A RESOURCE CONSUMPTION MODEL (RCM) FOR PROCESS DESIGN

by

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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has been approved by the Examining Committee for the thesis requirement for the Doctor of Philosophy degree in Industrial Engineering at the December 1997 graduation.

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To my daughters, Samantha and Gabrielle, for their unknowing support through my Ph.D. endeavor.

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ABSTRACT

Varieties of production economic models exist (e.g., return on investment analysis, break-even analysis, cost estimating, and design for manufacture) to aid production process design for product manufacture. These models, however, fail to integrate sufficiently the concepts of cost, production cycle time, production capacity, and utilization. The methodologies typically rely upon these factors being separately analyzed, but do not guarantee that they are. Some methodologies use a narrow production volume range, or worse, one production volume in their calculations, which limits additional insight into economies of scale.

The resource consumption model for process design (RCM) is the result of several years of research into better models for the analysis and selection of process design alternatives. RCM is a decision support methodology that provides greater understanding, fidelity and sensitivity analysis to process design than other techniques. RCM's foundational concept is that part production consumes resources that can be translated into cost, time, and utilization metrics. RCM accounts for all resources, which can be equipment, labor, energy, material, tooling, and other consumables used by alternative process designs. It characterizes resources generically and avoids the need for terms such as "fixed costs," "variable costs," overhead," and so forth. For each resource, RCM performs quantity-based, time-based, and system-based calculations for a production volume range and determines the controlling condition. Resource calculations are accumulated to compare alternatives. Results are shown in both tabular and graphical

formats. A computer model that uses several modern programming technologies was developed to integrate RCM concepts.

RCM concepts are applied to a manufacturing process design problem to demonstrate the method and the type of results and insights that RCM provides. A number of questions about the problem are addressed using RCM. A comprehensive modeling of process alternatives is very difficult, if not impossible, without RCM. RCM successfully demonstrates that new process design models can be developed utilizing mathematically intensive concepts and implemented using modern computational tools.

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CHAPTER I

INTRODUCTION

Problem Definition

The manufacturing process involves a transformation of raw materials into finished goods. Customers express their needs, product designers transform customer needs into product and part specifications, manufacturing selects the processes and produces the products, and the customers purchase the products. The goal in the transformation process is to derive the best methods to produce the best product while maintaining customer and marketing functional requirements.

Management must consider many factors before making decisions. The organization must determine the size of facilities, the equipment needed, materials to use, labor requirements, quality levels, and whether to make the part in house or purchase from vendors. These are just a few examples. These factors become intermingled where changing one changes the other. There are many trade off decisions to consider, such as the substitution of mechanization for labor.

It is sometimes assumed that product design, capacity, and process design are sequential decisions. In fact, these decisions need to be considered simultaneously. The way the product is designed affects how many people buy it, which affects production capacity, which affects the process and the costs to produce the product, which affects how many people can afford to buy it. This logic can be represented as a circle with customers at the center (Vonderembse and White, 1996), as shown in Figure 1. Because a circle has no beginning or end, it should be considered as a whole. If these decisions are not viewed as a whole, a decision in product design that might offer the best technical solution could cause the product to fail because it makes the product less attractive to the customer or increases the cost of the product beyond the affordable reach of most consumers.

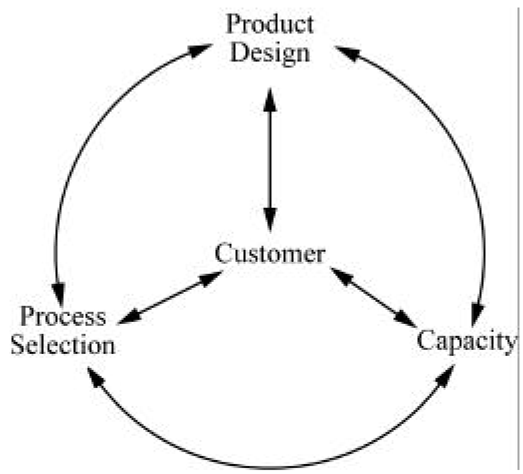

Figure 1. Product Design, Process Design, and Capacity

It is well understood that the design phase accounts for most final product cost. It has been estimated that as much as 70 to 80 percent of the total cost of producing a product is determined during the conceptual and detailed design stages (DeGarmo and Bontadelli, 1997) and therefore, product decisions made at this point are critical (see Figure 2). Although designers use a variety of analytical tools, such as finite element analysis, structural analysis, and dynamic analysis, to ensure the performance and reliability of their product designs, less emphasis has been placed at this stage on manufacturing process design. Process selection should be integrated with decisions about product design and production capacity.

A variety of analytical techniques are available to help make process design decisions. They include investment analysis, "design for" methodologies, process planning rules and handbooks, break-even analyses, capacity analyses, and cost estimations. What guides the selection of a process? In the past, the driving factor has been lowest manufacturing cost. More recently, companies have realized that time-to-market is often a more important consideration. Despite whether time or cost is most important, both should be understood.

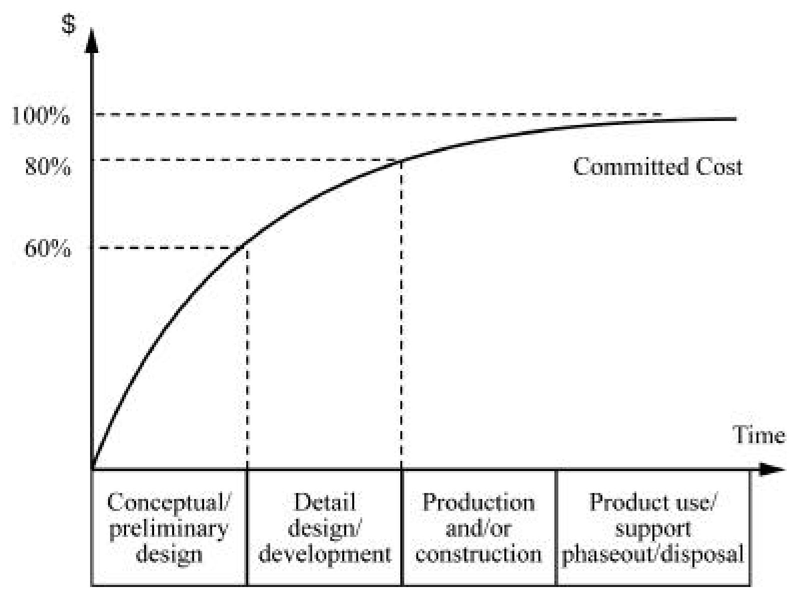

Figure 2. Product Life Cycle Cost

The techniques mentioned above all have their appropriate application. The problem is that these methodologies do not sufficiently integrate the concepts of cost, production cycle time, production capacity, and utilization from within one technique. Some methodologies use a narrow production volume range, or worse, one production volume in their calculations. This limits additional insight into economies of scale. The analyst is often left to investigate these factors independently. There is no guarantee, however, that all factors are considered. Computational requirements often make the methodologies difficult to understand which also limit their application within industry.

Over approximately the last forty to fifty years, few advances in time and cost analytical techniques have occurred. This is ironic when considering how computer technology has advanced, yet the technology has not been well applied in this area. Much of the work has been to optimize specific manufacturing process parameters but not to improve cost and time analyses together. Managers in today's competitive environment need to utilize the available technology, to have better economic models available to them, and to integrate these systems with other company information systems to maximize the company's competitiveness. The "Resource Consumption Model for Process Design" attempts to provide such a tool.

RCM Overview

The resource consumption model for process design (RCM) is the result of several years of research into better models for analyzing and selecting process design alternatives. Figure 3 depicts the many components contained within RCM. This figure is briefly described, then RCM methodology is further developed throughout this paper.

When a product is designed, process design decisions must be made that determine how it will be manufactured. Various alternatives are conceived that satisfy the product's functional requirements. For each alternative, resources that the process consumes are identified. Within RCM, each resource gets defined by fifteen parameters, some of which are cost-based, time-based, and system-based. RCM incorporates the parameters in its calculations and determines whether quantity, time, or system constraint conditions control the resources results. Depending upon the level of detail the user requires, RCM can display cost, time, and utilization results for an individual resource, multiple resources, an individual alternative, or for alternatives within the problem. The nature of the graphs and tabulated results change depending upon the user's selection. RCM is an iterative process, which means that the user may reinvestigate alternatives or resources as necessary.

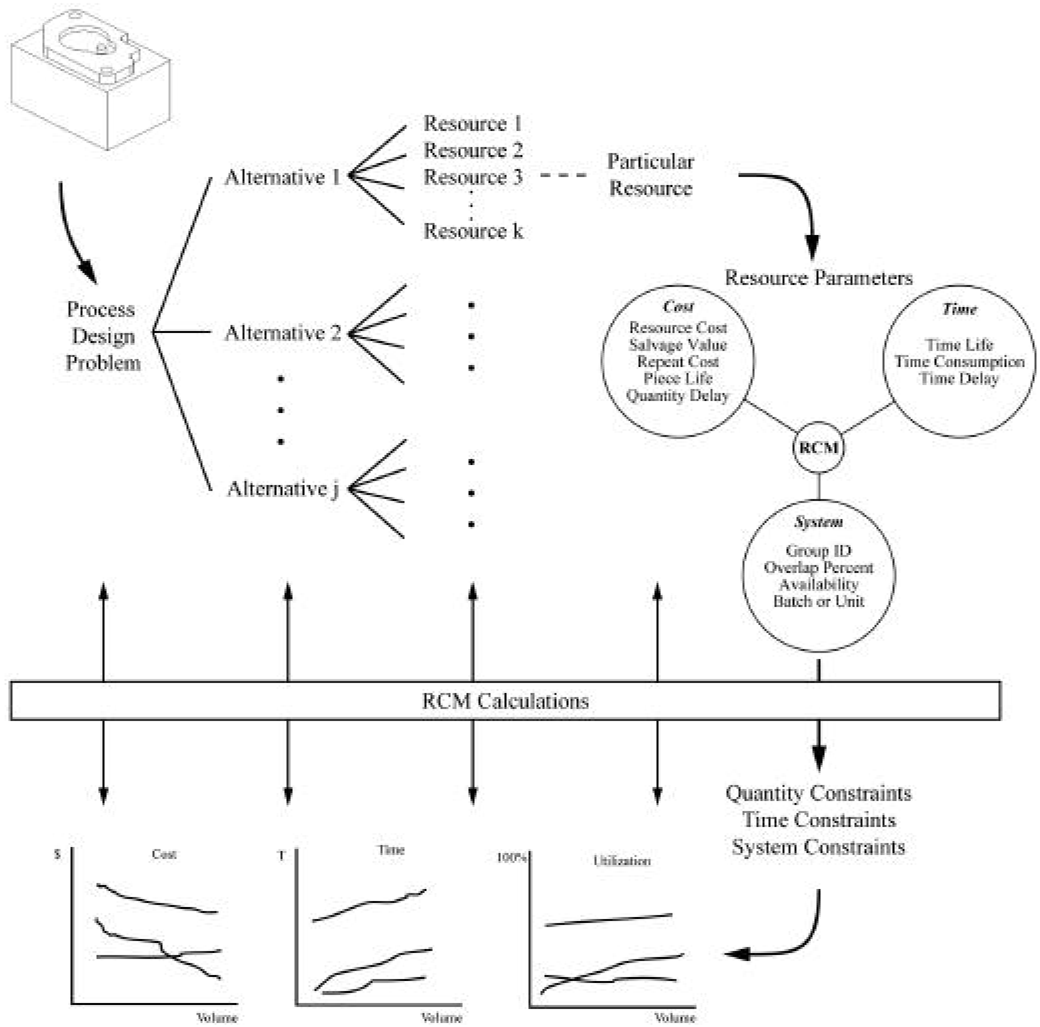

Figure 3. Model Overview

RCM considers cost, production cycle time, and capacity within one methodology. RCM is based upon the following concepts that are further explained, developed, and demonstrated in subsequent sections.

- The manufacturing conversion process consumes resources.
- The quantity of a product that can be produced by a resource is constrained by either the resource's intrinsic time life, sometimes called shelf life, or its intrinsic piece production capability.
- It is not always obvious which constraint applies and at what production volume.
- A resource, once fully consumed, is either replenished, or the maximum production capacity is reached.
- When resources are consumed together, system effects (i.e., capacity) must be included in the analysis.
- Part costs, production cycle time and utilization must be investigated together before the "best" alternative production process can be selected. Cost, time, and utilization tradeoffs must be considered.
- Different alternatives may be best at different production volumes.

RCM's foundational concept is that part production consumes resources that can be translated into cost, time, and utilization metrics. Resources can be equipment, labor, energy, material, tooling, purchased components, and other consumables used by the process. All resources are described in a simple yet consistent manner. A generic characterization avoids the need for terms such as "fixed costs," "variable costs," "overhead," and so forth. The parameters that RCM contains are explained in detail in Chapter 3, and they are shown for a problem in Table 2, page 59.

For some resources, such as materials and energy, resource consumption and spending on that resource are closely aligned. For other resources, such as machine tools, spending clearly does not match consumption one for one. Yet, some resources, such as 50-gallon drums of cutting fluid, are somewhere between these examples. RCM captures the resource cost by exactly how it is purchased and makes no assumption about unit cost until it is used. In this approach, RCM shows that until a resource is fully consumed, its unit cost is higher than the simple per unit cost calculations. Figure 4 demonstrates this point for a welding wire resource. The wire is purchased in 1000 pound spools but only a small amount is consumed for each unit of production, therefore its average product cost depends on specific production volumes. At a production volume of approximately 1500, 3000, and 4500 units, the spool is replenished. The point to understand is that, except for resources purchased and consumed in a one to one relationship, all resources exhibit this cost behavior.

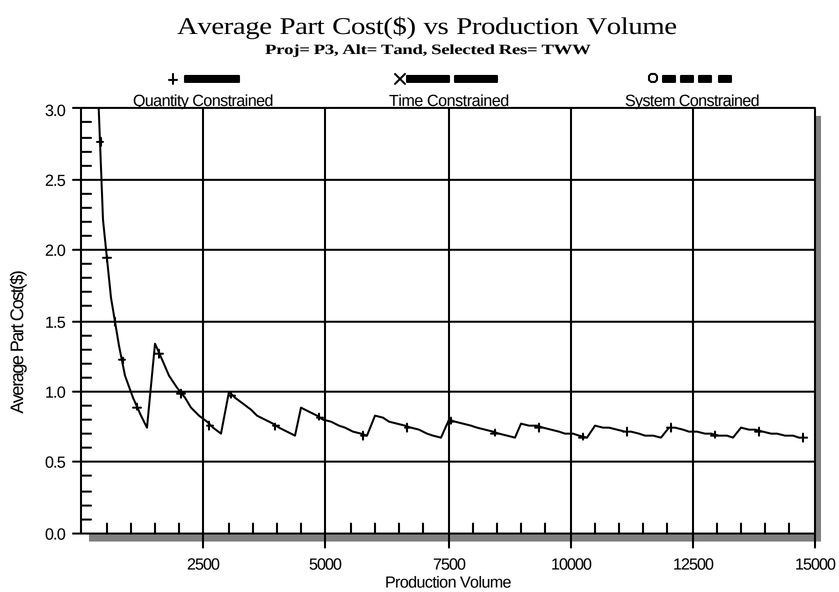

Figure 4. Welding Wire Resource Average Cost

RCM can be used in many different ways. Sometimes, a quick comparison of alternatives is wanted. RCM provides alternative comparison for cost, time, and utilization, demonstrated in Figure 5, Figure 6, and Figure 7. Other times, interest in knowing the individual resource costs and how they affect the alternative's costs is needed. RCM can calculate the cost for an individual resource, as shown in Figure 8, and it can show the alternative's composition cost, shown in Figure 9. Whether the analysis is started with alternatives or with resources can depend upon personal preference. Nevertheless, a resource-by-resource analysis is generally preferred until one's ability to apply RCM is mastered. This approach provides better understanding of each resource before attempting to understand the alternative. An application flowchart provided later (see Figure 23 in Chapter 3), discusses the application sequence. The various analyses that RCM performs and how results are obtained are explained below.

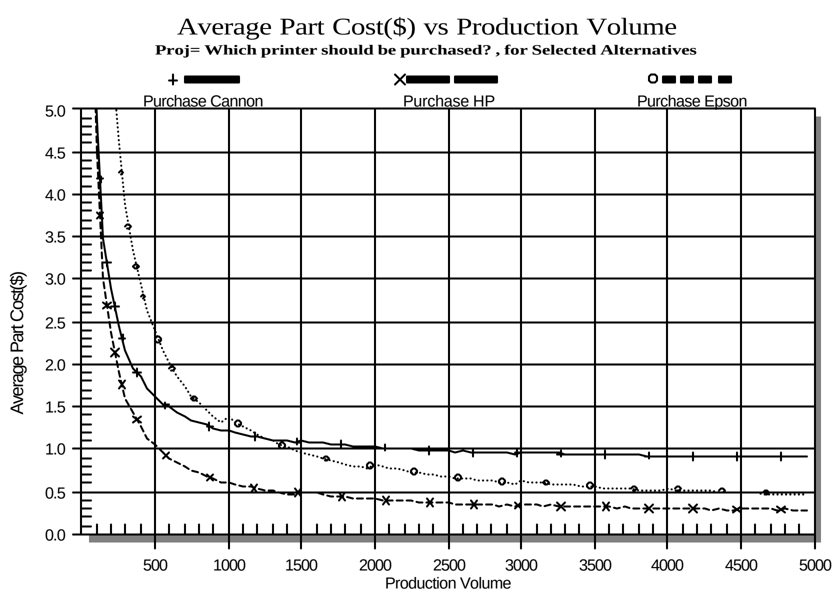

Figure 5. RCM - Cost Comparison of Alternatives

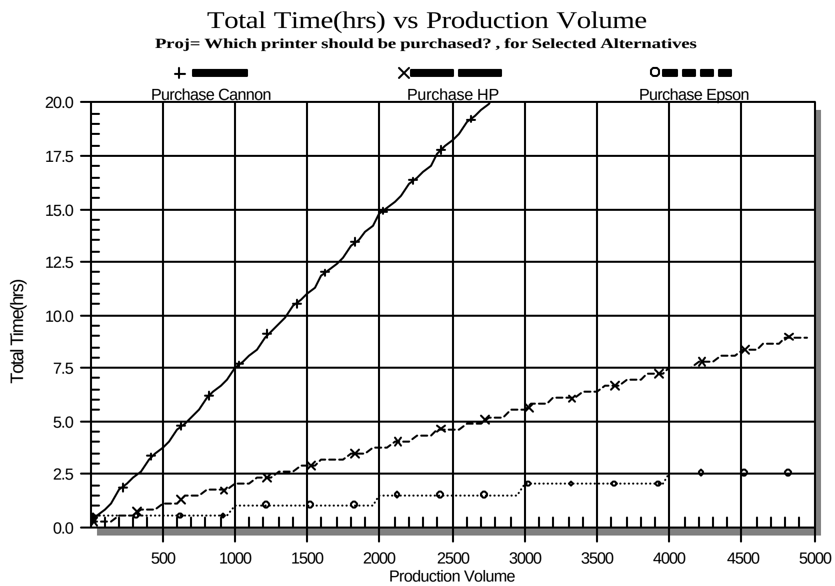

Figure 6. RCM - Time Comparison of Alternatives

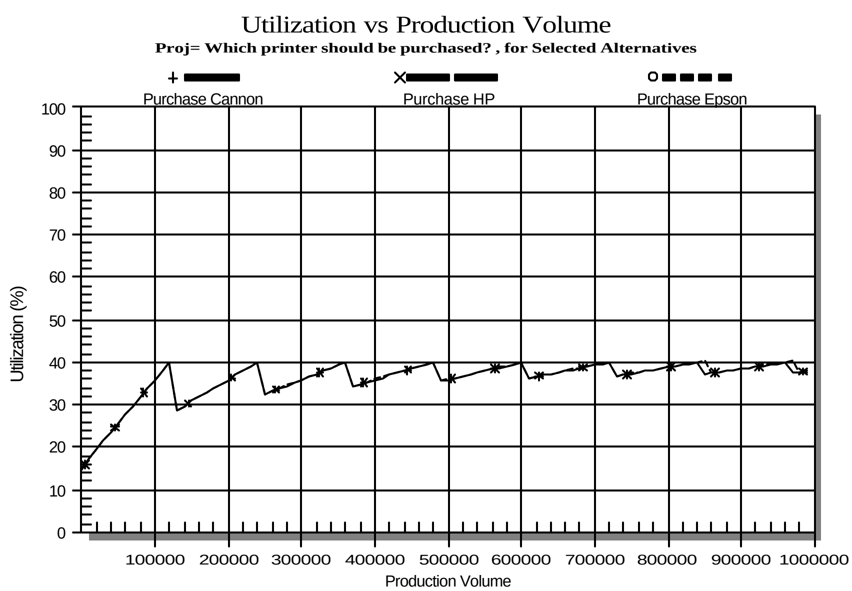

Figure 7. RCM - Utilization Comparison of Alternatives

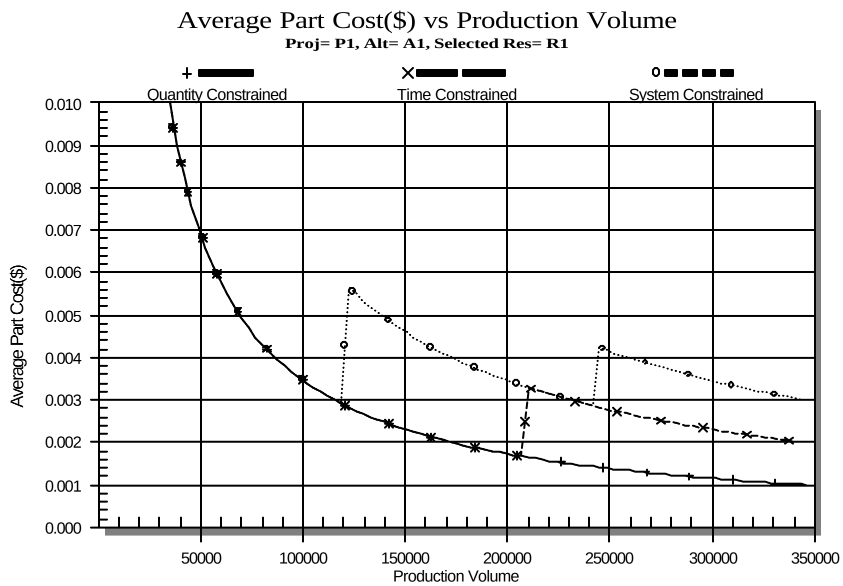

Figure 8. RCM - Cost Analysis for an Individual Resource

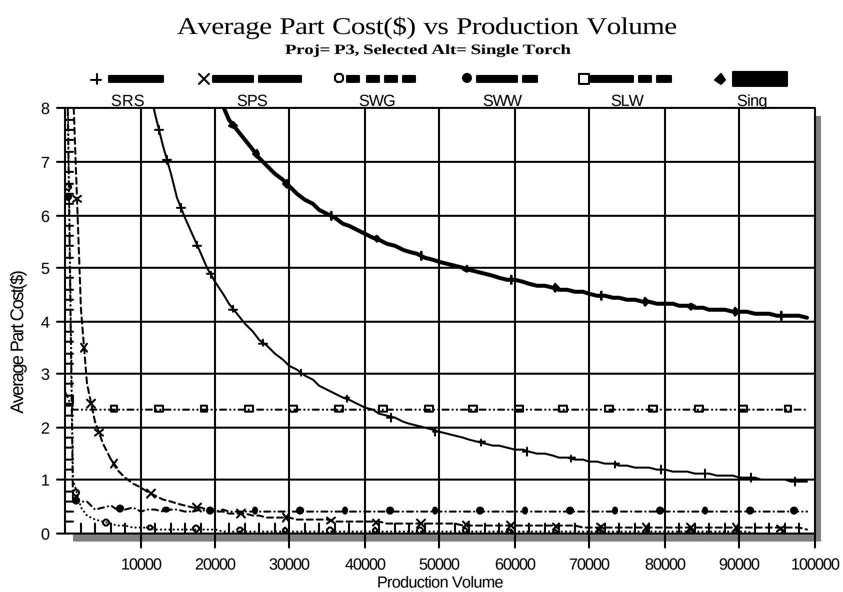

Figure 9. Alternative Component Costs

Resources do not last forever; there are limits. RCM considers three conditions, called constraints. The first two constraints, quantity-based life and time-based life, pertain to the intrinsic life of a resource. The third constraint is based upon the system capacity. When a resource reaches any of the above constraints, it is considered fully consumed and must be replenished. RCM performs the necessary time-based, quantity-based and system-based calculations across a production volume range and determines which constraint applies.

Quantity-based life is easy to understand. It is based upon resource consumption as each part is produced. Under this constraint condition, resources must be replaced after a certain number of parts are produced. Items commonly called “consumables,” such as material, welding wire, nuts and bolts, energy, and so forth, are good examples where resource lives are limited by part production. For example, if six-foot lengths of bar stock are purchased and each part requires one inch, then the bar is replenished after 72 parts.

Equipment and people also have quantity-based lives. For example, a machine tool can be consumed after a certain production quantity because its gears and other internal mechanisms have reached their designed lives. An employee resource is conceptually a little more difficult to comprehend. Consider employees who work in harsh environments, such as foundry chip and grind operations. The employee can be considered “used up” or “consumed” when the muscular and skeletal ailments force medical leaves (and medical claims) after many repetitive cycles.

Time-based life is also relatively easy to understand. It reflects actual length of time, in actual clock hours, that the resource should last. Probably the best illustrations of this constraint are shelf or obsolescence lives, where after a certain amount of time, the resource is no longer useful. A chemical material, for example, that is not used in a certain amount of time may decay or become inert. Technology-based equipment, such as computers, have obsolescence lives. Because of obsolescence, computers may need replacement before they actually wear out. Unavailability of repair parts can also make equipment obsolete. Unit cost increases when a resource reaches its time life before its part life. The resource can provide more production by its time ran out. A resource's time-based life seldom matches the financial accounting depreciation life, and in fact, may be either longer or shorter than depreciation life.

Some resources often fall clearly into one of the above two conditions, but not always. Again, consider chemical materials, such as paint purchased by the gallon. Assume that a gallon can paint 128 parts. Depending upon the rate of consumption the gallon of paint might spoil and never reach its per-gallon production capability. Therefore, the unit paint cost is not known until more is known about consumption rates.

The last constraint condition is called "system constraint" and is based upon process capacity – sometimes called "system" capacity. It considers the maximum production rate of the whole system under examination, which is influenced by factors such as availability of resources, days worked, shifts worked, machine production rates, and task concurrency.

As an example of system constraint, consider a machine tool that can produce 10,000 parts per year based upon three shifts of operation and requires labor to load and unload it. If management decides to purchase labor for only one shift of operation, then the machine tool's design capacity is never attained. Another example is when the machine tool waits for a person to complete a setup. Long setups decrease machine productivity.

Traditionally, capacity calculations have been associated with production analysis and not process costing and selection. RCM acknowledges that capacity must be considered when determining cost and it performs capacity analysis internally. Some methodologies, such as investment analysis and accounting cost analysis, have difficulty including capacity analysis.

RCM specifies that all of the above constraint conditions must be analyzed properly to determine product cost, time, and utilization. These constraints directly affect resource replenishment cycles. RCM does not overlook that a certain process design might require the purchase of more than one machine tool at a given production volume. RCM analyzes the constraint conditions and calculates the number of resources required.

A last RCM concept is that cost and time calculations should be performed over a broad production volume range. A look at results for a production range provides better insight into economies of scale and resource capacity constraints. Unit cost may be significantly reduced at higher production volumes. As product cost is reduced, the market price might also be reduced to stimulate demand. At higher production volumes, the number of resources required must be calculated so that management can make sure that the additional resources can be accommodated.

RCM analyses consider all of the above factors and provides greater understanding, fidelity and sensitivity analysis than other methodologies. Simple selection on a computer screen, shown in Figure 10, controls the desired level of detail. Alternative and resource selections are controls on another form. After selection is made, RCM calculates cost, time, utilization, and summary results. The results are shown in a tabular format on a "Summary" page and in a graphical format on the "Cost," "Time," and "Utilization" pages. Notice in Figure 10 that RCM can calculate both average and total values with a simple option selection. The selection of Average versus Total is independent from the selection of Current/All and Resources/Alternatives on this screen.

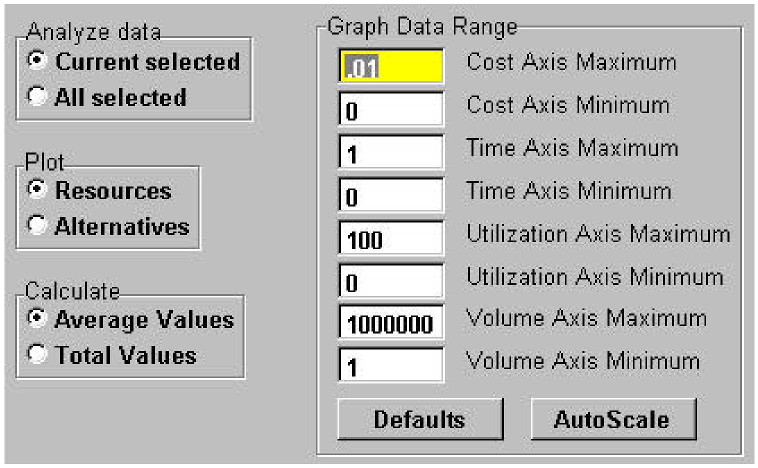

Figure 10. RCM Plotting Options

In Figure 10, the combinations of “Current Selected Resource,” “All Selected Resources,” “Current Selected Alternatives,” and “All Selected Alternatives” are provided. Figure 11 conceptually illustrates the Cost, Time, and Utilization graphs, and the Summary Table calculations when the current selected resource is of interest. The three graphs are for cost, time, and utilization results. On these graphs, quantity, time, and system constraint curves are provided. The summary table (see Appendix B, Table 4) includes cost calculations for all three constraints, the number of resources required, production time, and utilization. The time and utilization figures represent the system constraint values.

Figure 12 illustrates RCM graphs and Summary Table when all selected resources are of interest. A comparison between specific resources can be obtained. The summary table (see Appendix B, Table 5) includes the cost, production time, and utilization results for the selected resources. The quantity, time, and system constraint calculations control the plotted lines.

