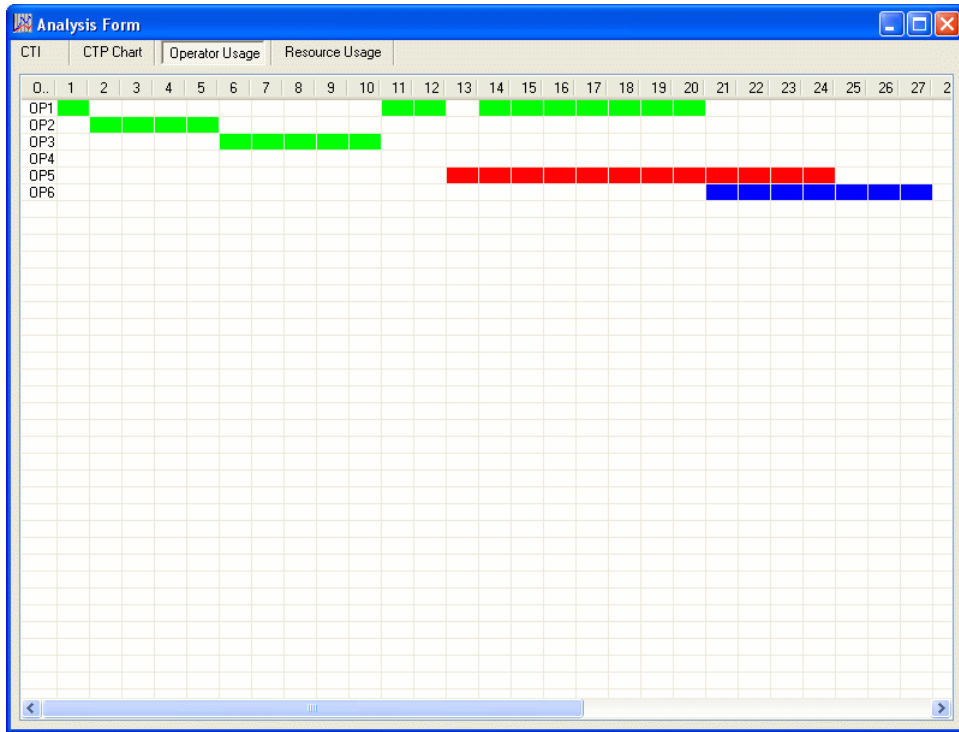


Figure 66: Operator usage

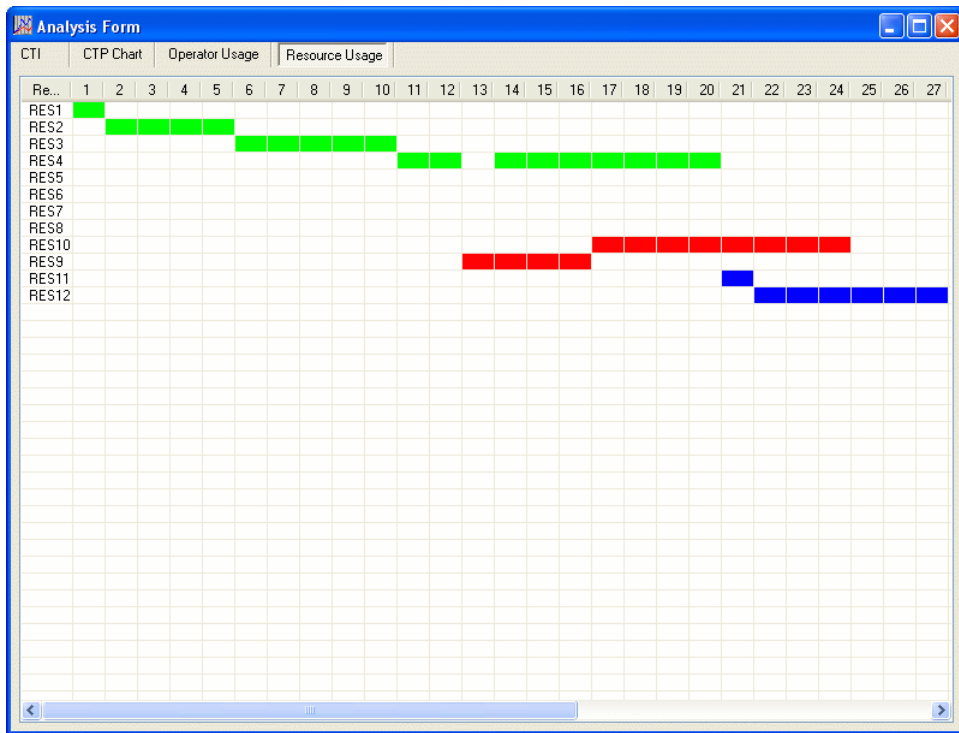


Figure 67: Resource usage.

This Cost-Time Profiler is currently in version 1.0, and further enhancements of its functions might be designed in the future. We believe that the development of more trial cases and its future use with real industrial companies will bring more functionality and user required options, but for now it is a first step to illustrate the concepts of IE-CTP and facilitate their diffusion in the industrial environment of Virginia Tech.

6. USE AND APPLICATIONS OF THE IE-CTP

6.1. Analysis of the areas (slice the CTP)

One of the interesting uses for the IE-CTP would be to analyze what is the impact of each of the components of the CTP in the final composition of the CTI or area under the CTP curve. This type of analysis would enable the analysts to prioritize decisions and choose courses of action for the improvement of activities, as well as to observe who in the network of suppliers would be responsible for important fractions of the total product cost and why.

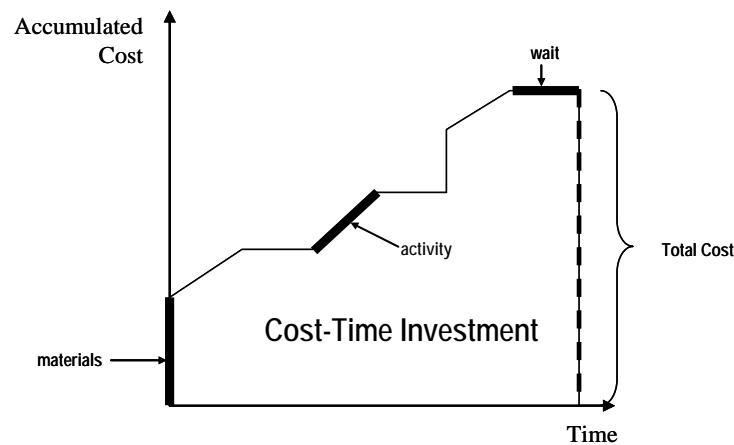


Figure 68: A Cost-Time Profile

For convenience of use we present here **Figure 68**, with a typical Cost-Time Profile. We can notice that the chart has two dimensions: A *time* dimension in the horizontal axis and a *cost* dimension in the vertical axis. Given this bi-dimensionality, it is possible to analyze the composition of the areas using any of the two axes, and obtain different diagnostics and insights. We will examine both dimensions in the following subsections, and we will think of the area under the curve (metaphorically) as a cake, then the examinations that will be conducted will reflect this metaphor.

6.1.1. Slice the CTP horizontally

Figure 69 presents an example of horizontal slicing on a CTP. As we can see, the execution portion of an activity causes a trapezoid-shaped area (Area 2), and any material release would cause a rectangular area (Area 1).

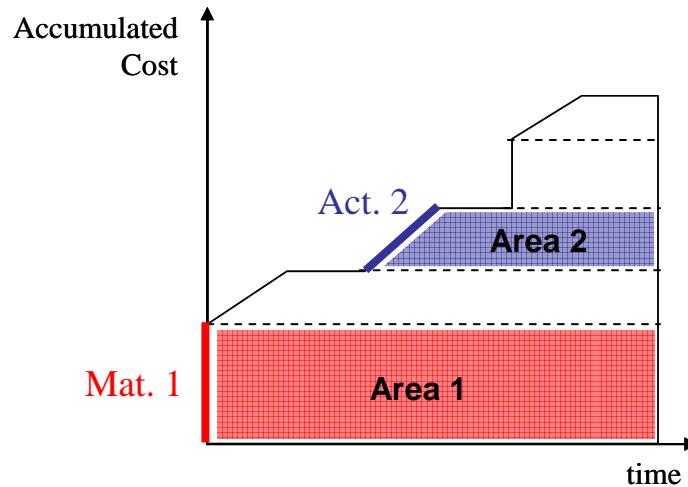


Figure 69: Horizontal slices on a CTP

In this type of representation, it is interesting to observe several things:

- Waits are not directly accounted when analyzing the CTP in this manner. However, it is evident that they have influence over *all* of the activities and material releases present in the CTP before the wait. In fact, waits can be critical for the CTP, and they are the main target of value stream management and other time-centered improvement methodologies.
- The area contribution that an activity or a material release brings to the CTI does not depend on how much area the previous activities have added. It only depends on the characteristics of the activity (duration and cost rate) or the material release (dollar amount of the material release) and the time from its end to the finishing time of the project (or product), what was called $(Y-X_i)$ in the notation presented in section 5.1. From this point of view, it is clear that it would be advisable to have the activities that occur towards the beginning of the process being as economic as possible, or performing as many activities as late as possible. This corresponds to the scenario presented in section 5.2.6.,

and it can be accomplished transforming sequential activities into parallel activities, reducing the waits so the whole CTP is compressed in time or speeding up the performance of activities so the whole project is completed faster.

- Continuing with the discussion from the previous bullet, the strategy of *postponement* comes to mind as relevant for the reduction of the CTI. Performing activities as late as possible has been proposed as part of the optimization of the CTI. The analysis and improvement of the production process could lead to new ways of building the product, transforming sequential activities into parallel ones. This conversion to parallel could be related not only to the logical structure of the activities but also to the use of shared resources and organization of a production line. The redistribution of activities into workstations could create processes not only with smaller cycle times but also shorter makespans.
- Since we sliced the CTP in the cost dimension, it makes sense that the contribution of each CTP component is basically *how much new height* they brought to the CTP, meaning *how much cost*. The time dimension is not the direct responsibility of an activity, because it is the result of the placement of the activity in the structure of the project. The analysis of cost becomes important (in the traditional sense it has always been) to understand and gauge the impact activities and material releases have on the final CTP, and the person or team performing these activities become responsible for the cost improvement initiatives to reduce their CTI area contribution. The time impact the components might have is essentially out of the control of the person or team responsible for the point performance of the activity, so at that moment the person or team responsible for the whole product, product family, manufacturing process or manufacturing cell have to analyze the structure (process map) of the process and make decisions related to organization of workcells and product flow through the process.

6.1.2. Slice the CTP vertically

Another way to look at the CTP, perpendicular to the one presented in the previous subsection, is to slice the CTP vertically. An example of this type of slicing is presented in **Figure 70**.

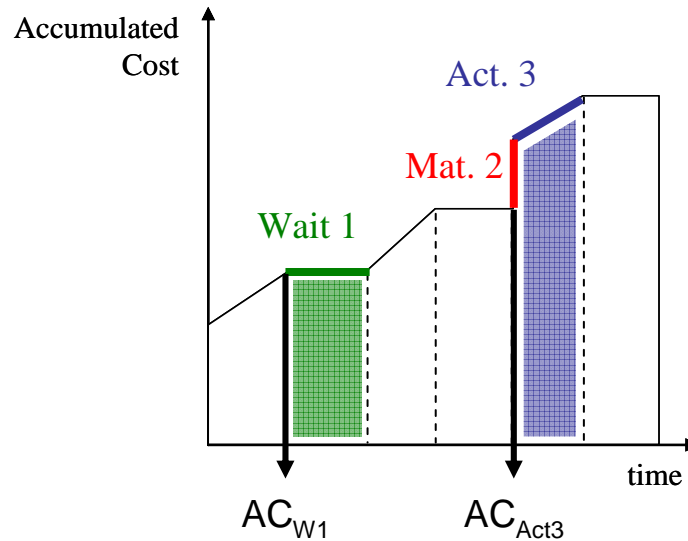


Figure 70: Slice the CTP vertically

In this type of analysis, the contribution of the three main components of the CTP are visible, however, the contribution of material releases goes associated with the component that immediately follows after them. Some observations specific to this form of slicing the CTP are presented in the following bullets.

- The impact of a wait is the accumulated cost at the beginning of that wait (AC_{W1} in **Figure 70**) multiplied by the duration of the wait. This way of analyzing the CTP highlights the importance of reducing or eliminating waiting periods. This also emphasizes the importance of the greatest improvements achieved at the beginning of a value stream improvement process (which are usually time related).
- The impact of an activity can be found multiplying the accumulated cost at the beginning of the activity (AC_{Act3} in **Figure 70**) by the duration of the activity and adding the triangular area caused during the performance of the activity

(Area 2 in section 5.1.4). Again, it is highly dependent on the accumulated cost that previous components have created.

- Material releases increase the accumulated cost instantaneously, therefore they do have an impact on the CTP, but since they do not have a time dimension, any time-compression improvement will not modify the contribution of a material release to the CTP. Material releases are best analyzed when slicing the CTP *horizontally*.

6.1.3. Analysis of the CTP “slicing”

Both points of view (horizontal, cost-based slicing and vertical, time-based slicing) provide different insights into the structure of the problem and the role of each component in the accumulation of cost and Cost-Time Investment. However, the types of analysis that can be performed vary depending on the direction that we choose to look at the picture.

- When sliced horizontally (cost-based) it is possible to distinguish the cost-time impact of each activity or material release measuring the areas of the trapezoidal shapes that are formed (Area 1 or 2 in section 7.1.1.). It would also mean that *earlier* activities might have very important impacts on the CTP because their contribution will be locked from the moment they happen until the end of the project. Therefore, the search would be to find improvement (and investment) opportunities in those *earlier* activities to reduce their lasting impact on the CTI.
- When sliced vertically (time-based), it is interesting to notice that the impact of each activity depends on the cost that has accumulated up until that point. That brings up the point of responsibility: Activities closer to the right of the CTP are responsible for more of the accumulated cost of the product, because in the event of a failure or quality problem that renders the product unusable or forces to scrap it, the loss includes all the activities and materials that have been performed so far. Therefore, it is important to find opportunities for

quality and consistency improvement in the activities that occur *later* in the process of the product.

- The two previous bullet points appear to present a contradiction: The first one says focus on *early* activities, and the second one says improve *later* activities. However, it is not a contradiction, rather a confirmation of the intuition that industrial engineers have had for a long time: All parts of a production process are important and deserve analysis and improvement. The two slicing styles present two different ways to analyze and measure the impact of any improvement project, and the final message of this subsection is that there is no magic formula that tells the engineer where to focus her efforts, but CTP provides an interesting mechanism to quantify the impact of any changes to the production process through cost and time analysis.

6.2. How to build the enterprise network for the IE-CTP

As its name implies it, the IE-CTP is a construction where more than one company (or business unit) is involved. This very nature makes the construction of the IE-CTP an exercise in relationships between companies.

The process to create and implement an IE-CTP must begin with an internal examination, followed by an assessment of the network and finally an implementation and follow-up phase. The following subsections will present the steps for the implementation of the IE-CTP.

6.2.1. Internal assessment

In this phase, the company must examine several issues before jumping on to the implementation of the IE-CTP.

- *Identification of parts and services to be performed externally:* The company must conduct a “make or buy” analysis with important components and systems of the product. Questions such as “Is this part strategically important

for the company?”, “Does the part contain technological or otherwise proprietary knowledge of the company?”, “Will the company have a cost advantage manufacturing this part?”, will need to be answered to decide if the part or component will be manufactured in house or acquired externally.

- *Identification of the company’s position in the supply network:* In section 4.4.2. the different basic topologies of supply networks were presented. In that section, it was clear that *Republics* were not the most desirable environment for IE-CTP implementations. This undesirability came from the point-to-point nature of the relationships, where individual (two-party) alliances were required and there was not a set of standard rules for the whole network. However, *Kingdoms* and *Baronies* were attractive for inter-enterprise tools. It was also specified that the power of a company in a network depended of its position in it, and it should be clear that a King or Baron should have enough muscle to “convince” other members of the network to take part in an exercise such as this one. If the company is just a supplier in the network, the IE-CTP idea will need to be pitched to the heavyweights in the network and championed by them, otherwise it will be very hard to mobilize the network of companies for this purpose.

6.2.2. Assessment of the supply network

The second step for the successful construction of an IE-CTP network is the assessment of the supply network, to rationalize its supplier base and also start building the necessary relationships with them.

- *Choose the supplier base:* Usually, lean thinking suggests that the kind of relationships that must be established to support lean collaborations demand greater commitment, effort and dedication that just casual supplier-buyer relationships. Therefore, to increase the possibilities for collaboration a smaller supplier base is required. At this point is important to take several criteria into account when choosing partners on a network; things like their performance record in relation to the core company; if they share the same business values as the core company; if they are willing to give and receive

technical assistance for lean improvements; if they are active innovators of products and services and if they are interested in participating in the design of the components, systems and products that they will supply to the core company.

- *Establish the bases for lean collaboration with partners:* As it was mentioned in section 4.4.5., relationships should be stable, cooperative and provide clear benefits for both parties involved. These partners should be chosen for long term commitments, so clear rules of interaction should be established, but also the daily interaction will show that, if both companies act the way they are supposed to, trust should start building up. *Trust* is not a quantitative business result; it is a human image of the other's actions and the perception that we can count on the other party to do what they are supposed to do. Trust is not declared by contract or built by formulas; it slowly develops through daily interaction. Also, the practice of *mutual technical* assistance helps to develop lean collaboration. This is not an altruistic or selfless proposition; it benefits both the provider and the recipient of the assistance. Since both companies are trying to create long-term working relationships, helping a partner will have the beneficial effect that the partner will be in better health and will be able to continue interacting positively with our company. Finally, the exercise of *joint technological innovation* will increase the knowledge that both companies can create and share. At the beginning, it is usual that the buyer company furnishes the blueprints and technical specifications of the parts and components that the supplier will manufacture, but with the technical improvement of the suppliers they can start being more responsible for the development of the part and its engineering. If the technological expertise is developed, that makes the supplier stronger and empowers the buyer to focus on their core technologies and rely on the suppliers for peripheral and support technologies (which are core for the supplier).

6.2.3. Implementation and operation phase

IE-CTP can be used in different ways. Depending on its application, the requirements for its operation will vary.

- *One Time IE-CTP*: If the IE-CTP will be built for just one time, a traditional clipboard and stopwatch approach can be followed. Similar to the construction of a value stream map, it would require only following the process and taking down the activities, their sequence, the resources they use and then gathering the information about their costs per unit of time (both Accounting and Production Management should possess this information).
- *Dynamic IE-CTP*: If the idea is to periodically calculate the IE-CTP, a first pass with the clipboard and stopwatch to know the process is necessary. It would then be followed by the periodical updating of average values, using the weekly or monthly production cost report of the company. The value of this approach would be to follow the development of the Cost-Time Investment for the product over time.
- *Real Time IE-CTP*: If the desire is to report on the state of the process in real time, it would be necessary to have an ERP or production control system with real time capabilities. The continuous monitoring of the system would make possible the generation of an IE-CTP per shift, per day or per hour. Discrepancies would be detected quickly and examined to determine if action is required.

The need to use the IE-CTP as a monitoring tool will probably not force any companies to modify their existing information systems; rather, the type of capabilities that are present should be taken advantage of in order to monitor the process of the product and its CTP. In any case, even at the most basic level, the construction of the IE-CTP will bring insight to the company as to the importance of using well the resources and the understanding of the way cost accumulates in relationship to the way the processes are organized and ran.

6.3. Challenges for companies that wish to implement the IE-CTP

In this chapter we have presented the necessary steps to build the network of companies that is required to use the IE-CTP. Now we will present some challenges that these companies face, and the common theme is resistance to change. Some of these ideas are introduced by Rivera et. al. (2006c).