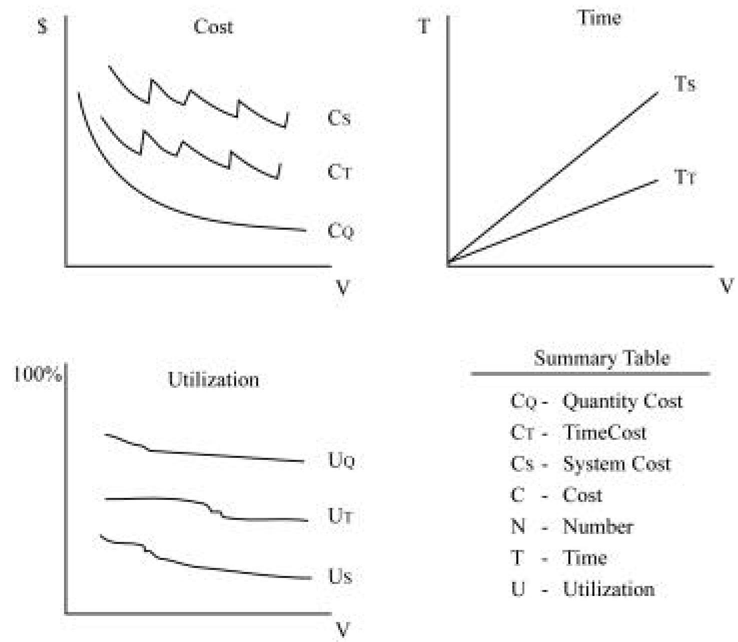

Figure 11. RCM Results with Current-Resource Selected

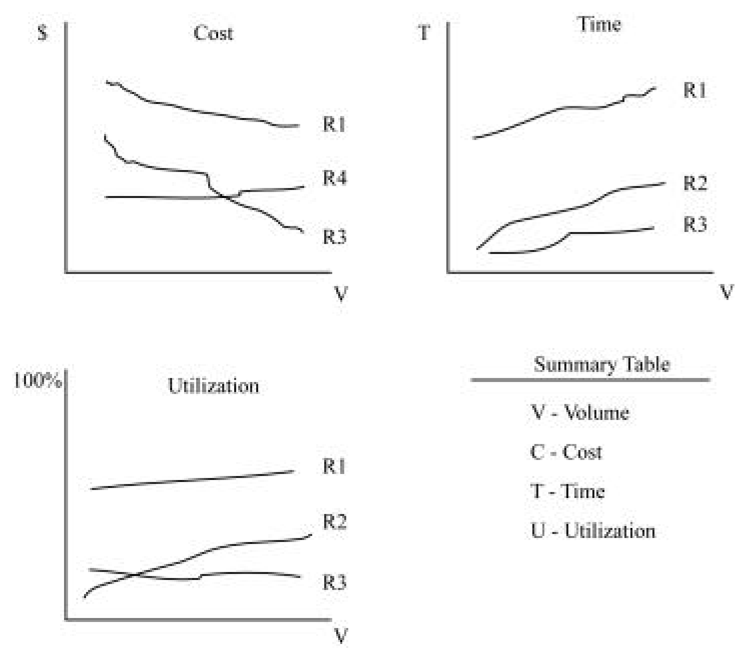

Figure 12. RCM Results with All Resources Selected

Figure 13 illustrates RCM graphs and Summary Table when the current alternative is of interest. The graphs show a bold line for the selected alternative results, and below it, up to six selected resources results are shown. This option provides information about the relative contribution of resources to the entire alternative results. The summary table (see Appendix B, Table 6) includes cost, production time, and utilization for the alternative.

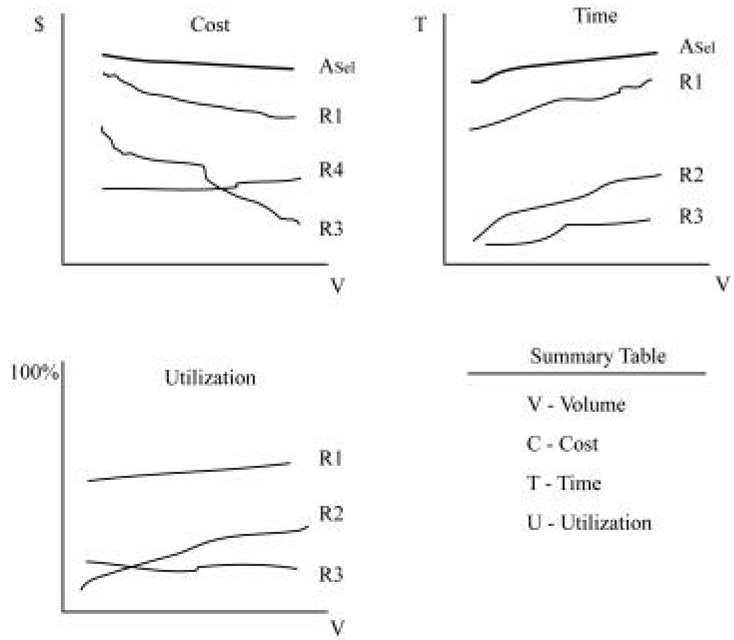

Figure 13. RCM Results with Current-Alternative Selected

Figure 14 illustrates RCM graphs and Summary Table when all selected alternatives are of interest. This provides comparisons between alternatives. The summary table (see Appendix B, Table 7) includes cost, production time, and utilization for the best alternative. Additionally, the best alternative's identification value is shown in this table so that one can quickly see which alternative is best at a specific production volume. The summary table clearly shows that at a specific production volume, different alternatives can be best based upon cost, time, or utilization criterion.

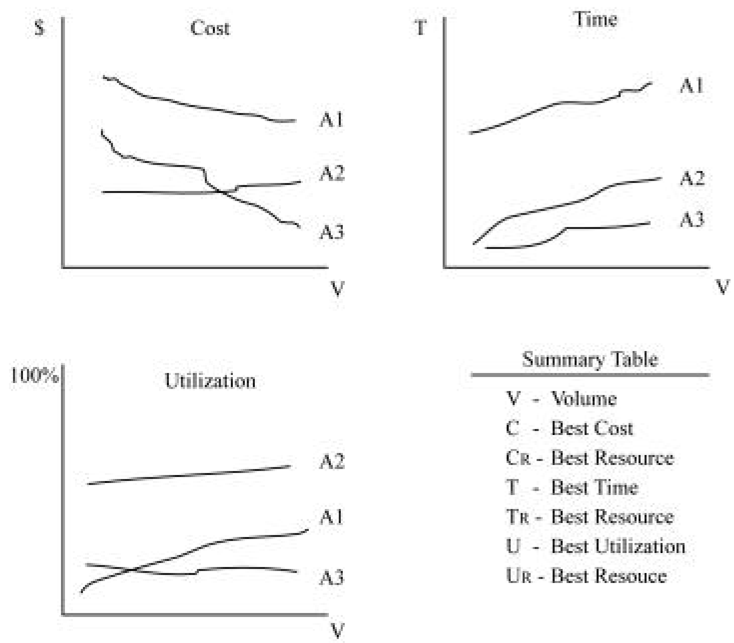

Figure 14. RCM Results with All Alternatives Selected

As alternatives or resources are investigated, it is important to understand how improving or changing parameter values change results. The power of RCM's computer model is that access to all forms of calculations and results is easy.

Process Design

"Process" describes the way in which a product is made. "Process design" determines the most appropriate manufacturing processes and the order in which they should be performed to produce a given part or product. An effective process design is one key to satisfying company and customer needs (Vonderembse and White, 1996). The design should consider an organization's products, facilities, people, equipment, short-term and long-term goals, relationships of all company's resources, and the best use of the resources to achieve customers' needs while meeting the company's operation plans. Process design ultimately translates into company capability, product cost, marketing strategies, customer responsiveness, and profitability. Finding a design that meets present needs and is flexible enough to meet future needs for new and changing products is essential. Good process design produces superior products and enhances an organization's ability to compete in today's world markets.

Detailed design occurs at different levels in a company. It can involve selecting the proper facilities for the entire process, it can involve the selection of equipment, or it can be the selection of feeds and speeds for a particular machine. For a machined part, the process plan details the operations required, the raw material, the preferred tooling, fixtures, feeds, speeds, and machine time.

Consider the part show in Figure 15. Assume that the part's function has been determined and that the design shown is one that provides the desired functionality. The company must decide how it will manufacture the product, its cost, and whether delivery schedules can be met. Some questions that can be asked are: What material should the part be made from? What equipment should machine the part features? Should conventional or NC equipment be used? Should one tool be used to reduce tool changes, or should two tools be used to optimize machining rates realizing that a tool change is required? What are the setup requirements? Can any features on the product be changed for the benefit of machining? Should the machining parameters be set at aggressive rates with more tool changes, or should they be set conservatively?

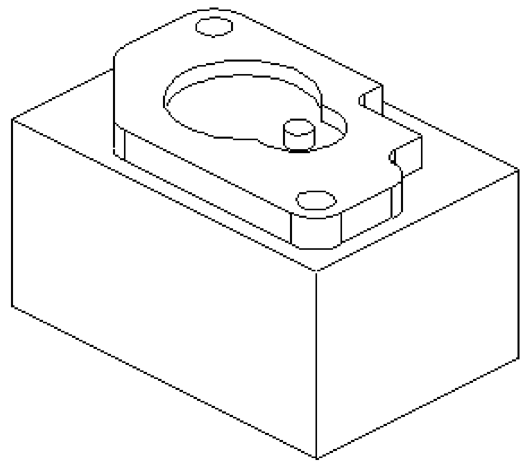

Figure 15. Customer Product

Production rate and volume are also important. If high production volume is expected, consider more expensive but faster equipment. If production volume is low, general-purpose equipment might be better. Consider operational issues also. Does the company plan to work one, two, or three shifts? What production lot size is planned? Should any work be subcontracted? What effect does the production schedule have on equipment availability?

The manufacturing options can lead to an overwhelming combination of alternatives. However, the more alternatives investigated, the better the opportunity to achieve overall cost and time goals. Whatever analytical methods are used, they must efficiently evaluate alternatives. RCM’s computer model provides relatively easy comparison of many alternatives.

Manufacturing Strategies for Process Design

Process design should be consistent with an organization’s overall strategy. If the organization’s strategy is quick product delivery, overall production time becomes the critical factor and process resources that reduce production times are favored. If an organization's strategy is to be the low cost producer, then product cost becomes the important factor and a process design using low cost resources is favored.

Cost-Based Strategies

Cost-based strategies focus on cost reduction throughout the organization to produce the lowest unit cost. In the past, many firms had emphasized mass production and few product variations to achieve low unit cost. Automation has played a significant role in mass production by reducing costs. Other systems, such as labor incentive systems, also were implemented with a goal to reduce cost by precisely describing the method and time to perform tasks.

Many believe that an overemphasis on unit cost can lead to manufacturing systems that are more expensive as a whole. Some believe that a focus on cost leads many companies to over invest in inventories, since inventories artificially increase production volume. Some believe that cost strategies result in organizations that are not responsive to changing customer needs. Others believe that many U.S. companies focus too much on cost and not enough on quality. The Japanese, during the 1970s, proved that they could compete on cost and on quality.

Time-Based Strategies

Organizations are beginning to recognize that time can be used as a competitive advantage because of the value that customers place on it. A shift in focus from cost to time may become most important for the next generation of managers and executives. Organizations that had switched their focus from cost reduction to quality improvement learned that efforts to improve quality often resulted in cost reductions. Firms that focus on time may also capture quality improvements and cost reductions (Vonderembse and White, 1996).

A time-based strategy seeks competitive advantage by quickening the pace of critical organizational processes. Several principles for time reduction include performing tasks concurrently, eliminating redundant steps, combining activities, and making processes more efficient. If implementing these principles causes changes in cost, then both cost and time effects must be investigated before process design decisions are made.

One very popular time-based strategy is Just-in-Time (JIT). JIT is a business strategy for designing production systems that are more responsive to precisely timed customer delivery requirements. This strategy focuses on reducing lead times, reducing setup times, and improving product quality, but primarily on eliminating waste.

Sometimes time and cost are directly linked. Incentive pay systems, for example, use time study techniques that attempt to reduce both time and cost. The focus of the incentive system is on labor cost, but as time decreases system capacity often increases.

Resource-Based Strategies

Resource-based strategies focus on obtaining the most out of manufacturing resources. Capacity, the intrinsic capability of a resource, and utilization, the extent to which management uses capacity, are two measurement metrics. Two examples of resource-based strategies are presented below.

Materials requirements planning (MRP) systems are widely used scheduling tools in manufacturing organizations. These computer-based information systems merge data about the structure of the manufactured product (e.g., the bill of materials), availability of its subassemblies and parts (e.g., inventory information), and lead times with the requirements imposed by customer orders and forecasts. The result is information about when part orders must be placed, in what quantity, and when work should begin to satisfy customers' demands. Although MRP is often thought of as a scheduling methodology, MRP can form the basis for much more detailed capacity calculations. The nature of the available capacity becomes a continually evolving parameter in MRP. Order releases touch off a series of capacity requirements on the machines and equipment required for part production. Unavailable resources directly affect the master schedule.

Another resource-based strategy is Theory of Constraints (TOC). Eli Goldratt and Robert Fox, developers of TOC (Goldratt and Fox, 1987), argue that operating expense should be assigned only to bottleneck resources. Theory of Constraints gets its name from the concept that a constraint is anything that prevents a system from achieving higher performance relative to its goal.

The TOC procedure emphasizes getting maximum utilization and return from bottleneck resources and not burdening products for consuming time on nonbottleneck resources (Goldratt and Fox, 1987). A bottleneck is any resource that has capacity equal to or less than the demand placed on it. A nonbottleneck resource, on the other hand, is one that has capacity greater than the demand placed on it. The reason TOC focuses on bottlenecks is that bottlenecks determine output for the entire production process. Increasing throughput for bottlenecks increases throughput for the system. Management must consider how to improve bottleneck resources.

In RCM, every resource has intrinsic constraints and operational constraints. Its intrinsic constraints are based on the number of pieces that it can produce, or the number of pieces it can produce before its shelf life is reached. The operational constraint is based upon availability of other resources, and time interaction with other resources. All resources are replenished at some point in production, whether it is a material resource, a labor resource, or a machine tool resource. So in a sense, all resources can become constraints. RCM calculates the number of resources required at different production volumes. If the calculations show that two machine tools are required but management wants only one machine to be purchased, then the machine tool is a constraint resource.

Flexibility-Based Strategies

Flexibility can be defined as a collection of properties of a manufacturing system that support changes in production activities or capabilities (Carter, 1987). These changes can be due to either internal or external factors. One technology that facilitates the flexible strategy is a flexible manufacturing system (FMS). FMSs use computer and information technology to integrate material handling, robotics, and computer aided process planning with cellular manufacturing. FMSs also allow an organization to produce highly specialized designs. An FMS can quickly and efficiently make switches among a family of parts. The greatest benefits of FMSs are derived when a company has midvolume production, a variety of similar parts, and unknown customer order patterns. Although the cost of some FMSs is high, it is believed that their advantage is reduction in total throughput time. Some suggest that FMS goes beyond the specific equipment and flexibility becomes part of the organization's operational strategy (Singh, 1996), and that FMSs provide competitive advantage.

Another flexibility-based strategy centers on an agility concept (Fliedner and Vokurka, 1997). Agility is the ability to market a broad range of low cost, high quality products and services with short lead times and in varying volumes with high levels of customization, successfully. Some believe that the competitive environment of the global marketplace is producing more sophisticated customers who demand more variety, better quality, and greater service reliability and response time. Product life cycles are shortening and product proliferation is expanding. Consequently, the agility strategy promotes responsiveness as a company's competitive edge. Agility merges four distinct competencies: cost, quality, dependability and flexibility. Agility is different from flexibility in that it addresses fast response to unanticipated demand, whereas flexibility addresses response to known demand. Agility strategies include both internal and external initiatives. Internal initiatives include business process reengineering, adoption of new technology and management tools for cycle time and order response time reduction, teamwork, employee empowerment, and employee education and training. External initiatives focus upon supply channel performance improvements including partnerships, outsourcing, schedule sharing, and technology adoptions. Each of these initiatives contributes to the attainment of the four dimensions of agility in varying degrees.

RCM and Computer Integrated Manufacturing

Although disagreement exists around the specific definition of computer integrated manufacturing[1] (CIM), describing CIM as the integration of manufacturing and information technology is fair. Manufacturing technology consists of the manufacturing equipment that uses some form of digital information to assist or control its logical operations. A computer numerically controlled (CNC) milling machine is one example where the machine path is programmed by a computer aided manufacturing (CAM) system. Information technology combines data and decision analysis methodologies to generate manufacturing logic. An example is an expert system for computer aided process planning (CAPP) that determines optimal machine feeds and speeds. As many companies strive to attain higher levels of CIM, considering how new tools and techniques fit into the overall CIM philosophy is important.

[1] Dr. Harrington, who published a landmark book "Computer Integrated Manufacturing" in 1973, did not want to see CIM become another buzzword.

Figure 16 illustrates how RCM and other CIM component technologies work together. CIM includes many more components than what is shown in this figure, but illustrated are the significant interfaces between RCM and components of CIM.

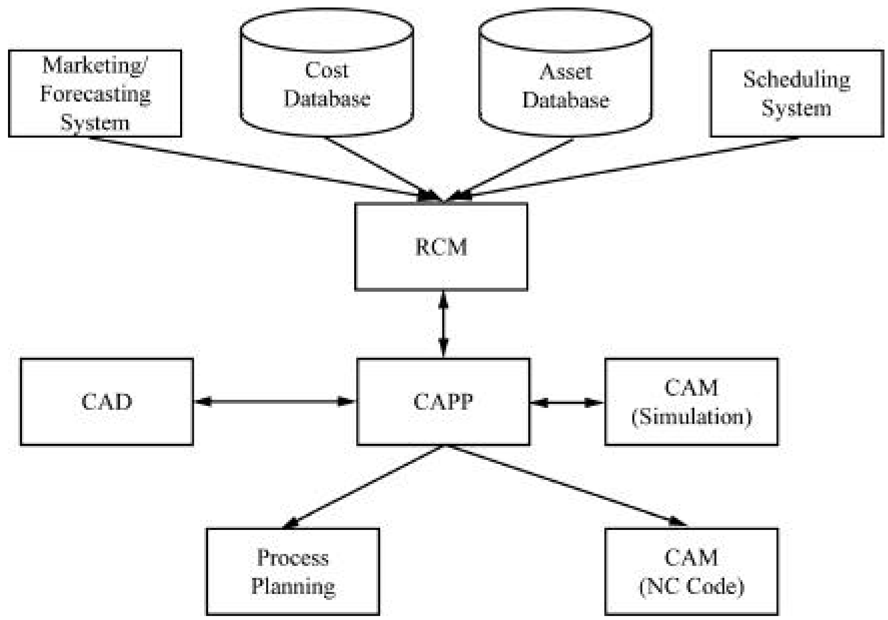

Figure 16. RCM and CIM

Computer aided design (CAD) is used to create or modify an engineering design, and can include geometric modeling, stress and strain analysis, and simulation of part movement. It allows companies to produce part designs rapidly, describes part features, materials, tolerances, and create part geometry files. During design, decisions must be made about the manufacturability of part features. It is at this point, that a CAPP system is used. CAPP's role is to determine machine selection, machine routings, process sequence, feeds and speeds, tool selection, and setup requirements. In order for CAPP to make these decisions, the production economics and cycle time must be considered. RCM quickly assesses cost, time, and utilization information. In doing so, RCM considers resources required (Asset Database), costs (Cost Database), equipment availability (Production System), and production volume (Marketing/Forecasting System). Time information can be generated from machining simulations provided by CAM. CAPP information is coordinated with RCM analyses.

During this process, communication between the CIM components is essential, since information generated by one component must be quickly considered by other components. Common information should be used from the appropriate database. RCM's computer program was modeled in a database environment specifically to illustrate this concept.

At the completion of computer aided process planning, process plans are produced, and machining programs can be generated for numerically controlled (NC) machine tools. Various databases can be updated to reflect the changes in resource utilization and production plans.

Organizations can respond more quickly to customers with the proper application of CIM. When the components are properly combined, these components can yield synergistic results.

RCM Research Scope and Goals

The focus of this research is on the development of new methodology that provides better analysis of process design alternatives. RCM considers and integrates process cost, production cycle time, resource requirements, capacity and resource utilization. RCM derives production cost, time, and utilization directly from the resources that the production process consumes. It accounts for economy of scale effects and clearly shows product cost and cost reduction potential. RCM is developed as an analysis technique and not an optimization technique.

To provide quick analysis of many alternatives, RCM includes a computer model that integrates RCM concepts. The development of a computer model was necessary due to the mathematically intensive nature of RCM. In process design, the more alternatives considered, the more likely a good decision can be made.

RCM is not designed to support any single manufacturing strategy. Instead, it is a methodology that can help evaluate process designs within many strategies. RCM can help reconcile the various manufacturing strategies by showing the advantages and disadvantages of each.

Some strategies compete directly with others. For example, JIT promotes reducing batch sizes and inventory. However, it can be argued that reducing the batch sizes may produce more setups and undesirable results, such as higher costs and less learning advantage. TOC promotes that inventory should exist before bottleneck operations, something JIT argues against. Resource-based strategies argue for 100 percent utilization while JIT approaches argue for 100 percent availability – completely opposite of each other.

Some companies invest in mass production equipment and sometimes realize high costs if product demand forecasts are not reached. RCM demonstrates the risk, in cost and time, between process design alternatives at different production volume levels. Mass production equipment might still be the best choice even if it is not fully utilized. Some companies specifically want to have “reserve” capacity. RCM calculates utilization and clearly shows the differences between alternatives.

RCM’s computer model was developed within a database programming environment. This environment was specifically chosen to reinforce the concept that

RCM must be integrated with other database systems. A database approach to process design evaluation is unique, yet believed to be essential if RCM is to become a part of a computer integrated manufacturing solution.

This chapter provided an overview of RCM concepts. Chapter 2 compares RCM with other process design methodologies. Chapter 3 provides RCM equations and analyses. In Chapter 4, RCM concepts are applied to an industrial problem to demonstrate the method and the type of results and insights that RCM provides. RCM was developed for discrete parts manufacturing; however, it can be applied to other types of production environments. Chapter 5 summarizes the major findings and conclusions for RCM.

CHAPTER II

CURRENT PROCESS DESIGN METHODOLOGIES AND A COMPARISON WITH RCM

This chapter provides background to the more common methodologies used to analyze and select process designs. Each methodology is reviewed and then compared with RCM. The methodologies are presented in an order based upon their similarity with RCM, and where one methodology's ideas might support the understanding of others.

A single universally accepted approach does not exist. Return on investment analysis techniques are strongly preferred in industrial engineering, but they do have advantages and disadvantages discussed below. In fact, all methodologies have advantages and disadvantages. An immediate comparison with RCM provides an understanding of each methodology's strengths and weaknesses. Keep in mind, as the various techniques are presented, that the goal is to improve product and process design decisions.

Cost Accounting and Activity-Based Costing (ABC)

The accounting function is typically divided into two categories: financial accounting and cost accounting. Financial accounting is designed to meet external information needs and to comply with generally accepted accounting principles, whereas cost accounting attempts to satisfy internal information needs and provides product costing information (Barfield, Raiborn, and Kinney, 1994). Financial accounting is not intended to provide detailed product and process cost information, so it is ignored as a competing methodology. However, it should be noted that financial ratio analyses that are based upon financial accounting data provide company performance measures that may be useful when addressing a company's strategies, strengths, and comparisons with other companies.

Traditional cost systems provide the linkage between revenues earned and the expenses of producing products (Cooper and Kaplan, 1991). They measure accurately resources consumed in proportion to units produced, i.e., production volume. Such resources include direct labor, materials, machine time, and energy. These traditional cost systems have failed to keep up with the major changes in companies' production processes and production strategies. Specifically, these systems fail to recognize activities and transactions that are unrelated to production volume. A closer look at cost accounting, and more specifically, activity-based costing systems, follows.

Overview

The most significant weakness in the traditional volume-based cost systems occurs when the allocation basis does not match a product's resource consumption. This is most recognized when labor intensive organizations convert to capital intensive (automated) production systems and continue to allocate indirect costs using direct-labor hours. The automated equipment uses less labor and is allocated a smaller amount of overhead though it consumes much more overhead (e.g., equipment depreciation, energy, maintenance, and engineering).

Activity-based cost systems have emerged in recent years[2] and give managers more accurate cost information about operations (Harrison and Sullivan, 1996). Activity-based systems differ from their unit-based counterparts because they model consumption,

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[2] Hamilton Church pioneered ABC concepts almost one hundred years ago. Church disagreed with the practice of allocating all overhead based on direct labor cost and suggested that special "cost pools" be used in assigning specific types of overhead to individual products (Harrison and Sullivan, 1996).

not spending. ABC systems estimate the quantities of resources used by various activities and link these to activities performed for individual products. The ABC systems better reflect the underlying production economics and by that provide better guidance for manager decisions. As products and production processes become more diverse, ABC systems provide more accurate information than unit-based systems.

ABC systems commonly use a two-stage allocation methodology (Cooper and Kaplan, 1991). In the first stage, ABC acknowledges that different departments or functional areas, called “cost pools” consume resources at different levels. ABC systems identify “cost drivers” such as the number of setups, setup hours, number of products, number of production lots, or production lot size, when allocating costs to the pools. Notice that drivers may be count or duration based. One challenge with ABC is to identify the correct drivers and the proper number of drivers. In the second stage, costs are allocated to specific products that place demands for activities.

Case writing and field research have revealed that ABC systems need two new sets of activities, batch and product-sustaining, to explain the demands that individual products have on organization resources (Cooper, 1990). Batch-related activities, such as setting up a machine to produce a different product, are done each time a batch of goods is processed. Product sustaining activities, such as information systems and engineering resource activities, enable individual products to be produced and sold. A last category of expenses called “facility-sustaining” includes taxes, housekeeping, landscaping, maintenance, and security. These are necessary to provide a factory that can produce products. ABC eventually allocates these to all products.

Figure 17 illustrates an ABC hierarchical expense model with four expense categories: facility, product, batch, and unit. Not all ABC systems use four categories. Some rely only on two.

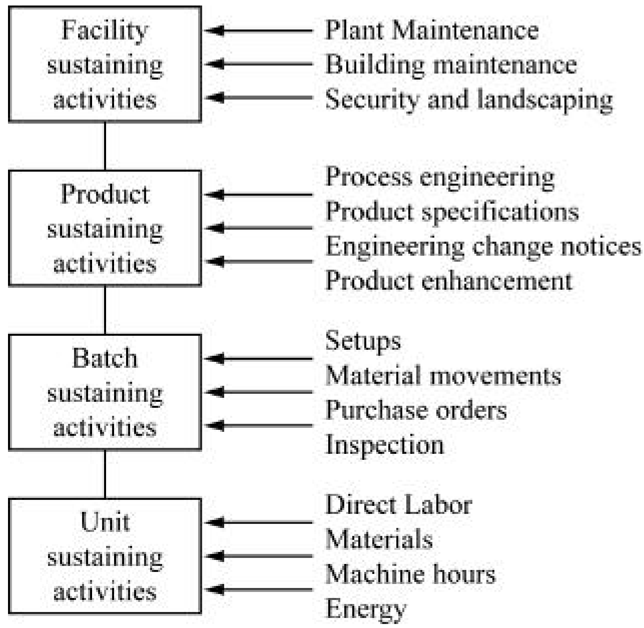

Figure 17. ABC Hierarchical Model of Expenses

Whenever a resource is not used to its full capacity, planned or unplanned, companies face the problem of how to assign capacity resource expenses to the products and services that consume these resources. Companies must decide upon a denominator volume to calculate the unit cost of using the capacity resource. Several choices have been discussed by ABC advocates: theoretical capacity, practical capacity, normal volume, and budgeted volume (Cooper and Kaplan, 1991). Theoretical capacity is defined by taking the unit cycle time and dividing it into a 24-hour day. Virtually no companies use theoretical capacity, since it represents a standard that can never be practically achieved. Practical capacity reduces the 24-hour day by normal downtime, preventive maintenance, scheduled downtime, and other planned delays. Some proponents of ABC suggest that excess or idle capacity should become a separate line item in the financial reports. With this approach, the expense of excess capacity is highlighted for management action and not buried in product costs. This approach appears to make much sense but it has not yet become very popular. Budgeted capacity, where planned daily production hours are used instead of 24 hours, is the most popular. It correlates to the production plan. Budgeted capacity, however, does not provide information about the potential unit costs when the resource is fully utilized. Normal capacity is similar to budgeted capacity except that it is based upon normal market expectations. Some have found that practical capacity provides a much better estimate of the long-run cost of using capacity resources (Cooper and Kaplan, 1991).

Comparison with RCM

Financial accounting information aggregates costs at too high a level to be useful for process design decisions. RCM can use some information from the financial accounts, such as capital equipment and expense costs, but this is the extent of their similarity.

RCM has many parallel concepts to activity-based costing. Most significant is the concept of “resource consumption.” Both ABC and RCM methods concentrate on specific resources consumed by product production. Both eliminate the distinction between direct and indirect costs and treat all costs as variable. The major difference between the methods is that ABC is predominately an after-the-fact approach whereas RCM is a before-the-fact approach. In other words, ABC calculates costs after the product processes have been purchased and put in operation, whereas RCM is used before resource purchases. ABC is an allocation methodology whereas RCM is a decision support methodology. RCM is best used during the early design phase (see Figure 2, page 3) where product costs can be most influenced. ABC is not as well suited to analyze the costs of new production processes since it relies essentially on existing cost data. ABC may eventually be used as a decision making tool but at this point it is not fully developed to do this.

ABC provides a good structure for cost (illustrated in Figure 17). Both ABC and RCM consider unit level and batch level expenses at approximately the same level of detail. Data requirements are similar for both. Any resource cost, including product sustaining expenses, can be included in RCM; however, this approach is discouraged unless they significantly differ between process design alternatives. Management of facility level expenses is often independent from production process management. RCM is a process selection methodology and does not require that all costs be allocated.

Another RCM advantage is that it includes capacity calculations at the system level and illustrates the effect graphically. The graphs can be interpreted directly to understand capacity and utilization levels for any process design resource. Figure 18 shows that higher costs exist for the system than for the resources piece or time lives. This level of detail applies for each individual resource and for any process design alternative. The RCM resource availability parameter a_r, which represents the hours in a day that a resource is available, can be adjusted to portray practical, normal, and budgeted capacity. RCM can calculate capacity because it includes several time-based parameters.

RCM addresses both production cycle time and cost. ABC might use time as a driver, but its focus is on cost. RCM does not reconcile or optimize cost and time. Nevertheless, it does show how various process designs compare with respect to both metrics. RCM's time calculations can predict product production responsiveness.

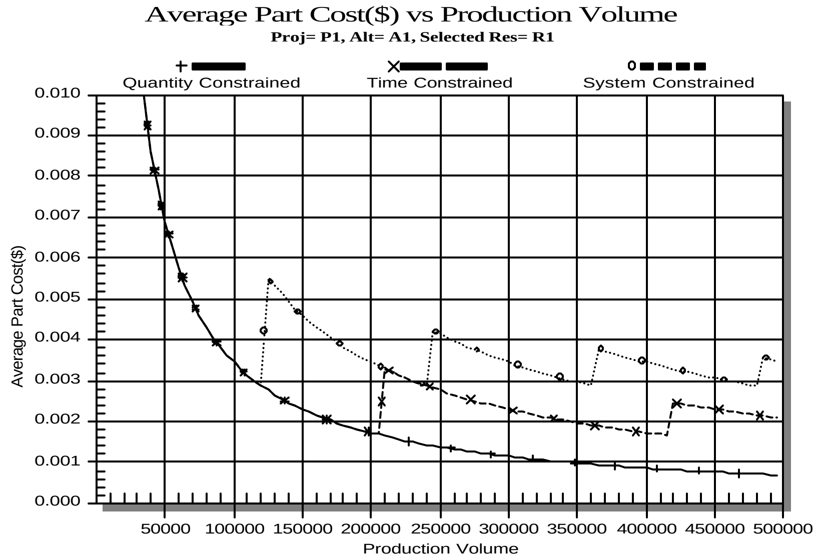

Figure 18. RCM Capacity Illustration

RCM's computer model contains graphical results that clearly show cost, time, and utilization information. ABC, by comparison, is a numerical methodology. By graphing RCM's numeric results, the user gains a much better understanding of costs, time, and capacity, and the factors that influence them. The interactive computer model provides easy changes to input values and easy access to results that enables effective sensitivity analysis. Data requirements for RCM are greater than for ABC, however, many RCM variables can be estimated and then varied during sensitivity analysis.

Engineering Economics and Return on Investment Analysis

Engineering economy[3] is the discipline concerned with the economic aspects of

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[3] A pioneer in the field was Arthur M. Wellington, a civil engineer who in the later part of the nineteenth century specifically addressed the role of economic analysis in engineering projects. His particular are of interest was railroad building in the United States.

engineering (Wellington, 1887). The principles and methodology of engineering economy are an integral part of daily management of corporations (DeGarmo, Sullivan, and Bontadelli, 1997). Engineering economics provides the mathematical foundation to calculate investment net present value (NPV), future value (FV), and internal rates or return (IRR) that include tax effect considerations.

Internal rate of return, often called return on investment (ROI), is a measure that was developed earlier in this century to help in the management of the new multi-activity corporations that were then forming. IRR was used as an indicator of the efficiency of diverse operating departments for evaluating requests for new capital investment and as an overall measure of the financial performance of the entire company (Cooper and Kaplan, 1991).

Overview

A capital expenditure opportunity entails a cash outlay with the expectation of future benefits over several years. In engineering economics, cash flow profiles that estimate future costs and benefits similar to that shown in Figure 19 are created. The cash flow profile consists of a net investment, expected annuities over the span of years, and a salvage value at the end of the investment life. When comparing two alternatives, the expected difference in cash flows is used. Once the net cash flows are known, net present value, future value, or internal rate of return calculations can be made (Lutz, 1982). Net present value uses a cost of capital rate to discount all cash flows back to point zero. An investment is deemed viable when its NPV is positive. The internal rate of return method calculates the interest rate that equates the sum of the present values of positive cash flows to that of the negative cash flows. The investment is deemed viable when the calculated interest rate is greater than the company’s cost of capital. Whether

NPV or IRR is better can be argued. Some believe that NPV is better during high inflation periods, but others believe that NPV improperly favors proportionally higher cost investments than IRR. The argument is not settled or debated within this dissertation.

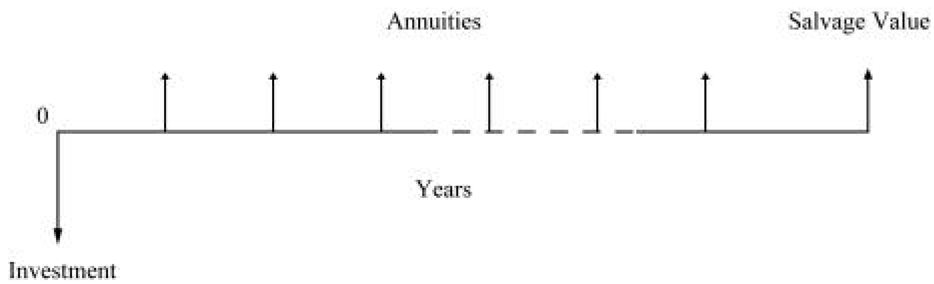

Figure 19. Cash Flow Diagram

Engineering economics is a very popular way to evaluate process designs. Engineering economics contains the concept of “time value of money," which more accurately reflects real investment effects and therefore makes it better than simple payback calculations. Cost accounting is the source of much of the cost data needed in engineering economy studies (DeGarmo, Sullivan, and Bontadelli, 1997).

Comparison with RCM

In engineering economics, a decision is based upon one calculation - either the internal rate of return or the net present value. Although this is an important financial metric that can always be calculated, management must also have an understanding of unit costs, production times, and capacity. These latter metrics are not provided directly by engineering economics methodology but they are in RCM.

Both engineering economics and RCM are alternative evaluation techniques. The IRR compares two alternatives at a time, whereas RCM can compare many (six in the computer-based model) at a time. The ability to compare several alternatives with each other provides a better understanding about the degree of differences between the alternatives and what contributes to the differences.

RCM performs cost, time and utilization calculations, and these calculations are made over a range of production volumes. IRR is based upon production volume and IRR's sensitivity analysis involves additional calculations for several different production volumes. The burden of producing cash flow calculations for many alternatives is cumbersome in the IRR method. RCM provides a much better view of the effects of production volume on various alternatives and where cost reduction potential exists. Engineering economics uses accounting depreciation life whereas RCM uses actual expected resource life. Depreciation life does not always correspond to actual useful life. In this regard, engineering economics is criticized that it has a short-term focus.

RCM does not directly use the time value of money concept. It does contain the ability to include various types of growth or decay cost functions. Besides, the timing of the acquisition of funds and the cost of capital is often a financial management issue separate from the process design issue.

Engineering economics does not calculate capacity and it assumes that this calculation is done elsewhere. High IRR's can result when the investment analysis has forgotten capacity calculations, for its savings are not consistent with the actual resource requirements.

RCM considers a process design's resources in much more detail than IRR and provides greater sensitivity analysis since more parameter values can easily be questioned. It can show which resources contribute most to an alternative's cost. Sometimes changing a few parameter values can improve an alternative's comparison with others.

Finally, engineering economics places the attention on cost and not cycle time. There may be times when an alternative with a lower IRR, but a faster production cycle, is preferred. Alternatives that have nearly equal costs but different production cycle times are equivalent with IRR. Typically, the alternative with the faster production time is preferred. It must be recognized that tradeoffs between cost and production cycle time do exist.

Break-Even Analysis

Often there is a choice between two alternatives where one of them may be more economical under one set of conditions and the other may be more economical under another set of conditions. Finding a value for one parameter that makes the other equal is called the break-even point (Grant, Ireson, and Leavenworth, 1976).

Overview

The break-even economic evaluation technique is useful in relating fixed and variable costs to the number of hours of operation, the number of units produced, or other measures of operational activity. In each case, the primary interest is the break-even point in that it identifies the range of the decision variable within which the most desirable economic outcome may occur (Fabrycky and Blanchard, 1991). Break-even analysis has been applied to make-or-buy evaluations, lease-or-buy evaluations, and equipment selection evaluation. Figure 20 illustrates a typical break-even diagram.

For equipment selection, the break-even diagram typically graphs cost versus production volume or hours of operation. An alternative is represented by a linear line that starts at zero production volume and some fixed cost, usually the investment cost. The slope of the line represents the variable costs for the equipment operation. Additional lines for several alternatives may be shown. Theory suggests that a higher investment in equipment usually results in lower variable costs, and a lower equipment investment results in higher variable production costs. The crossing of the two lines represents the “break-even” point

– the point where both investments result in the same production cost at the same production volume. One alternative costs less below the break-even point and the other alternative costs less above the break-even point. Given this comparison and a production forecast, management can decide between the two alternatives.

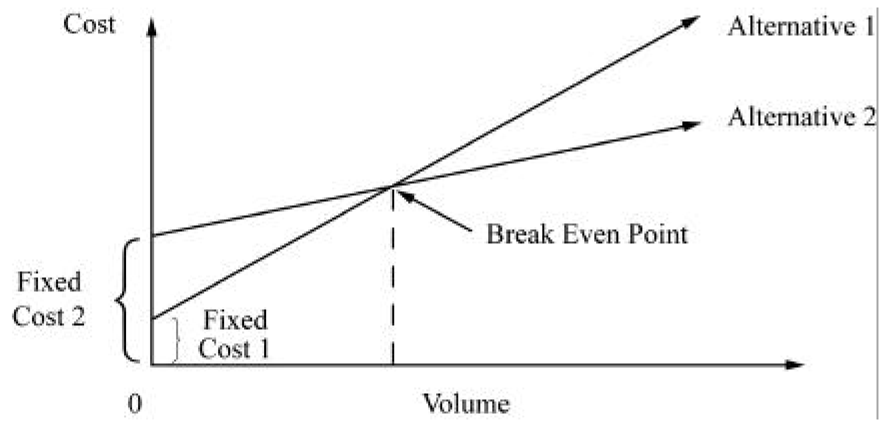

Figure 20. Break-Even Diagram

Process design is based upon expected production volume. If the demand for a product is low, general-purpose equipment is usually preferred. If production demand is high, more specialized and automated equipment becomes viable. Volume becomes the driving factor in lowering the costs of goods and services, therefore, using volume as the independent variable in break-even analysis seems appropriate.

Comparison with RCM

Break-even analysis and RCM have similarities. Both consider volume effects on costs, build an alternative's cost from resources, have the idea of break even, and rely on a graphic portray of costs for alternatives.

There are many differences, however, between the two techniques. RCM considers all expenses variable whereas break-even analysis has both fixed and variable expenses. RCM provides detailed analysis for all resources, not just alternatives. Besides cost, RCM also includes time and utilization calculations and graphs. Capacity calculations are internal in RCM and any resource, including fixed, may need replenishment. Tabular results are provided for all calculations in RCM.

The major disadvantage of break-even analysis is that it over simplifies reality. It assumes a linear relationship for variable costs. This is true only when resources can be purchased in lot sizes of one. Break-even analysis does not account for fixed expenses that need to be replenished. In RCM, alternatives can have several production volumes where one alternative is better than the other. In break-even analysis, there is only one break-even point.

RCM contains much more detail about alternatives that can be modified for sensitivity analysis. RCM provides investigation into an alternative's components to discover which components influence cost the most.

Cost Estimating

Cost estimating is concerned with cost determination and evaluation of engineering design. When used as a noun the estimate implies an evaluation of a design expressed as cost. When used as a verb, it means to appraise or to determine. A cost estimator is the person responsible for providing the estimate (Ostwald, 1984). For companies that compete in today's marketplace, cost estimating is a critical function since it provides information about what products in the future may cost. In contrast, cost accounting keeps track of what products currently cost.

Overview

The cost estimating process integrates the experience and expertise of many company employees. A detailed cost estimate requires that the overall project be broken down into small tasks called the work breakdown structure (WBS). Different tasks are then estimated using different methods appropriate for the task. The method chosen depends on the expertise of the company, the availability of information, and the type of work to be performed (Winchell, 1989).

There are various cost estimating methods: detailed estimating, direct estimating, estimating by analogy, firm quotes, handbook estimating, staffing methods, and statistical and parametric estimating (Sullivan and Luxhoj, 1996). Detailed estimating involves the accumulation of cost estimates from the lowest possible level of the work breakdown structure. Direct estimating is a judgmental estimate done by an expert estimator. Estimating by analogy is similar to direct estimating but also includes the use of a previous estimate similar to the product under investigation. Historical cost data, handbooks, and databases are commonly used when estimating by analogy. Handbooks and reference books contain information on almost every conceivable type of product, part, supply, equipment, raw material, or finished product. One must be careful to use this information carefully and consider how it may vary by geographic area and specific product. In-house historical cost estimating data is sometimes viewed as a necessity for good cost estimating (Stewart, Wyskida, and Johannes, 1995). Firm quotes from vendors or suppliers are one of the most accurate methods for obtaining cost estimates for purchased components. Staffing methods, sometimes called conference methods (Winchell, 1989), ask experienced managers to estimate the number of labor hours or machine hours required to complete a task. Statistical and parametric estimates use historical data but make modifications to the data based on such things as inflation, weight requirements, power, size, production, and volume.

The detailed analysis is the most reliable method of estimating (Winchell, 1989). As its name implies, it includes a complete examination of all the important factors involved in the production of a manufactured item. Detailed analysis includes the following steps:

1. Calculate raw material usage.
2. Process each individual component.
3. Compute the production time.
4. Determine the equipment required.
5. Determine the required tools, gages, and special fixtures.
6. Determine any additional equipment needed for inspection and testing.

Detailed analysis requires extra work and additional time for its completion but its accuracy is much greater than other methods.

The major elements to be determined by cost estimating include the cost of labor, material, manufacturing cost, and time. Estimating material costs usually begins with the bill of materials (BOM) for the product. From the BOM, make versus buy decisions are required. If a buy decision is considered, then supplier quotes must be obtained. Quotes are evaluated based on costs, product quality, delivery times, delivery reliability, and other factors. When products are to be manufactured from within, materials, labor and manufacturing costs must be estimated. Again, vendor quotes may be obtained to compare raw materials and component parts. Methods to estimate labor times (and cost) include time study, standard data computations, work hour reports, Gantt charts, critical path methods (CPM), learning curve models, process planning equations, simulation techniques and work sampling (Winchell, 1989). The costs of manufacturing activities, such as fabrication, assembly, testing, and other production processes are usually based on historical records and the experience of the manufacturing engineer. Functional cost equations, standard time data, and a variety of process planning tools and computer software may be used. Process design analysis may recognize that manufacturing cost and time tradeoffs exist. For example, machine cycle time may be reduced but tooling costs (due to aggressively using the tool) may increase. Some analyses attempt to optimize these tradeoffs.

The cost estimating function does not produce exact cost and time data, but rather estimates that have a high probability of falling within an acceptable range.

Comparison with RCM

RCM is similar to the detailed cost estimating methods. RCM requires a work breakdown schedule and requires resource consumption to be identified. RCM uses only one relatively simple database structure and a consistent method for describing resources. RCM treats all costs as variable and does need to classify costs with accounting terms (e.g., fixed, variable, overhead, and periodic). For any production process, RCM requires 1) the identification of resources consumed, 2) resource cost information, and 3) resource time information. RCM calculates cost, times, and utilization metrics from within its computer model. Cost estimating may use many sources and analyses.

RCM and cost estimating both rely on accurate cost information. The methods by which this data is obtained are similar for both. Since RCM attempts to calculate future costs, historic information is less valuable than current and future cost information. Historical information may be used when a faster estimate is needed.

Capacity, often neglected in cost estimating techniques, is built into RCM. This may be of particular interest especially when cost estimating by analogy because capacity is easy to overlook. Cost estimation by analogy is often less accurate when a new process design does not have a similar process in the company. Process planning tools are very useful for both RCM and cost estimating. In a computer integrated environment, a logical interface is needed between process planning tools and RCM for estimating times.

RCM can be used at any level in the work breakdown structure. In practice, it is recommended that RCM use a bottom up approach where the analysis starts resource by resource, but this is only a matter of preference.

Design For Manufacture (DFM) Models

Before the Industrial Revolution, customer needs and the products and production systems used to meet these needs were simple. One person took the product through design and manufacture. Today's products are informationally dense and complex, require vast amounts of specialized knowledge, face continual and rapid change, and involve many people and production processes. The interactions between the various facets of the manufacturing system are complex, and decisions made concerning one aspect have consequences that extend to others. In its broadest sense, design for manufacture is concerned with comprehending these interactions and using this knowledge to optimize the manufacturing system for effective quality, cost, and delivery (Veilleux and Petro, 1988).

Overview

Ultimately, the goal of design for manufacture is to facilitate the design of functionally and visually appealing products with mechanical reliability, to manufacture these products effectively, to introduce the products, and to market them in a timely manner.

Design for manufacture (DFM) guidelines are systematic and codified statements of good design practice that have been empirically derived from years of design and manufacturing experience (Veilleux and Petro, 1988). If correctly followed, they should result in a product that is inherently easier to manufacture. Various forms of the design guidelines have been stated by different authors (Boothroyd and Dewhurst, 1983), (Riley, 1983), (Groover, 1987) that include:

1. Design for a minimum number of parts.
2. Develop a modular design.
3. Reduce part variations.
4. Design parts to be multi-functional.
5. Design parts for ease of fabrication.
6. Avoid separate fasteners.
7. Reduce assembly directions; design for top-down assembly.
8. Maximize compliance; design for ease of assembly.
9. Reduce handling; design for handling and presentation.
10. Avoid flexible components.

Quantitative evaluation methods have been developed in recent years. These methodologies allow the design engineer to rate the manufacturability of the design quantitatively, and in doing so, provide a step by step procedure. The design for assembly (DFA) method developed by G. Boothroyd and P. Dewhurst (Boothroyd and Dewhurst, 1983) is perhaps the most widely used of these quantitative methods. Many assembly factors are considered and the analysis suggests an assembly method. A second quantitative methodology, known as the Hitachi assemblability evaluation method (AEM), is another proprietary method.

In another book by Boothroyd, Dewhurst, and Knight (Boothroyd, Dewhurst, and Knight, 1994) DFM is expanded and includes information on design for manual assembly, design for high-speed automatic assembly and robot assembly, design for machining, design for printed circuit board manufacture and assembly, design for injection molding, design for sheet metalworking, design for die casting, and design for power metal processing. These chapters take a similar approach to providing guidelines for each manufacturing process.

Comparison with RCM

DFM provides guidelines for product design and is usually subjective or qualitative, not quantitative, and there is an assumption that following DFM rules results in lower process design costs. However, this may not always be the case. Consider the DFM rule of reducing the number of parts in an assembly. If this rule were followed to its extreme, then all products would be produced by single part processes, such as casting, injection molding, and laser cutting. However, casting is known to have advantages and disadvantages and not all parts can be cast. Equipment, tooling, and mold costs are generally high and this process typically requires high volume production. Product redesign is also more costly. The integration of dissimilar materials to take advantage of materials structural properties is more difficult in casting. Breaking a complex single part into sub-components that are easier to manufacture, sacrificing higher assembly cost for low overall manufacturing cost is sometimes better. Guidelines and rules may provide a basis for product design, but adherence to a rule might result in higher overall manufacturing cost.

DFM can help the formulation and identification of alternatives. Can a product be made with fewer parts? Can assembly method changes enable an automated approach? Can part tolerances be changed? Should the product be injection molded? Should the casting be changed to a stamping and weldment? These questions lead to the need to investigate different product and process design alternatives.

Other Methodologies

Group Technology

Group technology (GT) is an approach to design and manufacturing that seeks to reduce manufacturing system information content by identifying and exploiting the sameness or similarity of parts based on their geometric shape and/or similarities in their production process. GT is implemented by using classification and coding systems to identify and understand part similarities. As a DFM tool, GT can be used to improve product design efficiency by identifying similar parts and eliminating the need for the new design, or by reducing the design time by modifying an existing part (Veilleux and Petro, 1988). Specifically, GT implies the notion to exploit similarities in three distinct ways: 1) by performing like activities together, 2) by standardizing similar tasks, and 3) by efficiently storing and retrieving information about recurring designs (Wang and Li, 1991).

Value Engineering

In 1961, Lawrence D. Miles in his book Techniques of Value Analysis and Engineering (Miles, 1961) defined value analysis (VA) as "an organized creative approach which has for its purpose the efficient identification of unnecessary cost, i.e., cost which provides neither quality nor use nor life nor appearance nor customer features." The philosophy of VA is implemented through a systematic rational process consisting of a series of techniques, including (1) function analysis, (2) creative alternative generating techniques, and (3) measurement techniques for evaluating the value of present and future concepts (Demarle and Shillito, 1982). The value measurement is represented simplistically as a ratio of the sum of positive benefit factors to the sum of specific cost factors. VA can prescreen a large list of alternatives and reduce them to a smaller subset for further investigation.

Manufacturing Process Design Rules

Process design is influenced by whether a company's production volume categories it as a job, batch, or mass production environment. Given this categorization and additional factors, such as variety of parts, suggestions about process design have been made by Groover (Groover, 1987) and Vonderembse (Vonderembse and White, 1996). Charts, similar to the one shown in Figure 21, have been generated that illustrate the rules.

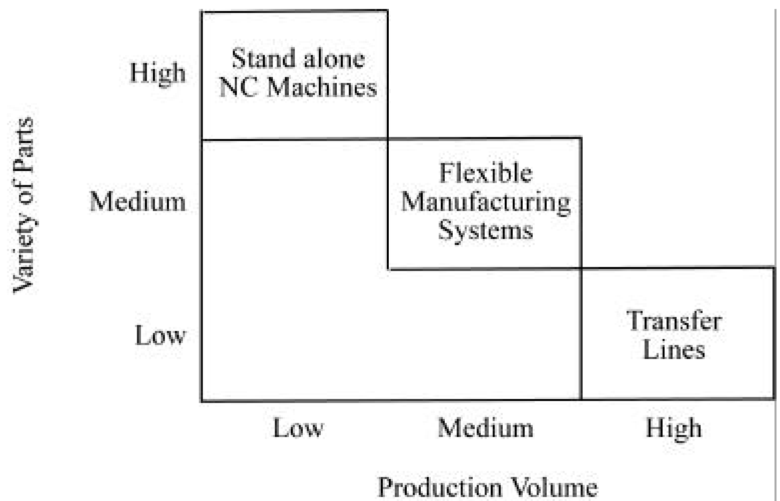

Figure 21. Flexible Manufacturing Systems

Figure 21 shows, very simply, how product volume and part variety can lead to selecting either stand alone NC machines, flexible manufacturing systems, or transfer lines. Diagrams that are more elaborate have been generated. For example, Ashby (Ashby, 1992) has investigated and produced process selection charts, similar to the one shown in Figure 22, that suggest feasible production processes based upon part design

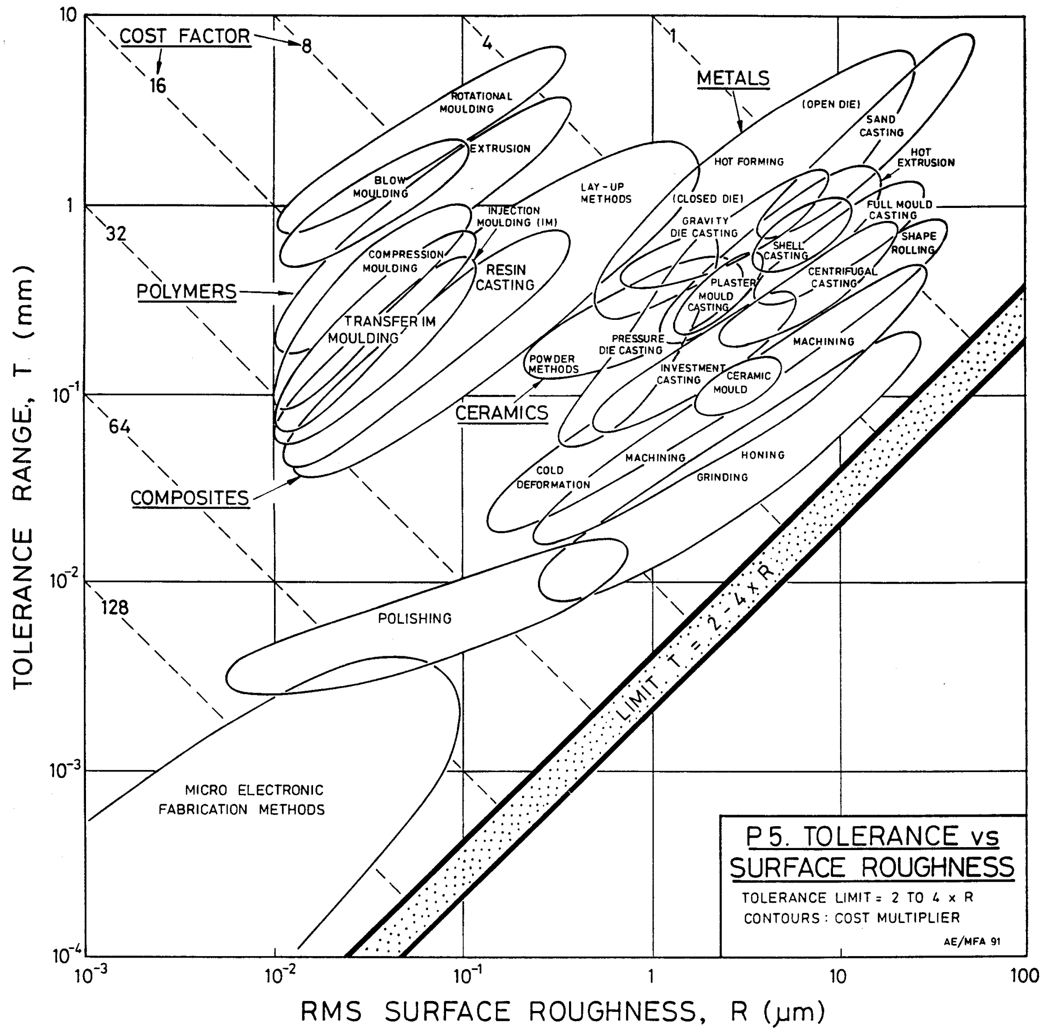

Figure 22. Ashby's Process Selection Chart.

Source: Reprinted, by permission, from M. F. Ashby

features such as minimum section thickness, surface area, weight, information content, material melting temperature, material hardness, tolerance range, and surface roughness.

Figure 21 and Figure 22 represent the extremes, simple and complex, of process design and selection graphs.

Computer Aided Process Planning Systems

In recent years, the demand for integrated, more effective computer aided process planning (CAPP) systems has drastically increased. Many engineers and academic researchers are practicing and studying CAPP. CAPP remains a key component in CIM, and the development of CAPP that meets the needs of CIM implementation is an ever increasing challenge in the manufacturing industry (Wang and Li, 1991). Process plans involve consideration of many factors in part production, such as the manufacturing process, machine tools and equipment, tooling, part dimensional tolerances, surface finish, and cost.

CAPP refers to automating the process planning function by means of computer systems (Groover, 1996). CAPP systems are designed around either of two approaches: 1) retrieval systems or 2) generative systems. Retrieval CAPP systems, also known as variant CAPP systems, are based on GT and parts coding and suggest that similar plans for similar parts be retrieved from a computer database. A similar plan can be modified as necessary. Generative CAPP systems create the process plan using systematic procedures that simulates a human planner. Generative CAPP systems can be defined as systems that synthesize process information to create a process plan for a new component automatically (Chang and Wysk, 1985). Decision logic and optimization formulae are encoded into the system itself and reduce human input required to a minimum (Wang and Li, 1991).

Expert Systems

Because CAPP requires a large amount of human expertise, research has begun to apply knowledge-based techniques and expert systems for CAPP. Knowledge-based systems developed from the field of artificial intelligence (AI), which is a branch of computer science. AI was developed to attempt to simulate human intelligence in a computer. Many of these systems are far from being operative (Wang and Li, 1991), however, results show that these systems will soon become one of the most promising techniques for process planning. Considering previous discussion, one realizes that a productive CAPP system must contain a tremendous amount of knowledge-facts about the machine and shop environment plus rules about sequencing machining operations. Furthermore, the system should be flexible because facts and rules in the database require constant updating.

Unlike traditional CAPP systems where logic is captured line by line in a computer program, expert systems store knowledge in a special manner so that it is possible to add, delete, and modify facts and rules in the knowledge base without rewriting the program. A production rule specifies what to do if something is true and usually takes the form of IF-THEN logic. For example, the following paraphrase of a rule might appear somewhere in the expert system: IF stock is not available THEN consider casting. In traditional programming languages, the continual addition of rules can easily create intertwined and complex code sometimes called “spaghetti” code.

Unfortunately, many expert systems expectations are premature (Wang and Li, 1991). Some false expectations include such things as: expert systems can solve any problem currently solved by human experts; expert systems can be quickly prototyped and expanded; expert systems may be the answer to all of our software problems.

Comparisons with RCM

Most of the above methodologies are better designated as "alternative identification" techniques instead of "evaluation" techniques. Retrieval CAPP systems are based on an existing database of process plans and are not adequate for investigating new process designs. Generative CAPP systems use unique tools for specific process designs under consideration that may provide time estimates for RCM. VA techniques lack tools to evaluate cost, time, and capacity, and to compare alternatives properly. Ashby's charts help identify appropriate process designs, yet they concentrate more on product material features instead of production cost and production time.

CAPP systems are useful at examining many alternative process plans from a capability viewpoint and they can help narrow the alternatives to a set of most viable. CAPP systems typically do not include information about the operational systems, specifically resource availability and capacity, and rely on other systems for this analysis.

RCM's goal is to supplement, not replace, CAPP. In a CIM environment, RCM analyses can be coordinated with other system tools. In this manner, RCM might be considered as one component module to an overall CAPP system.

RCM Advantages and Disadvantages Summary

Many different methodologies and tools have been discussed. These techniques if properly applied, can produce significant improvements in product quality, manufacturing system productivity, and life cycle cost. A comparison of the various methodologies and tools with respect to a variety of criteria is provided in Table 1. This table uses a rating scale from zero to ten (poor to excellent, respectively) to designate how effectively a technique considers the criteria.