- *Lack of awareness:* By now, practically every company has heard about supply chain collaboration. However, there is a mental gap that has to be covered to see the need for integration with other supply network partners; the realization that each company's role is not limited to perform a service or sell a product to another one, rather to play an integral part in the satisfaction of the end customers' needs.
- *Cost and profit allocation:* The collaborative (or lean) supply chain threatens to blur the frontiers between companies, due to its increased levels of integration and cooperation. Once the improvement projects in the supply chain start rendering benefits, it will be necessary to have an agreement in place to share both costs incurred and profits received in a fair and visible manner for all the members of the supply network.
- *Greater inertia than a single company:* Supply networks are composed of multiple companies, and they are more than the sum of their components (due to member interactions, synergies and conflicts). Supply chains can get set in routines, where certain practices happen because "we have always done it this way," and there is not a centralized person or authority to evaluate and change the practice. This decentralization makes changes harder and reaction to unexpected circumstances more painful.
- *Visibility versus security:* The tradeoff between shared information and improved security plays an interesting role in the supply network. On one hand, it is important that member companies have easy and adequate access to the relevant information about costs and processes. On the other hand, the information system should have an adequate level of security, since

proprietary information is being exchanged, and it will be important to keep it from unauthorized access.

- *Commitment and trust:* The need for the establishment of long-term relationships has been emphasized throughout this chapter. However, it's not easy to start having these types of relationships immediately. Western culture has traditionally favored competition over cooperation. Taking the first step towards the construction of these relationships will imply serious commitments towards long term relationships and some "leaps of faith" taken with the expectation that the other party will uphold their end of the bargain. On the other hand, if the leading company abandons these commitments at the sight of trouble, trust will evaporate and it will be so much harder to rebuild than the first time around. As in human relationships, trust and commitment between partner companies are hard to build, but if they are not nurtured and respected, they will not survive. A change of attitude towards other companies is required to enter the IE-CTP network.

7. SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

7.1. Summary

The objective of this research is to develop and present a tool that companies can apply to measure the cost and time impact of a manufacturing process, in particular when the process spans more than one company or business unit. The research was always conducted with the lean manufacturing and lean thinking frameworks in mind, since these philosophies have been showing great results in the last fifteen years and promise to continue having a positive effect on company operations for the immediate future. Companies that have lean thoughts can apply the CTP to monitor the cost and time impact of their operations and improvements, and the IE-CTP as a tool to extend the lean concepts into their supply chains and integrate operations with their partner companies to create lean extended enterprises or lean supply chains.

In this project, the simultaneous attention to cost and time have made possible the identification of the measurable monetary impact that the timing of costs, activities, waits and material releases have on the direct cost of the product. These considerations make the CTP and IE-CTP an important tool that can be used to complement value stream mapping when characterizing a production process.

The subject matter starts with the introduction of the basic concepts of Cost-Time Profiling. activities, materials and waits are presented and explained, as well as the procedure to build a basic Cost-Time Profile for a single company. The basic point of these first sections is to present and demonstrate how the cost-time performance of the manufacturing process can be easily accounted for, and to guide the user through the procedure to build a Cost-Time Profile. The construction of the activity schedule, parallel to the calculation of the cost rates of the different components of the CTP take the user to the determination of the actual cost being incurred at each time unit, and the evolution of

the accumulated cost finally leads to the graph of the Cost-Time Profile and the calculation of the area under that curve, which is the Cost-Time Investment.

Then the extension of the CTP concepts, to be applied in an Inter-Enterprise environment is presented, showing that there will be new activities to consider (information and material exchanges and transportation activities), as well as new actors in the supply network (transportation providers). A numerical example is introduced to illustrate the effect of these new considerations.

In chapter 4, some issues that affect the construction of CTPs and IE-CTPs were discussed, such as the effects of batching on the CTI results, the interaction of the CTP concepts and information needs with the different accounting systems that companies use, and more specifically, the treatment of direct cost, overhead and profit that would be consistent with the construction of the IE-CTP. Finally, an examination of the role that relationships and interaction between companies might have on the IE-CTP was discussed. This chapter was intended to bring some of the concepts of the IE-CTP to a point where it is practical to apply them, and to contrast them with the marketplace realities and considerations.

Chapter 5 presents different tools and mechanisms for the improvement of the IE-CTP, or better yet, the improvement of the CTI. The first section outlines the evolution of a mathematical model, from the first basic linear programming model based on the project management literature to the last one, a mixed integer programming model that considers not only logical precedence constraints but also constraints due to operator and resource sharing between activities. The outcome of this section is to present the complete model that is applicable to single or multi-enterprise environment. The second part presents an examination of generic scenarios that would lead to improvements in the CTI through different “area-under-the-curve reducing”, as well as the phases or “waves” of improvement that would occur during the implementation of lean thinking and how do they match the generic scenarios presented before. Section 5.4. presents a brief simulation study that was performed to assess the impact of batching, information

exchange mechanisms and reduction of “waits” on the CTI. These simulation models were developed in Arena, and the procedure followed and the summarized results showed the expected impacts on the CTP were consistent with what was expected. Finally in this chapter, the IE-CTP software tool is presented. This tool was developed for a CHPM (Center for High Performance Manufacturing) designated project, and its general structure and user navigation were presented here. It is the hope of CHPM and of the author that this tool will be used by CHPM member companies to measure and improve the CTP of their products, both if they are manufactured completely in-house or if they need the participation of several companies.

Finally, Chapter 6 presents uses and applications of the IE-CTP. The first section covers the analysis of the IE-CTP, looking for different ways to interpret both the cost and the time dimensions. It is demonstrated that every improvement project might be worth considering because projects could improve the CTP by changing the time or cost dimensions, or both at the same time. Section 6.2. focuses on the requirements and steps for the construction of the IE-CTP network of companies, discussing issues such as relationships amongst them and the logical sequence of generic steps that would be advisable to follow to implement the IE-CTP. Finally, section 6.3. outlines some of the main challenges will face (and have to overcome) in order to implement the IE-CTP. This discussion highlights the importance of building lean collaboration ties within the network of companies, and also issues of trust, information sharing and cost and profit sharing and disclosure. Tools such as the IE-CTP should not be used unilaterally by big companies to reap all the benefits of information sharing for themselves; they should be a platform to build better and more sustainable relationships that will help companies to have a better future and a stronger presence in the business community.

7.2. Conclusions and contributions of this research

7.2.1. *The re-examination of the CTP methodology.*

The Cost-Time Profile is not a new concept; it was developed in the Westinghouse Corporation since the 1970s. However, its application and diffusion had been slow at best, given that it was mainly conceived as a tool for internal use. Jack Fooks published his book “Profiles for Performance” (Fooks, 1993) with the main concepts and applications of the CTP, but it still did not generate massive interest in the professional audience.

This research has re-examined the CTP with the belief that in this time of lean manufacturing diffusion and profound interest towards all the concepts of lean thinking, the time dimension has become increasingly important in any type of measurement. The popularity of value stream mapping shows that many companies are interested in tools to compress their processes in the time dimension; and the intuition that smooth and quick flow of the product through the process are desirable characteristics is stronger than ever. However, not much has been explicitly done to quantify the economic impact of the improvements in the time dimension, and even less to examine the *interaction* between time and money during the manufacturing process.

The Cost-Time Profile is a simple to understand, easy to build tool that offers valuable insights into process performance and process improvement, always considering the cost and time dimensions and their inevitable interactions. This research has examined these concepts in some detail and proposed methodologies to build, analyze, improve and even modify the manufacturing process to optimize the CTP. It is the hope of the author and the other senior researchers involved that many of the future research questions posed in a following section will be studied and ideas for their realization will be proposed in the short-term future.

7.2.2. Inter-Enterprise CTP.

The CTP, as it was mentioned above, is a very worthy tool in itself; however, the main concepts had already been described as a tool for use on a single company. An important motivation for looking beyond the boundaries of one company lies in the realization that today most products with a little more than a minimal degree of complexity will have in their processes the intervention of more than one company. Corporations are trying to follow managerial mantras such as “concentrate in your core competencies, outsource everything else”, and it is a tangible reality than in many cases more than just a company it’s a network of companies, a supply network, even a lean Extended Enterprise the entity that is creating products for final users.

Lean extended enterprises, lean supply chains and other similar denominations are especially interesting and promising towards the near future, because they go beyond the notion that suppliers just sell a product to another company; they rather attempt to integrate several companies in what is called “lean enterprises” or “extended enterprises”, with the basic idea that the network of companies should be considered an integrated entity and that collaboration in many aspects of strategy, tactic decisions and daily operations should be improved to offer customers a better offer of value.

Also, large corporations may have more than one business unit contributing in the process of a product, manufacturing parts and components for other business units. The Inter-enterprise nature of their joint work is in the nature of their everyday work.

In this context, it was a natural extension to examine the CTP in a multi-company context: What differences would it have with the single-company CTP; which issues would arise that would require especial attention for the implementation of the IE-CTP; what would be the challenges that companies would face in its implementation. This Dissertation tackled some of these issues and pointed towards some others that will be of interest in the near future.

7.2.3. Optimization models.

The Cost-Time Profile can be used as a visualization tool; much like a value stream map can be drawn to identify the current state of the process. However, these tools would not be of much use if they were not accompanied by methodologies for their implementation and process improvement. In this research work, the structure of the manufacturing process was examined using the notation and tools of project management, and a series of mathematical models of increasing complexity were developed. The final model takes into consideration the sequence of activities and their use of resources and operators to create a new schedule of activities that considers those constraints and offers the best possible CTI as the objective function. The model is a mixed-integer program, and it can be applied to any process that can be modeled using the standard linear programming notation for project management.

7.2.4. Scenarios for CTP improvement.

Another type of improvement, different than the re-organization of the schedule through mathematical modeling, was proposed and presented in this project. It consisted in looking at the process variables (cost rates, duration of activities, lengths of waits, use of materials) and, based on their expected impact in the CTI, propose generic scenarios that would improve the bottom line of the company and the economic impact of the process. These seven generic scenarios were presented in section 5.2.

Then, we presented the sequence of application of lean tools and techniques for an improvement project, and followed its successive phases, evaluating their impact on the process and its CTI. A case study was followed with numerical examples that illustrated the potential of the CTP and IE-CTP as tools for the evaluation of the bottom line impact of process improvements.

7.2.5. Framework to implement the IE-CTP on a supply network

After presenting the main theoretical concepts of the IE-CTP, it was necessary to address the issues of implementation, information exchange, relationship between companies and the development of trust, because all of them are indispensable for the use and implementation of the IE-CTP. This research work presented a framework for implementation that considered important issues and also contained the acknowledgment that even though the current state of relations between companies will not always support the use of a tool such as the IE-CTP, it is a desirable future and all companies should try to move to closer integration with their network of companies.

7.2.6. IE-CTP software development.

A software tool was developed to organize the information, perform the calculations and display the results of CTP and IE-CTP exercises. Its clear and simple interface makes it user-friendly and adapted to the expectations of computer users today. The author of this research work developed the logic and programming concepts, and external assistance was obtained for the implementation of the graphical interface and end-user implementation. The details and logical flow were presented in chapter 5.

7.3. Future Research Areas

As it is always the case with new measurement and management instruments, after the basic presentation and implementation proposed on an initial research work (such as this Dissertation), many questions and avenues of inquiry remain open. In this case, the research opportunities reflect the potential for expanding the uses and applications of the IE-CTP; to examine its interaction with other tools and established company systems; to be applied to the particular interests of the researcher or his economic environment and to interact with related interests of other researchers.

7.3.1. Application of IE-CTP in non-manufacturing environments

A first potential application that could make use of the IE-CTP is environments different than manufacturing. There is nothing that makes the CTP concepts not applicable to services and other industries; in fact, every activity consumes resources, costs money and takes a certain amount of time, so every economic activity would be a candidate for the application of CTP and IE-CTP. Two important types of industries deserve closer examination.

- *Services*: There are different kinds of services, and some would probably be easier to study using the CTP methodology. Good candidates are those where the service is highly standardized and repeatable, such as laying new carpet (highly dependent on the square footage, otherwise repeatable), painting (the main driver would be the area to be painted), lawn mowing and air travel. Services that are more customized and respond to the needs and special features the customer exhibits (or wants) would be less interesting for the CTP, because they usually work with averages or plain overcharging based on worst-case scenarios. Haircuts and hair styling are more personalized, home remodeling, fashion design and tailoring service and in general highly customized and specific services are harder to examine using the CTP methodology. In general, a priori costing is important for them and that is one of the reasons that customized products and services are (proportionally) more expensive than the more standard variety.
- *Projects*: By projects we understand specific, highly customized endeavors with relatively high cost and a complex structure of activities and resources. Projects can be a prime application for CTP, given the magnitude of the resources that they use and their long time spans, which will make the impact of the cost-time investment more important. The CTP might be used for the financial monitoring of the project and its cash flow. An interesting point that would need to be studied is the treatment of project advances and partial payments, because if the project starts with an advance, that would require a treatment entirely opposite to that of a cost or material release. We might be dealing with “negative” areas and their economic impact, and this could

make the use of CTP in project situations similar to the tool of *project balance* in the engineering economics literature.

7.3.2. Application of IE-CTP for analysis of capital investment opportunities

When a process improvement demands the purchase of a new piece of equipment, it would be interest to quantify the impact of the new machine on the process using the CTP. If all the other parameters of the process continue as they have been, we could argue that the positive changes are due to the presence of the new machine and that impact might be assessed using the CTP. It would be necessary to examine the interaction and congruency between the CTP and some other financial tools such as ROI.

7.3.3. CTP in high-interest (inflation) environments

One of the parameters that are necessary to weight the impact of the CTI and obtain the direct cost figure is the interest rate that the company applies for its cost of capital or for attractive projects. In the United States the inflation and real interest rates have been relatively low in recent times, however, many other countries have suffered from high (even hyper-elevated) inflation rates, which bring with them not only high relative interest rates but also high real interest rates (due to increased risk).

In a low-interest economic environment, the impact that the CTI has on the Direct cost is moderate at best; its best chance to be very important in the direct cost calculations is to have projects with very long makespans. However, in a high-interest economic environment, the time component becomes very urgent and the potential impact of the CTI might be a fair percentage of the direct cost. It would be interesting to analyze what would this impact be and how this kind of time pressure (due to high interest rates and high inflation) could be an important driver to stimulate companies to time-compress their value streams and implement lean and agile concepts in their operations.

7.3.4. Integration of IE-CTP with traditional costing systems

Some of the concepts of the CTP depend on the implementing companies having JIT capabilities and real-time information. It would be interesting to examine what would be the interaction between the CTP and a real accounting system. Accounting systems often register a transaction even before any real money changes hands, and the CTP would require real-time information to be accurate. Real-time, cash-flow (rather than causation) based accounting information systems would be required to interact with the CTP, but the traditional accounting systems consider the amounts of expenses but do not concern themselves too much with their timing, unless the expense happens outside a reporting period. Generally, activities and expenses that occur within the reporting month would be treated equally by the accounting system, ignoring when exactly the activities happened. Traditional accounting systems ignore timing if it is contained within the reporting period (month), CTP needs continuous and detailed timing of the activities.

7.3.5. Transfer prices between Business Units of the same company

The price that a supplier quotes the core company has been considered composed of direct cost, overhead assignment and profit margin. However, there is another kind of price that could come into play, and that is the *transfer price*. Specifically, we call transfer price the price a business unit charges another business unit under the same corporate denomination (sister business units of the same parent company). The composition of the transfer price has its own complexities; it is not as straightforward as direct cost + overhead + profit. Transfer prices are used for a variety of corporate functions, such as minimizing taxes the company would need to pay for international money transfers, to move money where it is more convenient to report it and to subsidize operations in certain locations of the world to make their results more attractive to investors and local governments, to mention a few. It would be interesting to examine the impact that transfer prices could have on the IE-CTP, especially when they are not calculated following the same logic as the CTP.

7.3.6. Integration with leanness Measurements

After two years of discussion and exchange of ideas with HungDa Wan, researcher of the DEA-Leanness Measurement, it has been evident that both subject areas share many goals and characteristics: The desire to measure leanness, the consideration of both cost and time investments and also the interest in creating a useful tool that can be applied by companies and practitioners. With this in mind, an important research avenue will be the unification of both DEA-Leanness and Cost-Time Profile, to offer an integrated process that takes both concepts into consideration, and to ensure consistency between the two measures.

REFERENCES

Allen, J., Robinson, C., and Stewart, D., (2001), *Lean Manufacturing: A plant floor guide*, Society of Manufacturing Engineers, Dearborn, MI.

Arbos, L. C., (2002), "Design of a rapid response and high efficiency service by lean production principles: Methodology and evaluation of variability of performance," *International Journal of Production Economics*, 80, 169-183.

Banks, J., et. al. (2001). *Discrete Event System Simulation*, Prentice Hall, Upper Saddle River, NJ.

Barker, R.C. (1994). The Design of Lean Manufacturing Systems Using Time based Analysis. *International Journal of Operations & Production Management*, 14 (11), 86-96.

Bell, S., (2006), *Lean Enterprise Systems: Using IT for Continuous Improvement*, John Wiley & Sons, Hoboken, NJ.

Boyer, K.K. (1996). An assessment of managerial commitment to lean production. *International Journal of Operations & Production Management*, 16 (9), 1996, 48-59.

Callen, J. L., Fader, C., and Krinsky, I., (2000,) "Just-in-time: a cross-sectional plant analysis," *International Journal of Production Economics*, 63, 277-301.

Comm, C. L. and Mathaisel, D. F. X., (2000), "A paradigm for benchmarking lean initiatives for quality improvement," *Benchmarking: An International Journal*, 7(2), 118-127.

Conner, G., (2001), *Lean Manufacturing for the Small Shop*, Society of Manufacturing Engineers, Dearborn, MI.

Cooper R, Slagmulder R, (1999) *Supply Chain Development for the Lean Enterprise Interorganizational Cost Management*, Productivity, Portland, OR.

Corbett, T. (2000) Throughput accounting and activity-based costing: the driving factors behind each methodology. *Journal of Cost Management*, v.14, n.1, p.37-45.

Detty, R. B., and Yingling, J. C., (2000), "Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study," *International Journal of Production Research*, 38(2), 429-445.

Diekmann, J.E., Balonick, J., Krewedl, M., Troendle, L. (2003). Measuring Lean Conformance. Proceedings of the *11th Annual Conference of the International Group of Lean Construction*, Blacksburg, VA.

Feld, W. M., (2000), *Lean Manufacturing: Tools, Techniques, and How to Use Them*, The St. Lucie Press/APICS Series on Resource Management, Alexandria, VA.

Fogarty, D. W., (1992), "Work in process: performance measures," *International Journal of Production Economics*, 26, 169-172.

Fooks, J. H., (1993), *Profiles for Performance: Total Quality Methods for Reducing Cycle Time*, Addison-Wesley, Reading, MA.

Groesbeck, R. (2005). Class Notes for the course in Production Systems Improvement. Virginia Tech, Blacksburg.

Hillier, F.S. Liebermann, G.J. (1995). *Introduction to Mathematical Programming*. McGraw-Hill, New York.

Hopp, W. J. and Spearman, M. L., (2000), *Factory Physics: Foundations of Manufacturing Management*, McGraw-Hill, New York, NY.

Ishikawa, K. (1985). *What Is Total Quality Control?: The Japanese Way*. Prentice Hall, New York, NY.

Japan Mgmt Assoc, (1989). *Kanban Just-In-Time at Toyota: Management Begins at the Workplace*. Productivity Press. Portland, Oregon.

Jina, J., Bhattacharya, A. K., and Walton, A. D., (1997), "Applying lean principles for high product variety and low volumes: some issues and propositions," *Logistics Information Management*, 10 (1), 5-13.

Jones, D. T. and Womack, J. P., (2002), *Seeing the Whole: Mapping the Extended Value Stream*, Lean Enterprise Institute, Inc., Brookline MA.

Jordan, J.A., Michel, F.J. (2001). *The Lean Company: Making the Right Choices*. Dearborn: Society of Manufacturing Engineers.

Kaplan, R. Cooper, R. (1997). *Cost and Effect*. Harvard Business School Press, Cambridge, MA.