Table 1. Comparison of RCM with Other Techniques

Criteria	RCM	ABC	ROI	Break-Even	Cost Estimates	DFM
Cost Analysis	9	9	10	4	6	5
Time Analysis	9	0	0	0	3	3
Capacity Analysis	9	3	0	0	3	3
Production Requirements Analysis	9	0	0	2	3	0
Unit Cost Calculations	9	9	5	5	8	8
Investment Analysis	4	2	9	2	3	2
Sensitivity Analysis	9	8	6	4	3	9
Simplicity	4	6	5	9	8	7
Implementation	4	4	7	8	7	2

0 = Low; 10 = High

CHAPTER III

RESOURCE CONSUMPTION MODEL ANALYSES

Overview

RCM contains the following components: cost, time and utilization analyses; an application algorithm; and a computer program model. The computer model contains a database structure for information, and provides a tool for calculating, displaying, and graphing the results. Chapter 1 explained RCM concepts and provided the philosophical framework for its application methodology. This chapter develops RCM's cost, time and utilization equations. The application algorithm provides the sequence of steps for applying RCM. The computer program model[4] implements RCM's methodology and demonstrates the concepts in an integrated environment. The database structure gathers and organizes all model information. A table and three graphs display the computational results. The graphic displays help make the results comprehensible. The need and integration for these components will become apparent within this chapter.

The approach that this chapter takes is to step through the application algorithm, pause to develop RCM equations, and provide illustrations to support the analyses. A simple process design example – the selection of a desktop computer printer – is analyzed in the process. Chapter 4 applies RCM to an industrial process design problem to demonstrate its capability further.

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[4] For this research, Microsoft Visual Foxpro ®, version 3.0b was used to develop the computer model. It is recognized that RCM can be implemented in many other computer programming environments.

Application Algorithm

Figure 23 provides a flowchart for RCM's application algorithm. The step numbers in this flowchart correspond with step numbers below. Keep in mind that RCM is an iterative process where detailed exploration and results may lead to reconsidering earlier information and results.

Step 1: Identify the problem being addressed. Stating the problem being addressed is helpful. Companies usually consider many problems concurrently that require decisions. Let P represent a set of problems being considered such that $P = \{P_i, i = 1, n\}$, where P_i represents a single problem.

A problem might be to determine one machining operation on a particular part; it might include more than one operation; or it might include all operations required to produce a part or family of parts. Examples of problems are: "Which CNC milling machine should we purchase?", "Should we purchase welding robots for the new products or continue to use a manual method?", "Should the product be produced as a casting or a weldment?", "Is this product feature really needed? What will it cost to add it?"

Understand that RCM is a problem investigation tool, not a project ranking. Other problem or project ranking systems might be used with RCM information, but this is not the intended scope for RCM. RCM's computer program model provides quick and easy investigation of problems in detail so that many more problems and alternatives can be concomitantly investigated with greater fidelity than with other analytical techniques.

Step 2: Identify alternate solutions to the problem. For each problem, P_i, viable alternatives need to be identified such that $P_i = \{A_{ij}, j = 1, l\}$. Each problem can have a different number of alternatives. RCM provides an easy method to construct, manage,

Figure 23. RCM Application Flowchart

and analyze alternatives so that the user can construct a larger variety of alternatives. An alternative might be a completely different approach a process design or it might be a modification of individual parameter values within a design. Consider the problem of deciding whether to robotically weld a new product. Clearly, two alternatives are "robotically weld" and "manually weld." However, the robotic weld alternative can be further broken down into a decision between two robot vendors whose robots have different operating parameters, costs, and capabilities. Another set of alternatives might contain different robot welding speeds, realizing that faster welding produces a higher throughput but possibly consumes more welding supplies, electricity, and equipment downtime. In RCM, it becomes relatively easy to create a brand new alternative by modifying any individual parameters. The modification of individual parameters also provides as basis for sensitivity analysis.

Step 3: Identify resources that comprise each alternative and resource parameter values. For each problem's alternative, A_{ij}, identify resources consumed such that $A_{ij} = \left\{ R_{ijk}, k = 1, m \right\}$. Each problem's alternative may contain its own subset of resources. A resource is anything needed by the process to produce a part. Examples of resource are material, labor, processing equipment, transport equipment, energy, tooling, fixtures and dies, subassembly components, and maintenance or other support services.

RCM's information requirements increase the most here since alternatives can contain many resources. As various process design alternatives and resources increase, the need for data management within a database structure becomes apparent. Table 2 contains RCM model data for the printer selection problem that has three alternatives, and six or eight resources per alternative. Although the table's information may appear to

Table 2. Resource Parameters and Values for Printer Selection Problem

take much time to gather, the situation is not as difficult as it appears. Many parameter values remain the same for several alternatives. Default values in the computer model are often adequate. Unknown parameter values can be estimated. In fact, sensitivity analysis becomes possible by constructing alternatives that use different parameter value estimates. Certainly, better estimates increase RCM result's quality but there remains a trade off between model accuracy and model development time, and the user must still decide how detailed the model should become.

The current computing environment makes information management and calculations very efficient. The computer-based model[5] for RCM runs well on a personal computer. Before describing the specific data requirements for RCM, the computer model is briefly discussed to demonstrate how information is managed. An understanding of the computer model improves the understanding of data requirements and how the computer model is used to support RCM.

Computer Model Overview

Figure 24 shows RCM's startup window. RCM is presented in a paged visual approach. The Visual Foxpro® model has six pages titled Data, Plotting, Cost, Time, Utilization, and Summary, that the user can easily switch between pages by selecting the page heading tab with the mouse. In this event driven interface, the order of selection is not specific, it all depends on what the user wishes to investigate.

The Data page contains project, alternative, and resource information organized in three interrelated grids. Functionally, the user selects a problem to investigate by clicking on it with the mouse. When this happens, all alternatives that the problem contains appear in the

[5] RCM's was modeled on a Pentium 166mHz computer with 32MB of RAM. Minimum requirements are a 80386sx processor with 8MB of RAM.

second grid. When an alternative is selected with the mouse, all resources that the alternative contains appear in the third grid. The three grids make it easy to “zoom in” and “zoom out” to different detail levels.

The information displayed within the grids is held in three separate database tables called PROJECTS, ALTERNATIVES, and RESOURCES. Table 2 represents the information contained in the RESOURCES table except that the ID fields are not shown. Data can be entered and revised in the tables in Foxpro’s interactive environment, or it can be revised in RCM’s computer model.

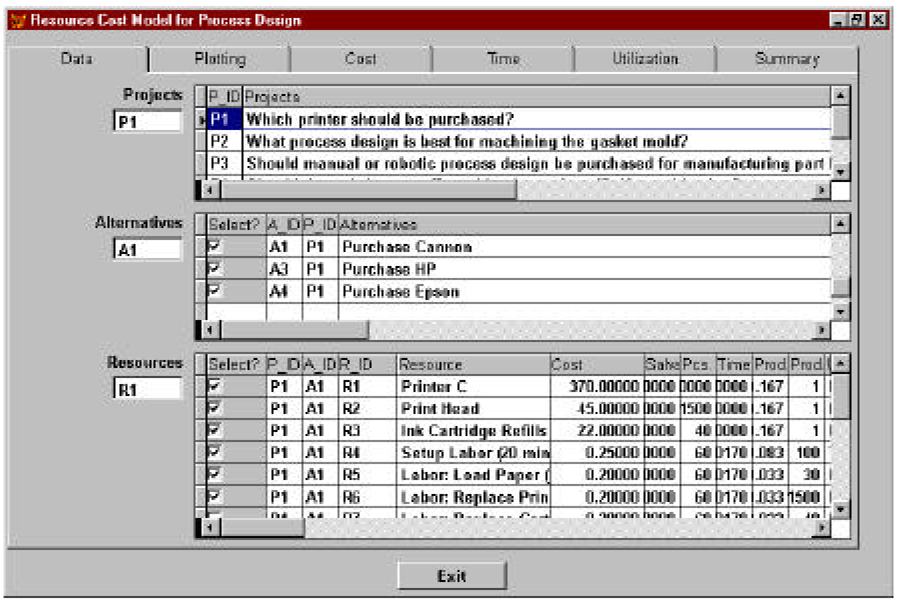


Figure 24. Problems, Alternatives and Resources

The Plotting page gathers information on what is to be plotted, alternatives or resources, and how it is to be plotted. This is the page where the production volume range is specified. The Plotting page is shown in Figure 25, and this figure is referenced several times as RCM equations are developed.

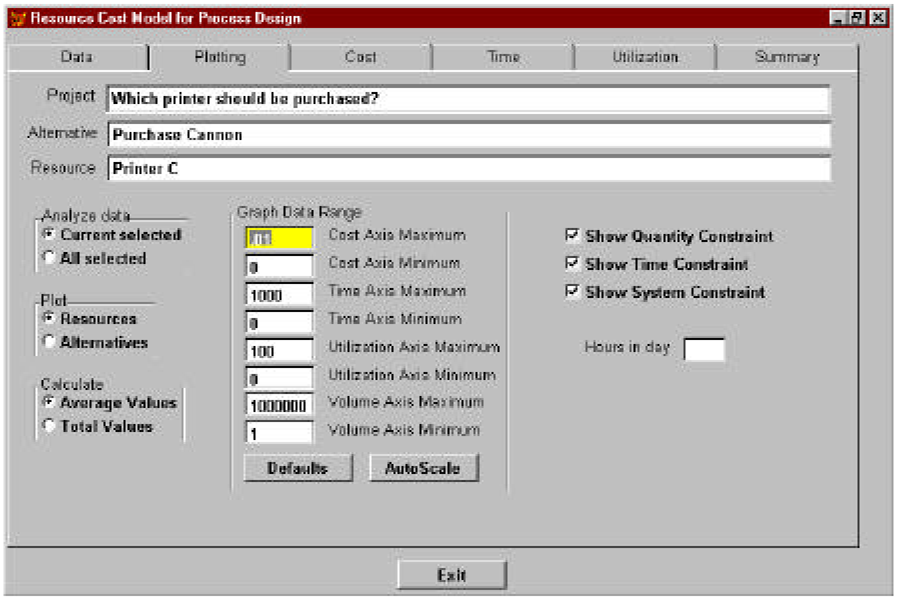
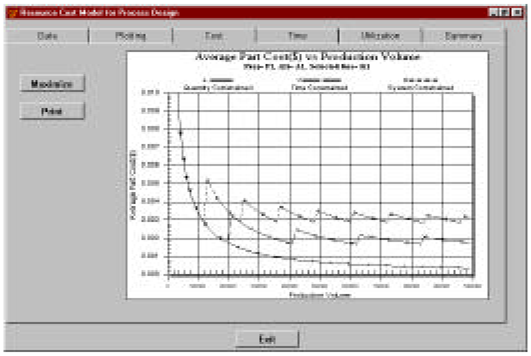


Figure 25. Plotting Page Features

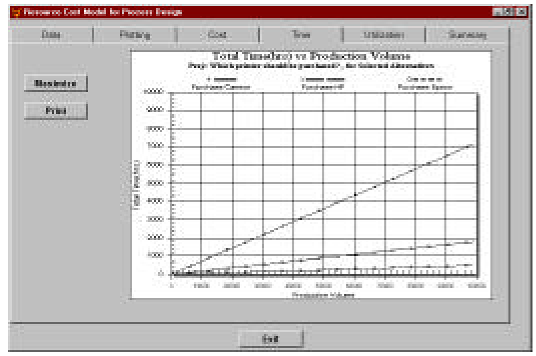
After Data and Plotting selections are made, the user compares alternatives and resources by viewing results on the Cost, Time, Utilization, and Summary pages, shown in Figure 26. All calculations occur in the background and are based upon user selections. The Cost, Time, and Utilization pages provide graphic results, whereas the Summary page provides tabular results. The user explores the details of a specific alternative or resource by changing Data or Plotting page selections and then viewing results on the remaining pages. The detailed calculations for a particular resource, for example, are obtained by selecting a specific resource line with the computer's mouse.

Data Requirements

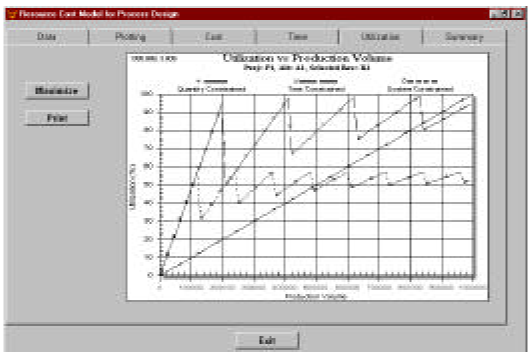
The parameters shown in Table 2 (page 59) column headings are briefly described in this section. Many RCM parameters are easily understood from these descriptions; however, a better understanding may be gained from succeeding sections as RCM's



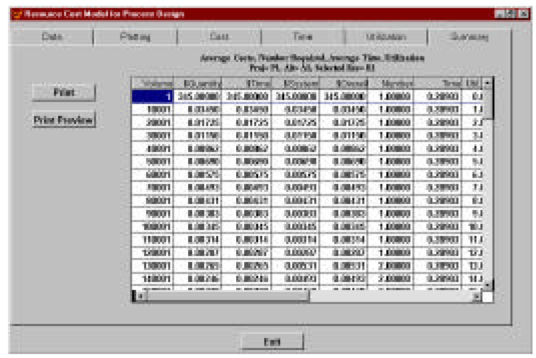
a. Cost



b. Time



c. Utilization



d. Summary

Figure 26. Cost, Time, Utilization, and Summary Pages

equations are developed. The parameters are grouped in the descriptions below for the reader’s convenience. Figure 27 shows most of the resource parameters and groups them by their function within cost, time, and system calculations. A summary of model parameters, with descriptions, is provided in Appendix A.

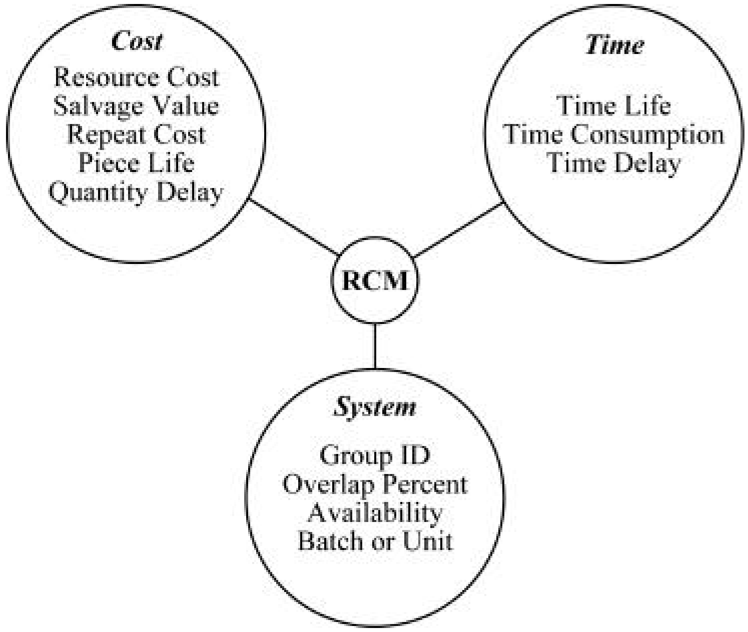


Figure 27. Model Parameters by Function

Resource Name, Project ID, Alternative ID, and Resource ID

The Resource Name should be something meaningful since it is printed on various reports and shown on several computer screens. The Project ID, Alternative ID, and Resource ID are identifier parameters that support the relational database structure for three database tables. By design, they must be unique since they are used as primary keys in the database tables. These ID's can be coded to something meaningful, such as accounting asset codes or inventory tracking codes, or they can be a simple identifiers, such as P1, P2, A1, A3, R1, and R3. These three parameters can be seen in Figure 24 but are not shown in Table 2 since they are only identifiers. The PROJECTS and ALTERNATIVES database tables provide longer fields to describe the short ID's more fully.

Purchase Price and Salvage Value

Purchase Price and Salvage Value take on traditional definitions. Purchase price, however, should reflect the lot purchase price. If five hundred pumps are purchased, then the Purchase Price is for the entire lot and not for each unit. A unit price is calculated by RCM. RCM provides the capability to explore lot sizing issues but not in the traditional economic order quantity (EOQ) manner. EOQ attempts to optimize lot sizes whereas RCM uses an iterative approach to investigate lot sizing issues without optimization algorithms.

Piece Life and Time Life

Most resources have both a Piece Life and Time Life. The Piece Life describes how many production units can be produced with this resource before it is considered fully consumed. For some resources, such as a spool of welding wire, piece life is obvious – after producing a certain number of parts the spool is empty and must be replaced. A ream of paper, by definition, has a piece life of 5000 units. For other resources, such as a machine tool, piece life is not as obvious but should still reflect the part production where the resource is fully consumed. A machine tool might have a design life of one million cycles, when it is replaced because most of its internal mechanisms are worn beyond repair.

The Time Life of a resource is the number of actual clock hours before the resource becomes obsolete, inert, or perishes. Another way to think about time life is shelf life. Time Life for some resources, such as food, chemicals, film, and rubber is obvious since their properties change as they are stored. For other resources, such as highly technical computerized equipment, time life is dictated from obsolescence. Time Life, however, is not depreciation life. Depreciation life is an accounting and tax defined number, not an actual life number. A machine tool, for example, may have a time life that far exceeds its depreciation life. Other “capital” resources, such as computers, may have time lives that are often shorter than depreciation lives since they may become quickly obsolete. Some resources, such as chemicals or perishable tooling, might be expensed on the accounting books but have long shelf lives. In fact, neither the resource’s Piece Life nor Time Life should be related to accounting depreciation lives. These lives should be based upon the best estimates of the actual values.

There may be cases where both time and piece lives are meaningful. A gallon of paint resource might have a Piece Life of 300 units and a Time Life of one year. For some resources, one life might have a much greater meaning that the other. A small spool of welding wire, for example, might have a piece life of 50 units but a time life of more than 10 years. The user need not be concerned with which life is more important since RCM’s calculations determine and demonstrate it.

Sometimes the Piece Life and Time Life are related to the purchase price of a resource. For example, a larger welding wire spool may be purchased that provides for more pieces to be produced. Another example might be specialized cutting tool inserts for milling that may cost more but offer a longer production life and require fewer tool changes. Yet another example is the purchase of better quality chemicals that may cost more but have a longer shelf life. RCM can explore relationships between resource lives and cost, and being concerned ahead of time about the effects is not necessary for the user.

Production Time and Production Pieces

When a resource is used, it consumes a certain amount of production time. This time becomes the Production Time parameter value. It is not floor to floor cycle time.

Floor to floor cycle time is calculated by RCM. At the end of the production time, a number a production pieces results. RCM calls this the Production Pieces parameter. Usually only one unit is produced within the production time. There may be instances, however, where more than one part is produced within the unit production time. Consider a tube sawing operation where one cut is made on the center of raw stock and two parts are produced. In this example, a minimum of two units are produced within the production time. Some resources such as raw material, do not have a production time associated with them and adopt the controlling resource's cycle time. A machine tool, for example, might have a four minute production time and the tooling (another resource) adopts the machine tool's production time. The production time value may not necessarily be static. It may depend on how aggressively management chooses to use the resource. When this happens, other resource parameter values may be affected. For example, more aggressive feed and speed settings on a milling machine reduce production time but increase the electricity resource costs, maintenance resource costs, and probably perishable tooling (i.e., insert) cost.

Batch Resource

The Batch Resource parameter is used to designate resources as either batch or unit resources. This parameter is set to "true" for batch resources and set to "false" for unit resources. Every time a batch resource is used, it provides many parts to be produced. This value is not the result of the intrinsic nature of the resource's consumption but rather based upon management lot size decisions. For example, a machine setup might be good forever, but management may decide to change parts frequently and perform additional setups. For batch resources, the production lot size should be placed in the Production Pieces parameter. For resources that are truly one time costs (over the product's life), the resource Production Pieces parameter can be set to infinity (currently accomplished by entering 9,999,999,999 for the parameter value).

When RCM calculates availability for the system, batch resource availability is not included. RCM assumes batch resources are available when needed. This might be a strong assumption but it is the conservative way of handling this problem. If one wants a batch resource to affect system availability, the batch resource can be redefined as a unit resource, or delay resources can be included.

Percent Overlap, Grouping ID, and Resource Availability

The Grouping ID and Percent Overlap provide the means of handling concurrent operations. Some resources are consumed concurrently with other resources while others are consumed sequentially. Resources consumed concurrently are given the same Grouping ID value, and resources consumed sequentially are given different values. For one group of resources, RCM calculates the controlling production time. When a sequentially consumed resource's production time overlaps with other resources, then the Percent Overlap parameter can be increased to a value greater than zero. The Percent Overlap parameter value is set between zero, for no overlap, to one, for 100 percent overlap. It should be noted that this value represents a percent of its own production time. For example, if a resource has a 40 minute production time and a percent overlap of 20 percent, then the overlap is eight minutes.

Resource Availability is the hours each day that a resource is available. This parameter is closely tied to the capacity of a resource; therefore, it should be defined according to the capacity definition for the company. Capacity was discussed in Chapter 2, where it was suggested that "practical" capacity be used. This implies that many resources typically have a Resource Availability value somewhere between 18 and 22 hours. When a resource's availability is low and it is part of a series of operations, overall throughput is affected. Stated differently, the resource becomes the "bottleneck" resource. Understanding which resources are bottlenecks is important, since improving the bottleneck usually improves system throughput.

Time Delay, Quantity Delay, Repeat Types, and Repeat Values

Some resource costs do not begin at point zero in volume or time, and some expenditures do not repeat at their initial value when they are replenished. For example, maintenance on new equipment might not occur for a year or until five thousand parts have been produced and each time the cost might be higher than the previous time. RCM handles this situation with two delay parameters called Time Delay and Quantity Delay, and three repeat cost parameters called Repeat Type, Value1, and Value2. These parameters are more fully described below as the quantitative analysis is developed.

Resource Computations

Step 4: Calculate the resources' quantity, time, and system constraint information. To calculate overall costs, production time, and utilization for resources, RCM must determine which factors are responsible for producing the overall results. Recall that RCM considered three possible cost, time, and utilization scenarios for each resource: 1) that its unit cost, time, and utilization are constrained by the intrinsic quantity of parts that can be produced by the resource 2) that its unit cost, time and utilization are constrained by the time life of the resource, or 3) that its unit cost, time and utilization are constrained by the system in which it operates. Although there are various ways to develop the analysis, the development is easiest to understand by first developing quantity constraint equations, followed by time constraint equations, and finally system constraint equations.

RCM is a volume-based methodology. To be thorough in its analysis, RCM's calculations occur over a production volume range. For the computer model, one hundred volume-based calculations are included. The user chooses the smallest and largest volumes of interest, and RCM divides this range into one hundred individual points. One hundred points provide good visual feedback on RCM graphs. The model can easily include any number of production volume points, but computation time increases. The quantity, time, and system constraint calculations for each individual resource become the building blocks for higher order aggregate calculations.

Quantity Constraint Analysis

A resource is constrained by its intrinsic ability to produce a certain number of parts, designated by q_r. For some resources, such as machine tools, this constraint implies that the machine tool becomes worn out after a certain number of cycles. For other resources, such as consumables like material, welding wire, bar stock, and a heat of molten metal, q_r represents the maximum number of pieces that can be produced from the resource. For example, a steel bar twelve feet long that produces twelve one foot long parts has $q_r = 8$.

RCM's Production Pieces parameter, p_r, represents the number of pieces produced each time a resource is used. Most of the time p_r equals 1 , but RCM provides the flexibility of letting it be something other than 1. An example of p_r not equal to 1 is a punch press operation equipped with a special die that produces more than one part with each stroke. Note that p_r, by definition, is always less than q_r. Let Q represent a given production volume. The resource being consumed sees the effective production volume as follows:

$$\text{Effective Production Volume} = \left\lceil \frac{Q}{p_r} \right\rceil \tag{3.1}$$

The ceiling function, represented by $\lceil \ \rceil$, is used throughout RCM since RCM's focus is on discrete manufactured products. Equation 3.1 ensures that the effective production volume remains a discrete value. The number of resources required, N_r, at a given production volume is calculated as

$$N_r = \left\lceil \left\lceil \frac{Q}{p_r} \right\rceil \frac{1}{q_r} \right\rceil \tag{3.2}$$

Understand that N_r represents the number of replenishments of a resource based upon how it is purchased and not the actual number of resources. For example, if welding wire is purchased one spool at a time and a spool can produce 500 parts, a N_r value of three says that three spools should be purchased, not three parts.

Let c_r represent the resource cost and s_r represent the resource salvage value. The net resource cost, C_r, is simply the difference between its purchase price and salvage value.

$$C_r = c_r - s_r \tag{3.3}$$

The total resource cost, CT_r, is calculated as

$$CT_r = N_r \, C_r \tag{3.4}$$

The average resource cost, CA_r, becomes

$$C_{A_r} = \frac{C_{T_r}}{Q} \tag{3.5}$$

At a single value of Q, equations 3.4 and 3.5 are not that informative. However, RCM calculates costs across one hundred points. With a sufficiently wide production volume range selected, RCM can show when resource replenishments are required.

Consider the purchase of a small desktop inkjet printer costing $260, which has a $10 salvage life, and expected to last 250,000 printed pages. In this example, c_r = 260, s_r = 10, p_r = 1, and q_r = 250,000. Over a production range of 1,000,000 parts (in this example, the parts are actually printed pages) RCM produces the graph shown in Figure 28. Both the x-axis and y-axis ranges are controlled by user input on the Plotting page (see Figure 25, page 62).

Several important concepts are explained from Figure 28. First, the repeated spikes in the graph represent points where the resource must be replenished. If the

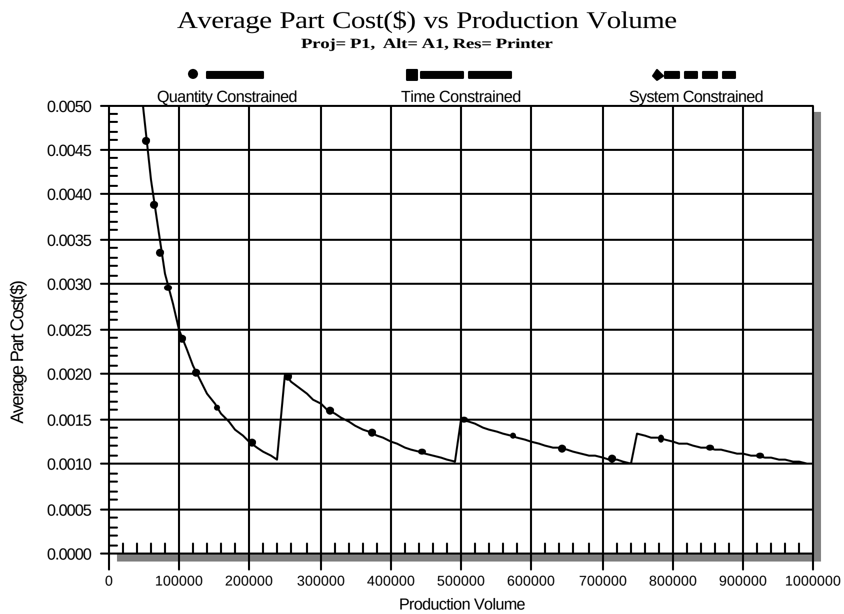


Figure 28. Quantity Constrained Graph for Printer Resource

product life cycle is 1,000,000 pieces, RCM shows that four printers are required. This may not be a significant discovery since replenishment occurs every 250,000 parts, the Quantity Life parameter. However, sometimes it is less obvious and may be overlooked. A resource with a shorter quantity life has many more peaks.

Second, the average cost per part does not increase back to its beginning value with additional purchases. This displays the “economy of scale” effect. Economy of scale has been researched by others (Ostwald, 1989), however, RCM’s computer model clearly demonstrates this effect. With economy of scale, the effect of a 10% product demand forecast error is less severe at 600,000 units than at 100,000 units. It is interesting that in recent years, “economy of scale” has received negative criticism as company downsizing has gained in popularity, yet RCM clearly displays this realistic situation.

Thirdly, as production volume increases, the average cost per part approaches an asymptote. How quickly the asymptote is reached depends on the value for q_r. In accounting practice, resources designated as expense items are often assigned a unit cost based upon the total cost divided by the quantity life. RCM demonstrates that the accounting unit cost calculation is valid only when the resource is fully consumed. There are risks associated with over purchasing resources in that they may not be fully consumed, and the true resultant unit costs vary with consumption. This problem is more likely to occur in job or batch manufacturing environments, which are more typical, than in high volume production environments. The accounting approach to unit costs is only valid when resources can be purchased in a one-to-one relationship to production. This can occur for some resources, such as electricity, where a company pays for exactly what it uses, but it does not apply to many other resources purchased in lot sizes greater than one. The above observations are applicable to any resource.

In Figure 28, average cost versus production volume was shown. Sometimes knowing total cost is of interest. RCM's computer model provides this need by selecting the "Total Values" option on the Plotting page (see Figure 25, page 62). The total cost graph for the above example is shown in Figure 29. It displays an expected stair step graph where each step represents the need for another resource purchase. A different cost axis range has been selected to accommodate the total cost values.

Since the quantity constrained calculations are relatively simple to understand, explaining several other RCM features, calculations, and capabilities is convenient at this point. RCM includes two parameters, Quantity Delay and Time Delay, designated by w_r and h_r, respectively. These parameters delay the initial cost until the either the production volume becomes w_r, or the passage of h_r hours. A "maintenance" resource is a good example of both quantity and time delays since the first maintenance expense

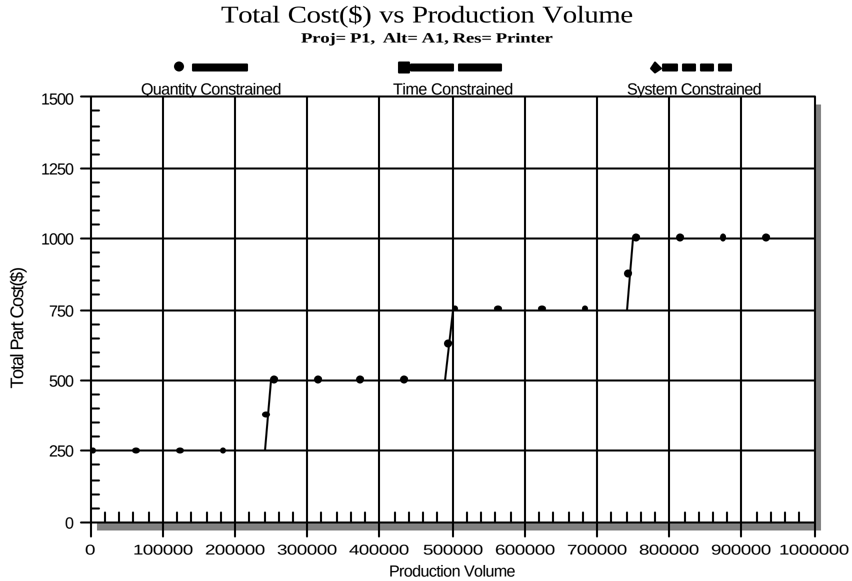


Figure 29. Quantity Constrained Graph for Total Cost

typically occurs after the resource has been in use for some time. When quantity delay is present, the production volume where cost begins must be determined. Let Q' represent the delayed production volume. Q' is calculated as follows:

$$Q' = 0 \qquad \text{for } Q - w_r \leq 0 \tag{3.6}$$

$$Q' = Q - w_r \qquad \text{for } Q - w_r > 0$$

Q' replaces Q in equations 3.1 and 3.2. Quantity delay, where $w_r = 300{,}000$, is demonstrated in Figure 30. The representation of quantity delay appears logical. A delayed resource purchase does not affect current costs, but when it occurs, its cost can be distributed across all units produced. Replenishments repeat, but the repeat cycle is not necessarily synchronized with other resource replenishments. There can be a benefit to delaying resource purchases, especially when the resource’s life-cycle ends before the occurrence of the delayed resource expense. For example, a company may choose to

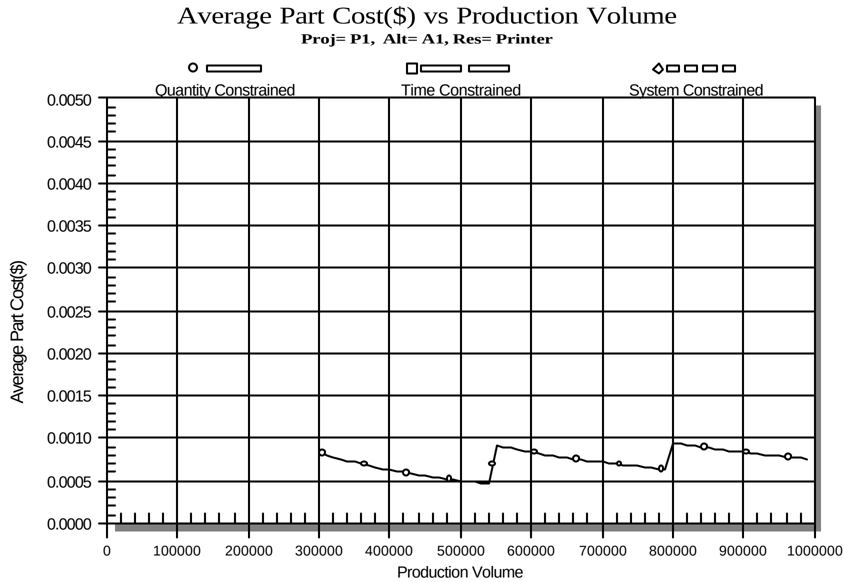


Figure 30. Quantity Constrained Graph with Quantity Delay

outsource the production of a product before performing a major machine tool overhaul. Similarly, an automobile may be replaced before having to replace its engine. If the engine overhaul is really anticipated, its cost should be factored into the per mile vehicle cost, but not until the point when it occurs. A delayed purchase affects the timing of costs.

Another situation that RCM provides for is that some resource expenditures do not repeat at their initial values. Some may decrease, as it may occur with quantity discounts or learning curves, while others may increase, as it may occur with maintenance expenses. RCM provides for this effect with three parameters. The first parameter, k_r, identifies the repeat function type. This value is based upon how the functions have been programmed in the computer model. RCM's computer model currently contains three types of repeat functions: constant, linear, and exponential. For "constant" type, k_r = 0, for "linear", k_r = 1, and for "exponential", k_r = 2. Figure 31 conceptually illustrates these repeat function types.

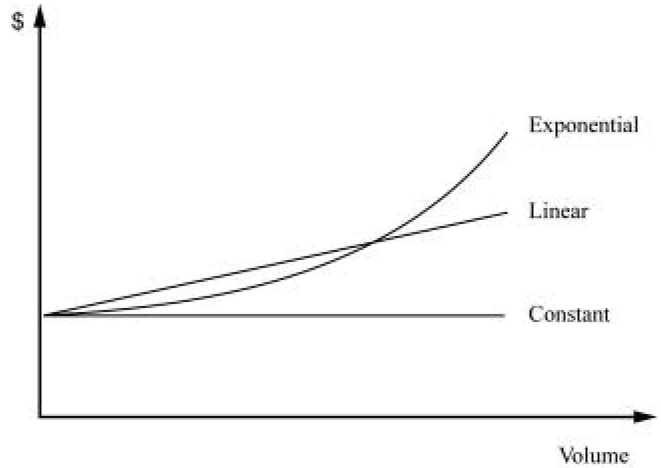


Figure 31. Repeat Function Types

RCM includes two additional parameters, $v1_r$ and $v2_r$, that further define the repeat cost functions. For the constant resource repeat cost, k_r, $v1_r$ and $v2_r$ are all set to zero. For linear growth, k_r is set to 1, and $v1_r$ and $v2_r$ are used as decay and stop values, respectively. Consider a linear growth situation where the resource repeat cost decreases 10 percent with each additional purchase. For this repeat function type, $v1_r$ = -.1. When the initial resource cost is equal to 100, the additional unit purchase values are 90, 80, 70, 60, and so forth.

The cumulative resource cost, equation 3.4, is used again substituting $\left(c_r - s_r\right)$ for the resource's net cost, C_r.

$$C_{T_r} = \left(c_r - s_r\right) N_r . \tag{3.7}$$

For the cumulative linear growth, C_{T_r} is calculated as:

$$C_{T_r} = \left(c_r - s_r\right) N_r \left(1 + \frac{\left(N_r - 1\right) v1_r}{2}\right). \tag{3.8}$$

The parameter $v1_r$ is allowed to be negative or positive, therefore C_{T_r} may grow or diminish with production volume. When $v1_r$ is negative, equation 3.8 can become negative, which does not have any practical meaning. RCM recognizes this and internally ensures that $C_{T_r} \geq 0$. However, there may be instances when the cost decay or growth should be stopped at a specific value. RCM's second parameter, $v2_r$ is used to define a stop value. To stop the decrease at 70, $v2_r$ should be set to .7. Notice that $v2_r$ is defined as a percentage of the original value. By definition, when $v1_r$ is negative, then $v2_r \leq 1$, and when $v1_r$ is positive, $v2_r > 1$. The number of resources purchased until the decay or growth reaches its stop value is calculated as follows:

$$N_{STOP} = \mathrm{int}\left(\frac{v2_r - 1}{v1_r} + 1\right). \tag{3.9}$$

To demonstrate this equation, suppose $v1_r$ = -.1 and $v2_r$ = .7, meaning that the resource cost diminishes until it reaches 70% of its initial value. N_{STOP} is calculated to be four, meaning that after the fourth purchase, the cost of additional purchases remains constant.

The cumulative cost linear function with a stop value is as follows:

$$C_{T_r} = \left(c_r - s_r\right) N_r \left(1 + \frac{\left(N_r - 1\right) v1_r}{2}\right), \text{ for } N_r = 1 \text{ to } N_{STOP} \tag{3.10}$$

$$C_{T_r} = \left(c_r - s_r\right) N_{STOP} \left(1 + \frac{\left(N_{STOP} - 1\right) v1_r}{2}\right) +$$

$$\left(c_r - s_r\right)\left(1 + N_{STOP} v1_r - v1_r\right)\left(N_r - N_{STOP}\right), \text{ for}$$

$N_r = \left(N_{STOP} + 1\right) \; to \; \infty$.

Figure 32 displays the total cost graph for the example provided for Figure 29, page 75, but adds a linear decay where k_r = 1, $v1_r$ = -.1 and $v2_r$ = .7. The total cost graph was chosen instead of the average cost graph because it better demonstrates visually the linear decay effects. The decay effect is still subtle for the values provided.

The third repeat function type provided by RCM is for compound growth; k_r = 2. For compound growth or decay, the decay factor is applied to the immediately preceding value instead of the original value as with linear decay. For example, when C_r = 100 and $v1_r$ = .2, the unit repeat cost take on the values 100, 120, 144, 172.8, 207.36, and so forth.

The total cost equation with compound growth becomes

$$C_{T_r} = \left(c_r - s_r\right)\left(\frac{\left(1 + v1_r\right)^{N_r}}{v1_r}\right) \tag{3.11}$$

Equation 3.11 may be recognized as the future value of an annuity calculation (Grant, Ireson, and Leavenworth, 1976).

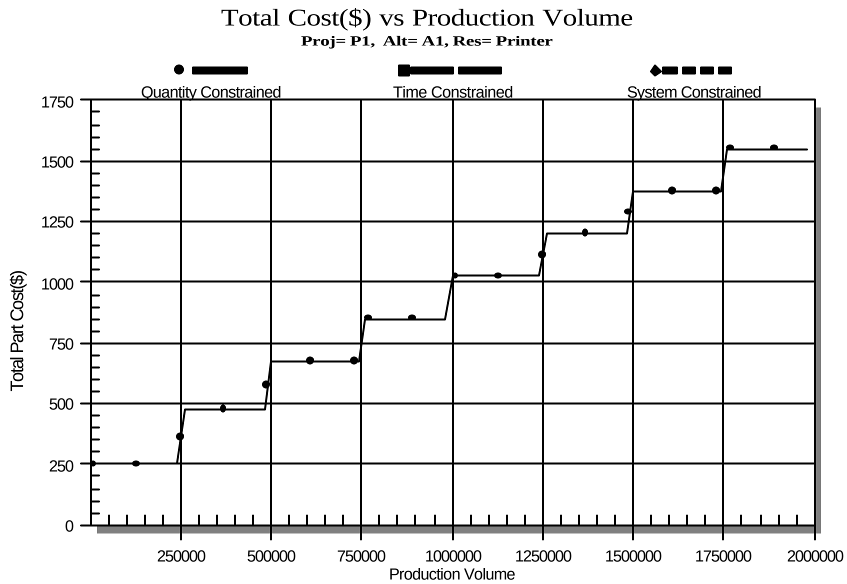


Figure 32. Total Cost Quantity Constraint with Linear Decay

Figure 33 displays the total cost graph with the same data used Figure 29, page 75, but adds exponential decay cost where k_r = 2, $v1_r$ = -.1. In this scenario, the unit cost starts at \$250 and increases 10% for each additional purchase.

RCM's repeat cost functions demonstrate how RCM can be extended in flexibility and in complexity. Additional user defined functions can be developed as needed, but for now, three are included that sufficiently demonstrate the concept and RCM's versatility in managing repeat functions. RCM uses a programming object called "rcmrepeatcost"

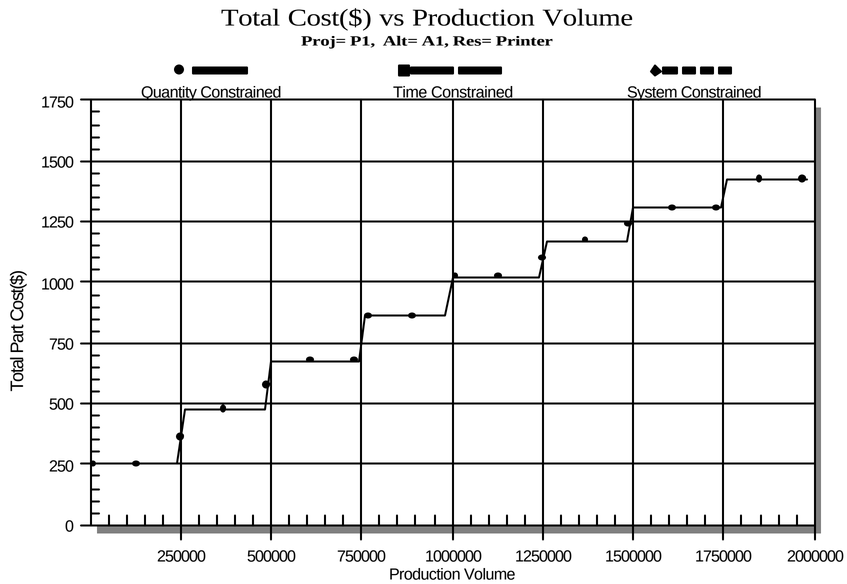


Figure 33. Total Cost Quantity Constraint with Exponential Decay

to calculate repeat cost. This object calculates the quantity constraint costs using a *case* structure, provided in Figure 34, which can be modified by the user to include other

```
PROCEDURE rcmrepeatcost
LPARAMETERS lnNumPur, lnResDecayType , lnResDecayValue, lnResDecayValue2
DO CASE
    CASE lnResDecayType = 1        && Linear decay.
        lnTurnOffNumber = int( ((lnResDecayValue2 - 1)/lnResDecayValue) + 1)
        if (lnNumPur[1] <= lnTurnOffNumber) or (lnTurnOffNumber < 0) then
            lnTotalResCost = lnNetCost * lnNumPur[1]*(1 + ((lnNumPur[1] -1) * lnResDecayValue/2))
        else
            lnTotalResCost = (lnNetCost * lnTurnOffNumber  * (1 + ((lnTurnOffNumber - 1) * lnResDecayValue/2)));
                + lnNetCost * ( 1 + (lnTurnOffNumber * lnResDecayValue) - lnResDecayValue)* (lnNumPur[1]-
lnTurnOffNumber)
        endif
    CASE lnResDecayType = 2        && Exponential decay.
        lnTotalResCost = lnNetCost * ((((1 + lnResDecayValue ) ^ lnNumPur[1])-1)/lnResDecayValue )  && Future value
of annuity
    OTHERWISE   && No Decay
        lnTotalResCost = lnNetCost * lnNumPur[1]
ENDCASE
```

Figure 34. CASE Program Structure for Implementing Function Types

repeat function types.

Thus far, only one of three factors of interest, namely cost, has been developed. RCM also provides production time and utilization calculations. For the quantity constraint condition, time-based calculations are not meaningful. Time calculations become meaningful when the time constraint and system constraint analyses are developed.

The quantity constraint resource utilization is calculated using the following equation:

$$U_r = \frac{Q}{N_r \ q_r} \tag{3.12}$$

A graph for quantity constraint utilization is shown in Figure 35. In this example,

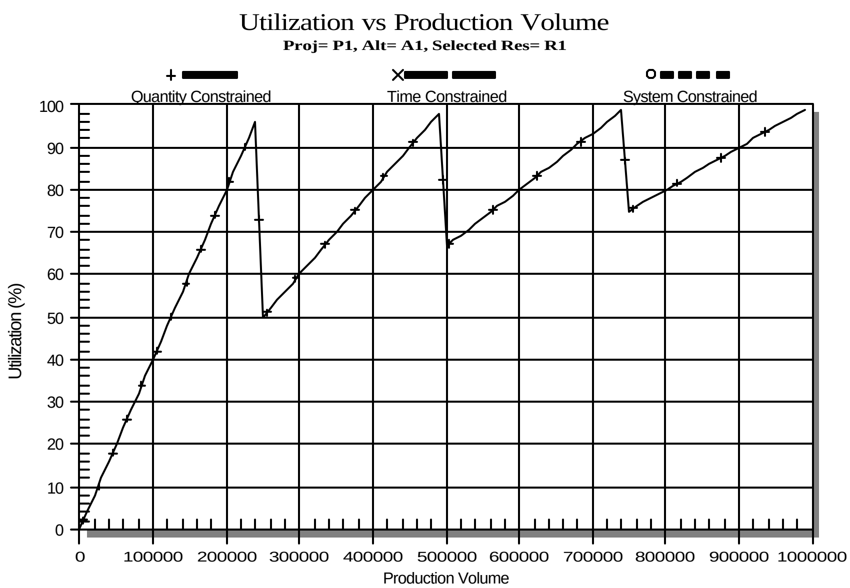


Figure 35. Utilization Graph for Quantity Constrained Resource

the quantity life, q_r, was purposely set to 250,000 units to demonstrate what happens to utilization when additional resources are purchased.

Time Constraint Analysis

The resource time constraint analysis considers various time-based parameters to calculate the number of resource purchases required. There are three major differences between the quantity constraint and time constraint conditions: 1) the production time consumed by the resource is considered, 2) time life instead of quantity life is used, and 3) time delays for resource purchases now have meaning.

Let t_r be the production cycle time, in hours, consumed by the resource each time it is used. The equation for total production time TT_r for production quantity Q is as follows:

$$TT_r = \left\lceil \frac{Q}{p_r} \right\rceil t_r \tag{3.13}$$

Recall from equation (3.1) that $\left\lceil \frac{Q}{p_r} \right\rceil$ is the effective production volume.

The average production time is calculated as follows:

$$TA_r = \frac{TT_r}{Q} \tag{3.14}$$

TT_r and TA_r are graphed on the time versus production volume curves. In the computer model, the user selects the "Time" page to view these graphs. When a single resource is being considered, the graph of total production time is more interesting than the average production time. Figure 36 demonstrates the total time graph for a single resource. Both the average and total time graphs are of interest when alternatives are compared.

The number of resources required, N_r, based upon the resource time life parameter, l_r, is determined in equations (3.15) and (3.16). The value for l_r is based upon full clock time with 24 hours per day and 365 days per year. Therefore, a resource with a one year time life contains 8760 hours ($24 \;\; hrs/day \times 365 \;\; days/year$).

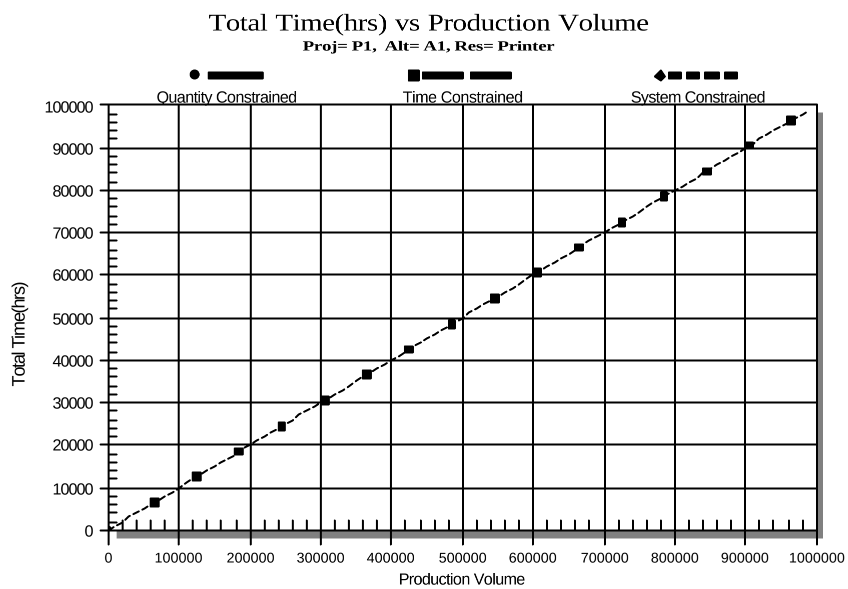


Figure 36. Time Constrained Time Graph for Printer Resource

$$N_r = \left\lceil \left\lceil \frac{Q}{p_r} \right\rceil \frac{t_r}{l_r} \right\rceil \tag{3.15}$$

or simply

$$N_r = \left\lceil \frac{T_{T_r}}{l_r} \right\rceil \tag{3.16}$$

Once N_r is calculated, the resource total cost and average costs are calculated using equations (3.4) and (3.5), page 71.

As an example, let $p_r = 0$, $t_r = 0.1$, and $l_r = 35040$. The resulting time constraint cost graph is shown in Figure 37.

The resource's time availability affects how many purchases are required. A resource that has a time life of two years but is available only 50% of the time has only a one year an effective life. RCM's availability parameter, a_r, represents how many hours

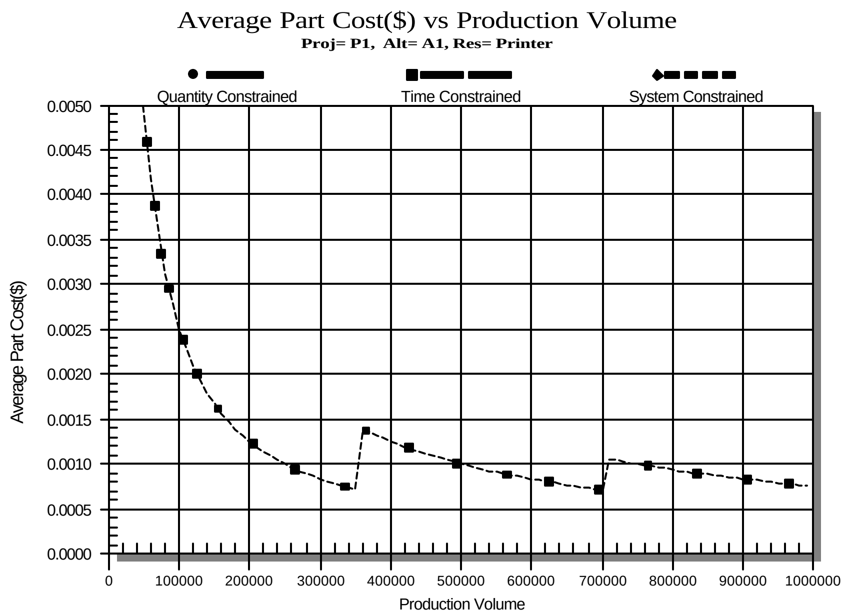


Figure 37. Time Constrained Cost Graph for Printer Resource

in a day the resource is available and can take on values between zero and 24. An adjusted life variable, l'_r, is calculated as follows:

$$l'_r = l_r \left(\frac{a_r}{24} \right) \tag{3.17}$$

Substituting this into equation (3.16) provides the following equation:

$$N_r = \left[\frac{24 \ T_{T_r}}{a_r \ l_r} \right] \tag{3.18}$$

As an example, let $a_r = 12$, which means the resource is available only half the time, while using the same values for Figure 37 and Figure 36. The resultant cost and time graphs are shown in Figure 38 and Figure 39, respectively. They demonstrate, as expected, that average part cost has doubled and that twice the number of resources are required.

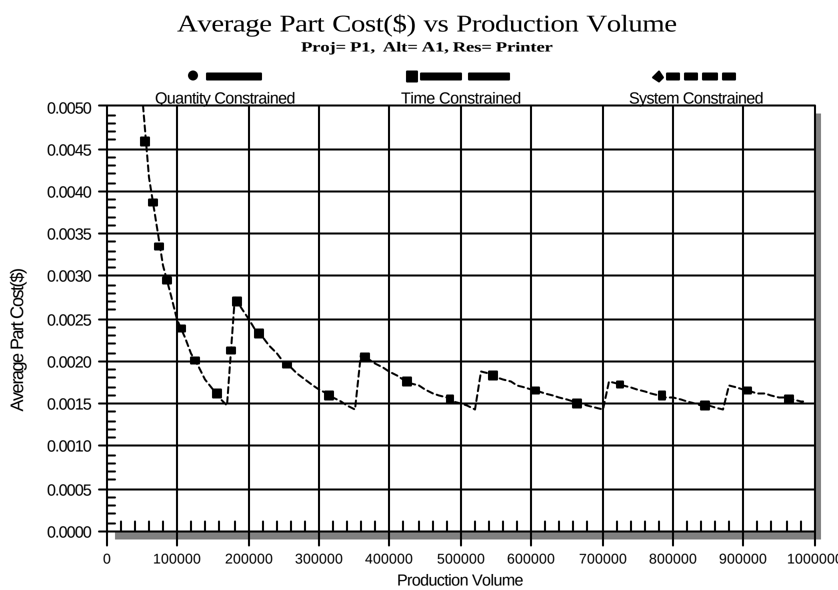


Figure 38. Time Constrained Cost Graph with 50% Availability

The last modification for the time constraint condition is for time delays, designated by the parameter h_r. When a time delay exists, RCM must determine the quantity of parts that would have been produced during this time and then delay the cost and time calculations by this quantity. Let Q'_T represent the production volume delay. Q'_T is calculated as follows:

$$Q'_T = \frac{h_r \ \ p_r}{t_r} \tag{3.19}$$

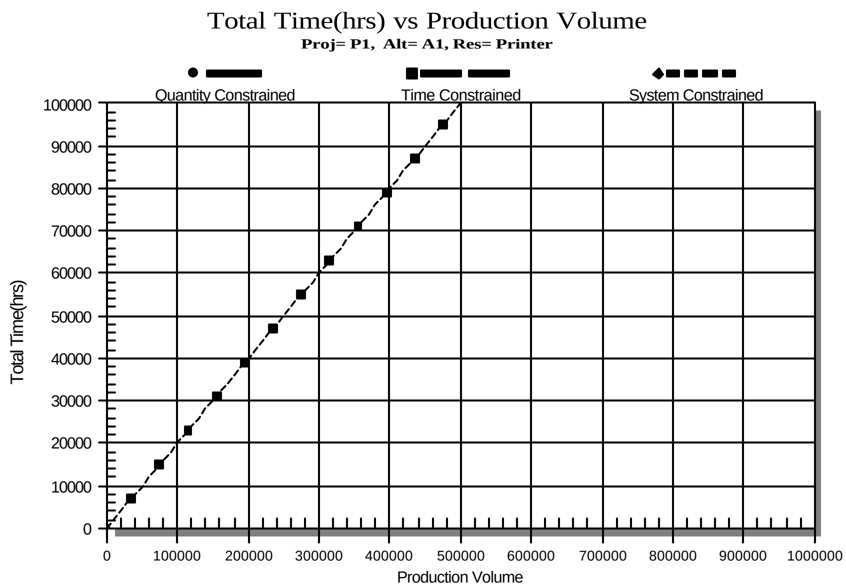


Figure 39. Time Constrained Time Graph for Printer Resource with 50% Availability

This equation was determined by setting $N_r = 1$ in equation (3.15) and solving for Q. Equation (3.15) was used since it was not yet adjusted for resource availability. When both quantity delay and a time delay values exist, RCM compares Q'_T and w_r, and selects the larger value as Q'_T. The quantity delay, Q' is calculated in the same manner as in equation (3.6).

$$\begin{aligned} Q' &= 0 && \text{when } Q - Q'_T \leq 0 \\ Q' &= Q - Q'_T && \text{when } Q - Q'_T > 0 \end{aligned} \tag{3.20}$$

Q' then replaces Q in equations (3.15) and (3.13).

Figure 40 demonstrates the effect of a 10,000 hour time delay.

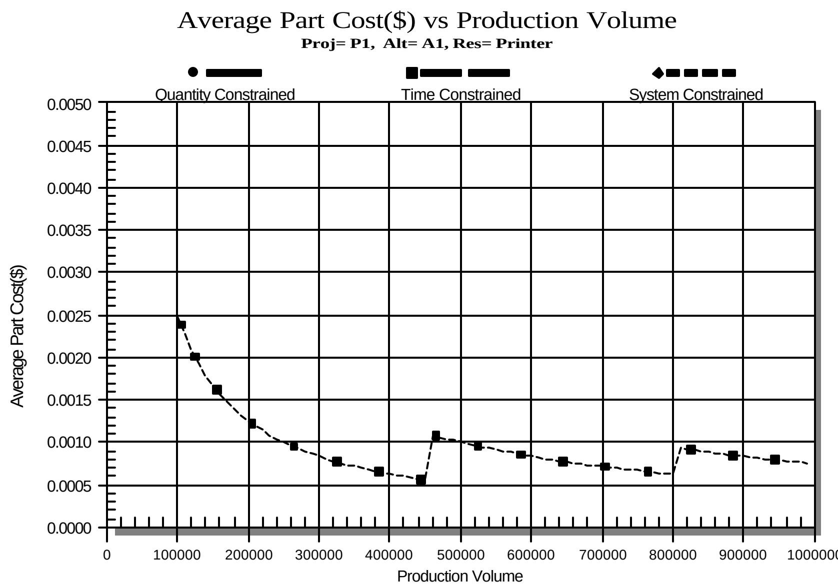


Figure 40. Time Constrained Cost Graph with Time Delay

The effect of time delay on time calculations is to move time forward. This is demonstrated in Figure 41.

Utilization for time constraint is calculated using equation (3.21). The utilization is the total production time divided by the time life of the resource based on the number of resource purchases.

$$U_r = \frac{T_{T_r}}{N_r t_r} \tag{3.21}$$

System Constraint Analysis

The significant differences between system constraint and quantity and time constraints conditions are 1) system constraint considers all resources consumed by an alternative, 2) production time must reflect the total cycle time for all resources including any activity sequences, and 3) the availability, a_r, is determined as the bottleneck resource availability.

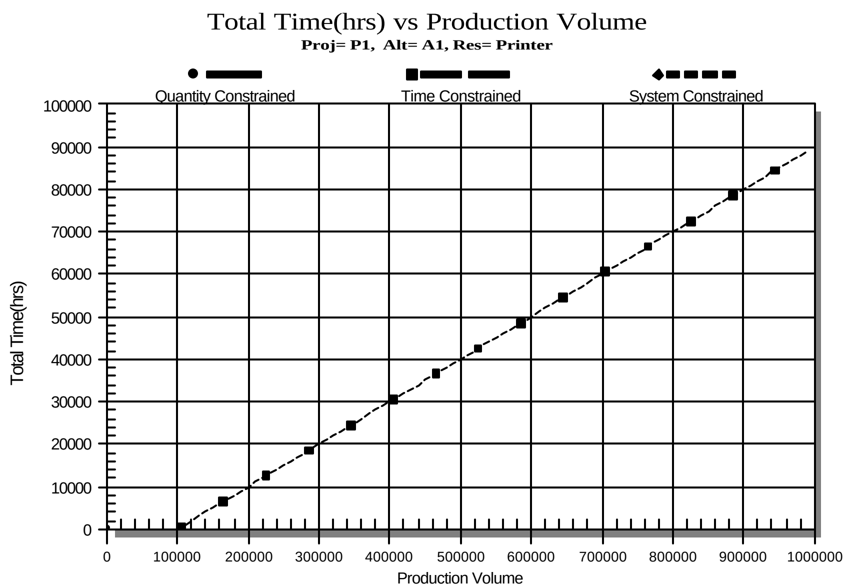


Figure 41. Time Constrained Total Time Graph with Time Delay

Figure 42 shows several important concepts about how RCM considers the interaction of resources. Consider an alternative that contains eight resources, labeled r_1, r_2, $r_3, \dots$ r_8. Some resources are consumed in parallel while others are consumed in sequence. In the computer printer example, the printer, paper, ink, and electricity all are used together; therefore, they are designated as belonging to one group. The grouping parameter, g_r, is provided in RCM and is assigned a sequential number. In the illustration, r_1, r_2, r_3, and r_4 are assigned to group 1. When the printer runs out of ink, a labor resource is required to change ink cartridges. Since this activity must occur in sequence, its grouping value is assigned the value 2. Figure 42 illustrates a situation where three groups exist.