Karlsson, C., Ahlstrom, P. (1996). Assessing changes towards Lean Production. *International Journal of Operations & Production Management*, 16(2). 24-41.

Kelton, D., Sadowski, D., Sadowski, R. (2002). *Simulation with Arena*. McGraw-Hill, Boston, MA.

Kojima, S., Kaplinsky, R. (2004). The use of a lean production index in explaining the transition to global competitiveness: the auto components sector in South Africa. *Technovation*, 24 (3), 199-206.

Li, S., Rao, S., Ragu-Nathan, T.S., Ragu-Nathan, B. (2005). Development and validation of a measurement instrument for studying supply chain management practices. *Journal of Operations Management*, March.

Liker, J. (1997). *Becoming Lean: Inside stories of U.S. Manufacturers*. Productivity Press, Portland, OR.

Martinez, A., Perez, M. (2001). Lean Indicators and Manufacturing Strategies. *International Journal of Operations & Production Management*, 21(11). 1433-1451.

Maskell, B. and Baggaley, B., (2004), *Practical Lean Accounting*, Productivity Press, New York , NY.

McIvor, R., (2001), Lean supply: the design and cost reduction dimensions, *European Journal of Purchasing and Supply Management*, 7, 227-242.

Monden, Y. (1998). *Toyota Production System: an integrated approach to just-in-time*. Institute of Industrial Engineers, Norcross, GA.

Nachtmann, H. and Al-Rifai, M.H. (2004). An application of Activity Based Costing in the air conditioner manufacturing industry, *The Engineering Economist*, 49:221–236.

Ohno, T., (1988), *Toyota Production System*, Productivity Press, Portland, OR.

Ramaswamy, N. R., Selladurai, V., and Gunasekaran, A., (2002), “Just-in-time implementation in small and medium enterprises,” *Work Study*, 51(2), 85-90.

Rentes, A. F., Van Aken, E. (2003). *Creating Lean Measurement from Value Stream Mapping*.

Richardson, T. (1996). *Total Quality Management*. Thomson Delmar Learning, New York.

Rivera, L. and Chen F. F., (2006a), “Cost-time profiling: putting monetary measures onto value stream maps,” Proceedings of the *Annual Industrial Engineering Research Conference*, Orlando, FL.

Rivera, L. and Chen F. F., (2006b), “Cost-Time Profiling: Impact of Lean Tools on the Cost-Time Investment of a Product,” Proceedings of the 16th *Flexible Automation and Intelligent Manufacturing International Conference*, Limerick, Ireland.

Rivera, L., Wan, H., Chen, F., Lee, W.M. (2006c). *Beyond Partnerships: The power of Lean Supply Chains*. Chapter in the book “*Trends in Supply Chain Design and Management: Technologies and Methodologies*”, soon to be published by Springer.

Rother, M., Shook, J., (1998), *Learning to See – Value Stream Mapping to Add Value and Eliminate Muda*, The Lean Enterprise Institute, Brookline, MA.

Sanchez, A. M. and Perez, M. P., (2001), “Lean indicators and manufacturing strategies,” *International Journal of Operations and Production Management*, 21(11), 1433-1451.

Shah, R., Ward, P.T. (2003). Lean manufacturing: context, practice bundles, and performance. *Journal of Operations Management*, 21, 129–149.

Sipper, D. and Bulfin, R. L. JR., (1997), *Production Planning, Control, and Integration*, McGraw-Hill, New York, NY.

Soriano-Meier, H., Forrester, P.L. (2002). A model for evaluating the degree of leanness of manufacturing firms. *Integrated Manufacturing Systems*, 13 (2), 104-109.

Tapping, D., Shuker, T., Luyster, T. (2002). *Value Stream Management*. New York: Productivity Press.

White, R. E., Pearson, J. N., and Wilson, J. R., (1999), "JIT Manufacturing: A survey of implementations in small and large U.S. manufacturers," *Management Science*, 45(1), 1-15.

Womack, J. P., Jones, D. T., and Roos, D., (1990), *The Machine that Changed the World*, Macmillan, New York, NY.

Womack, J. P. and Jones, D. T., (1996), *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Simon and Schuster, New York, NY.

Womack, J. P. and Jones, D. T., 2005, *Lean Solutions*, Free Press, New York, NY.

APPENDICES

Appendix A: Details of the examples of batching.

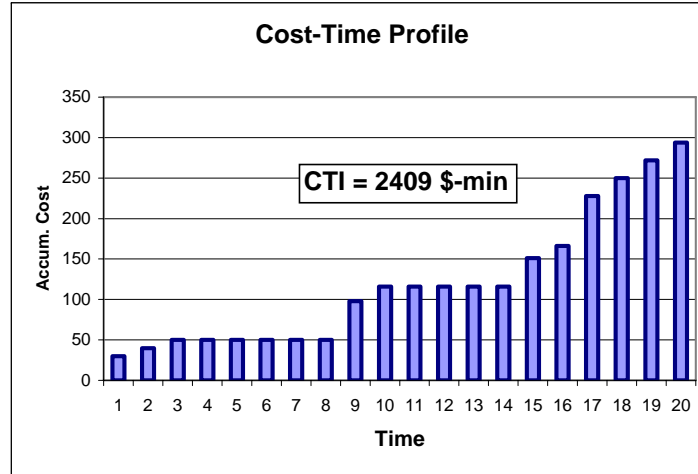
Base Case: Manufacture 1 unit

| Activity | Cost-Rate | Materials | Duration | Begin | End |
|----------|-----------|-----------|----------|-------|-----|
| A | 10 | 20 | 3 | 1 | 3 |
| Wait1 | 0 | 0 | 5 | 4 | 8 |
| B | 18 | 30 | 2 | 9 | 10 |
| Wait2 | 0 | 0 | 4 | 11 | 14 |
| C | 15 | 20 | 2 | 15 | 16 |
| D | 22 | 40 | 4 | 17 | 20 |

20

| Time | Activity | Cost-Rate | Materials | Accum Cost |
|------|----------|-----------|-----------|------------|
| 1 | A | 10 | 20 | 30 |
| 2 | A | 10 | 0 | 40 |
| 3 | A | 10 | 0 | 50 |
| 4 | W1 | 0 | 0 | 50 |
| 5 | W1 | 0 | 0 | 50 |
| 6 | W1 | 0 | 0 | 50 |
| 7 | W1 | 0 | 0 | 50 |
| 8 | W1 | 0 | 0 | 50 |
| 9 | B | 18 | 30 | 98 |
| 10 | B | 18 | 0 | 116 |
| 11 | W2 | 0 | 0 | 116 |
| 12 | W2 | 0 | 0 | 116 |
| 13 | W2 | 0 | 0 | 116 |
| 14 | W2 | 0 | 0 | 116 |
| 15 | C | 15 | 20 | 151 |
| 16 | C | 15 | 0 | 166 |
| 17 | D | 22 | 40 | 228 |
| 18 | D | 22 | 0 | 250 |
| 19 | D | 22 | 0 | 272 |
| 20 | D | 22 | 0 | 294 |

CTI 2409

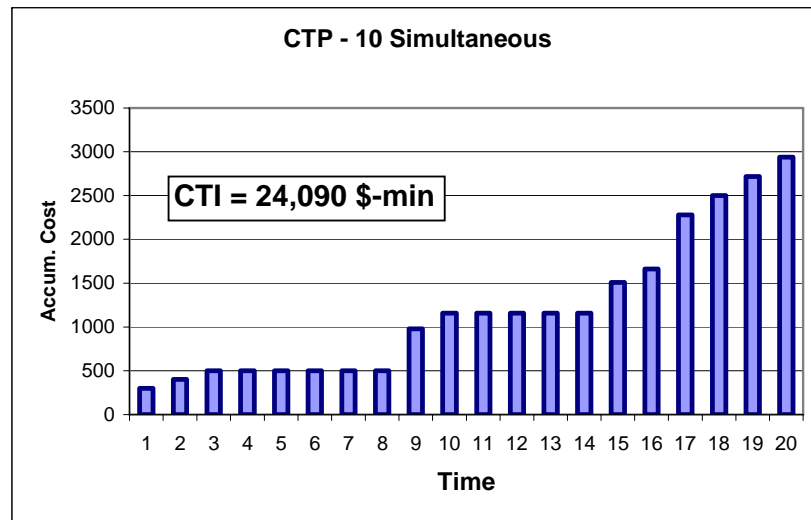


Case 1: Manufacture 10 units simultaneously

| Activity | Cost-Rate | Materials | Duration | Begin | End |
|----------|-----------|-----------|----------|-------|-----|
| A | 10 | 20 | 3 | 1 | 3 |
| Wait1 | 0 | 0 | 5 | 4 | 8 |
| B | 18 | 30 | 2 | 9 | 10 |
| Wait2 | 0 | 0 | 4 | 11 | 14 |
| C | 15 | 20 | 2 | 15 | 16 |
| D | 22 | 40 | 4 | 17 | 20 |

| Time | Activity | Cost-Rate | Materials | Accum. Cost |
|------|----------|-----------|-----------|-------------|
| 1 | A | 10 | 20 | 300 |
| 2 | A | 10 | 0 | 400 |
| 3 | A | 10 | 0 | 500 |
| 4 | W1 | 0 | 0 | 500 |
| 5 | W1 | 0 | 0 | 500 |
| 6 | W1 | 0 | 0 | 500 |
| 7 | W1 | 0 | 0 | 500 |
| 8 | W1 | 0 | 0 | 500 |
| 9 | B | 18 | 30 | 980 |
| 10 | B | 18 | 0 | 1160 |
| 11 | W2 | 0 | 0 | 1160 |
| 12 | W2 | 0 | 0 | 1160 |
| 13 | W2 | 0 | 0 | 1160 |
| 14 | W2 | 0 | 0 | 1160 |
| 15 | C | 15 | 20 | 1510 |
| 16 | C | 15 | 0 | 1660 |
| 17 | D | 22 | 40 | 2280 |
| 18 | D | 22 | 0 | 2500 |
| 19 | D | 22 | 0 | 2720 |
| 20 | D | 22 | 0 | 2940 |

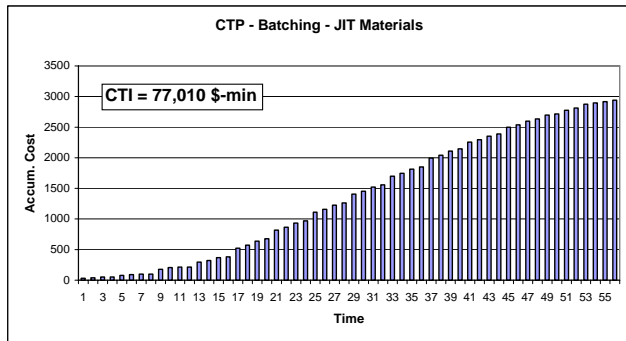
CTI 24090



Case 2: Batch for an order, JIT Materials

| Activity | Cost-Rate | Materials | Duration | Begin | End |
|----------|-----------|-----------|----------|-------|-----|
| A | 10 | 20 | 3 | 1 | 3 |
| Wait1 | 0 | 0 | 5 | 4 | 8 |
| B | 18 | 30 | 2 | 9 | 10 |
| Wait2 | 0 | 0 | 4 | 11 | 14 |
| C | 15 | 20 | 3 | 15 | 17 |
| D | 22 | 40 | 3 | 18 | 20 |

20

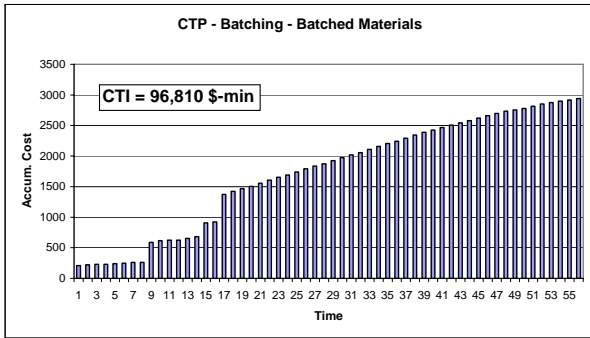


| Time | ACT-1 | ACT-2 | ACT-3 | ACT-4 | ACT-5 | ACT-6 | ACT-7 | ACT-8 | ACT-9 | ACT-10 | Cost-Rates | Materials | Accum. Cost |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|------------|-----------|-------------|
| 1 | A | | | | | | | | | | 10 | 20 | 30 |
| 2 | A | | | | | | | | | | 10 | | 40 |
| 3 | A | | | | | | | | | | 10 | | 50 |
| 4 | W1 | | | | | | | | | | 0 | | 50 |
| 5 | W1 | A | | | | | | | | | 10 | 20 | 80 |
| 6 | W1 | A | | | | | | | | | 10 | | 90 |
| 7 | W1 | A | | | | | | | | | 10 | | 100 |
| 8 | W1 | W1 | | | | | | | | | 0 | | 100 |
| 9 | B | W1 | A | | | | | | | | 28 | 50 | 178 |
| 10 | B | W1 | A | | | | | | | | 28 | | 206 |
| 11 | W2 | W1 | A | | | | | | | | 10 | | 216 |
| 12 | W2 | W1 | W1 | | | | | | | | 0 | | 216 |
| 13 | W2 | B | W1 | A | | | | | | | 28 | 50 | 294 |
| 14 | W2 | B | W1 | A | | | | | | | 28 | | 322 |
| 15 | C | W2 | W1 | W1 | | | | | | | 25 | 20 | 367 |
| 16 | C | W2 | W1 | W1 | | | | | | | 15 | | 382 |
| 17 | D | W2 | B | W1 | A | | | | | | 50 | 90 | 522 |
| 18 | D | W2 | B | W1 | A | | | | | | 50 | | 572 |
| 19 | D | C | W2 | W1 | A | | | | | | 47 | 20 | 639 |
| 20 | D | C | W2 | W1 | W1 | | | | | | 37 | | 676 |
| 21 | D | W2 | B | W1 | A | | | | | | 50 | 90 | 816 |
| 22 | D | W2 | B | W1 | A | | | | | | 50 | | 866 |
| 23 | D | C | W2 | W1 | A | | | | | | 47 | 20 | 933 |
| 24 | D | C | W2 | W1 | W1 | | | | | | 37 | | 970 |
| 25 | D | W2 | B | W1 | A | | | | | | 50 | 90 | 1110 |
| 26 | D | W2 | B | W1 | A | | | | | | 50 | | 1160 |
| 27 | D | C | W2 | W1 | A | | | | | | 47 | 20 | 1227 |
| 28 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1264 |
| 29 | D | W2 | B | W1 | A | | | | | | 50 | 90 | 1404 |
| 30 | D | W2 | B | W1 | A | | | | | | 50 | | 1454 |
| 31 | D | C | W2 | W1 | A | | | | | | 47 | 20 | 1521 |
| 32 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1558 |
| 33 | D | W2 | B | W1 | A | | | | | | 50 | 90 | 1698 |
| 34 | D | W2 | B | W1 | A | | | | | | 50 | | 1748 |
| 35 | D | C | W2 | W1 | A | | | | | | 47 | 20 | 1815 |
| 36 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1852 |
| 37 | D | W2 | B | W1 | A | | | | | | 50 | 90 | 1992 |
| 38 | D | W2 | B | W1 | A | | | | | | 50 | | 2042 |
| 39 | D | C | W2 | W1 | A | | | | | | 47 | 20 | 2109 |
| 40 | D | C | W2 | W1 | W1 | | | | | | 37 | | 2146 |
| 41 | D | W2 | B | W1 | A | | | | | | 40 | 70 | 2256 |
| 42 | D | W2 | B | W1 | A | | | | | | 40 | | 2296 |
| 43 | D | C | W2 | W1 | W1 | | | | | | 37 | 20 | 2353 |
| 44 | D | C | W2 | W1 | W1 | | | | | | 37 | | 2390 |
| 45 | D | W2 | B | W1 | A | | | | | | 40 | 70 | 2500 |
| 46 | D | W2 | B | W1 | A | | | | | | 40 | | 2540 |
| 47 | D | C | W2 | W1 | A | | | | | | 37 | 20 | 2597 |
| 48 | D | C | W2 | W1 | A | | | | | | 37 | | 2634 |
| 49 | D | W2 | B | W1 | A | | | | | | 22 | 40 | 2696 |
| 50 | D | W2 | B | W1 | A | | | | | | 22 | | 2718 |
| 51 | D | C | W2 | W1 | W1 | | | | | | 37 | 20 | 2775 |
| 52 | D | C | W2 | W1 | W1 | | | | | | 37 | | 2812 |
| 53 | D | W2 | B | W1 | A | | | | | | 22 | 40 | 2874 |
| 54 | D | W2 | B | W1 | A | | | | | | 22 | | 2896 |
| 55 | D | W2 | B | W1 | A | | | | | | 22 | | 2918 |
| 56 | D | W2 | B | W1 | A | | | | | | 22 | | 2940 |
| 57 | D | W2 | B | W1 | A | | | | | | 22 | | 2940 |
| 58 | | | | | | | | | | | | | |

CTI 77,010

Case 2: Batch for an order, Batched Materials

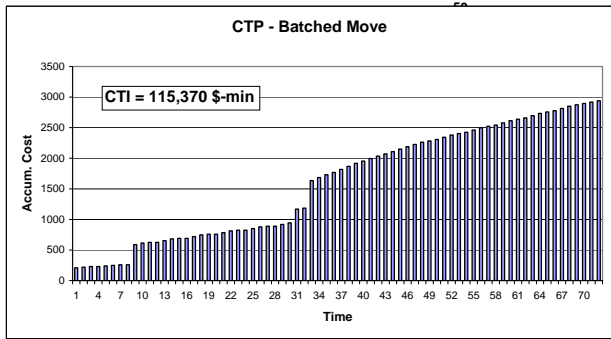
| Activity | Cost-Rate | Materials | Duration | Begin | End |
|----------|-----------|-----------|----------|-------|-----|
| A | 10 | 20 | 3 | 1 | 3 |
| Wait1 | 0 | 0 | 5 | 4 | 8 |
| B | 18 | 30 | 2 | 9 | 10 |
| Wait2 | 0 | 0 | 4 | 11 | 14 |
| C | 15 | 20 | 3 | 15 | 17 |
| D | 22 | 40 | 3 | 18 | 20 |