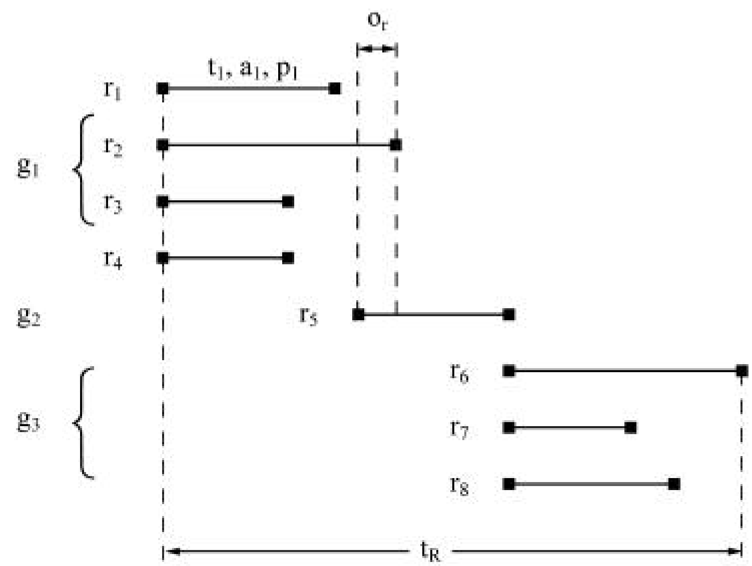


Figure 42. Resource Interactions for System Constraint

Within each group the controlling group time is determined as the longest individual resource time, taking into account the production piece parameter, p_r. There may be instances, however, when some activities can begin before the end of previous activities (i.e., some activities may overlap with others). RCM provides for this situation with an overlap parameter, o_r. The overlap for a resource effectively shortens its production time. In the illustration, resource r_5 has overlap and its production time is effectively shortened. RCM calculates the overall cycle time, t_R, as the sum of each group's controlling production time minus any overlap. One exception can occur when a single resource has overlap time that is greater than the sum of all other group times. When this condition occurs, then this resource controls the overall production time by itself.

For the time constraint condition, the clock is always ticking. If a resource becomes unavailable, it reduces the number of parts that can be produced in its time life. Consequently, the resource availability, a_r, must be considered. For all nonbatch resources, system availability is the smallest availability value for all resources. Batch resources are defined within RCM by the batch parameter, b_r, which is assigned a logical "false" value for nonbatch resources. RCM takes a conservative approach for batch resources by assuming that batch resources are always available when needed. For batch resources, $a_r = 24$. This parameter affects equations (3.17) and (3.18). If this assumption is too strong for a situation, a "delay" resource can be added to compensate for batch resource unavailability.

Once system production time and availability are determined, system constraint cost and time calculations are identical to those in equations (3.13), (3.15), and (3.18) except t_R and a_R are substituted for t_r and a_r, respectively. In the printer example provided, the resulting system constraint cost graph is provided in Figure 43.

The system constraint utilization is calculated in equation (3.22) as an average utilization for all resources. This equation differs slightly from the time constraint utilization equation (3.21) in that an adjustment for the increase in system time is made. System constraint utilization is always less than or equal to time constraint utilization.

$$U_r = \frac{t_t}{t_R} \frac{T_{T_r}}{N_r t_r} \tag{3.22}$$

The development of quantity, time, and system constraint equations for a resource is now complete. RCM always calculates all three constraints for a resource before it determines which constraint condition is the controlling condition for the resource. Often, the system constraint dominates – but not always – letting RCM do the calculations is best. For cost and time, the largest constraint condition becomes the resource's controlling values. The controlling utilization, however, becomes the utilization for system constraint. Figure 44, Figure 45, and Figure 46 demonstrate the graphs for cost, time, and utilization under quantity, time, and system constraints. The summary calculations for these graphs are provided in Table 4 in Appendix B. The summary table shows the cost under each constraint condition, the controlling cost, number of resources, and the controlling time and utilization.

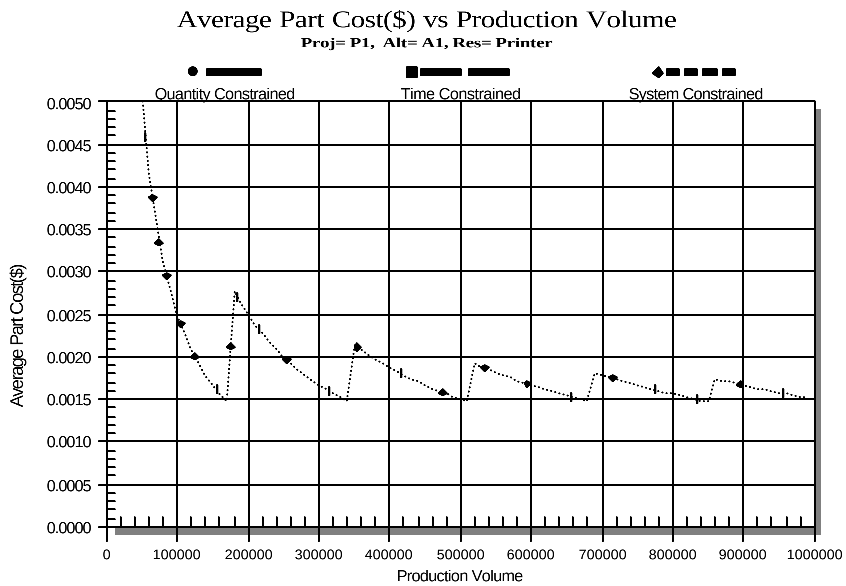


Figure 43. System Constrained Cost Graph for Printer Resource

Step 5: Interpret cost and time constraints for each resource. For each resource, explore the quantity, time, and system constraints to determine the following: which constraint condition controls, cost, time, and utilization, and by how much; if the results make sense; and if any resource modification can improve its cost and time effects. Reconsidering resources that should be included or excluded and to repeating the investigation process may be necessary.

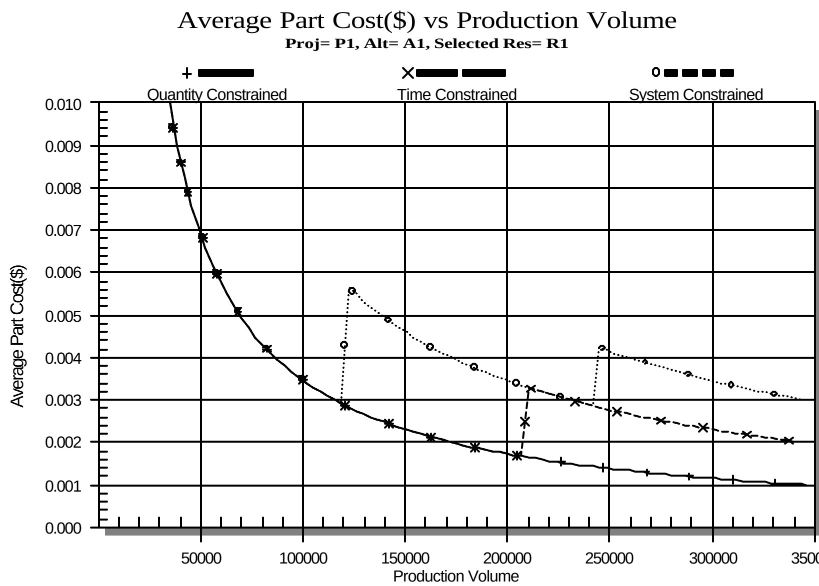


Figure 44. Resultant Cost Graph for Printer Resource

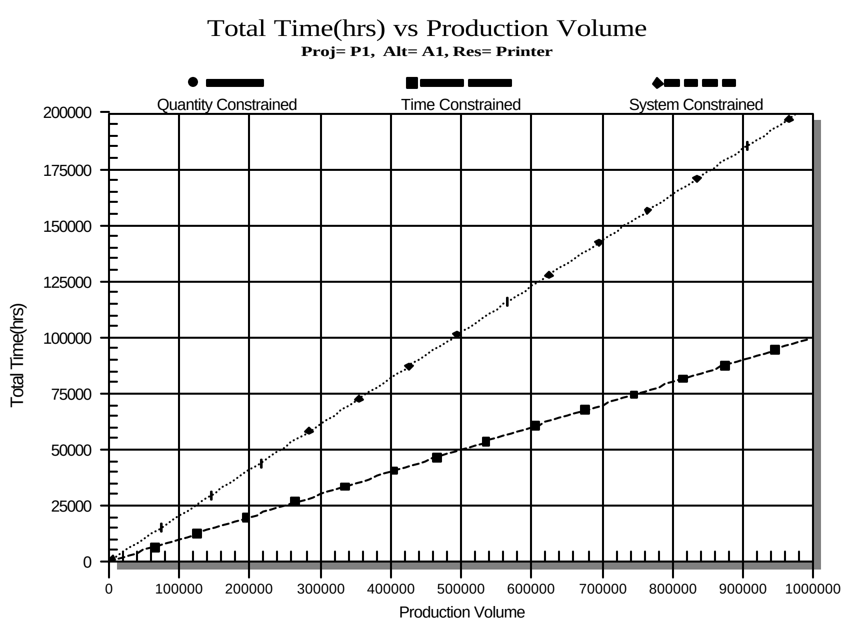


Figure 45. Resultant Time Graph for Printer Resource

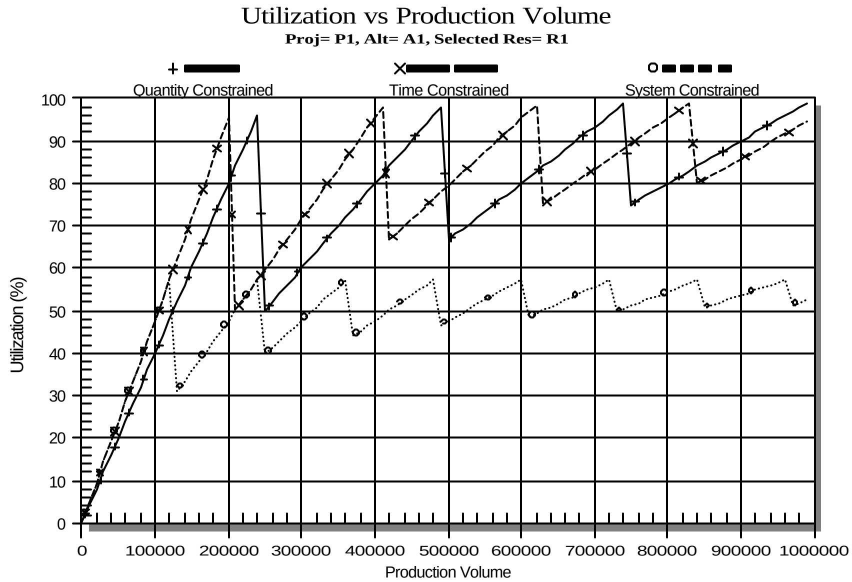


Figure 46. Resultant Utilization Graph for Printer Resource

In RCM, resources can be compared with each other by selecting “All Selected” and “Resources” in the options on the Plotting page (see Figure 25, page 62). When these options are selected, the resources designated as “selected” on the Data page (see Figure 24, page 61, Resources Grid) are analyzed. Up to six resources can be compared at any one time. Figure 47 and Figure 48 demonstrate the cost and time graphs with six resources selected. The summary table, when printed, shows the total costs, time, and average utilization for the resources selected. A summary table is shown in Table 5, Appendix B. The resource costs are derived from the controlling constraint condition as follows:

$$C_{A_r} = \max\left\{C_{A_{quantity}}, C_{A_{time}}, C_{A_{system}}\right\} \tag{3.23}$$

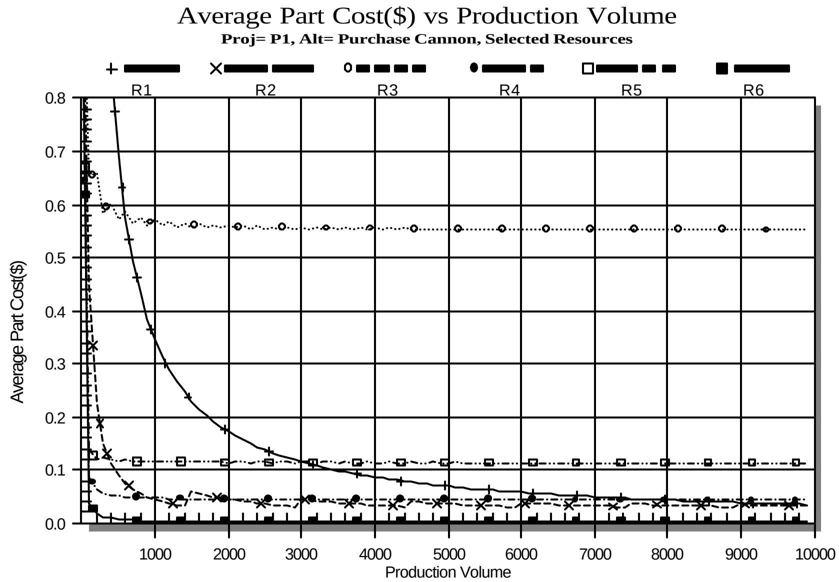


Figure 47. Cost Graph for Six Resources

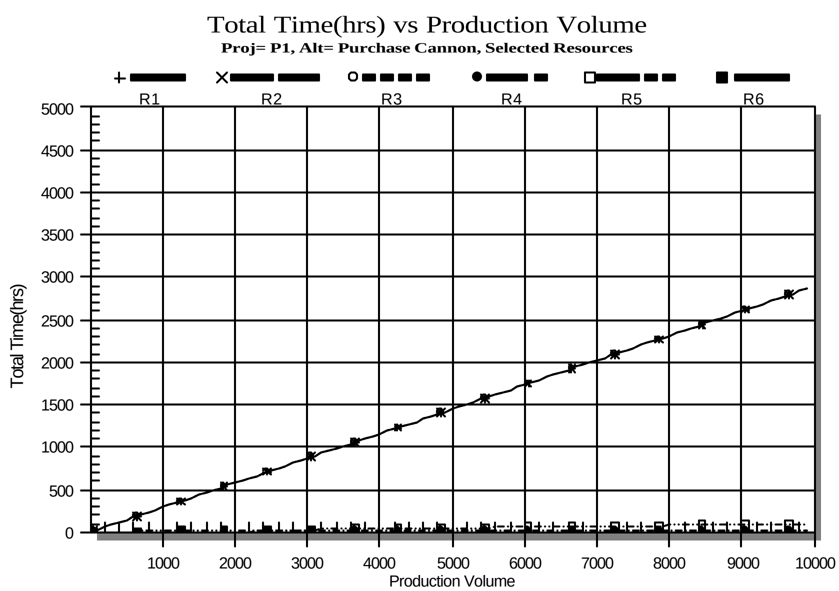


Figure 48. Time Graph for Six Resources

The resource time, T_{A_r}, is also based upon the controlling constraint condition.

$$T_{A_r} = \max\left\{T_{A_{quantity}}, T_{A_{time}}, T_{A_{system}}\right\} \tag{3.24}$$

Utilization for the resource, however, is based upon the average system utilization.

$$U_{A_r} = \frac{1}{R}\sum_{r=1}^{R} U_{system} \tag{3.25}$$

where R represents the number of selected resources. The comparisons show which resources are contributing most to the results and determine which resources are candidates for improvement.

Another form of the results can be gained by selecting "current selected" and "alternative" on the Plotting page. For the selected alternative, RCM accumulates cost, time, and utilization calculations for all of its resources. The cost graph shows the alternative cost based upon all resources, and includes the costs for up to six selected resources. A graph of how individual resource costs contribute to the overall costs is produced. The calculations are identical to those obtained by using equations (3.23), (3.24) and (3.25), except that all resources for the alternative, instead of just the selected resources, are used.

Alternatives Computations

Step 6: Interpret and compare alternatives at various production volumes. The RCM computer model allows up to six alternatives to be compared with each other based on cost, time, and utilization. The comparison is accomplished within the computer model by selecting the "All Selected" and "Alternatives" options on the Plotting page, and by selecting up to six alternatives on the "Data" page. RCM's portrayal of alternatives is similar to a break-even analysis, and different alternatives may become "best" at different production volumes. However, RCM's analyses are more thorough than break-even analysis since RCM includes both time and utilization calculations in addition to cost. An alternative that has the best cost may not necessarily have the best time.

The calculations for alternatives are performed by using equations (3.23), (3.24) and (3.25), except that all resources for the alternative are used, and that these calculations occur for all selected alternatives. Examples of the graphs for cost and time for three alternatives are shown in Figure 49 and Figure 50.

The summary table, Table 7, Appendix B, shows the best cost, time, and utilization results, and additionally, shows which alternative corresponds to the best resource.

Step 7: Identify bottleneck resources for the alternatives. By investigating the cost, time, utilization, and availability of individual resources, one can discover what factors and which resources are contributing most to an alternative's results. These resources should be carefully considered to decide if their parameter values can be improved. If they can be improved, make the changes and reinvestigate the effects.

Using RCM Results

Step 8: Summarize the results and make the process design decision. When an alternative has lower costs and shorter production times across all production volumes, then it is obviously the best alternative. However, some alternatives might be better in only one category of cost or time; and it might be better only within a certain production volume range. For example, Figure 49 and Figure 50 demonstrate a situation where two alternatives appear to have similar costs but one alternative offers a faster production

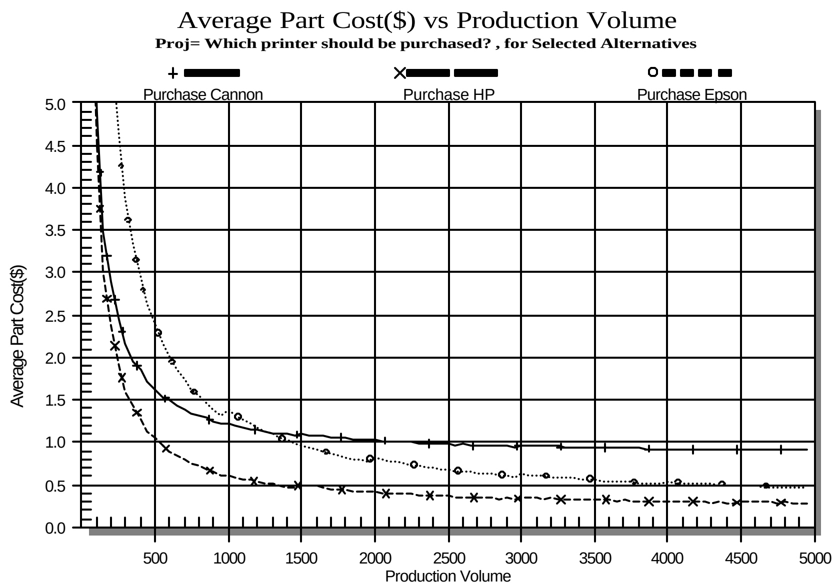


Figure 49. Average Cost Graph for Three Alternatives

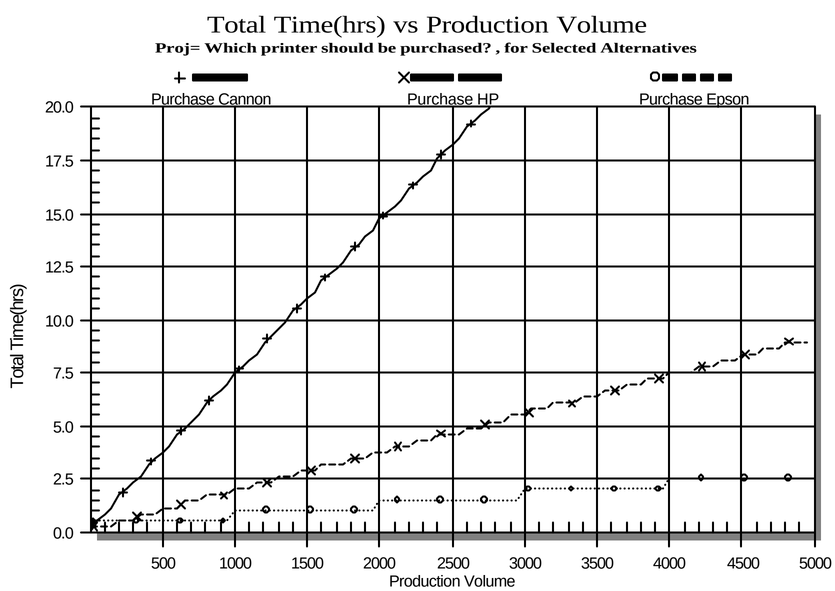


Figure 50. Total Time Graph for Three Alternatives

time. Depending on how important cost or time is to management, one alternative can be selected. RCM does not offer any methodology to reconcile time and cost issues, but it does clearly demonstrate the results.

When selecting the alternative, be certain to understand the advantages and disadvantages of each alternative across the production volume range. Product time and cost targets, when they exist, can be considered relative to each alternative. Sharing the results with marketing may be beneficial, so that a better understanding between volume costs, time issues, and pricing relationships occurs. For example, if manufacturing cost can be dramatically reduced at a higher volume, and if the manufacturing cost reduction can reduce product pricing, the reduced product price might stimulate sufficient demand to make the production volume achievable.

CHAPTER IV

RCM APPLICATION

This chapter demonstrates RCM methodology for an industrial process design problem. It is believed that the resources required for the process, their intrinsic time and quantity lives, their consumption, and the way that RCM is used represents many industrial processes.

Single versus Tandem Robotic Welding

Genesis Systems Group, integrators of robotic welding systems, have developed a robotic welding system called "tandem torch." Tandem torch welding is used for parts requiring the gas metal arc welding (GMAW) process. There are two basic approaches; mounting two torches in a fixed position and manipulating the parts by the robot, or using a specially designed torch that feeds two wires. The second approach is often less familiar, and it is illustrated in Figure 53.

Tandem welding provides the capability to weld, essentially, twice as fast as single torch systems. Tandem welding has existed for many years in dedicated welding systems, but the application of tandem welding principles with robots is a newer concept. It is realized that the tandem welding process requires correctly designed products and that not all parts can be successfully welded with this process. However, given the correct weld joint configurations, tandem welding may be the best alternative for a customer.

Problem Scenario

The problem being considered is whether the tandem torch robotic welding system process design or the single torch system process design should be used for a certain class of arc welded parts. Does either offer significant advantages over the other? Customers who currently weld products manually often approach Genesis with automation desires. Genesis must provide proper guidance to these customers so that the customers achieve both higher productivity and profitability. When several alternative process designs are possible, it is important that Genesis be able to explain the advantages and disadvantages of all process designs to the customers.

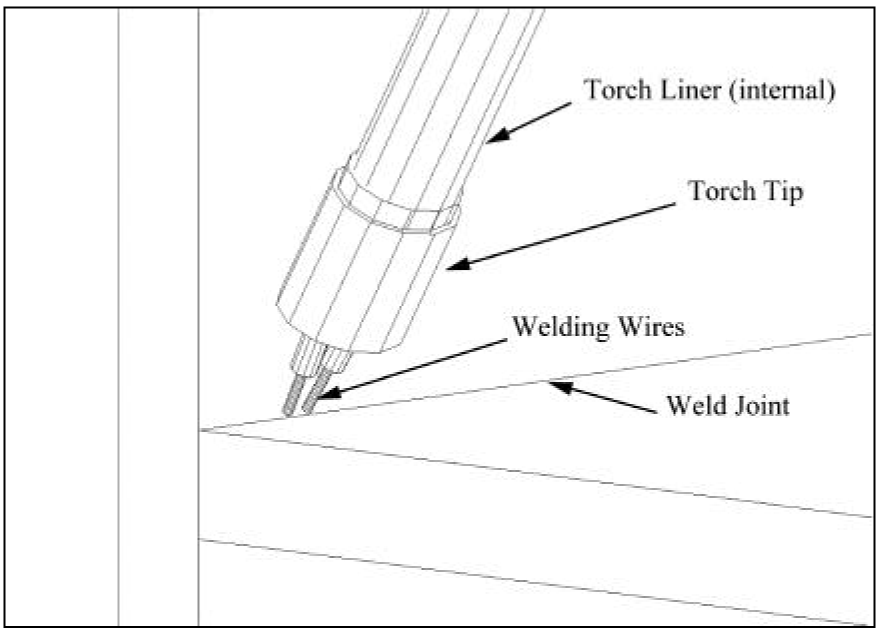


Figure 51. Tandem Torch Welding Process

Companies that plan to purchase either robotic welding process require answers to the following questions:

1. At what production volume is one process better than the other?
2. How does the production capacity compare for each process?
3. At a given production volume, what is the reserve capacity of each system?
4. How much time does it take to produce a certain quantity of parts?
5. At the break-even production volume, which resources are major contributors to cost? Which resources are worthy of further investigation? Which resources are of little significance? What is the total investment?
6. How does a company's operational plan affect cost and capacity?
7. What is the effect of higher than expected product demand?
8. If low part cost is the most important consideration, which system is recommended?
9. How significant is a 15 percent discount for welding wire?
10. What additional insights are gained using RCM?
11. How might manual welding compare to robotic welding?

Many other questions might be asked, but the above questions should suffice to demonstrate RCM methodology.

Parameter Values for the Model

The first step for applying RCM is identification of resources and resource parameter values. Through discussions with Genesis personnel[6] and with a welding supplies company[7], resources and values were established. Resources for robotic welding include the robotic system, fixtures, positioning table, power supplies, welding guns,

[6] Terry O'Connell, Genesis Systems Group, Davenport, Iowa, October and November, 1997.

[7] GenX, Rock Island, Illinois, October, 1997.

welding gun maintenance, welding wire, shielding gas, operational labor, and setup labor are included. Electricity and maintenance resources are intentionally excluded during the analysis because they were judged to be insignificant by Genesis. These resources, however, may be added easily to the analysis when desired.

For the system under investigation, the following assumptions apply:

1. Parts have 100 inches of weld, made up of six weld segments. A representative part and robot welding system are shown in Figure 52. The gas metal arc welding (GMAW) process with 0.045 inch wire and a 3/8 inch fillet weld is used. The two torch tandem welding process is used.

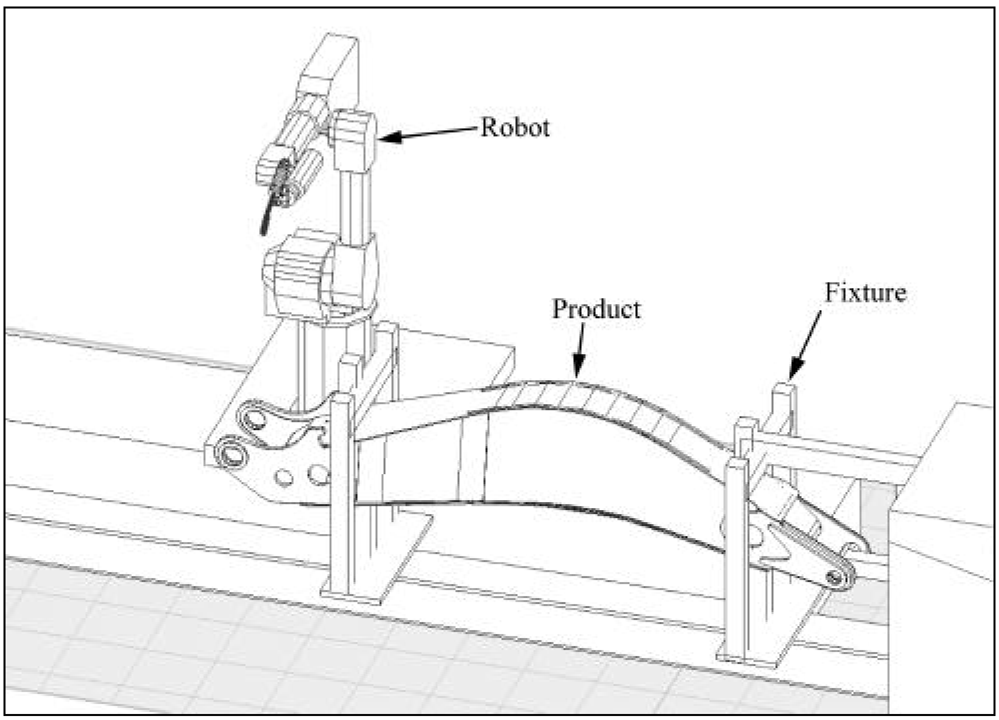


Figure 52. Representative Part and Robotic Welding System

2. The planned production volume is 100,000 parts.

3. Operators are available for two shifts 8-hour shifts. Operator break allowances are provided that reduce operator availability to 14 hours per day.
4. Additional part modifications for tandem welding are not required, however, limited joint access with two torches causes 5 percent of the 100 inches of welds to be done manually.
5. Both systems use a dual fixture positioning system. An operator loads and unloads parts at one station while the robot welds at the other station.

Table 3 shows the resources and parameter values used in RCM for this problem. For simplicity, all resources have a constant repeat cost function. Also, there are not any time delays and quantity delays. Table 3 provides each resource's ID that corresponds with graph legends.

Robotic System

The system cost includes the robot, fixtures, positioning devices, and systems engineering and integration. The cost for the tandem torch system is higher than the single torch system since additional engineering design is required. Manual welding requires only one weld fixture. Each robot system is expected to have a 10-year life, which is when the robots become technologically obsolete. It is assumed that the robot duty cycle is such that its time life is reached before its quantity life. The piece-life parameter is intentionally set high (999,999,999) to force time-life to be the controlling factor. Salvage value is $5000. Welding speed is 30 inches per minute for single torch, 60 inches per minute for tandem, and 15 inches per minute for manual. Cycle times are calculated as 0.057 hours for single torch, 0.031 hours for tandem torch, and 0.113 hours for manual. Cycle time includes weld time and 6 seconds for start and stop time (for the six weld segments), and assumes that 5 percent of the tandem torch welds are done

Table 3. Resources and Parameter Values for Single Versus Tandem Welding Systems

Resources and Parameter Values for Single Versus Tandem Welding Systems manually. The tandem torch system is available for 21.5 hours per days as opposed to 22 hours per day for the single torch system. The availability difference takes into account the greater complexity and higher expected downtime for tandem welding. For manual welding, operator availability is dictated by the operation plan.

Welding Power Supplies

Tandem torch welding requires two, more expensive, power supplies instead of one. Power supplies cost $30,000 for the tandem torch process compared with $12,000 for the single torch system. Power supplies are expected to last 15 years, when they become technologically obsolete. Again, as with the robot system, quantity life is set high so that the time life becomes the controlling factor. Salvage value is estimated at 30% of original cost. The power supplies adopt the cycle time and availability values from the robot system resource.