| Time | ACT-1 | ACT-2 | ACT-3 | ACT-4 | ACT-5 | ACT-6 | ACT-7 | ACT-8 | ACT-9 | ACT-10 | Cost-Rates | Materials | Accum. Cost |
|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|------------|-----------|-------------|
| 1 | A | | | | | | | | | | 10 | 200 | 210 |
| 2 | A | | | | | | | | | | 10 | | 220 |
| 3 | A | | | | | | | | | | 10 | | 230 |
| 4 | W1 | | | | | | | | | | 0 | | 230 |
| 5 | W1 | A | | | | | | | | | 10 | | 240 |
| 6 | W1 | A | | | | | | | | | 10 | | 250 |
| 7 | W1 | A | | | | | | | | | 10 | | 260 |
| 8 | W1 | W1 | | | | | | | | | 0 | | 260 |
| 9 | B | W1 | A | | | | | | | | 28 | 300 | 588 |
| 10 | B | W1 | A | | | | | | | | 28 | | 616 |
| 11 | W2 | W1 | A | | | | | | | | 10 | | 626 |
| 12 | W2 | W1 | W1 | | | | | | | | 0 | | 626 |
| 13 | W2 | B | W1 | A | | | | | | | 28 | | 654 |
| 14 | W2 | B | W1 | A | | | | | | | 28 | | 682 |
| 15 | C | W2 | W1 | A | | | | | | | 25 | 200 | 907 |
| 16 | C | W2 | W1 | W1 | | | | | | | 15 | | 922 |
| 17 | D | W2 | B | W1 | A | | | | | | 50 | 400 | 1372 |
| 18 | D | W2 | B | W1 | A | | | | | | 50 | | 1422 |
| 19 | D | C | W2 | W1 | A | | | | | | 47 | | 1469 |
| 20 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1506 |
| 21 | D | D | W2 | B | W1 | A | | | | | 50 | | 1556 |
| 22 | D | D | W2 | B | W1 | A | | | | | 50 | | 1606 |
| 23 | D | C | W2 | W1 | A | | | | | | 47 | | 1653 |
| 24 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1690 |
| 25 | D | D | W2 | B | W1 | A | | | | | 50 | | 1740 |
| 26 | D | D | W2 | B | W1 | A | | | | | 50 | | 1790 |
| 27 | D | C | W2 | W1 | A | | | | | | 47 | | 1837 |
| 28 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1874 |
| 29 | D | D | W2 | B | W1 | A | | | | | 50 | | 1924 |
| 30 | D | D | W2 | B | W1 | A | | | | | 50 | | 1974 |
| 31 | D | C | W2 | W1 | A | | | | | | 47 | | 2021 |
| 32 | D | C | W2 | W1 | W1 | | | | | | 37 | | 2058 |
| 33 | D | D | W2 | B | W1 | A | | | | | 50 | | 2108 |
| 34 | D | D | W2 | B | W1 | A | | | | | 50 | | 2158 |
| 35 | D | C | W2 | W1 | A | | | | | | 47 | | 2205 |
| 36 | D | C | W2 | W1 | W1 | | | | | | 37 | | 2242 |
| 37 | D | D | W2 | B | W1 | A | | | | | 50 | | 2292 |
| 38 | D | D | W2 | B | W1 | A | | | | | 50 | | 2342 |
| 39 | D | C | W2 | W1 | A | | | | | | 47 | | 2389 |
| 40 | D | C | W2 | W1 | W1 | | | | | | 37 | | 2426 |
| 41 | D | D | W2 | B | W1 | | | | | | 40 | | 2466 |
| 42 | D | D | W2 | B | W1 | | | | | | 40 | | 2506 |
| 43 | D | C | W2 | W1 | | | | | | | 37 | | 2543 |
| 44 | D | C | W2 | W1 | | | | | | | 37 | | 2580 |
| 45 | D | D | W2 | B | | | | | | | 40 | | 2620 |
| 46 | D | D | W2 | B | | | | | | | 40 | | 2660 |
| 47 | D | C | W2 | B | | | | | | | 37 | | 2697 |
| 48 | D | C | W2 | B | | | | | | | 37 | | 2734 |
| 49 | D | D | W2 | B | | | | | | | 22 | | 2756 |
| 50 | D | D | W2 | B | | | | | | | 22 | | 2778 |
| 51 | D | C | | | | | | | | | 37 | | 2815 |
| 52 | D | C | | | | | | | | | 37 | | 2852 |
| 53 | D | D | | | | | | | | | 22 | | 2874 |
| 54 | D | D | | | | | | | | | 22 | | 2896 |
| 55 | D | D | | | | | | | | | 22 | | 2918 |
| 56 | D | D | | | | | | | | | 22 | | 2940 |
| 57 | | | | | | | | | | | | | |
| 58 | | | | | | | | | | | | | |
| | | | | | | | | | | | | CTI | 96,810 |

Case 4: Batch for material handling requirements, move 5 units at a time between B and C

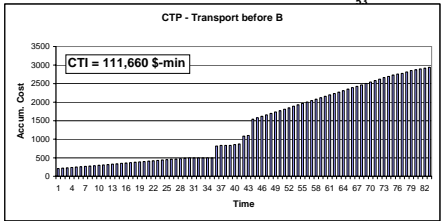
| Activity | Cost-Rate | Materials | Duration | Begin | End | Time | ACT-1 | ACT-2 | ACT-3 | ACT-4 | ACT-5 | ACT-6 | ACT-7 | ACT-8 | ACT-9 | ACT-10 | Cost-Rates | Materials | Accum. Cost | | |
|----------|-----------|-----------|----------|-------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|------------|-----------|-------------|--|--|
| A | 10 | 20 | 3 | 1 | 3 | 1 | A | | | | | | | | | | 10 | 200 | 210 | | |
| Wait1 | 0 | 0 | 5 | 4 | 8 | 2 | A | | | | | | | | | | 10 | | 220 | | |
| B | 18 | 30 | 2 | 9 | 10 | 3 | A | | | | | | | | | | 10 | | 230 | | |
| Wait2 | 0 | 0 | 4 | 11 | 14 | 4 | W1 | | | | | | | | | | 0 | | 230 | | |
| C | 15 | 20 | 3 | 15 | 17 | 5 | W1 | A | | | | | | | | | 10 | | 240 | | |
| D | 22 | 40 | 3 | 18 | 20 | 6 | W1 | A | | | | | | | | | 10 | | 250 | | |
| | | | 20 | | | 7 | W1 | A | | | | | | | | | 10 | | 260 | | |
| | | | | | | 8 | W1 | W1 | | | | | | | | | 0 | | 260 | | |
| | | | | | | 9 | B | W1 | A | | | | | | | | 28 | 300 | 588 | | |
| | | | | | | 10 | B | W1 | A | | | | | | | | 28 | | 616 | | |
| | | | | | | 11 | W2 | W1 | A | | | | | | | | 10 | | 626 | | |
| | | | | | | 12 | W2 | W1 | W1 | | | | | | | | 0 | | 626 | | |
| | | | | | | 13 | W2 | B | W1 | A | | | | | | | 28 | | 654 | | |
| | | | | | | 14 | W2 | B | W1 | A | | | | | | | 28 | | 682 | | |
| | | | | | | 15 | W2 | W1 | A | | | | | | | | 10 | | 692 | | |
| | | | | | | 16 | W2 | W1 | W1 | | | | | | | | 0 | | 692 | | |
| | | | | | | 17 | W2 | B | W1 | A | | | | | | | 28 | | 720 | | |
| | | | | | | 18 | W2 | B | W1 | A | | | | | | | 28 | | 748 | | |
| | | | | | | 19 | W2 | W1 | A | | | | | | | | 10 | | 758 | | |
| | | | | | | 20 | W2 | W1 | W1 | | | | | | | | 0 | | 758 | | |
| | | | | | | 21 | W2 | B | W1 | A | | | | | | | 28 | | 786 | | |
| | | | | | | 22 | W2 | B | W1 | A | | | | | | | 28 | | 814 | | |
| | | | | | | 23 | W2 | W1 | A | | | | | | | | 10 | | 824 | | |
| | | | | | | 24 | W2 | W1 | W1 | | | | | | | | 0 | | 824 | | |
| | | | | | | 25 | W2 | B | W1 | A | | | | | | | 28 | | 852 | | |
| | | | | | | 26 | W2 | B | W1 | A | | | | | | | 28 | | 880 | | |
| | | | | | | 27 | W2 | W1 | A | | | | | | | | 10 | | 890 | | |
| | | | | | | 28 | W2 | W1 | W1 | | | | | | | | 0 | | 890 | | |
| | | | | | | 29 | W2 | B | W1 | A | | | | | | | 28 | | 918 | | |
| | | | | | | 30 | W2 | B | W1 | A | | | | | | | 28 | | 946 | | |
| | | | | | | 31 | W2 | W1 | A | | | | | | | | 25 | 200 | 1171 | | |
| | | | | | | 32 | W2 | W1 | W1 | | | | | | | | 15 | | 1186 | | |
| | | | | | | 33 | D | W2 | B | W1 | A | | | | | | 50 | 400 | 1636 | | |
| | | | | | | 34 | D | W2 | B | W1 | A | | | | | | 50 | | 1686 | | |
| | | | | | | 35 | D | C | W2 | W1 | A | | | | | | 47 | | 1733 | | |
| | | | | | | 36 | D | C | W2 | W1 | A | | | | | | 37 | | 1770 | | |
| | | | | | | 37 | D | C | W2 | B | W1 | A | | | | | 50 | | 1820 | | |
| | | | | | | 38 | D | C | W2 | B | W1 | A | | | | | 50 | | 1870 | | |
| | | | | | | 39 | D | C | W2 | W1 | A | | | | | | 47 | | 1917 | | |
| | | | | | | 40 | D | C | W2 | W1 | W1 | | | | | | 37 | | 1954 | | |
| | | | | | | 41 | D | C | W2 | B | W1 | | | | | | 40 | | 1994 | | |
| | | | | | | 42 | D | C | W2 | B | W1 | | | | | | 40 | | 2034 | | |
| | | | | | | 43 | D | C | W2 | W1 | | | | | | | 37 | | 2071 | | |
| | | | | | | 44 | D | C | W2 | W1 | | | | | | | 37 | | 2108 | | |
| | | | | | | 45 | D | C | W2 | B | | | | | | | 40 | | 2148 | | |
| | | | | | | 46 | D | C | W2 | B | | | | | | | 40 | | 2188 | | |
| | | | | | | 47 | D | C | W2 | W1 | | | | | | | 37 | | 2225 | | |
| | | | | | | 48 | D | C | W2 | W1 | | | | | | | 37 | | 2262 | | |
| | | | | | | 49 | D | C | W2 | W1 | | | | | | | 22 | | 2284 | | |
| | | | | | | 50 | D | C | W2 | W1 | | | | | | | 22 | | 2306 | | |
| | | | | | | 51 | D | C | W2 | W1 | | | | | | | 37 | | 2343 | | |
| | | | | | | 52 | D | C | W2 | W1 | | | | | | | 37 | | 2380 | | |
| | | | | | | 53 | D | C | W2 | W1 | | | | | | | 22 | | 2402 | | |
| | | | | | | 54 | D | C | W2 | W1 | | | | | | | 22 | | 2424 | | |
| | | | | | | 55 | D | C | W2 | W1 | | | | | | | 37 | | 2461 | | |
| | | | | | | 56 | D | C | W2 | W1 | | | | | | | 37 | | 2498 | | |
| | | | | | | 57 | D | C | W2 | W1 | | | | | | | 22 | | 2520 | | |
| | | | | | | 58 | D | C | W2 | W1 | | | | | | | 22 | | 2542 | | |
| | | | | | | 59 | D | C | W2 | W1 | | | | | | | 37 | | 2579 | | |
| | | | | | | 60 | D | C | W2 | W1 | | | | | | | 37 | | 2616 | | |
| | | | | | | 61 | D | C | W2 | W1 | | | | | | | 22 | | 2638 | | |
| | | | | | | 62 | D | C | W2 | W1 | | | | | | | 22 | | 2660 | | |
| | | | | | | 63 | D | C | W2 | W1 | | | | | | | 37 | | 2697 | | |
| | | | | | | 64 | D | C | W2 | W1 | | | | | | | 37 | | 2734 | | |
| | | | | | | 65 | D | C | W2 | W1 | | | | | | | 22 | | 2756 | | |
| | | | | | | 66 | D | C | W2 | W1 | | | | | | | 22 | | 2778 | | |
| | | | | | | 67 | D | C | W2 | W1 | | | | | | | 37 | | 2815 | | |
| | | | | | | 68 | D | C | W2 | W1 | | | | | | | 37 | | 2852 | | |
| | | | | | | 69 | D | C | W2 | W1 | | | | | | | 22 | | 2874 | | |
| | | | | | | 70 | D | C | W2 | W1 | | | | | | | 22 | | 2896 | | |
| | | | | | | 71 | D | C | W2 | W1 | | | | | | | 22 | | 2918 | | |
| | | | | | | 72 | D | C | W2 | W1 | | | | | | | 22 | | 2940 | | |
| | | | | | | 73 | D | C | W2 | W1 | | | | | | | | | | | |
| | | | | | | 74 | D | C | W2 | W1 | | | | | | | | | | | |



CTI 115,370

Case 5a: Sequence the 10 units. All transported before B. Batched Materials

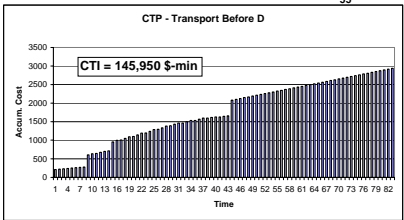
| Activity | Cost-Rate | Materials | Duration | Begin | End | Time | ACT-1 | ACT-2 | ACT-3 | ACT-4 | ACT-5 | ACT-6 | ACT-7 | ACT-8 | ACT-9 | ACT-10 | Cost-Rates | Materials | Accum. Cost |
|----------|-----------|-----------|----------|-------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|------------|-----------|-------------|
| A | 10 | 20 | 3 | 1 | 3 | 1 | A | | | | | | | | | | 10 | 200 | 210 |
| Wait1 | 0 | 0 | 5 | 4 | 8 | 2 | A | | | | | | | | | | 10 | | 220 |
| B | 18 | 30 | 2 | 9 | 10 | 3 | A | | | | | | | | | | 10 | | 230 |
| Wait2 | 0 | 0 | 4 | 11 | 14 | 4 | W1 | A | | | | | | | | | 10 | | 240 |
| C | 15 | 20 | 3 | 15 | 17 | 5 | W1 | A | | | | | | | | | 10 | | 250 |
| D | 22 | 40 | 3 | 18 | 20 | 6 | W1 | A | | | | | | | | | 10 | | 260 |
| | | | 20 | | | 7 | W1 | A | | | | | | | | | 10 | | 270 |
| | | | | | | 8 | W1 | A | | | | | | | | | 10 | | 280 |
| | | | | | | 9 | W1 | A | | | | | | | | | 10 | | 290 |
| | | | | | | 10 | W1 | A | | | | | | | | | 10 | | 300 |
| | | | | | | 11 | W1 | A | | | | | | | | | 10 | | 310 |
| | | | | | | 12 | W1 | A | | | | | | | | | 10 | | 320 |
| | | | | | | 13 | W1 | A | | | | | | | | | 10 | | 330 |
| | | | | | | 14 | W1 | A | | | | | | | | | 10 | | 340 |
| | | | | | | 15 | W1 | A | | | | | | | | | 10 | | 350 |
| | | | | | | 16 | W1 | A | | | | | | | | | 10 | | 360 |
| | | | | | | 17 | W1 | A | | | | | | | | | 10 | | 370 |
| | | | | | | 18 | W1 | A | | | | | | | | | 10 | | 380 |
| | | | | | | 19 | W1 | A | | | | | | | | | 10 | | 390 |
| | | | | | | 20 | W1 | A | | | | | | | | | 10 | | 400 |
| | | | | | | 21 | W1 | A | | | | | | | | | 10 | | 410 |
| | | | | | | 22 | W1 | A | | | | | | | | | 10 | | 420 |
| | | | | | | 23 | W1 | A | | | | | | | | | 10 | | 430 |
| | | | | | | 24 | W1 | A | | | | | | | | | 10 | | 440 |
| | | | | | | 25 | W1 | A | | | | | | | | | 10 | | 450 |
| | | | | | | 26 | W1 | A | | | | | | | | | 10 | | 460 |
| | | | | | | 27 | W1 | A | | | | | | | | | 10 | | 470 |
| | | | | | | 28 | W1 | A | | | | | | | | | 10 | | 480 |
| | | | | | | 29 | W1 | A | | | | | | | | | 10 | | 490 |
| | | | | | | 30 | W1 | A | | | | | | | | | 10 | | 500 |
| | | | | | | 31 | W1 | A | | | | | | | | | 10 | | 500 |
| | | | | | | 32 | W1 | A | | | | | | | | | 10 | | 500 |
| | | | | | | 33 | W1 | A | | | | | | | | | 10 | | 500 |
| | | | | | | 34 | W1 | A | | | | | | | | | 10 | | 500 |
| | | | | | | 35 | W1 | A | | | | | | | | | 10 | | 500 |
| | | | | | | 36 | B | | | | | | | | | | 18 | 300 | 518 |
| | | | | | | 37 | B | | | | | | | | | | 18 | | 536 |
| | | | | | | 38 | W2 | | | | | | | | | | 0 | | 536 |
| | | | | | | 39 | W2 | | | | | | | | | | 0 | | 536 |
| | | | | | | 40 | W2 | B | | | | | | | | | 18 | | 554 |
| | | | | | | 41 | W2 | B | | | | | | | | | 18 | | 572 |
| | | | | | | 42 | C | W2 | | | | | | | | | 15 | 200 | 587 |
| | | | | | | 43 | C | W2 | | | | | | | | | 15 | | 602 |
| | | | | | | 44 | D | W2 | B | | | | | | | | 40 | 400 | 642 |
| | | | | | | 45 | D | W2 | B | | | | | | | | 40 | | 682 |
| | | | | | | 46 | D | C | W2 | | | | | | | | 37 | | 719 |
| | | | | | | 47 | D | C | W2 | | | | | | | | 37 | | 756 |
| | | | | | | 48 | D | W2 | B | | | | | | | | 40 | | 796 |
| | | | | | | 49 | D | W2 | B | | | | | | | | 40 | | 836 |
| | | | | | | 50 | D | C | W2 | | | | | | | | 37 | | 873 |
| | | | | | | 51 | D | C | W2 | | | | | | | | 37 | | 910 |
| | | | | | | 52 | D | W2 | B | | | | | | | | 40 | | 950 |
| | | | | | | 53 | D | W2 | B | | | | | | | | 40 | | 990 |
| | | | | | | 54 | D | C | W2 | | | | | | | | 37 | | 1027 |
| | | | | | | 55 | D | C | W2 | | | | | | | | 37 | | 1064 |
| | | | | | | 56 | D | W2 | B | | | | | | | | 40 | | 1104 |
| | | | | | | 57 | D | W2 | B | | | | | | | | 40 | | 1144 |
| | | | | | | 58 | D | C | W2 | | | | | | | | 37 | | 1181 |
| | | | | | | 59 | D | C | W2 | | | | | | | | 37 | | 1218 |
| | | | | | | 60 | D | W2 | B | | | | | | | | 40 | | 1258 |
| | | | | | | 61 | D | W2 | B | | | | | | | | 40 | | 1298 |
| | | | | | | 62 | D | C | W2 | | | | | | | | 37 | | 1335 |
| | | | | | | 63 | D | C | W2 | | | | | | | | 37 | | 1372 |
| | | | | | | 64 | D | W2 | B | | | | | | | | 40 | | 1412 |
| | | | | | | 65 | D | W2 | B | | | | | | | | 40 | | 1452 |
| | | | | | | 66 | D | C | W2 | | | | | | | | 37 | | 1489 |
| | | | | | | 67 | D | C | W2 | | | | | | | | 37 | | 1526 |
| | | | | | | 68 | D | W2 | B | | | | | | | | 40 | | 1566 |
| | | | | | | 69 | D | W2 | B | | | | | | | | 40 | | 1606 |
| | | | | | | 70 | D | C | W2 | | | | | | | | 37 | | 1643 |
| | | | | | | 71 | D | C | W2 | | | | | | | | 37 | | 1680 |
| | | | | | | 72 | D | W2 | B | | | | | | | | 40 | | 1720 |
| | | | | | | 73 | D | W2 | B | | | | | | | | 40 | | 1760 |
| | | | | | | 74 | D | C | W2 | | | | | | | | 37 | | 1797 |
| | | | | | | 75 | D | C | W2 | | | | | | | | 37 | | 1834 |
| | | | | | | 76 | D | W2 | B | | | | | | | | 40 | | 1874 |
| | | | | | | 77 | D | W2 | B | | | | | | | | 40 | | 1914 |
| | | | | | | 78 | D | C | W2 | | | | | | | | 37 | | 1951 |
| | | | | | | 79 | D | C | W2 | | | | | | | | 37 | | 1988 |
| | | | | | | 80 | D | D | | | | | | | | | 22 | | 2010 |
| | | | | | | 81 | D | D | | | | | | | | | 22 | | 2032 |
| | | | | | | 82 | D | D | | | | | | | | | 22 | | 2054 |
| | | | | | | 83 | D | D | | | | | | | | | 22 | | 2076 |



CTI 111,660

Case 5b: Sequence the 10 units. All transported before D. Batched Materials

| Activity | Cost-Rate | Materials | Duration | Begin | End | Time | ACT-1 | ACT-2 | ACT-3 | ACT-4 | ACT-5 | ACT-6 | ACT-7 | ACT-8 | ACT-9 | ACT-10 | Cost-Rates | Materials | Accum. Cost |
|----------|-----------|-----------|----------|-------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|------------|-----------|-------------|
| A | 10 | 20 | 3 | 1 | 3 | 1 | A | | | | | | | | | | 10 | 200 | 210 |
| Wait1 | 0 | 0 | 5 | 4 | 8 | 2 | A | | | | | | | | | | 10 | | 220 |
| B | 18 | 30 | 2 | 9 | 10 | 3 | A | | | | | | | | | | 10 | | 230 |
| Wait2 | 0 | 0 | 4 | 11 | 14 | 4 | W1 | A | | | | | | | | | 10 | | 240 |
| C | 15 | 20 | 3 | 15 | 17 | 5 | W1 | A | | | | | | | | | 10 | | 250 |
| D | 22 | 40 | 20 | 18 | 20 | 6 | W1 | A | | | | | | | | | 10 | | 260 |
| | | | | | | 7 | W1 | W1 | A | | | | | | | | 10 | | 270 |
| | | | | | | 8 | W1 | W1 | A | | | | | | | | 10 | | 280 |
| | | | | | | 9 | B | W1 | A | | | | | | | | 300 | | 608 |
| | | | | | | 10 | B | W1 | W1 | A | | | | | | | 28 | | 636 |
| | | | | | | 11 | W2 | W1 | W1 | A | | | | | | | 10 | | 646 |
| | | | | | | 12 | W2 | B | W1 | A | | | | | | | 28 | | 674 |
| | | | | | | 13 | W2 | B | W1 | W1 | A | | | | | | 28 | | 702 |
| | | | | | | 14 | W2 | W1 | W1 | W1 | A | | | | | | 10 | | 712 |
| | | | | | | 15 | C | W2 | B | W1 | W1 | A | | | | | 43 | 200 | 955 |
| | | | | | | 16 | W2 | W1 | W1 | W1 | W1 | A | | | | | 43 | | 998 |
| | | | | | | 17 | W2 | W2 | W1 | W1 | W1 | A | | | | | 10 | | 1008 |
| | | | | | | 18 | C | W2 | B | W1 | W1 | A | | | | | 43 | | 1051 |
| | | | | | | 19 | C | W2 | B | W1 | W1 | A | A | | | | 43 | | 1094 |
| | | | | | | 20 | | | W2 | W1 | W1 | W1 | A | | | | 10 | | 1104 |
| | | | | | | 21 | | | W2 | W1 | W1 | W1 | A | | | | 43 | | 1147 |
| | | | | | | 22 | | | C | W2 | B | W1 | W1 | A | | | 43 | | 1190 |
| | | | | | | 23 | | | C | W2 | W1 | W1 | W1 | A | | | 10 | | 1200 |
| | | | | | | 24 | | | C | W2 | B | W1 | W1 | A | | | 43 | | 1243 |
| | | | | | | 25 | | | C | W2 | B | W1 | W1 | A | | | 43 | | 1286 |
| | | | | | | 26 | | | C | W2 | B | W1 | W1 | A | | | 10 | | 1296 |
| | | | | | | 27 | | | C | W2 | B | W1 | W1 | A | | | 43 | | 1339 |
| | | | | | | 28 | | | C | W2 | B | W1 | W1 | A | | | 43 | | 1382 |
| | | | | | | 29 | | | C | W2 | B | W1 | W1 | A | | | 10 | | 1392 |
| | | | | | | 30 | | | C | W2 | B | W1 | W1 | A | | | 43 | | 1435 |
| | | | | | | 31 | | | C | W2 | B | W1 | W1 | A | | | 33 | | 1468 |
| | | | | | | 32 | | | C | W2 | B | W1 | W1 | A | | | 0 | | 1468 |
| | | | | | | 33 | | | C | W2 | B | W1 | W1 | A | | | 33 | | 1501 |
| | | | | | | 34 | | | C | W2 | B | W1 | W1 | A | | | 33 | | 1534 |
| | | | | | | 35 | | | C | W2 | B | W1 | W1 | A | | | 0 | | 1534 |
| | | | | | | 36 | | | C | W2 | B | W1 | W1 | A | | | 33 | | 1567 |
| | | | | | | 37 | | | C | W2 | B | W1 | W1 | A | | | 33 | | 1600 |
| | | | | | | 38 | | | C | W2 | B | W1 | W1 | A | | | 0 | | 1600 |
| | | | | | | 39 | | | C | W2 | B | W1 | W1 | A | | | 15 | | 1615 |
| | | | | | | 40 | | | C | W2 | B | W1 | W1 | A | | | 15 | | 1630 |
| | | | | | | 41 | | | C | W2 | B | W1 | W1 | A | | | 15 | | 1630 |
| | | | | | | 42 | | | C | W2 | B | W1 | W1 | A | | | 15 | | 1645 |
| | | | | | | 43 | | | C | W2 | B | W1 | W1 | A | | | 15 | | 1660 |
| | | | | | | 44 | D | | | | | | | | | | 22 | 400 | 2082 |
| | | | | | | 45 | D | | | | | | | | | | 22 | | 2104 |
| | | | | | | 46 | D | | | | | | | | | | 22 | | 2126 |
| | | | | | | 47 | D | | | | | | | | | | 22 | | 2148 |
| | | | | | | 48 | | D | | | | | | | | | 22 | | 2170 |
| | | | | | | 49 | | D | | | | | | | | | 22 | | 2192 |
| | | | | | | 50 | | D | | | | | | | | | 22 | | 2214 |
| | | | | | | 51 | | D | | | | | | | | | 22 | | 2236 |
| | | | | | | 52 | | D | | | | | | | | | 22 | | 2258 |
| | | | | | | 53 | | D | | | | | | | | | 22 | | 2280 |
| | | | | | | 54 | | D | | | | | | | | | 22 | | 2302 |
| | | | | | | 55 | | D | | | | | | | | | 22 | | 2324 |
| | | | | | | 56 | | D | | | | | | | | | 22 | | 2346 |
| | | | | | | 57 | | D | | | | | | | | | 22 | | 2368 |
| | | | | | | 58 | | D | | | | | | | | | 22 | | 2390 |
| | | | | | | 59 | | D | | | | | | | | | 22 | | 2412 |
| | | | | | | 60 | | D | | | | | | | | | 22 | | 2434 |
| | | | | | | 61 | | D | | | | | | | | | 22 | | 2456 |
| | | | | | | 62 | | D | | | | | | | | | 22 | | 2478 |
| | | | | | | 63 | | D | | | | | | | | | 22 | | 2500 |
| | | | | | | 64 | | D | | | | | | | | | 22 | | 2522 |
| | | | | | | 65 | | D | | | | | | | | | 22 | | 2544 |
| | | | | | | 66 | | D | | | | | | | | | 22 | | 2566 |
| | | | | | | 67 | | D | | | | | | | | | 22 | | 2588 |
| | | | | | | 68 | | D | | | | | | | | | 22 | | 2610 |
| | | | | | | 69 | | D | | | | | | | | | 22 | | 2632 |
| | | | | | | 70 | | D | | | | | | | | | 22 | | 2654 |
| | | | | | | 71 | | D | | | | | | | | | 22 | | 2676 |
| | | | | | | 72 | | D | | | | | | | | | 22 | | 2698 |
| | | | | | | 73 | | D | | | | | | | | | 22 | | 2720 |
| | | | | | | 74 | | D | | | | | | | | | 22 | | 2742 |
| | | | | | | 75 | | D | | | | | | | | | 22 | | 2764 |
| | | | | | | 76 | | D | | | | | | | | | 22 | | 2786 |
| | | | | | | 77 | | D | | | | | | | | | 22 | | 2808 |
| | | | | | | 78 | | D | | | | | | | | | 22 | | 2830 |
| | | | | | | 79 | | D | | | | | | | | | 22 | | 2852 |
| | | | | | | 80 | | D | | | | | | | | | 22 | | 2874 |
| | | | | | | 81 | | D | | | | | | | | | 22 | | 2896 |
| | | | | | | 82 | | D | | | | | | | | | 22 | | 2918 |
| | | | | | | 83 | | D | | | | | | | | | 22 | | 2940 |
| | | | | | | | | | | | | | | | | | | | CTI 145,950 |



Appendix B: SIMAN code of the simulation model.

```

; Model statements for module: Create 1
;
75$ CREATE, 1,MinutesToBaseTime(0.0),Entity 1:MinutesToBaseTime(NORM( 80,2)):NEXT(76$);
76$ ASSIGN: Order Arrival.NumberOut=Order Arrival.NumberOut + 1:NEXT(27$);

;
;
; Model statements for module: Assign 8
;
27$ ASSIGN: RES1_CR=.0278:
RES2_CR=.0336:
RES3_CR=.3819:
RES4_CR=.0336:
RES5_CR=.2222:
RES6_CR=.1042:
RES7_CR=.1389:
RES8_CR=.2778:
RES9_CR=1.2153:
RES10_CR=.9722:
RES11_CR=.4167:
RES13_CR=.0336:
RES12_CR=.1389:
MAT_C=2:
MAT_E=1:
MAT_H=7:
TRANSP_K=10:
TRANSP_L=10:
MAT_N=15:NEXT(39$);

;
;
; Model statements for module: Hold 4
;
39$ QUEUE, Hold_A.Queue;

```

```

SCAN:          STATE(RES1)==IDLE_RES:NEXT(41$);

;
;
; Model statements for module:  Assign 22
;
41$          ASSIGN:          T_start_A=TNOW:NEXT(0$);

;
;
; Model statements for module:  Process 1
;
0$           ASSIGN:          A _ Order Reception.NumberIn=A _ Order Reception.NumberIn + 1:
108$        STACK,           A _ Order Reception.WIP=A _ Order Reception.WIP+1;
                                1:Save:NEXT(82$);

82$          QUEUE,          A _ Order Reception.Queue;
81$          SEIZE,          2,VA:
                                RES1,1:NEXT(80$);

80$          DELAY:          Normal(10,.2),,VA:NEXT(123$);

123$        ASSIGN:          A _ Order Reception.WaitTime=A _ Order Reception.WaitTime + Diff.WaitTime;
87$          TALLY:          A _ Order Reception.WaitTimePerEntity,Diff.WaitTime,1;
124$        ASSIGN:          A _ Order Reception.WaitCost=A _ Order Reception.WaitCost + Diff.WaitCost;
85$          TALLY:          A _ Order Reception.WaitCostPerEntity,Diff.WaitCost,1;
89$          TALLY:          A _ Order Reception.TotalTimePerEntity,Diff.StartTime,1;
90$          TALLY:          A _ Order Reception.TotalCostPerEntity,
                                Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;

113$        ASSIGN:          A _ Order Reception.VATime=A _ Order Reception.VATime + Diff.VATime;
114$        TALLY:          A _ Order Reception.VATimePerEntity,Diff.VATime,1;
118$        ASSIGN:          A _ Order Reception.VACost=A _ Order Reception.VACost + Diff.VACost;
115$        TALLY:          A _ Order Reception.VACostPerEntity,Diff.VACost,1;
79$          RELEASE:        RES1,1;
128$        STACK,           1:Destroy:NEXT(127$);

```

```

127$      ASSIGN:      A _ Order Reception.NumberOut=A _ Order Reception.NumberOut + 1:
                A _ Order Reception.WIP=A _ Order Reception.WIP-1:NEXT(21$);

;
;
; Model statements for module:  Assign 2
;
21$      ASSIGN:      T_end_A=TNOW:NEXT(42$);

;
;
; Model statements for module:  Hold 5
;
42$      QUEUE,      Hold_B.Queue;
                SCAN:      STATE(RES2)==IDLE_RES:NEXT(44$);

;
;
; Model statements for module:  Assign 23
;
44$      ASSIGN:      T_start_B=TNOW:NEXT(1$);

;
;
; Model statements for module:  Process 2
;
1$      ASSIGN:      B_Order Processing.NumberIn=B_Order Processing.NumberIn + 1:
                B_Order Processing.WIP=B_Order Processing.WIP+1;
159$     STACK,      1:Save:NEXT(133$);

133$     QUEUE,      B_Order Processing.Queue;
132$     SEIZE,      2,VA:
                RES2,1:NEXT(131$);

```

```

131$      DELAY:          Normal(40,1),,VA:NEXT(174$);

174$      ASSIGN:        B_Order Processing.WaitTime=B_Order Processing.WaitTime + Diff.WaitTime;
138$      TALLY:         B_Order Processing.WaitTimePerEntity,Diff.WaitTime,1;
175$      ASSIGN:        B_Order Processing.WaitCost=B_Order Processing.WaitCost + Diff.WaitCost;
136$      TALLY:         B_Order Processing.WaitCostPerEntity,Diff.WaitCost,1;
140$      TALLY:         B_Order Processing.TotalTimePerEntity,Diff.StartTime,1;
141$      TALLY:         B_Order Processing.TotalCostPerEntity,
                        Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
164$      ASSIGN:        B_Order Processing.VATime=B_Order Processing.VATime + Diff.VATime;
165$      TALLY:         B_Order Processing.VATimePerEntity,Diff.VATime,1;
169$      ASSIGN:        B_Order Processing.VACost=B_Order Processing.VACost + Diff.VACost;
166$      TALLY:         B_Order Processing.VACostPerEntity,Diff.VACost,1;
130$      RELEASE:      RES2,1;
179$      STACK,        1:Destroy:NEXT(178$);

178$      ASSIGN:        B_Order Processing.NumberOut=B_Order Processing.NumberOut + 1;
                        B_Order Processing.WIP=B_Order Processing.WIP-1:NEXT(22$);

;
;
;   Model statements for module:  Assign 3
;
22$      ASSIGN:        T_end_B=TNOW:NEXT(2$);

;
;
;   Model statements for module:  Separate 1
;
2$      DUPLICATE,      100 - 0:
                        1,183$,0:NEXT(182$);

182$      ASSIGN:        To_Supplier_1.NumberOut Orig=To_Supplier_1.NumberOut Orig + 1:NEXT(55$);
183$      ASSIGN:        To_Supplier_1.NumberOut Dup=To_Supplier_1.NumberOut Dup + 1:NEXT(45$);

```

```

;
;
;   Model statements for module:   Hold 11
;
55$   QUEUE,           Hold_C.Queue;
      SCAN:           STATE(RES3)==IDLE_RES:NEXT(57$);

;
;
;   Model statements for module:   Assign 30
;
57$   ASSIGN:          T_start_C=TNOW:NEXT(4$);

;
;
;   Model statements for module:   Process 4
;
4$    ASSIGN:          C_Operation.NumberIn=C_Operation.NumberIn + 1;
      C_Operation.WIP=C_Operation.WIP+1;
213$  STACK,           1:Save:NEXT(187$);

187$  QUEUE,           C_Operation.Queue;
186$  SEIZE,            2,VA:
      RES3,1:NEXT(185$);

185$  DELAY:           Normal(50,2),,VA:NEXT(228$);

228$  ASSIGN:          C_Operation.WaitTime=C_Operation.WaitTime + Diff.WaitTime;
192$  TALLY:           C_Operation.WaitTimePerEntity,Diff.WaitTime,1;
229$  ASSIGN:          C_Operation.WaitCost=C_Operation.WaitCost + Diff.WaitCost;
190$  TALLY:           C_Operation.WaitCostPerEntity,Diff.WaitCost,1;
194$  TALLY:           C_Operation.TotalTimePerEntity,Diff.StartTime,1;
195$  TALLY:           C_Operation.TotalCostPerEntity,
      Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
218$  ASSIGN:          C_Operation.VATime=C_Operation.VATime + Diff.VATime;

```



```

219$      TALLY:          C_Operation.VATimePerEntity,Diff.VATime,1;
223$      ASSIGN:         C_Operation.VACost=C_Operation.VACost + Diff.VACost;
220$      TALLY:          C_Operation.VACostPerEntity,Diff.VACost,1;
184$      RELEASE:       RES3,1;
233$      STACK,         1:Destroy:NEXT(232$);

232$      ASSIGN:         C_Operation.NumberOut=C_Operation.NumberOut + 1:
                        C_Operation.WIP=C_Operation.WIP-1:NEXT(23$);

;
;
;   Model statements for module:  Assign 4
;
23$      ASSIGN:         T_end_C=TNOW:NEXT(5$);

;
;
;   Model statements for module:  Separate 2
;
5$      DUPLICATE,      100 - 0:
                        1,237$,0:NEXT(236$);

236$      ASSIGN:         To_Supplier2.NumberOut Orig=To_Supplier2.NumberOut Orig + 1:NEXT(67$);
237$      ASSIGN:         To_Supplier2.NumberOut Dup=To_Supplier2.NumberOut Dup + 1:NEXT(58$);

;
;
;   Model statements for module:  Hold 15
;
67$      QUEUE,          Hold_J.Queue;
        SCAN:           STATE(RES5)==IDLE_RES:NEXT(69$);

;

```

```

;
; Model statements for module: Assign 34
;
69$      ASSIGN:      T_start_J=TNOW:NEXT(6$);

;
;
; Model statements for module: Process 5
;
6$       ASSIGN:      J_Operation.NumberIn=J_Operation.NumberIn + 1:
                J_Operation.WIP=J_Operation.WIP+1;
267$     STACK,      1:Save:NEXT(241$);

241$     QUEUE,      J_Operation.Queue;
240$     SEIZE,      2,VA:
                RES5,1:NEXT(239$);

239$     DELAY:      Normal(30,.5),,VA:NEXT(282$);

282$     ASSIGN:      J_Operation.WaitTime=J_Operation.WaitTime + Diff.WaitTime;
246$     TALLY:      J_Operation.WaitTimePerEntity,Diff.WaitTime,1;
283$     ASSIGN:      J_Operation.WaitCost=J_Operation.WaitCost + Diff.WaitCost;
244$     TALLY:      J_Operation.WaitCostPerEntity,Diff.WaitCost,1;
248$     TALLY:      J_Operation.TotalTimePerEntity,Diff.StartTime,1;
249$     TALLY:      J_Operation.TotalCostPerEntity,
                Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
272$     ASSIGN:      J_Operation.VATime=J_Operation.VATime + Diff.VATime;
273$     TALLY:      J_Operation.VATimePerEntity,Diff.VATime,1;
277$     ASSIGN:      J_Operation.VACost=J_Operation.VACost + Diff.VACost;
274$     TALLY:      J_Operation.VACostPerEntity,Diff.VACost,1;
238$     RELEASE:    RES5,1;
287$     STACK,      1:Destroy:NEXT(286$);

286$     ASSIGN:      J_Operation.NumberOut=J_Operation.NumberOut + 1:
                J_Operation.WIP=J_Operation.WIP-1:NEXT(33$);

```

```

;
;
;   Model statements for module:  Assign 14
;
33$       ASSIGN:           T_end_J=TNOW:NEXT(14$);

;
;
;   Model statements for module:  Batch 1
;
14$       QUEUE,           Prepare_Assembly.Queue;
289$      GROUP,           Entity.SerialNumber,Permanent:3,Last:NEXT(290$);

290$      ASSIGN:           Prepare_Assembly.NumberOut=Prepare_Assembly.NumberOut + 1:NEXT(54$);

;
;
;   Model statements for module:  Assign 29
;
54$       ASSIGN:           T_start_M=TNOW:NEXT(15$);

;
;
;   Model statements for module:  Process 13
;
15$       ASSIGN:           M_Assembly.NumberIn=M_Assembly.NumberIn + 1:
M_Assembly.WIP=M_Assembly.WIP+1;
320$      STACK,           1:Save:NEXT(294$);

294$      QUEUE,           M_Assembly.Queue;
293$      SEIZE,           2,VA:
RES6,1:NEXT(292$);

292$      DELAY:           Normal(90,2.5),,VA:NEXT(335$);