Weld Guns

The tandem system requires two guns that cost $3000 compared with $1000 for the single gun system, and they have no salvage values. Weld guns do not wear out. Instead, the weld gun tips and liners wear out. Weld guns have a 10-year time life. Piece life is set high so that the time life controls. Availability is 24 hours.

Weld Guns Tips and Liners

Weld gun tips cost $.60 each and liners cost $15 each. The tandem torch system contains two liners and two tips, one for each gun. Genesis does not estimate tips and liners piece lives. Instead, they simply recommend that tips be changed each 8-hour shift and that liners be changed every month. Their actual lives might be longer, but to ensure robot accuracy, they are periodically replaced. RCM can force time life to control the results with a large piece life value, but this is a case where data collection or experimentation may determine a better estimate of piece life. With a piece life estimate, RCM can show how close the resource quantity constraint is to time constraint. More aggressive weld schedules may cause tips and liners to need replacement sooner than their time lives.

Tip replacement times are 0.25 hours for the single torch system and 0.50 hours for the tandem torch system. Liners take 0.50 hours and 0.75 hours, respectively. These resources can be treated as batch resources and assigned to different resource groups to reflect the sequential nature of the replacement tasks.

Welding Wire

Welding wire is purchased in 1000-pound spools. Cost depends on usage. The range is between $.50 and $.60 per pound (.045 inch 70S3 wire). $.60 per pound is used for this analysis; therefore, the 1000-pound spool costs $600. For the weld joint and fillet size under investigation, approximately 11 pounds of weld wire is consumed per hour. It is calculated that the 1000-pound spool can produce 1636 parts, which becomes the piece life value. Welding wire has an infinite time life (it does not deteriorate over time), and the time life can be safely set at 10 years. Weld wire is available 24 hours per day.

Shielding Gas

The gas flow rate is constant for all alternatives. Therefore, the single torch system uses twice as much gas as the tandem torch system, and the manual system uses twice as much gas as the single torch system. The figures are the result of the differences in welding speed. Shielding gas can be purchased in bulk or in tanks, and bulk is approximately 30 percent less expensive. Welding companies often purchase welding gas in bulk and distribute it throughout the facility. In bulk, gas costs take on a one-to-one relationship with usage. Gas purchased in bulk costs $4 for 100 cubic feet. This is for a 90 percent argon and 10 percent carbon dioxide mixture. Approximately 10 cubic feet are used for each pound of weld for single torch robotic welding based upon a flow rate between 35 and 40 cubic feet per hour. It was earlier calculated that a 1000-pound spool produces 1636 pieces; therefore, each piece consumes 0.61 pounds of wire and 6.1 cubic feet of gas. This equates to approximately $0.24. The cost is $0.49 for manual welding and $0.12 for tandem welding. It is assumed that the gas has a one-half year time life.

Operation Labor

Labor is required to load and unload parts. Load and unload time is .025 hours. For tandem welding, 5 percent of the welds must be done manually, which equates to .006 hours. Total operator time for tandem welding becomes .031 hours. Cost and time lives depend on how labor is purchased. Is a welder purchased by the minute, hour, day, year, or life? The answer to this question may be often based upon a union contract or management policy. If welding is purchased by the hour, then its cost is $20 with a time life of one hour. If purchased by the day, then it costs $160 and has a time life of 8 hours. For this problem, it is assumed that welding labor is purchased by the minute. Its cost and time life become $0.33 and .017 hours. What is the piece life? Assume that a person can cycle once per second, then the piece life becomes 60. Management's operational policy is used to set the availability to 14 hours.

Setup Labor

Setup, a batch resource, must be done when the welding system is not operating. Setup therefore gets its own group designation. Its overlap percent is zero. It is assumed that the setup cost and time life are $0.33 and .017 hours, the same as operational labor. Setup for the single system is .250 hours compared with .500 hours for the tandem system. For manual welding, setup time is .250 hours. The operational plan's lot size is 2000 parts.

Manual Welding Notes

For manual welding, it is assumed that liners and tips may last an average of 250 percent longer than the single torch robotic system. An operator can adjust to varying welding conditions that the robotic system cannot. Also, manual welding speed is one-half the single torch robot welding speed, so the duty cycle for tips and liners is lower.

RCM Analysis

Data from Table 3 is entered into RCM's computer model. RCM's application flowchart suggests investigating each resource to determine whether its cost, time, and utilization behaviors appear correct. One can guess at the expected results and then question calculated results. Several examples illustrate this process.

Consider liners for the single torch system. Liner piece life was intentionally set high to force the time life constraint. RCM should confirm that the time constraint curve is greater than the piece constraint curve. Figure 53, produced by selecting only the liner resource and turning off the system constraint curve, confirms expectations. It shows that the repeat cost for liners is controlled by its time life (i.e., the time constraint curve is higher than the quantity constraint curve). Immediately, the graph shows how many parts can be produced by this liner. Since the liner is changed once a month, it can be seen that approximately 13,000 parts can be produced in during this time. Remember that thus far, system constraint has not been considered. Until system constraint effects are included, it makes little sense to say much about cost, except that it might be higher than shown. The utilization graph for this resource appears in Figure 54. Note that as production increases

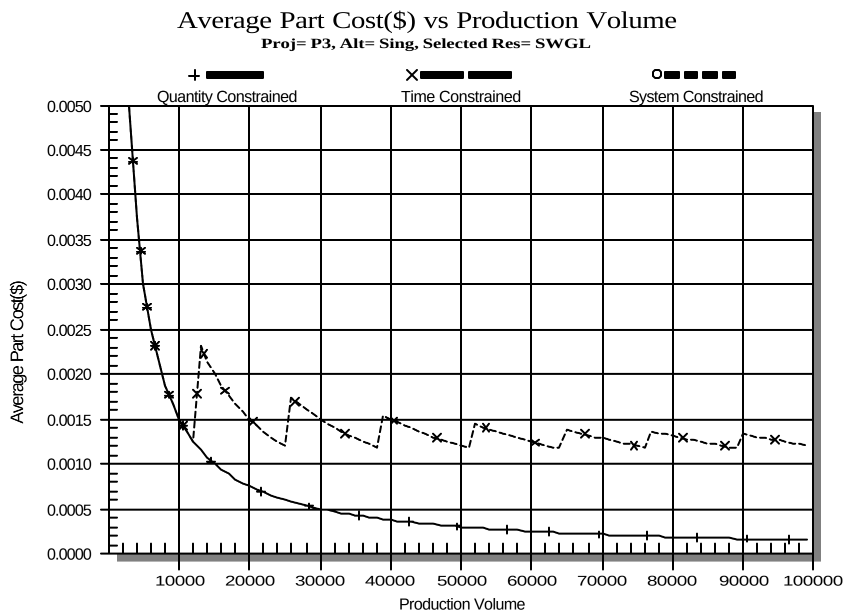


Figure 53. Average Cost for the Liner Resource

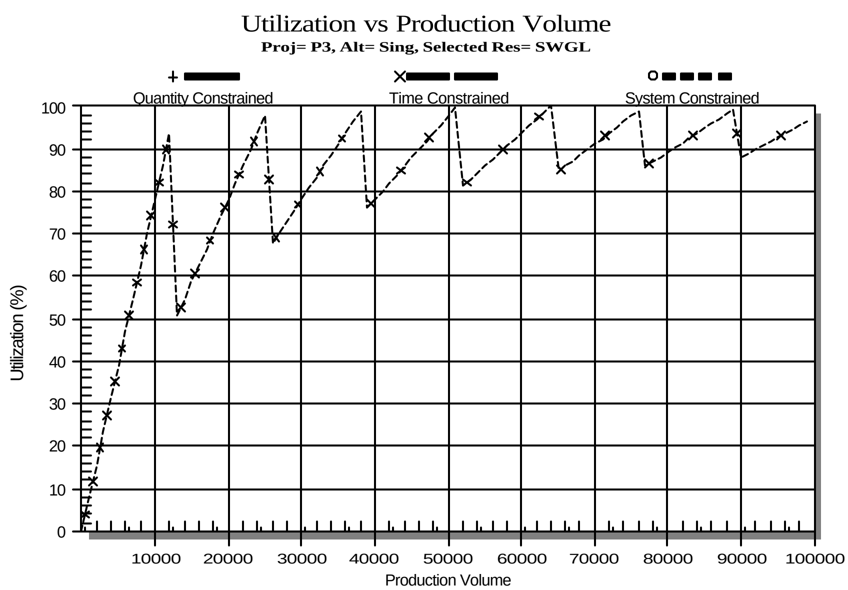


Figure 54. Average Utilization for the Liner Resource

the average utilization for liners is higher. Numeric results are provided in Table 8, Appendix B. The number of liners required at any production volume is provided in the Table 8. Although guessing the cost and utilization figures might have been difficult, the overall relationships appear correct.

Next, consider the cost a labor resource. This time, instead of taking a guess at what might be expected, the graph is generated and then interpreted. Figure 55 is the average cost graph for the tandem torch alternative's labor resource, not including system effects. Figure 56 is the corresponding utilization graph. The significance of these graphs is that when labor (or for that matter, any resource) can be purchased in small quantities, here, by the minute, the cost per unit is constant and utilization is high. The higher cost at small production quantity is the result of RCM's discrete calculations.

If labor were purchased by the hour or day, potentially, this resource might not be fully consumed. This can sometimes occur with setup labor, particularly when a company contracts setup with an external company. The external company might have a minimum charge, such as 4 hours.

Detecting time utilization on the utilization graph may be difficult, but the numeric results for utilization are clearly shown in Table 9, Appendix B. Sometimes, the tabulated results show information that may not be as obvious on a graph.

Finally, consider the batch resource, setup labor, for the tandem torch system. The cost and resource graphs are shown for this resource in Figure 57 and Figure 58. Both correspond with intuition in that they have repeat cycles of 2000 parts. The average time graph for a batch resource is not constant as it is with a non batch resource.

By stepping through the application of RCM resource by resource, a good understanding of each resource's cost, time, and utilization behavior is gained. There may be times when intermediate graphs are informative. Take for example, the average

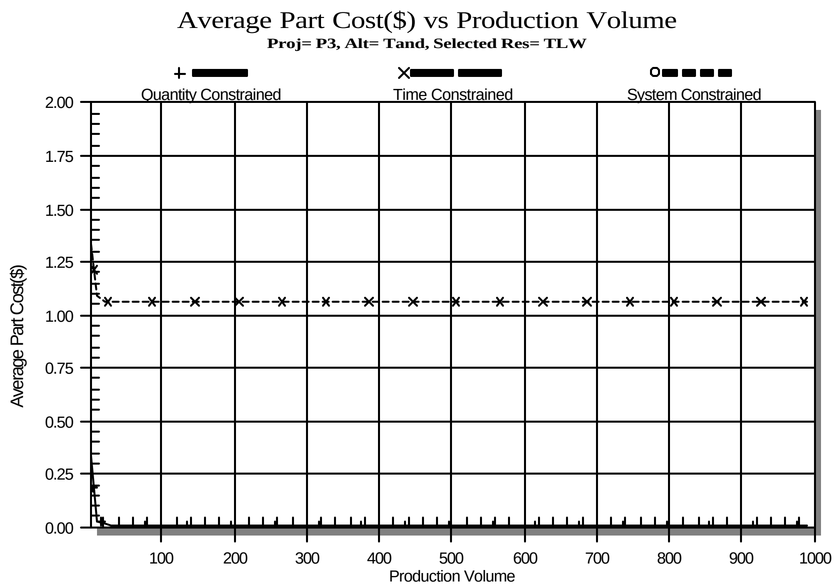


Figure 55. Average Cost for the Labor Resource

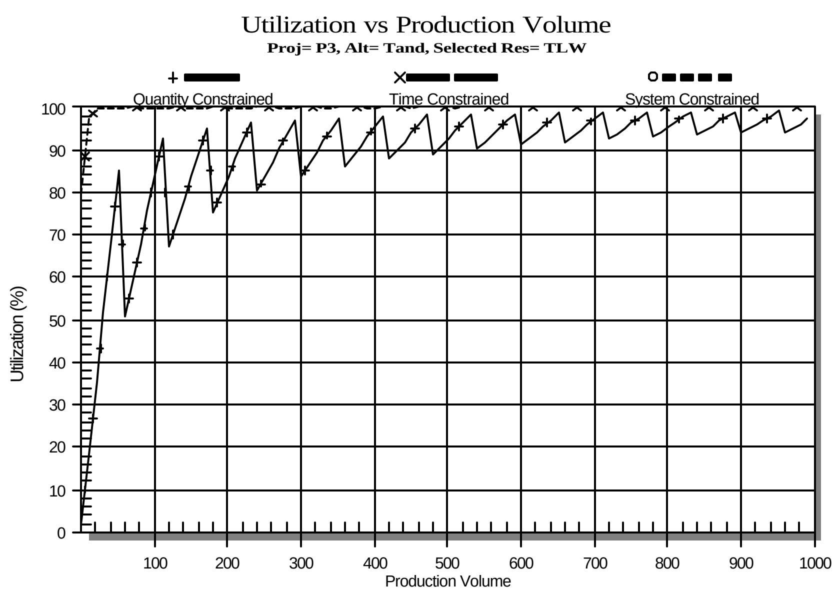


Figure 56. Average Utilization for the Labor Resource

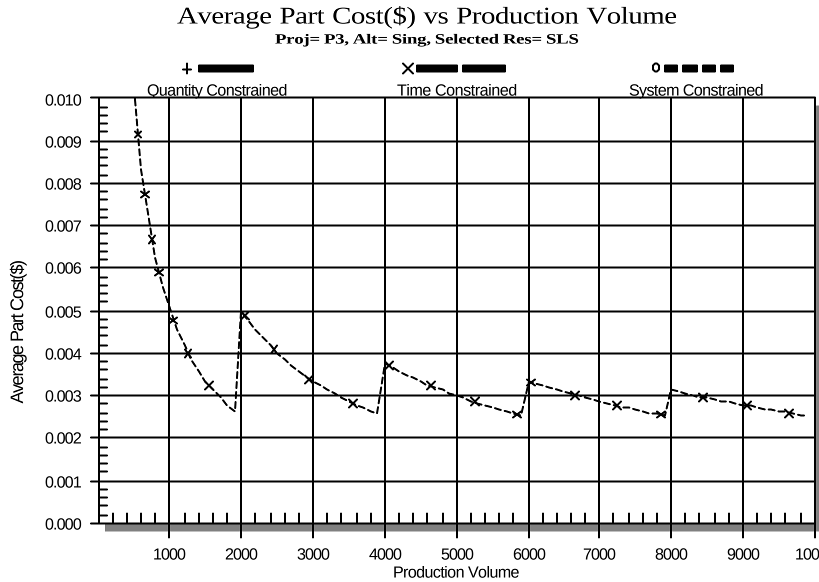


Figure 57. Average Cost for the Setup Labor Resource

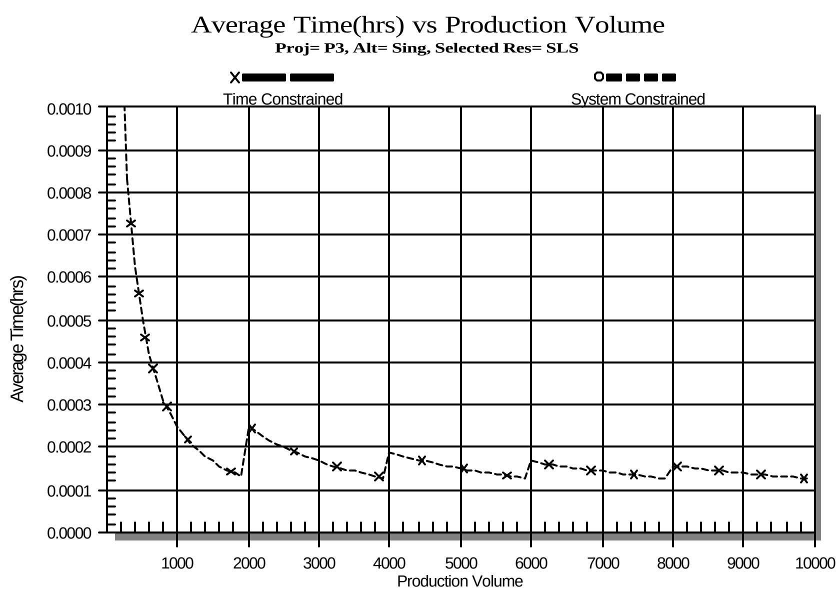


Figure 58. Average Time for the Setup Labor Resource

cost graph shown in Figure 59 (see Table 3, page 105 for legend descriptions). This is a "selected-resources" graph for the tandem torch system that includes only consumable items (i.e., welding wire, shielding gas, gun liners, and gun tips). This figure, by itself, provides insight into the relative cost of each resource at different production volumes. Management can question whether welding wire and shielding gas can be purchased at a lower price, since their cost is more significant than gun tip and gun liner costs.

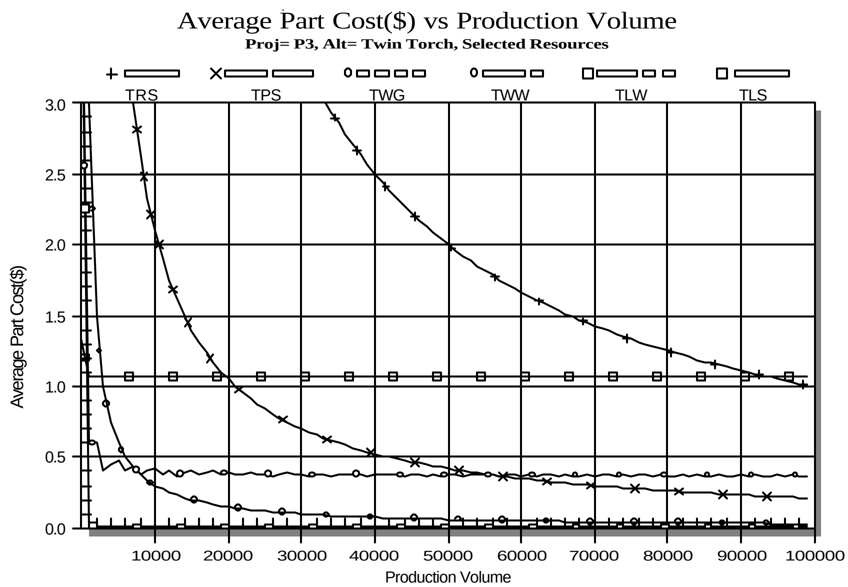


Figure 59. Average Cost for Tandem Torch Consumable Resources

Although the computer model graphs only six resources at a time, investigating resources in groups helps decide which resources are significant. Since Figure 59 showed that gun tip and gun liner costs are minimal, they can be excluded from further analysis. Figure 60 (see Table 3, page 105 for legend descriptions) demonstrates average resource costs for the remaining resources.

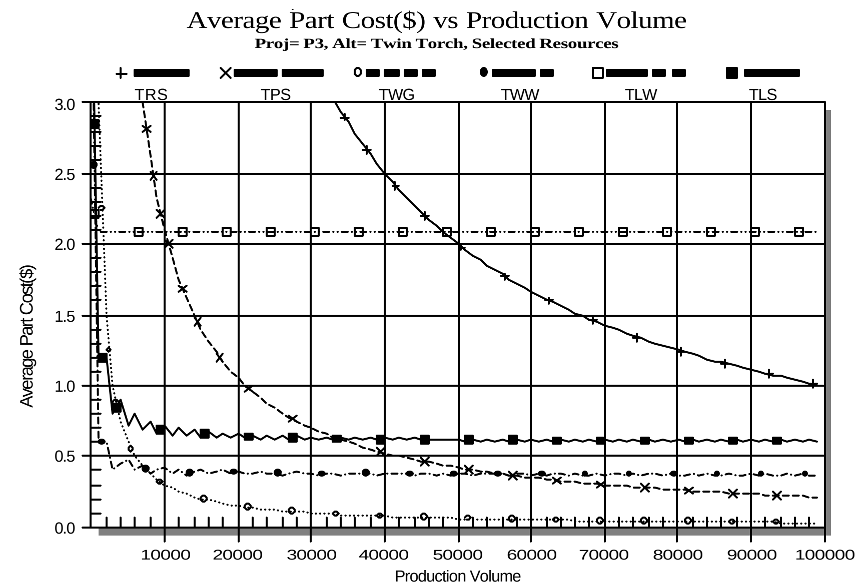


Figure 60. Average Cost for Tandem Torch, High Cost Resources

As resources are added, going back to investigate each resource to determine which constraint condition is controlling and whether improvement opportunities exist may be useful. For example, the welding wire average cost graph, Figure 61, demonstrates that the quantity constraint condition is controlling overall cost. It therefore makes no sense to purchase welding wire that has a longer shelf life. Instead, the question becomes how to reduce part cost by other means such as negotiating quantity discounts or finding lower cost suppliers.

The “selected-alternative” graph can help understand the composition of an alternative’s cost. Figure 62 (see Table 3, page 105 for legend descriptions) shows the average cost for the single torch system alternative with selected resources. It shows that the major components of cost vary with production volume. Labor cost becomes more significant after approximately 50,000 parts. The robotic system cost is more significant

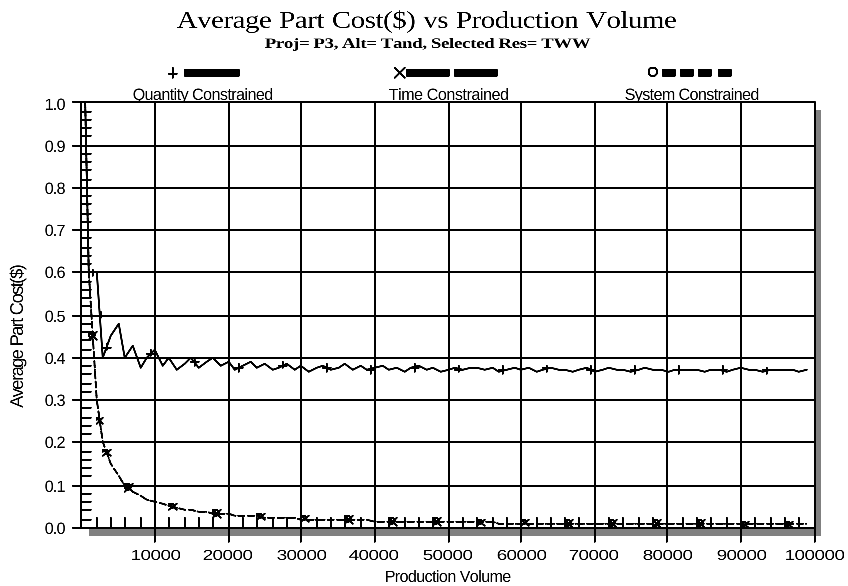


Figure 61. Average Cost for Welding Wire Resource

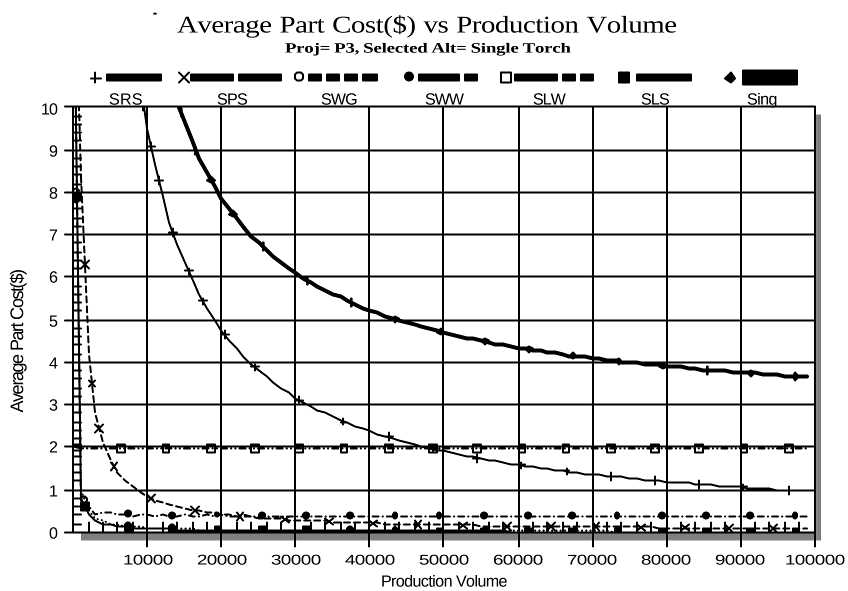


Figure 62. Average Cost Single Torch Alternative with Resources

under approximately 50,000 parts. Welding wire is the third most significant cost. RCM axis values can be easily modified to investigate any production volume or cost range of interest.

The figures provided above illustrate a few of the ways that RCM helps investigate cost, time, and utilization. These graphs and tabulated results can be generated for each alternative, and for each resource within an alternative.

Results and Conclusions

In this section, RCM's analysis techniques are used to answer the questions posed earlier.

Question 1. Figure 63 demonstrates the average cost for the single and tandem torch systems, and Figure 64 demonstrates the total time for these two alternatives. Table 11 provides the tabulated results. The break-even production volume for cost is approximately 20,000 parts. At a production volume above 20,000 parts, the tandem torch system is better. Below this value, the single torch system is better. The cost graph shows that the cost difference may not be very different. Further investigation into each alternative's resources may be required to understand the nature of the cost graphs. The time graph shows that the tandem torch system has a significant time advantage. Management can use both graphs to help decide which alternative is best under both cost and time metrics.

Question 2. Utilization graphs can be used to gain insight into capacity. Figure 65 and Figure 66 are utilization graphs for the tandem and single torch systems, respectively. Production volume range is intentionally set high to force a replenishment cycle for the resource (the point where the graph exhibits a step in the curve). The production volume at this point is the capacity for the resource. The tandem torch system

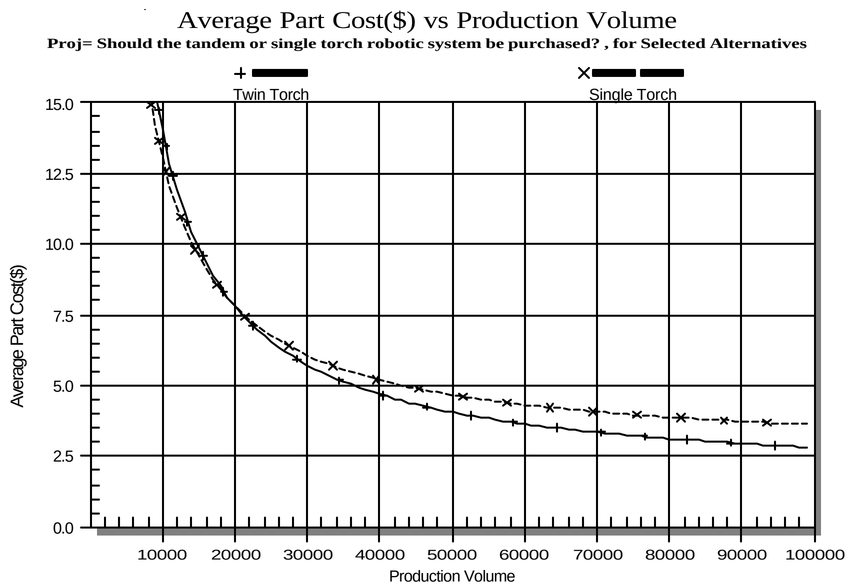


Figure 63. Average Cost Comparison, Single Versus Tandem Torch System

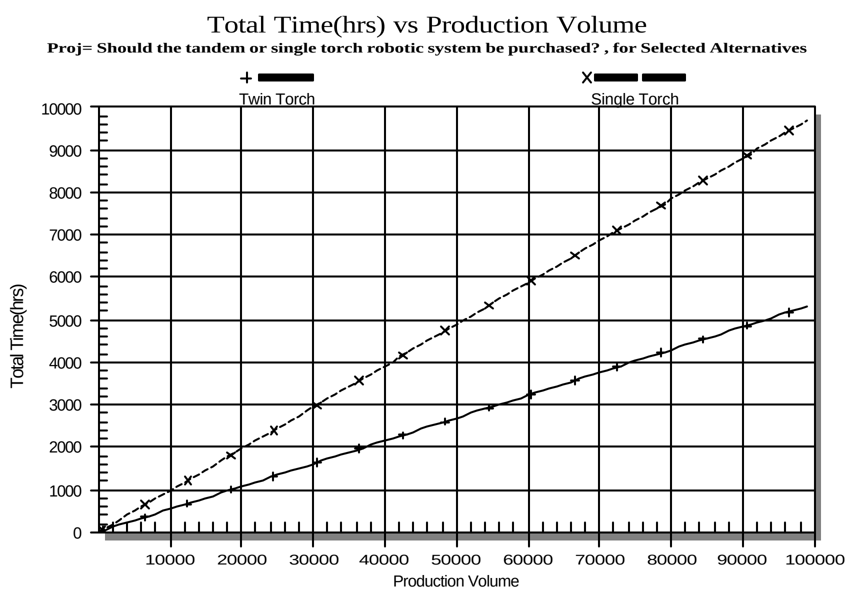


Figure 64. Total Time Comparison, Single Versus Tandem Torch System

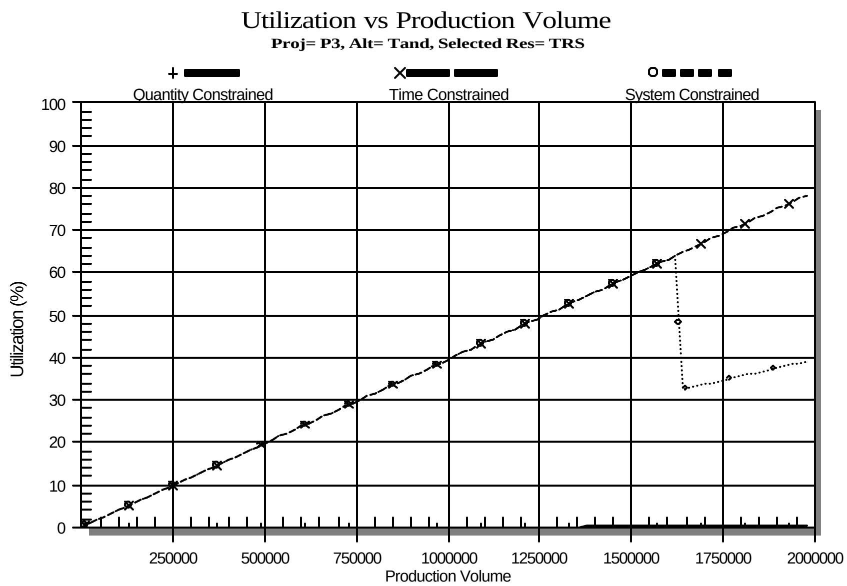


Figure 65. Utilization and Capacity for Tandem Torch

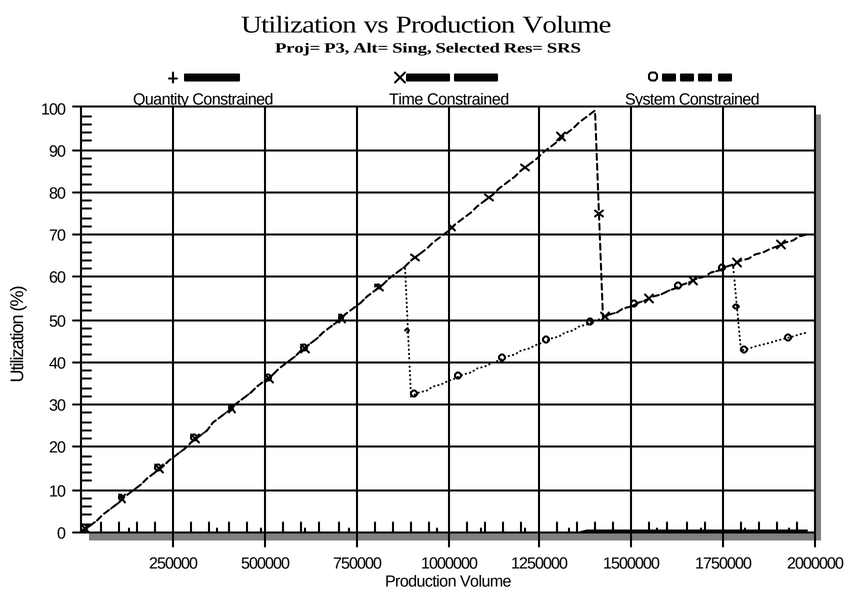


Figure 66. Utilization and Capacity for Single Torch

has a capacity of 1,640,000 parts, whereas the single torch system has a capacity of 895,000 parts. Recall that the time life for these resources is 10 years. Therefore, the yearly capacity of each system, including system constraint, is 164,000 and 89,500 parts. These figures account for overall cycle times and bottleneck resources (i.e., labor resource's 14 hours). If the yearly production demand is greater than these figures, then more than one robot system must be purchased. The tandem torch system produces more parts before it needs to be replaced. The utilization analysis can be used along with the break-even analysis in Question 1 to decide alternative selection.