```

```

335$      ASSIGN:      M_Assembly.WaitTime=M_Assembly.WaitTime + Diff.WaitTime;
299$      TALLY:      M_Assembly.WaitTimePerEntity,Diff.WaitTime,1;
336$      ASSIGN:      M_Assembly.WaitCost=M_Assembly.WaitCost + Diff.WaitCost;
297$      TALLY:      M_Assembly.WaitCostPerEntity,Diff.WaitCost,1;
301$      TALLY:      M_Assembly.TotalTimePerEntity,Diff.StartTime,1;
302$      TALLY:      M_Assembly.TotalCostPerEntity,
Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
325$      ASSIGN:      M_Assembly.VATime=M_Assembly.VATime + Diff.VATime;
326$      TALLY:      M_Assembly.VATimePerEntity,Diff.VATime,1;
330$      ASSIGN:      M_Assembly.VACost=M_Assembly.VACost + Diff.VACost;
327$      TALLY:      M_Assembly.VACostPerEntity,Diff.VACost,1;
291$      RELEASE:    RES6,1;
340$      STACK,      1:Destroy:NEXT(339$);

339$      ASSIGN:      M_Assembly.NumberOut=M_Assembly.NumberOut + 1:
M_Assembly.WIP=M_Assembly.WIP-1:NEXT(34$);

;
;
; Model statements for module: Assign 15
;
34$      ASSIGN:      T_end_M=TNOW:NEXT(70$);

;
;
; Model statements for module: Hold 16
;
70$      QUEUE,      Hold_N.Queue;
SCAN:      STATE(RES7)==IDLE_RES:NEXT(72$);

;
;
; Model statements for module: Assign 35
;
72$      ASSIGN:      T_start_N=TNOW:NEXT(16$);

```

```

;
;
;   Model statements for module:  Process 14
;
16$      ASSIGN:      N_Packaging.NumberIn=N_Packaging.NumberIn + 1:
                        N_Packaging.WIP=N_Packaging.WIP+1;
371$      STACK,      1:Save:NEXT(345$);

345$      QUEUE,      N_Packaging.Queue;
344$      SEIZE,      2,VA:
                        RES7,1:NEXT(343$);

343$      DELAY:      Normal(50,2),,VA:NEXT(386$);

386$      ASSIGN:      N_Packaging.WaitTime=N_Packaging.WaitTime + Diff.WaitTime;
350$      TALLY:      N_Packaging.WaitTimePerEntity,Diff.WaitTime,1;
387$      ASSIGN:      N_Packaging.WaitCost=N_Packaging.WaitCost + Diff.WaitCost;
348$      TALLY:      N_Packaging.WaitCostPerEntity,Diff.WaitCost,1;
352$      TALLY:      N_Packaging.TotalTimePerEntity,Diff.StartTime,1;
353$      TALLY:      N_Packaging.TotalCostPerEntity,
                        Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
376$      ASSIGN:      N_Packaging.VATime=N_Packaging.VATime + Diff.VATime;
377$      TALLY:      N_Packaging.VATimePerEntity,Diff.VATime,1;
381$      ASSIGN:      N_Packaging.VACost=N_Packaging.VACost + Diff.VACost;
378$      TALLY:      N_Packaging.VACostPerEntity,Diff.VACost,1;
342$      RELEASE:    RES7,1;
391$      STACK,      1:Destroy:NEXT(390$);

390$      ASSIGN:      N_Packaging.NumberOut=N_Packaging.NumberOut + 1:
                        N_Packaging.WIP=N_Packaging.WIP-1:NEXT(74$);

;
;
;   Model statements for module:  Assign 39
;

```

```

74$      ASSIGN:      T_start_P=TNOW:
                          T_end_N=TNOW:NEXT(17$);

;
;
;   Model statements for module:  Process 15
;
17$      ASSIGN:      P_FG_Storage.NumberIn=P_FG_Storage.NumberIn + 1:
                          P_FG_Storage.WIP=P_FG_Storage.WIP+1;
422$     STACK,      1:Save:NEXT(394$);

394$     DELAY:      2400,,VA:NEXT(403$);

403$     TALLY:      P_FG_Storage.TotalTimePerEntity,Diff.StartTime,1;
404$     TALLY:      P_FG_Storage.TotalCostPerEntity,
                          Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
427$     ASSIGN:      P_FG_Storage.VATime=P_FG_Storage.VATime + Diff.VATime;
428$     TALLY:      P_FG_Storage.VATimePerEntity,Diff.VATime,1;
432$     ASSIGN:      P_FG_Storage.VACost=P_FG_Storage.VACost + Diff.VACost;
429$     TALLY:      P_FG_Storage.VACostPerEntity,Diff.VACost,1;
442$     STACK,      1:Destroy:NEXT(441$);

441$     ASSIGN:      P_FG_Storage.NumberOut=P_FG_Storage.NumberOut + 1:
                          P_FG_Storage.WIP=P_FG_Storage.WIP-1:NEXT(35$);

;
;
;   Model statements for module:  Assign 17
;
35$      ASSIGN:      T_end_P=TNOW:NEXT(37$);

;
;
;   Model statements for module:  Hold 3
;

```

```

37$      QUEUE,      Hold_O.Queue;
        SCAN:      STATE(RES8)== IDLE_RES:NEXT(73$);

;
;
; Model statements for module: Assign 38
;
73$      ASSIGN:      T_start_O=TNOW:NEXT(18$);

;
;
; Model statements for module: Process 16
;
18$      ASSIGN:      O_Shipping.NumberIn=O_Shipping.NumberIn + 1;
        O_Shipping.WIP=O_Shipping.WIP+1;
473$     STACK,      1:Save:NEXT(447$);

447$     QUEUE,      O_Shipping.Queue;
446$     SEIZE,      2,VA:
        RES8,1:NEXT(445$);

445$     DELAY:      Normal(10,.4),,VA:NEXT(488$);

488$     ASSIGN:      O_Shipping.WaitTime=O_Shipping.WaitTime + Diff.WaitTime;
452$     TALLY:      O_Shipping.WaitTimePerEntity,Diff.WaitTime,1;
489$     ASSIGN:      O_Shipping.WaitCost=O_Shipping.WaitCost + Diff.WaitCost;
450$     TALLY:      O_Shipping.WaitCostPerEntity,Diff.WaitCost,1;
454$     TALLY:      O_Shipping.TotalTimePerEntity,Diff.StartTime,1;
455$     TALLY:      O_Shipping.TotalCostPerEntity,
        Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;

478$     ASSIGN:      O_Shipping.VATime=O_Shipping.VATime + Diff.VATime;
479$     TALLY:      O_Shipping.VATimePerEntity,Diff.VATime,1;
483$     ASSIGN:      O_Shipping.VACost=O_Shipping.VACost + Diff.VACost;
480$     TALLY:      O_Shipping.VACostPerEntity,Diff.VACost,1;
444$     RELEASE:    RES8,1;
493$     STACK,      1:Destroy:NEXT(492$);

```

```

492$      ASSIGN:      O_Shipping.NumberOut=O_Shipping.NumberOut + 1:
                        O_Shipping.WIP=O_Shipping.WIP-1:NEXT(36$);

;
;
; Model statements for module:  Assign 18
;
36$      ASSIGN:      CTI=CTI_Entity(1,1):
                        T_end_O=TNOW:NEXT(20$);

;
;
; Model statements for module:  Record 1
;
20$      TALLY:      Cost_Time_Investment,CTI,1:NEXT(19$);

;
;
; Model statements for module:  Dispose 1
;
19$      ASSIGN:      Exit_Sysyem.NumberOut=Exit_Sysyem.NumberOut + 1;
495$     DISPOSE:     Yes;

;
;
; Model statements for module:  Hold 12
;
58$      QUEUE,      Hold_E.Queue;
          SCAN:      STATE(RES13)==IDLE_RES:NEXT(60$);

;
;

```



```

; Model statements for module: Assign 31
;
60$      ASSIGN:      T_start_E=TNOW:NEXT(7$);

;
;
; Model statements for module: Process 6
;
7$       ASSIGN:      E_Info_To_Supl.NumberIn=E_Info_To_Supl.NumberIn + 1:
                    E_Info_To_Supl.WIP=E_Info_To_Supl.WIP+1;
525$    STACK,       1:Save:NEXT(499$);

499$    QUEUE,       E_Info_To_Supl.Queue;
498$    SEIZE,       2,VA:
                    RES13,1:NEXT(497$);

497$    DELAY:       Normal(20,.4),,VA:NEXT(540$);

540$    ASSIGN:      E_Info_To_Supl.WaitTime=E_Info_To_Supl.WaitTime + Diff.WaitTime;
504$    TALLY:       E_Info_To_Supl.WaitTimePerEntity,Diff.WaitTime,1;
541$    ASSIGN:      E_Info_To_Supl.WaitCost=E_Info_To_Supl.WaitCost + Diff.WaitCost;
502$    TALLY:       E_Info_To_Supl.WaitCostPerEntity,Diff.WaitCost,1;
506$    TALLY:       E_Info_To_Supl.TotalTimePerEntity,Diff.StartTime,1;
507$    TALLY:       E_Info_To_Supl.TotalCostPerEntity,
                    Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
530$    ASSIGN:      E_Info_To_Supl.VATime=E_Info_To_Supl.VATime + Diff.VATime;
531$    TALLY:       E_Info_To_Supl.VATimePerEntity,Diff.VATime,1;
535$    ASSIGN:      E_Info_To_Supl.VACost=E_Info_To_Supl.VACost + Diff.VACost;
532$    TALLY:       E_Info_To_Supl.VACostPerEntity,Diff.VACost,1;
496$    RELEASE:    RES13,1;
545$    STACK,       1:Destroy:NEXT(544$);

544$    ASSIGN:      E_Info_To_Supl.NumberOut=E_Info_To_Supl.NumberOut + 1:
                    E_Info_To_Supl.WIP=E_Info_To_Supl.WIP-1:NEXT(29$);

;

```

```

;
; Model statements for module: Assign 10
;
29$      ASSIGN:      T_end_E=TNOW:NEXT(61$);

;
;
; Model statements for module: Hold 13
;
61$      QUEUE,      Hold_F.Queue;
          SCAN:      STATE(RES9)==IDLE_RES:NEXT(63$);

;
;
; Model statements for module: Assign 32
;
63$      ASSIGN:      T_start_F=TNOW:NEXT(8$);

;
;
; Model statements for module: Process 7
;
8$       ASSIGN:      F_Sup1.NumberIn=F_Sup1.NumberIn + 1;
          F_Sup1.WIP=F_Sup1.WIP+1;
576$    STACK,      1:Save:NEXT(550$);

550$    QUEUE,      F_Sup1.Queue;
549$    SEIZE,      2,VA:
          RES9,1:NEXT(548$);

548$    DELAY:      Normal(40,1),,VA:NEXT(591$);

591$    ASSIGN:      F_Sup1.WaitTime=F_Sup1.WaitTime + Diff.WaitTime;
555$    TALLY:      F_Sup1.WaitTimePerEntity,Diff.WaitTime,1;
592$    ASSIGN:      F_Sup1.WaitCost=F_Sup1.WaitCost + Diff.WaitCost;

```

```

553$      TALLY:      F_Sup1.WaitCostPerEntity,Diff.WaitCost,1;
557$      TALLY:      F_Sup1.TotalTimePerEntity,Diff.StartTime,1;
558$      TALLY:      F_Sup1.TotalCostPerEntity,
                    Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;

581$      ASSIGN:     F_Sup1.VATime=F_Sup1.VATime + Diff.VATime;
582$      TALLY:      F_Sup1.VATimePerEntity,Diff.VATime,1;
586$      ASSIGN:     F_Sup1.VACost=F_Sup1.VACost + Diff.VACost;
583$      TALLY:      F_Sup1.VACostPerEntity,Diff.VACost,1;
547$      RELEASE:    RES9,1;
596$      STACK,      1:Destroy:NEXT(595$);

595$      ASSIGN:     F_Sup1.NumberOut=F_Sup1.NumberOut + 1:
                    F_Sup1.WIP=F_Sup1.WIP-1:NEXT(30$);

;
;
; Model statements for module: Assign 11
;
30$      ASSIGN:      T_end_F=TNOW:NEXT(64$);

;
;
; Model statements for module: Hold 14
;
64$      QUEUE,       Hold_G.Queue;
          SCAN:       STATE(RES10)==IDLE_RES:NEXT(66$);

;
;
; Model statements for module: Assign 33
;
66$      ASSIGN:      T_start_G=TNOW:NEXT(9$);

;

```

```

;
;   Model statements for module:  Process 8
;
9$      ASSIGN:      G_Sup1.NumberIn=G_Sup1.NumberIn + 1:
                        G_Sup1.WIP=G_Sup1.WIP+1;
627$    STACK,      1:Save:NEXT(601$);

601$    QUEUE,      G_Sup1.Queue;
600$    SEIZE,      2,VA:
                        RES10,1:NEXT(599$);

599$    DELAY:      Normal(80,4),,VA:NEXT(642$);

642$    ASSIGN:      G_Sup1.WaitTime=G_Sup1.WaitTime + Diff.WaitTime;
606$    TALLY:      G_Sup1.WaitTimePerEntity,Diff.WaitTime,1;
643$    ASSIGN:      G_Sup1.WaitCost=G_Sup1.WaitCost + Diff.WaitCost;
604$    TALLY:      G_Sup1.WaitCostPerEntity,Diff.WaitCost,1;
608$    TALLY:      G_Sup1.TotalTimePerEntity,Diff.StartTime,1;
609$    TALLY:      G_Sup1.TotalCostPerEntity,
                        Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
632$    ASSIGN:      G_Sup1.VATime=G_Sup1.VATime + Diff.VATime;
633$    TALLY:      G_Sup1.VATimePerEntity,Diff.VATime,1;
637$    ASSIGN:      G_Sup1.VACost=G_Sup1.VACost + Diff.VACost;
634$    TALLY:      G_Sup1.VACostPerEntity,Diff.VACost,1;
598$    RELEASE:    RES10,1;
647$    STACK,      1:Destroy:NEXT(646$);

646$    ASSIGN:      G_Sup1.NumberOut=G_Sup1.NumberOut + 1:
                        G_Sup1.WIP=G_Sup1.WIP-1:NEXT(31$);

;
;
;   Model statements for module:  Assign 12
;
31$     ASSIGN:      T_start_K=TNOW:
                        T_end_G=TNOW:NEXT(10$);

```

```

;
;
;   Model statements for module:  Process 9
;
10$      ASSIGN:      K_Transp_to_Core.NumberIn=K_Transp_to_Core.NumberIn + 1:
K_Transp_to_Core.WIP=K_Transp_to_Core.WIP+1;
678$     STACK,      1:Save:NEXT(650$);

650$     DELAY:      Normal(90,3),,VA:NEXT(659$);

659$     TALLY:      K_Transp_to_Core.TotalTimePerEntity,Diff.StartTime,1;
660$     TALLY:      K_Transp_to_Core.TotalCostPerEntity,
Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
683$     ASSIGN:      K_Transp_to_Core.VATime=K_Transp_to_Core.VATime + Diff.VATime;
684$     TALLY:      K_Transp_to_Core.VATimePerEntity,Diff.VATime,1;
688$     ASSIGN:      K_Transp_to_Core.VACost=K_Transp_to_Core.VACost + Diff.VACost;
685$     TALLY:      K_Transp_to_Core.VACostPerEntity,Diff.VACost,1;
698$     STACK,      1:Destroy:NEXT(697$);

697$     ASSIGN:      K_Transp_to_Core.NumberOut=K_Transp_to_Core.NumberOut + 1:
K_Transp_to_Core.WIP=K_Transp_to_Core.WIP-1:NEXT(32$);

;
;
;   Model statements for module:  Assign 13
;
32$      ASSIGN:      T_end_K=TNOW:NEXT(14$);

;
;
;   Model statements for module:  Hold 7
;
45$      QUEUE,      Hold_D.Queue;
SCAN:      STATE(RES4)==IDLE_RES:NEXT(47$);

```

```

;
;
;   Model statements for module:  Assign 25
;
47$      ASSIGN:          T_start_D=TNOW:NEXT(3$);

;
;
;   Model statements for module:  Process 3
;
3$      ASSIGN:          D_Info_To_Sup2.NumberIn=D_Info_To_Sup2.NumberIn + 1:
                          D_Info_To_Sup2.WIP=D_Info_To_Sup2.WIP+1;
729$    STACK,          1:Save:NEXT(703$);

703$    QUEUE,          D_Info_To_Sup2.Queue;
702$    SEIZE,          2,VA:
                          RES4,1:NEXT(701$);

701$    DELAY:          Normal(70,3),,VA:NEXT(744$);

744$    ASSIGN:          D_Info_To_Sup2.WaitTime=D_Info_To_Sup2.WaitTime + Diff.WaitTime;
708$    TALLY:          D_Info_To_Sup2.WaitTimePerEntity,Diff.WaitTime,1;
745$    ASSIGN:          D_Info_To_Sup2.WaitCost=D_Info_To_Sup2.WaitCost + Diff.WaitCost;
706$    TALLY:          D_Info_To_Sup2.WaitCostPerEntity,Diff.WaitCost,1;
710$    TALLY:          D_Info_To_Sup2.TotalTimePerEntity,Diff.StartTime,1;
711$    TALLY:          D_Info_To_Sup2.TotalCostPerEntity,
                          Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
734$    ASSIGN:          D_Info_To_Sup2.VATime=D_Info_To_Sup2.VATime + Diff.VATime;
735$    TALLY:          D_Info_To_Sup2.VATimePerEntity,Diff.VATime,1;
739$    ASSIGN:          D_Info_To_Sup2.VACost=D_Info_To_Sup2.VACost + Diff.VACost;
736$    TALLY:          D_Info_To_Sup2.VACostPerEntity,Diff.VACost,1;
700$    RELEASE:        RES4,1;
749$    STACK,          1:Destroy:NEXT(748$);

748$    ASSIGN:          D_Info_To_Sup2.NumberOut=D_Info_To_Sup2.NumberOut + 1:
                          D_Info_To_Sup2.WIP=D_Info_To_Sup2.WIP-1:NEXT(24$);

```

```

;
;
; Model statements for module: Assign 5
;
24$      ASSIGN:      T_end_D=TNOW:NEXT(48$);

;
;
; Model statements for module: Hold 8
;
48$      QUEUE,      Hold_H.Queue;
          SCAN:      STATE(RES11)==IDLE_RES:NEXT(50$);

;
;
; Model statements for module: Assign 26
;
50$      ASSIGN:      T_start_H=TNOW:NEXT(11$);

;
;
; Model statements for module: Process 10
;
11$      ASSIGN:      H_Sup2.NumberIn=H_Sup2.NumberIn + 1:
          H_Sup2.WIP=H_Sup2.WIP+1;
780$     STACK,      1:Save:NEXT(754$);

754$     QUEUE,      H_Sup2.Queue;
753$     SEIZE,      2,VA:
          RES11,1:NEXT(752$);

752$     DELAY:      Normal(10,.2),,VA:NEXT(795$);

```

```

795$      ASSIGN:      H_Sup2.WaitTime=H_Sup2.WaitTime + Diff.WaitTime;
759$      TALLY:      H_Sup2.WaitTimePerEntity,Diff.WaitTime,1;
796$      ASSIGN:      H_Sup2.WaitCost=H_Sup2.WaitCost + Diff.WaitCost;
757$      TALLY:      H_Sup2.WaitCostPerEntity,Diff.WaitCost,1;
761$      TALLY:      H_Sup2.TotalTimePerEntity,Diff.StartTime,1;
762$      TALLY:      H_Sup2.TotalCostPerEntity,
                    Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
785$      ASSIGN:      H_Sup2.VATime=H_Sup2.VATime + Diff.VATime;
786$      TALLY:      H_Sup2.VATimePerEntity,Diff.VATime,1;
790$      ASSIGN:      H_Sup2.VACost=H_Sup2.VACost + Diff.VACost;
787$      TALLY:      H_Sup2.VACostPerEntity,Diff.VACost,1;
751$      RELEASE:    RES11,1;
800$      STACK,      1:Destroy:NEXT(799$);

799$      ASSIGN:      H_Sup2.NumberOut=H_Sup2.NumberOut + 1:
                    H_Sup2.WIP=H_Sup2.WIP-1:NEXT(25$);

;
;
;      Model statements for module:  Assign 6
;
25$      ASSIGN:      T_end_H=TNOW:NEXT(51$);

;
;
;      Model statements for module:  Hold 9
;
51$      QUEUE,      Hold_I.Queue;
          SCAN:      STATE(RES12)==IDLE_RES:NEXT(53$);

;
;
;      Model statements for module:  Assign 27
;
53$      ASSIGN:      T_start_I=TNOW:NEXT(12$);

```



```

;
;
;   Model statements for module:  Process 11
;
12$      ASSIGN:      I_Sup2.NumberIn=I_Sup2.NumberIn + 1:
                        I_Sup2.WIP=I_Sup2.WIP+1;
831$      STACK,      1:Save:NEXT(805$);

805$      QUEUE,      I_Sup2.Queue;
804$      SEIZE,      2,VA:
                        RES12,1:NEXT(803$);

803$      DELAY:      Normal(60,1.5),,VA:NEXT(846$);

846$      ASSIGN:      I_Sup2.WaitTime=I_Sup2.WaitTime + Diff.WaitTime;
810$      TALLY:      I_Sup2.WaitTimePerEntity,Diff.WaitTime,1;
847$      ASSIGN:      I_Sup2.WaitCost=I_Sup2.WaitCost + Diff.WaitCost;
808$      TALLY:      I_Sup2.WaitCostPerEntity,Diff.WaitCost,1;
812$      TALLY:      I_Sup2.TotalTimePerEntity,Diff.StartTime,1;
813$      TALLY:      I_Sup2.TotalCostPerEntity,
                        Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
836$      ASSIGN:      I_Sup2.VATime=I_Sup2.VATime + Diff.VATime;
837$      TALLY:      I_Sup2.VATimePerEntity,Diff.VATime,1;
841$      ASSIGN:      I_Sup2.VACost=I_Sup2.VACost + Diff.VACost;
838$      TALLY:      I_Sup2.VACostPerEntity,Diff.VACost,1;
802$      RELEASE:    RES12,1;
851$      STACK,      1:Destroy:NEXT(850$);

850$      ASSIGN:      I_Sup2.NumberOut=I_Sup2.NumberOut + 1:
                        I_Sup2.WIP=I_Sup2.WIP-1:NEXT(26$);

;
;
;   Model statements for module:  Assign 7
;

```

```

26$          ASSIGN:          T_start_L=TNOW:
                               T_end_I=TNOW:NEXT(13$);

;
;
;   Model statements for module:  Process 12
;
13$          ASSIGN:          L_Transp_to_Core.NumberIn=L_Transp_to_Core.NumberIn + 1:
                               L_Transp_to_Core.WIP=L_Transp_to_Core.WIP+1;
882$         STACK,          1:Save:NEXT(854$);

854$         DELAY:          Normal(150,3),,VA:NEXT(863$);

863$         TALLY:          L_Transp_to_Core.TotalTimePerEntity,Diff.StartTime,1;
864$         TALLY:          L_Transp_to_Core.TotalCostPerEntity,
                               Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
887$         ASSIGN:          L_Transp_to_Core.VATime=L_Transp_to_Core.VATime + Diff.VATime;
888$         TALLY:          L_Transp_to_Core.VATimePerEntity,Diff.VATime,1;
892$         ASSIGN:          L_Transp_to_Core.VACost=L_Transp_to_Core.VACost + Diff.VACost;
889$         TALLY:          L_Transp_to_Core.VACostPerEntity,Diff.VACost,1;
902$         STACK,          1:Destroy:NEXT(901$);

901$         ASSIGN:          L_Transp_to_Core.NumberOut=L_Transp_to_Core.NumberOut + 1:
                               L_Transp_to_Core.WIP=L_Transp_to_Core.WIP-1:NEXT(28$);

;
;
;   Model statements for module:  Assign 9
;
28$          ASSIGN:          T_end_L=TNOW:NEXT(14$);

```

PROJECT, "Base Model", "Leonardo Rivera", , , Yes, Yes, Yes, Yes, No, No, Yes, No, No;

ATTRIBUTES: T_start_A:
T_start_B:
T_start_C:
T_start_D:
T_start_E:
T_start_F:
T_start_G:
T_start_H:
T_start_I:
T_start_J:
T_start_K:
T_start_L:
T_start_M:
T_start_N:
T_start_O:
T_start_P:
T_end_A:
T_end_B:
T_end_C:
T_end_D:
T_end_E:
T_end_F:
T_end_G:
T_end_H:
T_end_I:
T_end_J:
T_end_K:
T_end_L:
T_end_M:
T_end_N:
T_end_O:
T_end_P:
CTI;

VARIABLES: E_Info_To_Supl.NumberOut,CLEAR(Statistics),CATEGORY("Exclude");
A _ Order Reception.NumberOut,CLEAR(Statistics),CATEGORY("Exclude");

```

M_Assembly.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
G_Sup1.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
N_Packaging.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
H_Sup2.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
E_Info_To_Sup1.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
C_Operation.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
G_Sup1.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
O_Shipping.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
I_Sup2.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
F_Sup1.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
L_Transp_to_Core.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
A __ Order Reception.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
Order Arrival.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
F_Sup1.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
M_Assembly.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
H_Sup2.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
To_Supplier2.NumberOut Orig,CLEAR(Statistics),CATEGORY("Exclude"):
G_Sup1.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
H_Sup2.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
G_Sup1.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
D_Info_To_Sup2.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
O_Shipping.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
M_Assembly.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
G_Sup1.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
To_Supplier2.NumberOut Dup,CLEAR(Statistics),CATEGORY("Exclude"):
P_FG_Storage.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
A __ Order Reception.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
J_Operation.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
L_Transp_to_Core.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
B_Order Processing.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
O_Shipping.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
B_Order Processing.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
I_Sup2.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
L_Transp_to_Core.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
O_Shipping.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
M_Assembly.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
L_Transp_to_Core.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
P_FG_Storage.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):

```

K_Transp_to_Core.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
 E_Info_To_Sup1.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
 G_Sup1.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
 O_Shipping.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
 I_Sup2.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
 TRANSP_K,CLEAR(System),CATEGORY("User Specified-User Specified"):
 TRANSP_L,CLEAR(System),CATEGORY("User Specified-User Specified"):
 P_FG_Storage.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
 A __ Order Reception.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
 B_Order Processing.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
 D_Info_To_Sup2.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
 H_Sup2.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
 RES1_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 D_Info_To_Sup2.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
 RES2_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 I_Sup2.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
 D_Info_To_Sup2.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
 RES3_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 N_Packaging.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
 To_Supplier_1.NumberOut Orig,CLEAR(Statistics),CATEGORY("Exclude"):
 RES4_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 N_Packaging.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
 J_Operation.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
 RES5_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 B_Order Processing.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
 F_Sup1.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
 C_Operation.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
 RES6_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 M_Assembly.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
 E_Info_To_Sup1.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
 RES7_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 B_Order Processing.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
 RES8_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 M_Assembly.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
 K_Transp_to_Core.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
 RES10_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 RES9_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
 C_Operation.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):

C_Operation.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
E_Info_To_Sup1.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
J_Operation.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
RES11_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
K_Transp_to_Core.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
A _ Order Reception.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
N_Packaging.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
RES12_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
I_Sup2.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
H_Sup2.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
Exit_Sysyem.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
RES13_CR,CLEAR(System),CATEGORY("User Specified-User Specified"):
E_Info_To_Sup1.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
To_Supplier_1.NumberOut Dup,CLEAR(Statistics),CATEGORY("Exclude"):
J_Operation.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
D_Info_To_Sup2.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
H_Sup2.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
MAT_C,CLEAR(System),CATEGORY("User Specified-User Specified"):
MAT_E,CLEAR(System),CATEGORY("User Specified-User Specified"):
C_Operation.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
MAT_H,CLEAR(System),CATEGORY("User Specified-User Specified"):
I_Sup2.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
MAT_N,CLEAR(System),CATEGORY("User Specified-User Specified"):
K_Transp_to_Core.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
F_Sup1.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
P_FG_Storage.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
B_Order Processing.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
L_Transp_to_Core.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
A _ Order Reception.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
N_Packaging.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
B_Order Processing.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
H_Sup2.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
E_Info_To_Sup1.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
D_Info_To_Sup2.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
C_Operation.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
J_Operation.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
M_Assembly.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
F_Sup1.VATime,CLEAR(Statistics),CATEGORY("Exclude"):

```

A __ Order Reception.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
N_Packaging.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
P_FG_Storage.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
Prepare_Assembly.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
O_Shipping.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"):
F_Sup1.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
F_Sup1.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
J_Operation.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
J_Operation.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
G_Sup1.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
C_Operation.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
O_Shipping.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
I_Sup2.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
K_Transp_to_Core.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
N_Packaging.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
D_Info_To_Sup2.WaitTime,CLEAR(Statistics),CATEGORY("Exclude");

```

QUEUES:

```

A __ Order Reception.Queue,FIFO,,AUTOSTATS(Yes,,):
B_Order Processing.Queue,FIFO,,AUTOSTATS(Yes,,):
N_Packaging.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_A.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_F.Queue,FIFO,,AUTOSTATS(Yes,,):
H_Sup2.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_G.Queue,FIFO,,AUTOSTATS(Yes,,):
C_Operation.Queue,FIFO,,AUTOSTATS(Yes,,):
G_Sup1.Queue,FIFO,,AUTOSTATS(Yes,,):
O_Shipping.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_B.Queue,FIFO,,AUTOSTATS(Yes,,):
D_Info_To_Sup2.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_H.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_C.Queue,FIFO,,AUTOSTATS(Yes,,):
M_Assembly.Queue,FIFO,,AUTOSTATS(Yes,,):
F_Sup1.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_N.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_D.Queue,FIFO,,AUTOSTATS(Yes,,):
Prepare_Assembly.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_I.Queue,FIFO,,AUTOSTATS(Yes,,):
I_Sup2.Queue,FIFO,,AUTOSTATS(Yes,,):

```

```
Hold_O.Queue,FIFO,,AUTOSTATS(Yes,,):
E_Info_To_Supl.Queue:
Hold_E.Queue,FIFO,,AUTOSTATS(Yes,,):
Hold_J.Queue,FIFO,,AUTOSTATS(Yes,,):
J_Operation.Queue,FIFO,,AUTOSTATS(Yes,,);
```

```
PICTURES: Picture.Airplane:
Picture.Green Ball:
Picture.Blue Page:
Picture.Telephone:
Picture.Blue Ball:
Picture.Yellow Page:
Picture.EMail:
Picture.Yellow Ball:
Picture.Bike:
Picture.Report:
Picture.Van:
Picture.Widgets:
Picture.Envelope:
Picture.Fax:
Picture.Truck:
Picture.Letter:
Picture.Box:
Picture.Woman:
Picture.Package:
Picture.Man:
Picture.Diskette:
Picture.Boat:
Picture.Red Page:
Picture.Green Page:
Picture.Red Ball;
```

```
RESOURCES: RES10,Capacity(1),,,COST(58.332,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES11,Capacity(1),,,COST(25,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES12,Capacity(1),,,COST(8.334,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES13,Capacity(1),,,COST(2.0136,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES1,Capacity(1),,,COST(16.68,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES2,Capacity(1),,,COST(2.0136,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
```



```

RES3,Capacity(1),,,COST(22.914,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES4,Capacity(1),,,COST(2.0136,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES5,Capacity(1),,,COST(13.32,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES6,Capacity(1),,,COST(6.252,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES7,Capacity(1),,,COST(8.334,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES8,Capacity(1),,,COST(16.68,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
RES9,Capacity(1),,,COST(72.918,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,);

TALLIES:      D_Info_To_Sup2.WaitCostPerEntity,,DATABASE(,"Wait Cost Per
Entity","Process","D_Info_To_Sup2"):
      F_Sup1.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","F_Sup1"):
      O_Shipping.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","O_Shipping"):
      A _ Order Reception.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","A _ Order
Reception"):
      N_Packaging.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","N_Packaging"):
      K_Transp_to_Core.TotalCostPerEntity,,DATABASE(,"Total Cost Per
Entity","Process","K_Transp_to_Core"):
      F_Sup1.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","F_Sup1"):
      J_Operation.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","J_Operation"):
      C_Operation.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","C_Operation"):
      E_Info_To_Sup1.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","E_Info_To_Sup1"):
      M_Assembly.WaitTimePerEntity,,DATABASE(,"Wait Time Per Entity","Process","M_Assembly"):
      H_Sup2.WaitTimePerEntity,,DATABASE(,"Wait Time Per Entity","Process","H_Sup2"):
      B_Order Processing.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","B_Order
Processing"):
      L_Transp_to_Core.VATimePerEntity,,DATABASE(,"VA Time Per
Entity","Process","L_Transp_to_Core"):
      G_Sup1.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","G_Sup1"):
      A _ Order Reception.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","A _
Order Reception"):
      N_Packaging.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","N_Packaging"):
      G_Sup1.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","G_Sup1"):
      O_Shipping.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","O_Shipping"):
      J_Operation.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","J_Operation"):
      N_Packaging.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","N_Packaging"):
      C_Operation.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","C_Operation"):
      B_Order Processing.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","B_Order
Processing"):

```

```

I_Sup2.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","I_Sup2"):
O_Shipping.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","O_Shipping"):
D_Info_To_Sup2.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","D_Info_To_Sup2"):
G_Sup1.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","G_Sup1"):
F_Sup1.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","F_Sup1"):
M_Assembly.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","M_Assembly"):
E_Info_To_Sup1.TotalCostPerEntity,,DATABASE("Total Cost Per
Entity","Process","E_Info_To_Sup1"):
I_Sup2.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","I_Sup2"):
C_Operation.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","C_Operation"):
I_Sup2.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","I_Sup2"):
F_Sup1.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","F_Sup1"):
J_Operation.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","J_Operation"):
A _ Order Reception.WaitCostPerEntity,,DATABASE("Wait Cost Per Entity","Process","A _ Order
Reception"):
E_Info_To_Sup1.WaitTimePerEntity,,DATABASE("Wait Time Per
Entity","Process","E_Info_To_Sup1"):
L_Transp_to_Core.TotalCostPerEntity,,DATABASE("Total Cost Per
Entity","Process","L_Transp_to_Core"):
H_Sup2.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","H_Sup2"):
P_FG_Storage.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","P_FG_Storage"):
B_Order Processing.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","B_Order
Processing"):
M_Assembly.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","M_Assembly"):
D_Info_To_Sup2.WaitTimePerEntity,,DATABASE("Wait Time Per
Entity","Process","D_Info_To_Sup2"):
C_Operation.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","C_Operation"):
H_Sup2.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","H_Sup2"):
O_Shipping.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","O_Shipping"):
K_Transp_to_Core.VACostPerEntity,,DATABASE("VA Cost Per
Entity","Process","K_Transp_to_Core"):
A _ Order Reception.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","A _ Order
Reception"):
K_Transp_to_Core.TotalTimePerEntity,,DATABASE("Total Time Per
Entity","Process","K_Transp_to_Core"):
P_FG_Storage.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","P_FG_Storage"):
F_Sup1.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","F_Sup1"):
N_Packaging.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","N_Packaging"):

```

```

G_Sup1.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","G_Sup1"):
J_Operation.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","J_Operation"):
N_Packaging.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","N_Packaging"):
B_Order Processing.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","B_Order
Processing"):
D_Info_To_Sup2.TotalCostPerEntity,,DATABASE("Total Cost Per
Entity","Process","D_Info_To_Sup2"):
E_Info_To_Sup1.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","E_Info_To_Sup1"):
J_Operation.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","J_Operation"):
M_Assembly.WaitCostPerEntity,,DATABASE("Wait Cost Per Entity","Process","M_Assembly"):
H_Sup2.WaitCostPerEntity,,DATABASE("Wait Cost Per Entity","Process","H_Sup2"):
M_Assembly.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","M_Assembly"):
I_Sup2.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","I_Sup2"):
L_Transp_to_Core.VACostPerEntity,,DATABASE("VA Cost Per
Entity","Process","L_Transp_to_Core"):
A _ Order Reception.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","A _
Order Reception"):
D_Info_To_Sup2.VATimePerEntity,,DATABASE("VA Time Per Entity","Process","D_Info_To_Sup2"):
O_Shipping.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","O_Shipping"):
N_Packaging.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","N_Packaging"):
B_Order Processing.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","B_Order
Processing"):
I_Sup2.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","I_Sup2"):
O_Shipping.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","O_Shipping"):
E_Info_To_Sup1.TotalTimePerEntity,,DATABASE("Total Time Per
Entity","Process","E_Info_To_Sup1"):
G_Sup1.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","G_Sup1"):
A _ Order Reception.WaitTimePerEntity,,DATABASE("Wait Time Per Entity","Process","A _ Order
Reception"):
L_Transp_to_Core.TotalTimePerEntity,,DATABASE("Total Time Per
Entity","Process","L_Transp_to_Core"):
C_Operation.TotalCostPerEntity,,DATABASE("Total Cost Per Entity","Process","C_Operation"):
F_Sup1.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","F_Sup1"):
I_Sup2.WaitCostPerEntity,,DATABASE("Wait Cost Per Entity","Process","I_Sup2"):
B_Order Processing.TotalTimePerEntity,,DATABASE("Total Time Per Entity","Process","B_Order
Processing"):
C_Operation.WaitCostPerEntity,,DATABASE("Wait Cost Per Entity","Process","C_Operation"):
J_Operation.VACostPerEntity,,DATABASE("VA Cost Per Entity","Process","J_Operation"):

```

```

        E_Info_To_Sup1.WaitCostPerEntity,,DATABASE(,"Wait Cost Per
Entity","Process","E_Info_To_Sup1"):
        H_Sup2.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","H_Sup2"):
        H_Sup2.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","H_Sup2"):
        K_Transp_to_Core.VATimePerEntity,,DATABASE(,"VA Time Per
Entity","Process","K_Transp_to_Core"):
        P_FG_Storage.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","P_FG_Storage"):
        M_Assembly.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","M_Assembly"):
        G_Sup1.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","G_Sup1"):
        D_Info_To_Sup2.TotalTimePerEntity,,DATABASE(,"Total Time Per
Entity","Process","D_Info_To_Sup2"):
        Cost_Time_Investment,,DATABASE(,"Expression","User Specified","Cost_Time_Investment"):
        P_FG_Storage.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","P_FG_Storage");

OUTPUTS:      C_Operation.WaitTime + C_Operation.VATime,,C_Operation Total Accum Time,DATABASE(,"Total
Accum Time","Process",
        "C_Operation"):
        I_Sup2.WaitTime + I_Sup2.VATime,,I_Sup2 Total Accum Time,DATABASE(,"Total Accum
Time","Process","I_Sup2"):
        E_Info_To_Sup1.NumberOut,,E_Info_To_Sup1 Number Out,DATABASE(,"Number
Out","Process","E_Info_To_Sup1"):
        A _ Order Reception.NumberOut,,A _ Order Reception Number Out,DATABASE(,"Number
Out","Process",
        "A _ Order Reception"):
        M_Assembly.WaitTime,,M_Assembly Accum Wait Time,DATABASE(,"Accum Wait
Time","Process","M_Assembly"):
        B_Order Processing.WaitCost + B_Order Processing.VACost,,B_Order Processing Total Accum
Cost,DATABASE(,
        "Total Accum Cost","Process","B_Order Processing"):
        G_Sup1.VATime,,G_Sup1 Accum VA Time,DATABASE(,"Accum VA Time","Process","G_Sup1"):
        N_Packaging.VACost,,N_Packaging Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","N_Packaging"):
        L_Transp_to_Core.VATime + 0,,L_Transp_to_Core Total Accum Time,DATABASE(,"Total Accum
Time","Process",
        "L_Transp_to_Core"):
        H_Sup2.WaitCost + H_Sup2.VACost,,H_Sup2 Total Accum Cost,DATABASE(,"Total Accum
Cost","Process","H_Sup2"):
        H_Sup2.WaitCost,,H_Sup2 Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process","H_Sup2"):

```

```

E_Info_To_Sup1.WaitCost,,E_Info_To_Sup1 Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","E_Info_To_Sup1"):
K_Transp_to_Core.VACost + 0,,K_Transp_to_Core Total Accum Cost,DATABASE(,"Total Accum
Cost","Process",
"K_Transp_to_Core"):
E_Info_To_Sup1.WaitCost + E_Info_To_Sup1.VACost,,E_Info_To_Sup1 Total Accum
Cost,DATABASE(,"Total Accum Cost",
"Process","E_Info_To_Sup1"):
C_Operation.NumberOut,,C_Operation Number Out,DATABASE(,"Number
Out","Process","C_Operation"):
O_Shipping.VATime,,O_Shipping Accum VA Time,DATABASE(,"Accum VA
Time","Process","O_Shipping"):
I_Sup2.WaitTime,,I_Sup2 Accum Wait Time,DATABASE(,"Accum Wait Time","Process","I_Sup2"):
F_Sup1.VACost,,F_Sup1 Accum VA Cost,DATABASE(,"Accum VA Cost","Process","F_Sup1"):
L_Transp_to_Core.VATime,,L_Transp_to_Core Accum VA Time,DATABASE(,"Accum VA
Time","Process","L_Transp_to_Core"):
A __ Order Reception.NumberIn,,A __ Order Reception Number In,DATABASE(,"Number
In","Process","A __ Order Reception"):
I_Sup2.WaitCost + I_Sup2.VACost,,I_Sup2 Total Accum Cost,DATABASE(,"Total Accum
Cost","Process","I_Sup2"):
F_Sup1.WaitCost,,F_Sup1 Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process","F_Sup1"):
M_Assembly.VATime,,M_Assembly Accum VA Time,DATABASE(,"Accum VA
Time","Process","M_Assembly"):
A __ Order Reception.WaitCost + A __ Order Reception.VACost,,A __ Order Reception Total Accum
Cost,DATABASE(,
"Total Accum Cost","Process","A __ Order Reception"):
N_Packaging.WaitTime + N_Packaging.VATime,,N_Packaging Total Accum Time,DATABASE(,"Total
Accum Time","Process",
"N_Packaging"):
F_Sup1.WaitTime + F_Sup1.VATime,,F_Sup1 Total Accum Time,DATABASE(,"Total Accum
Time","Process","F_Sup1"):
H_Sup2.NumberOut,,H_Sup2 Number Out,DATABASE(,"Number Out","Process","H_Sup2"):
G_Sup1.WaitTime,,G_Sup1 Accum Wait Time,DATABASE(,"Accum Wait Time","Process","G_Sup1"):
G_Sup1.NumberOut,,G_Sup1 Number Out,DATABASE(,"Number Out","Process","G_Sup1"):
D_Info_To_Sup2.WaitCost,,D_Info_To_Sup2 Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","D_Info_To_Sup2"):
O_Shipping.WaitTime,,O_Shipping Accum Wait Time,DATABASE(,"Accum Wait
Time","Process","O_Shipping"):

```

```

        C_Operation.WaitCost + C_Operation.VACost,,C_Operation Total Accum Cost,DATABASE(,"Total
Accum Cost","Process",
        "C_Operation"):
        B_Order Processing.WaitTime + B_Order Processing.VATime,,B_Order Processing Total Accum
Time,DATABASE(,
        "Total Accum Time","Process","B_Order Processing"):
        M_Assembly.WaitCost,,M_Assembly Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","M_Assembly"):
        G_Sup1.VACost,,G_Sup1 Accum VA Cost,DATABASE(,"Accum VA Cost","Process","G_Sup1"):
        P_FG_Storage.VATime,,P_FG_Storage Accum VA Time,DATABASE(,"Accum VA
Time","Process","P_FG_Storage"):
        A _ Order Reception.WaitTime,,A _ Order Reception Accum Wait Time,DATABASE(,"Accum Wait
Time","Process",
        "A _ Order Reception"):
        L_Transp_to_Core.NumberIn,,L_Transp_to_Core Number In,DATABASE(,"Number
In","Process","L_Transp_to_Core"):
        N_Packaging.WaitCost + N_Packaging.VACost,,N_Packaging Total Accum Cost,DATABASE(,"Total
Accum Cost","Process",
        "N_Packaging"):
        F_Sup1.WaitCost + F_Sup1.VACost,,F_Sup1 Total Accum Cost,DATABASE(,"Total Accum
Cost","Process","F_Sup1"):
        O_Shipping.VACost,,O_Shipping Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","O_Shipping"):
        B_Order Processing.NumberOut,,B_Order Processing Number Out,DATABASE(,"Number
Out","Process","B_Order Processing"):
        I_Sup2.WaitCost,,I_Sup2 Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process","I_Sup2"):
        L_Transp_to_Core.VACost + 0,,L_Transp_to_Core Total Accum Cost,DATABASE(,"Total Accum
Cost","Process",
        "L_Transp_to_Core"):
        L_Transp_to_Core.VACost,,L_Transp_to_Core Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","L_Transp_to_Core"):
        O_Shipping.NumberOut,,O_Shipping Number Out,DATABASE(,"Number Out","Process","O_Shipping"):
        G_Sup1.WaitTime + G_Sup1.VATime,,G_Sup1 Total Accum Time,DATABASE(,"Total Accum
Time","Process","G_Sup1"):
        M_Assembly.VACost,,M_Assembly Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","M_Assembly"):
        J_Operation.WaitTime + J_Operation.VATime,,J_Operation Total Accum Time,DATABASE(,"Total
Accum Time","Process",

```

```

        "J_Operation"):
        P_FG_Storage.NumberOut,,P_FG_Storage Number Out,DATABASE(,"Number
Out","Process","P_FG_Storage"):
        K_Transp_to_Core.NumberIn,,K_Transp_to_Core Number In,DATABASE(,"Number
In","Process","K_Transp_to_Core"):
        G_Sup1.WaitCost + G_Sup1.VACost,,G_Sup1 Total Accum Cost,DATABASE(,"Total Accum
Cost","Process","G_Sup1"):
        M_Assembly.WaitTime + M_Assembly.VATime,,M_Assembly Total Accum Time,DATABASE(,"Total Accum
Time","Process",
        "M_Assembly"):
        E_Info_To_Sup1.VATime,,E_Info_To_Sup1 Accum VA Time,DATABASE(,"Accum VA
Time","Process","E_Info_To_Sup1"):
        P_FG_Storage.VATime + 0,,P_FG_Storage Total Accum Time,DATABASE(,"Total Accum
Time","Process","P_FG_Storage"):
        G_Sup1.WaitCost,,G_Sup1 Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process","G_Sup1"):
        O_Shipping.WaitCost,,O_Shipping Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","O_Shipping"):
        O_Shipping.WaitCost + O_Shipping.VACost,,O_Shipping Total Accum Cost,DATABASE(,"Total Accum
Cost","Process",
        "O_Shipping"):
        I_Sup2.NumberOut,,I_Sup2 Number Out,DATABASE(,"Number Out","Process","I_Sup2"):
        P_FG_Storage.VACost,,P_FG_Storage Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","P_FG_Storage"):
        A __ Order Reception.WaitCost,,A __ Order Reception Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process",
        "A __ Order Reception"):
        B_Order Processing.NumberIn,,B_Order Processing Number In,DATABASE(,"Number
In","Process","B_Order Processing"):
        D_Info_To_Sup2.VATime,,D_Info_To_Sup2 Accum VA Time,DATABASE(,"Accum VA
Time","Process","D_Info_To_Sup2"):
        H_Sup2.VATime,,H_Sup2 Accum VA Time,DATABASE(,"Accum VA Time","Process","H_Sup2"):
        D_Info_To_Sup2.NumberOut,,D_Info_To_Sup2 Number Out,DATABASE(,"Number
Out","Process","D_Info_To_Sup2"):
        I_Sup2.VATime,,I_Sup2 Accum VA Time,DATABASE(,"Accum VA Time","Process","I_Sup2"):
        N_Packaging.NumberIn,,N_Packaging Number In,DATABASE(,"Number In","Process","N_Packaging"):
        J_Operation.NumberIn,,J_Operation Number In,DATABASE(,"Number In","Process","J_Operation"):
        B_Order Processing.VATime,,B_Order Processing Accum VA Time,DATABASE(,"Accum VA
Time","Process",

```

```

    "B_Order Processing"):
    J_Operation.WaitCost + J_Operation.VACost,,J_Operation Total Accum Cost,DATABASE(,"Total
Accum Cost", "Process",
    "J_Operation"):
    C_Operation.NumberIn,,C_Operation Number In,DATABASE(,"Number In", "Process", "C_Operation"):
    M_Assembly.NumberOut,,M_Assembly Number Out,DATABASE(,"Number Out", "Process", "M_Assembly"):
    E_Info_To_Sup1.VACost,,E_Info_To_Sup1 Accum VA Cost,DATABASE(,"Accum VA
Cost", "Process", "E_Info_To_Sup1"):
    B_Order Processing.WaitTime,,B_Order Processing Accum Wait Time,DATABASE(,"Accum Wait
Time", "Process",
    "B_Order Processing"):
    C_Operation.VATime,,C_Operation Accum VA Time,DATABASE(,"Accum VA
Time", "Process", "C_Operation"):
    J_Operation.VATime,,J_Operation Accum VA Time,DATABASE(,"Accum VA
Time", "Process", "J_Operation"):
    P_FG_Storage.VACost + 0,,P_FG_Storage Total Accum Cost,DATABASE(,"Total Accum
Cost", "Process", "P_FG_Storage"):
    K_Transp_to_Core.NumberOut,,K_Transp_to_Core Number Out,DATABASE(,"Number
Out", "Process", "K_Transp_to_Core"):
    A _ Order Reception.VATime,,A _ Order Reception Accum VA Time,DATABASE(,"Accum VA
Time", "Process",
    "A _ Order Reception"):
    N_Packaging.WaitTime,,N_Packaging Accum Wait Time,DATABASE(,"Accum Wait
Time", "Process", "N_Packaging"):
    H_Sup2.NumberIn,,H_Sup2 Number In,DATABASE(,"Number In", "Process", "H_Sup2"):
    E_Info_To_Sup1.NumberIn,,E_Info_To_Sup1 Number In,DATABASE(,"Number
In", "Process", "E_Info_To_Sup1"):
    J_Operation.WaitTime,,J_Operation Accum Wait Time,DATABASE(,"Accum Wait
Time", "Process", "J_Operation"):
    D_Info_To_Sup2.VACost,,D_Info_To_Sup2 Accum VA Cost,DATABASE(,"Accum VA
Cost", "Process", "D_Info_To_Sup2"):
    H_Sup2.VACost,,H_Sup2 Accum VA Cost,DATABASE(,"Accum VA Cost", "Process", "H_Sup2"):
    A _ Order Reception.WaitTime + A _ Order Reception.VATime,,A _ Order Reception Total Accum
Time,DATABASE(,
    "Total Accum Time", "Process", "A _ Order Reception"):
    C_Operation.WaitTime,,C_Operation Accum Wait Time,DATABASE(,"Accum Wait
Time", "Process", "C_Operation"):
    I_Sup2.VACost,,I_Sup2 Accum VA Cost,DATABASE(,"Accum VA Cost", "Process", "I_Sup2"):

```



```

        K_Transp_to_Core.VATime,,K_Transp_to_Core Accum VA Time,DATABASE(,"Accum VA
Time","Process","K_Transp_to_Core"):
        K_Transp_to_Core.VATime + 0,,K_Transp_to_Core Total Accum Time,DATABASE(,"Total Accum
Time","Process",
        "K_Transp_to_Core"):
        D_Info_To_Sup2.WaitTime + D_Info_To_Sup2.VATime,,D_Info_To_Sup2 Total Accum
Time,DATABASE(,"Total Accum Time",
        "Process","D_Info_To_Sup2"):
        F_Sup1.NumberIn,,F_Sup1 Number In,DATABASE(,"Number In","Process","F_Sup1"):
        B_Order Processing.VACost,,B_Order Processing Accum VA Cost,DATABASE(,"Accum VA
Cost","Process",
        "B_Order Processing"):
        L_Transp_to_Core.NumberOut,,L_Transp_to_Core Number Out,DATABASE(,"Number
Out","Process","L_Transp_to_Core"):
        N_Packaging.VATime,,N_Packaging Accum VA Time,DATABASE(,"Accum VA
Time","Process","N_Packaging"):
        B_Order Processing.WaitCost,,B_Order Processing Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process",
        "B_Order Processing"):
        H_Sup2.WaitTime,,H_Sup2 Accum Wait Time,DATABASE(,"Accum Wait Time","Process","H_Sup2"):
        E_Info_To_Sup1.WaitTime,,E_Info_To_Sup1 Accum Wait Time,DATABASE(,"Accum Wait
Time","Process","E_Info_To_Sup1"):
        D_Info_To_Sup2.NumberIn,,D_Info_To_Sup2 Number In,DATABASE(,"Number
In","Process","D_Info_To_Sup2"):
        C_Operation.VACost,,C_Operation Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","C_Operation"):
        J_Operation.VACost,,J_Operation Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","J_Operation"):
        O_Shipping.WaitTime + O_Shipping.VATime,,O_Shipping Total Accum Time,DATABASE(,"Total Accum
Time","Process",
        "O_Shipping"):
        M_Assembly.NumberIn,,M_Assembly Number In,DATABASE(,"Number In","Process","M_Assembly"):
        E_Info_To_Sup1.WaitTime + E_Info_To_Sup1.VATime,,E_Info_To_Sup1 Total Accum
Time,DATABASE(,"Total Accum Time",
        "Process","E_Info_To_Sup1"):
        F_Sup1.VATime,,F_Sup1 Accum VA Time,DATABASE(,"Accum VA Time","Process","F_Sup1"):
        A _ Order Reception.VACost,,A _ Order Reception Accum VA Cost,DATABASE(,"Accum VA
Cost","Process",

```

```

        "A _ Order Reception"):
        N_Packaging.WaitCost,,N_Packaging Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","N_Packaging"):
        P_FG_Storage.NumberIn,,P_FG_Storage Number In,DATABASE(,"Number
In","Process","P_FG_Storage"):
        F_Sup1.NumberOut,,F_Sup1 Number Out,DATABASE(,"Number Out","Process","F_Sup1"):
        H_Sup2.WaitTime + H_Sup2.VATime,,H_Sup2 Total Accum Time,DATABASE(,"Total Accum
Time","Process","H_Sup2"):
        F_Sup1.WaitTime,,F_Sup1 Accum Wait Time,DATABASE(,"Accum Wait Time","Process","F_Sup1"):
        J_Operation.WaitCost,,J_Operation Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","J_Operation"):
        J_Operation.NumberOut,,J_Operation Number Out,DATABASE(,"Number
Out","Process","J_Operation"):
        G_Sup1.NumberIn,,G_Sup1 Number In,DATABASE(,"Number In","Process","G_Sup1"):
        C_Operation.WaitCost,,C_Operation Accum Wait Cost,DATABASE(,"Accum Wait
Cost","Process","C_Operation"):
        M_Assembly.WaitCost + M_Assembly.VACost,,M_Assembly Total Accum Cost,DATABASE(,"Total Accum
Cost","Process",
        "M_Assembly"):
        O_Shipping.NumberIn,,O_Shipping Number In,DATABASE(,"Number In","Process","O_Shipping"):
        D_Info_To_Sup2.WaitCost + D_Info_To_Sup2.VACost,,D_Info_To_Sup2 Total Accum
Cost,DATABASE(,"Total Accum Cost",
        "Process","D_Info_To_Sup2"):
        I_Sup2.NumberIn,,I_Sup2 Number In,DATABASE(,"Number In","Process","I_Sup2"):
        K_Transp_to_Core.VACost,,K_Transp_to_Core Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","K_Transp_to_Core"):
        N_Packaging.NumberOut,,N_Packaging Number Out,DATABASE(,"Number
Out","Process","N_Packaging"):
        D_Info_To_Sup2.WaitTime,,D_Info_To_Sup2 Accum Wait Time,DATABASE(,"Accum Wait
Time","Process","D_Info_To_Sup2");

REPLICATE,      30,,DaysToBaseTime(70),Yes,Yes,DaysToBaseTime(1),,,8,Minutes,No,No,,,Yes;

EXPRESSIONS:  CTI_Entity(1,1),
              (T_end_O - T_end_A)*(RES1_CR*(T_end_A - T_start_A))+ (RES1_CR*(T_end_A - T_start_A)**2)/2 +
              (T_end_O - T_end_B)*(RES2_CR*(T_end_B - T_start_B))+ (RES2_CR*(T_end_B - T_start_B)**2)/2 + (T_end_O -
              T_end_C)*(RES3_CR*(T_end_C - T_start_C)+ MAT_C)+ MAT_C*(T_end_C - T_start_C)+ (RES3_CR*(T_end_C -
              T_start_C)**2)/2 + (T_end_O - T_end_D)*(RES4_CR*(T_end_D - T_start_D))+ (RES4_CR*(T_end_D -

```

```

T_start_D)**2)/2 + (T_end_O - T_end_E)*(RES13_CR*(T_end_E - T_start_E)+MAT_E)+ MAT_E*(T_end_E - T_start_E)+
(RES13_CR*(T_end_E - T_start_E)**2)/2 + (T_end_O - T_end_J)*(RES5_CR*(T_end_J - T_start_J))+
(RES5_CR*(T_end_J - T_start_J)**2)/2 + (T_end_O - T_end_M)*(RES6_CR*(T_end_M - T_start_M))+
(RES6_CR*(T_end_M - T_start_M)**2)/2 + (T_end_O - T_end_N)*(RES7_CR*(T_end_N - T_start_N)+MAT_N)+
MAT_N*(T_end_N - T_start_N)+ (RES7_CR*(T_end_N - T_start_N)**2)/2 + (RES8_CR*(T_end_O - T_start_O)**2)/2 +
(T_end_O - T_end_F) * (RES9_CR * (T_end_F - T_start_F)) + ((RES9_CR * (T_end_F - T_start_F)**2)/2) +
(T_end_O - T_end_G) * (RES10_CR * (T_end_G - T_start_G)) + ((RES10_CR * (T_end_G - T_start_G)**2)/2) +
(T_end_O - T_end_K) * TRANSP_K + (T_end_O - T_end_H)*(RES12_CR*(T_end_H - T_start_H)+ MAT_H)+
MAT_H*(T_end_H - T_start_H)+ (RES12_CR*(T_end_H - T_start_H)**2)/2 + (T_end_O - T_end_I) * (RES5_CR *
(T_end_I - T_start_I)) + ((RES5_CR * (T_end_I - T_start_I)**2)/2) + (T_end_O - T_end_L) * TRANSP_L
;

```

```

ENTITIES:      Entity 1,Picture.Report,0.0,0.0,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,);

```

Vita

Leonardo Rivera obtained his Bachelor of Science in Industrial Engineering from Universidad del Valle, in his hometown of Cali, Colombia. He then worked for two years at a private university (Universidad Icesi) as a Research Assistant. Then, he went to Georgia Tech and earned his Masters in Industrial Engineering (M.S.I.E.) in 1996. He worked as Director for Technological Development in the Productivity Center of the Pacific Region, later designated the National Productivity Center for Colombia. After 2 years, the call of academia became urgent and he took a position as Instructor in the Industrial Engineering Department of Universidad Icesi, where he taught varied undergraduate subjects until 2003. In that year, he received a scholarship from the Fulbright – Colciencias program and came for the Ph.D. program in Industrial Engineering, in the Manufacturing Systems option at the Virginia Polytechnic Institute and State University. Here he worked under the guidance of Dr. F. Frank Chen in a Research Assistantship for a CHPM designated project, and also as a Teaching Assistant for several classes in the department, being instructor for the Facilities Planning class in the Spring of 2006. He was the recipient of the Burrows Fellowship for 2005 – 2006 and successfully defended this dissertation in August of 2006, a couple of weeks before moving back to his home country of Colombia.