Question 3. It is not stated whether the 100,000 parts is a yearly demand or a product life-cycle demand. Either way, Figure 65 and Figure 66 and the analysis from Question 2 helps answer the question about reserve capacity. If the 100,000 parts is a yearly figure, then the tandem torch system satisfies demand. The single torch system is unable to satisfy demand, and other solutions must be pursued with this alternative, such as purchasing two robotic systems, adding a third shift, reducing setup time, or by increasing lot sizes. If two systems are purchased, resource costs must be modified to take into account two purchases, and the overall utilization will be lower.

If the 100,000 were a product-life cycle demand, then each system has plenty of reserve capacity (1,540,000 parts for tandem and 795,000 parts for single). If this is the case, then management should consider finding additional parts to weld with the system.

Question 4. The total time graph, Figure 67, can be used to determine how much time is required to produce 100,000 parts. Approximately 13,000 hours are required for the single torch system, and approximately 10,500 hours for the tandem torch system.

Question 5. Figure 68 (see Table 3, page 105 for legend descriptions), produced by selecting the most significant resources for a "selected-alternative" plot option,

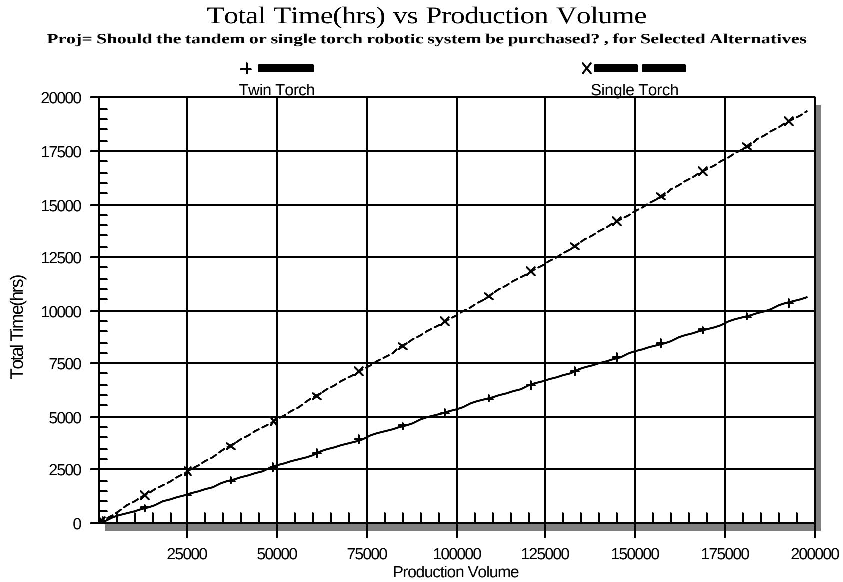


Figure 67. Total Time Comparison, Single Versus Tandem Torch System

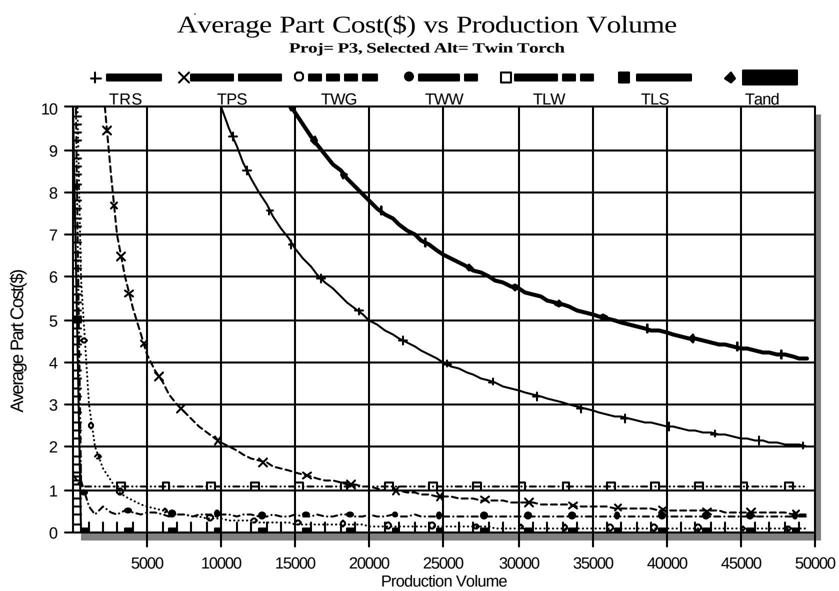


Figure 68. Average Cost Tandem Torch Alternative with Resources

demonstrates which resources compose the tandem torch system cost. At the 20,000 part break-even production volume, the robotic system resource cost is most significant. Operational labor and the power supplies cost are the next most significant. From the discussion for Figure 59, page 115, it was discovered that weld gun tips and gun liners were insignificant.

Labor cost may be difficult to lower since it might be controlled by union contract. Outsourcing this part may be an alternative to reducing cost. The cost of the robot system may be reduced by negotiating a lower price. Notice that the average cost for the robot system resource is reduced as more parts are produced. Also, recall from the discussion from Question 3 that the system capacity for the tandem torch system is 1,640,000 parts. As production volume increases, the cost of the robot system is much less significant. If the expected production volume were less than 20,000 parts, one wonders whether automation should be purchased at all. Question 11 addresses this point by comparing the cost of robotic welding with manual welding.

The total investment at the break-even point can be easily determined by switching one plot parameter from “average” to “total,” and adjusting the x-axis plot range. Figure 69 and Table 12 result when these changes are made. Total investment at the break-even point is approximately $156,000.

Question 6. The operational plan is changed to include two 10-hour shifts (18 hours), and to increase the production lot size to 6000 parts. The average cost to produce 100,000 parts decreases from approximately $2.83 to $2.58, approximately a 9 percent reduction. Figure 70 and Table 13 provide these results. On this graph, the newly created alternatives are labeled with the “Op2” extension.

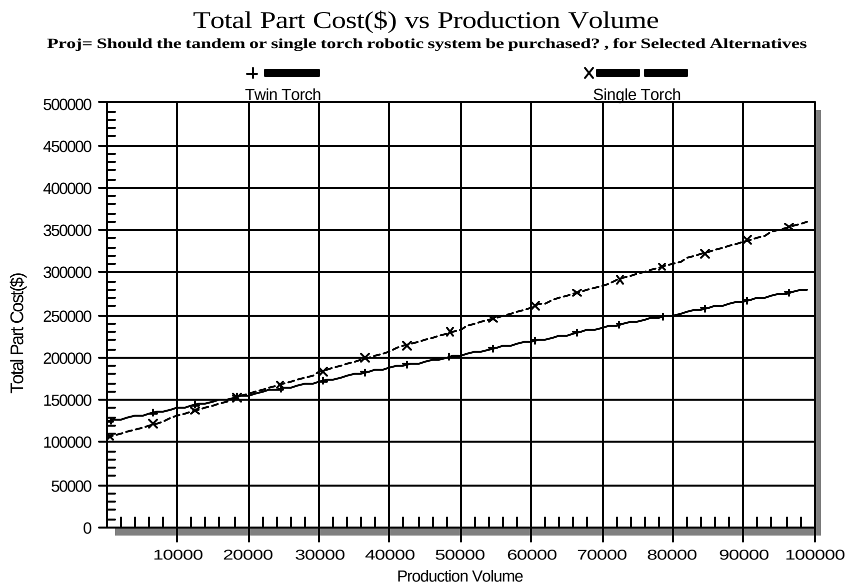


Figure 69. Total Cost Comparison, Single Versus Tandem Torch System

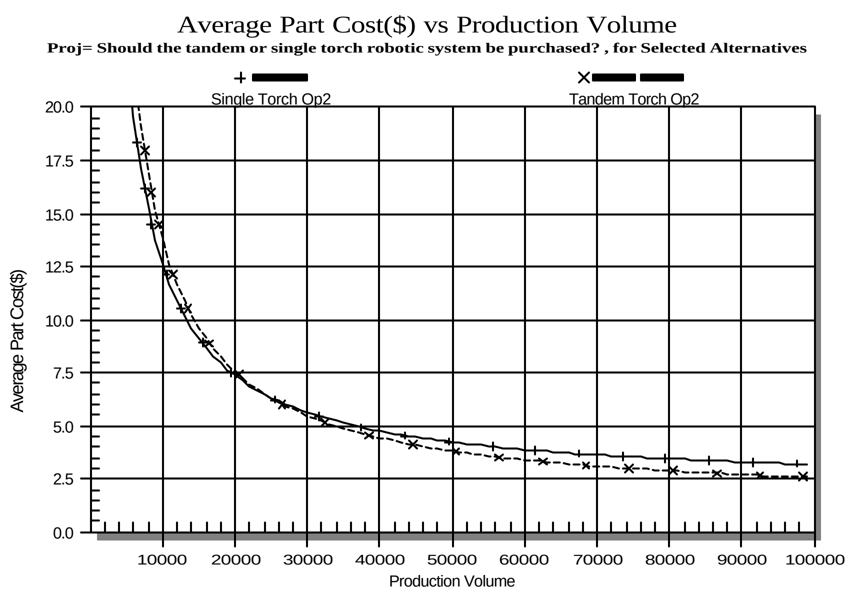


Figure 70. Average Cost Comparison with Operational Plan Changes

Another approach to answering this question is to develop two more alternatives, one for tandem and one for single that contain the changed parameters. Then all four alternatives can be plotted on one graph, as shown in Figure 71.

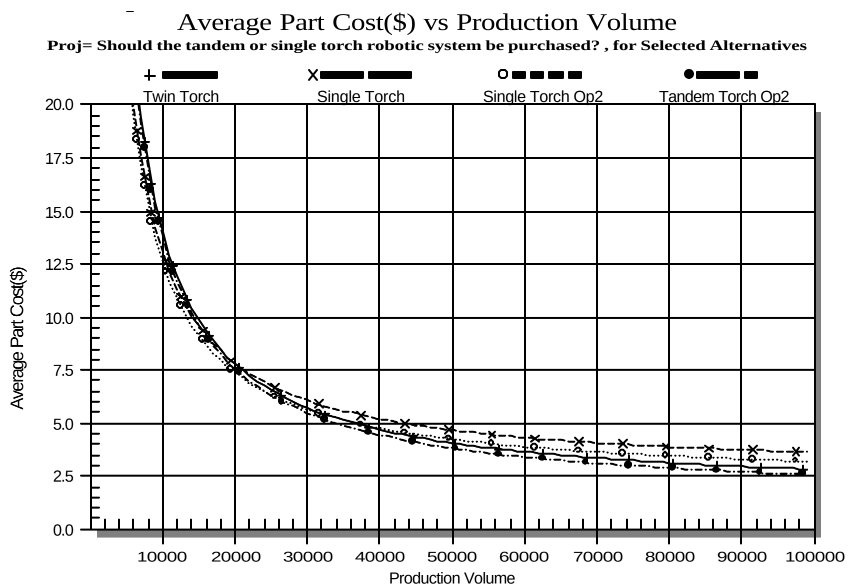


Figure 71. Average Cost Comparison, Operational Changes with New Alternatives

Question 7. If demand is greater than expected, the average cost per part is reduced, as illustrated in Figure 72. Comparing the results with the operational plan change results is interesting. Part costs can be reduced to approximately $1.75 with higher demand, which is greater than the effect of an operational plan change at lower volume.

Question 8. The selection of a process design to achieve low product cost, as already discussed, depends upon production volume and operational plans. It may prove interesting to consider manual welding with robotic welding to answer this question better (see question 11).

Question 9. Welding wire resource cost was discussed briefly for the tandem system with Figure 59, page 115, which showed that welding wire is the most expensive consumable item. A 15 percent reduction in its price is more significant than a 15 percent reduction in price for other consumables. For manual welding, the cost of gas becomes more significant since gas usage is constant over time. This is demonstrated in Figure 73. Recall that welding wire cost can be reduced from $.60 per pound to $.50 per pound as more wire is purchased. Increased product demand may provide a price reduction.

Question 10. Labor cost becomes significant as product demand increases. This illustrates the need to investigate thoroughly ways to reduce labor cost. An investigation into labor reduction may lead to both cost and time reductions. The operator labor time for tandem torch welding matches the robot cycle time exactly. A reduction in labor time benefits this alternative only with a corresponding reduction in welding time. If the operator welds more than 5 percent of the part, the operator time will control the overall cycle time.

The greater benefit of the tandem torch system is greater throughput, not lower cost. Throughput may be especially important if the welding operation is a bottleneck operation, since any reduction in time benefits the overall system.

A combination of increased product demand, larger lot sizes, three shifts of operation, and more aggressive supplies and equipment purchasing can significantly reduce product cost. Manual welding should be considered for low production parts.

Another interesting aspect occurs when the component part cost is considered. The component parts cost might be much higher than process costs. If so, then management should consider seriously how to reduce purchased component cost. Materials management concepts often suggest that management must concentrate on reducing purchased components cost.

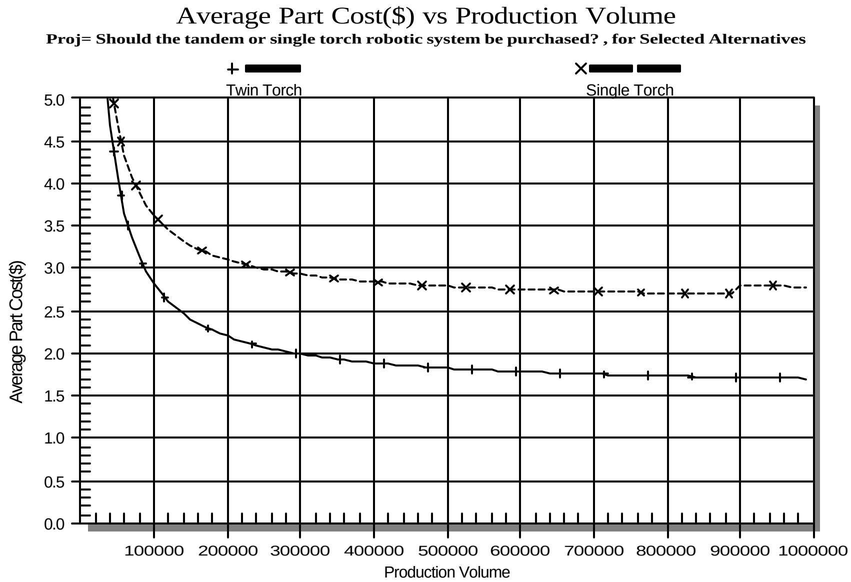


Figure 72. Average Cost Comparison at High Production Volume

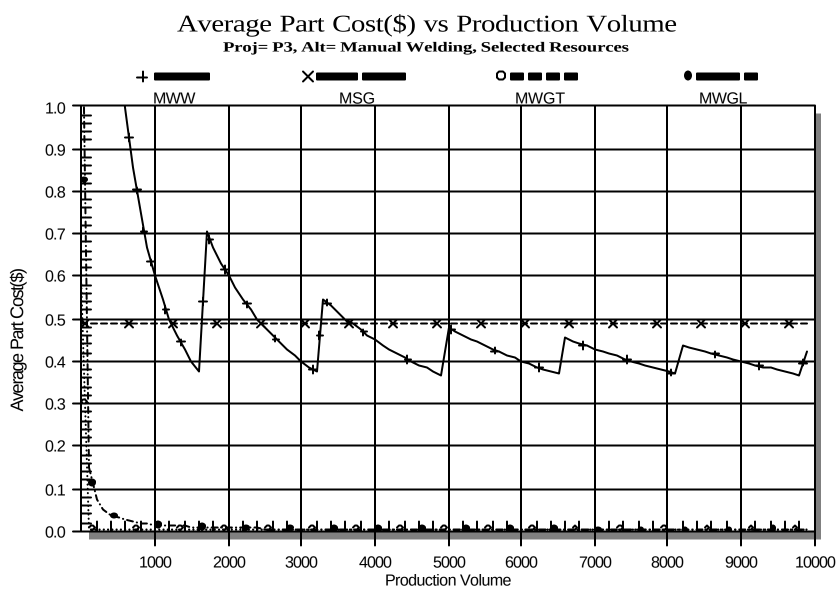


Figure 73. Average Cost for Manual Consumables

Question 11. Figure 74, Figure 75, and Table 14 add a manual welding alternative. They show that the average part cost is lowest for manual welding until 30,000 parts production, and then tandem torch is lower. It is interesting that the single torch system never has a lower part cost. Manual welding, as expected, is the slowest of all alternatives.

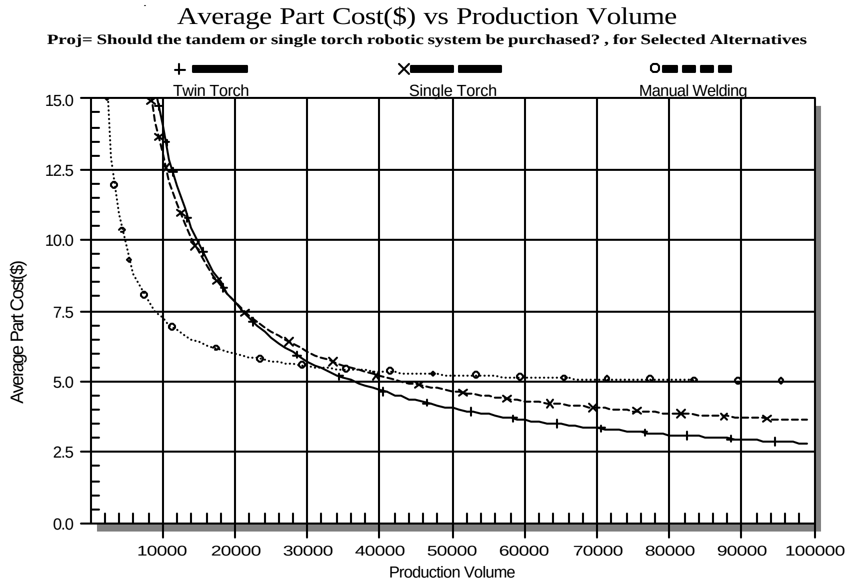


Figure 74. Average Cost for All Alternatives, Including Welding

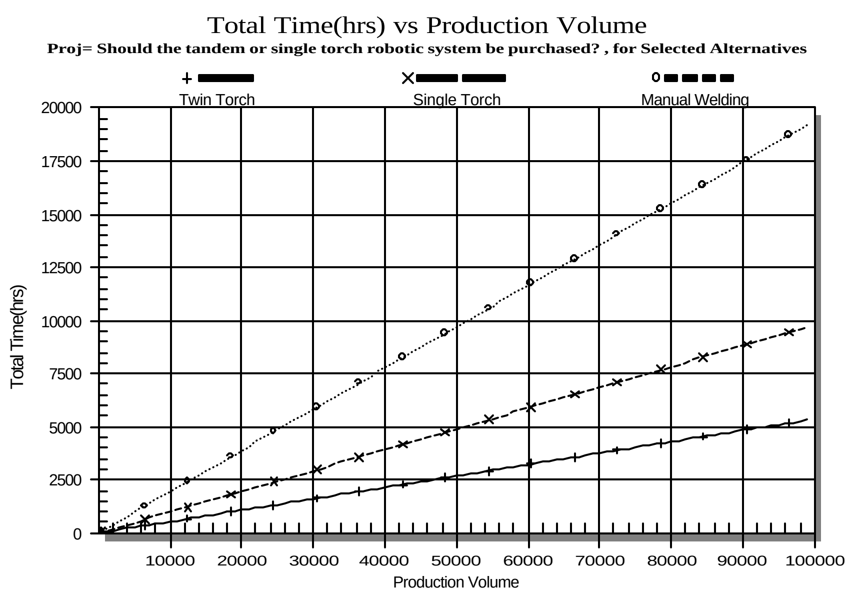


Figure 75. Total Time for All Alternatives, Including Welding

CHAPTER V

CONCLUSIONS AND FUTURE RESEARCH

RCM successfully addressed the questions raised about the welding system problem in Chapter IV. The comprehensive modeling of process alternatives that RCM achieves is very difficult, if not impossible, using cost accounting, engineering economics, cost estimating, break-even analysis, or other methodologies. RCM clearly illustrated how different alternatives compare in both cost and time. Engineering economics, break-even analysis, and cost accounting methods would not have provided any information about time. Only some process planning techniques address both cost and time factors, but these tools do not depict cost and time as accurately as RCM does. RCM easily provided both unit product cost and total product cost. Unit cost is information that management can relate to and act upon. Engineering economics, which gives management a return on investment figure, says nothing about unit cost. In addition, RCM clearly showed why one alternative costs what it does by representing component costs in a graphic format. Management can look at RCM results and take action to reduce specific resource costs. Cost accounting methods would have been difficult to use for non existing processes (i.e., robotic welding), and if applied would not have been as accurate.

Management can make long term strategic business decisions more confidently. The risks and opportunity to reduce or increase cost and time with production volume are easily understood with RCM. Reserve capacity, an important management planning figure, is not considered in most other process design methodologies. Knowing about reserve capacity provides a better understanding about additional investment required when production volume increases.

RCM successfully demonstrates that new process design models can be developed utilizing mathematically intensive concepts and implemented using modern computational tools.

RCM Significant Features

RCM offers the following significant features:

- RCM accounts for resources as they are actually consumed by a manufacturing process design. A “resource consumption” perspective is known to describe process costs more accurately. “Resource consumption” is a major concept in activity-based accounting theory. RCM considers how resources are consumed, not how they are allocated.
- RCM does not rely upon accounting approaches or financial accounting data. Instead, RCM accurately describes resources and how they are consumed. If a resource is expected to last 13 years, then a 13-year time life is used. If a resource is not fully consumed, RCM assigns its cost to the specific parts produced. If overhead factors are not relevant to a particular process, then RCM does not include them. Since RCM is a planning tool and not an accounting tool, not all costs have to be accounted for.
- RCM defines all resource lives to be variable. RCM eliminates the need to distinguish between fixed costs and variable costs. Instead, some resources have short consumption lives and others have long consumption lives. A consistent definition and structure for all resource parameters is provided. Though RCM has

many more parameters than most other methodologies, its consistent resource definition makes RCM easy to apply.

- RCM acknowledges that some resources are consumed over time and that others are consumed by part production. All resources have intrinsic time and piece lives. RCM calculates both time constraint and quantity constraint conditions and determines which condition controls the results. RCM also considers system effects, such as total cycle time, capacity, and availability. The user does not need to resort to other equations outside RCM.
- RCM's data requirements and data structure can be modeled in a database management system. This modeling approach provides an easy method for gathering, organizing and managing model data. The database approach can be implemented with existing company databases, and RCM's database information can be shared with other planning tools.
- A computer model implements RCM analyses. The computer model provides all calculations, provides a method to describe what is of interest, and shows the results in a variety of ways. Sensitivity analysis is achieved by changing values and observing the results, or by creating new alternatives based upon value changes and comparing alternatives side by side. The level of detail is controlled by the user.

RCM Assessment

W. Fabrycki, in his book Life-Cycle Cost and Economic Analysis (Fabrycki and Blanchard, 1991), states that a good cost model should contain the following characteristics:

1. Be comprehensive and include all relevant factors, and be reliable in terms of repeatability of results.
2. Represent the "dynamics" of the system or product being evaluated, and be sensitive relative to the relationships of key input parameters.
3. Be flexible to the extent that the analyst can evaluate overall system requirements, as well as the individual relationships of various system components. In the analysis process, one may wish to view the system as a whole; identify high-cost contributors; evaluate one or more specific components of the system as necessary, independent of other elements; initiate changes at the component level; and present the results in the context of the overall system.
4. Be designed in such a way as to be simple enough to allow for timely implementation. Unless the analyst can quickly use the method, it is of little value.
5. Be designed such that it can be easily modified to incorporate additional capabilities. It may be necessary to expand certain facets of the cost breakdown structure in order to gain additional visibility.

These criteria are used to assess RCM.

RCM goes beyond cost analysis, and includes time and utilization analyses. RCM considers the specific resources consumed in manufacturing for an alternative and how they are consumed. Three different consumption rates for each resource are considered: quantity constrained, time constrained, and system constrained. RCM performs calculations over a production volume range instead of at one production value. Equations are used within RCM and the results are repeatable.

Each resource is described by fifteen parameters. Some parameters are quantity-based and some are time-based. Other parameters (e.g., batch, overlap time, and availability) are for system analysis. RCM accounts for actual purchase patterns and the effects of over purchasing. Few assumptions are made within the model. RCM provides the means to identify the most relevant resources and to focus on these for in depth analysis. RCM attempts to model the real world accurately.

System dynamics are specifically considered in RCM by its system constraint calculations. A resource added in sequence having a long time consumption is immediately recognized by RCM. Resources whose times overlap with other resource times are also considered within RCM. RCM also considers resource availability and its effect on the entire system. Important input parameters can be discovered and manipulated to determine cause and effect relationships.

A high level of sensitivity analysis is provided. Individual resources, individual alternatives, several resources, and several alternatives can be considered side by side. The focus is easily shifted from low, to mid, to high volume production. Any cost, time, or utilization range can be investigated. Any input parameter can be quickly changed to assess its effect. Additional alternatives, based upon parameter changes, are quickly modeled and compared to existing alternatives. RCM graphs make the results easy to understand. The dynamic environment for RCM in unmatched by other methodologies. Detail that RCM incorporates makes it much more comprehensive than other methodologies.

Extensibility of RCM was shown in two areas. First, it was demonstrated how resource delay factors, both time and quantity, could be added to the analysis. The addition of delay was important for resources that do not begin at time zero. Second, linear and exponential repeat cost functions were added to the already existing constant repeat cost function. A program code segment (see Figure 34) was provided to show how additional cost functions are added to RCM. RCM provides a good framework for additional enhancements.

Limitations of RCM

Although RCM contains a complete set of time, cost, and utilization analyses, it has several limitations. One must understand these limitations when applying RCM to have meaningful results. Limitations become opportunities for future research. RCM provides a framework for analyzing cost, time, capacity, and volume interaction. The development of a commercially viable tool, however, will put the analysis in the hands of many to use.

RCM requires a modern computing environment for its use. Data requirements are high. The quality of results depends upon how accurately parameter values are known. The quantity of calculations almost demands graphic portrayal of results. RCM was initially modeled in a spreadsheet environment, but it was quickly discovered that a general-purpose computer software tool was not fast enough nor flexible enough. A more powerful database environment was selected which proved to contain adequate capability. It is believed that modeling RCM in a visual programming environment enables easy user interaction.

RCM currently takes a single product perspective and does not perform part aggregation. Time and quantity parameter values are for a single part. To include multiple parts it is necessary to note the results, including utilization information, and reapply the analysis by adjusting the availability parameter. When a part family is selected, the necessary adjustments are minimal.

The same limitation above pertains to resources. RCM currently does not accumulate results for the same resource consumed several times. A labor resource, for example, might be used to load and unload parts, to perform quality measurements, to fetch new raw material, and to set up the operation. RCM sees this as four separate labor resources instead of one, and utilization values for this single resource are not accumulated.

RCM assumes that the product design meets the minimal functionality and quality specifications. Sometimes, a relationship between levels of quality and process designs may exist. For example, one process design might produce to closer tolerances, or smoother surface finishes, or a longer product life, that exceeds the drawing specifications. Improving quality beyond design specifications may have value, and it may come with an increase in cost or time. RCM does not specifically address quality relationships with cost, time, and utilization. Certainly, RCM can model different quality levels as separate alternatives for comparison, but a quality parameter or function within RCM may be useful. As RCM becomes a part of the computer integrated environment, it is believed that opportunity exists for better integrated analyses.

Batch resources only have a quantity life in RCM. However, some batch resources may have a time life instead of quantity life or in addition to quantity life. For example, chemicals used in a plating operation might need to be recharged after a certain amount of time no matter how many pieces are produced. Methods of modeling this scenario may already exist in RCM, but they have not yet been thoroughly investigated.

Direct relationships between RCM parameters may exist. For example, RCM uses one salvage value. However, salvage value may depend on time (i.e., salvage value decreases with time). RCM can be modified to account for these relationships when they are determined to be significant. The inclusion of repeat cost delays and repeat cost function types demonstrated the extensibility of RCM.

RCM is best used for discrete, mid-volume production. Discrete equations were specifically developed. Insights provided by RCM are greater for low to mid-volume production than for high volume production.

Future Research

Many opportunities for additional research and enhancement exist for RCM. The RCM computer model, as with most computer software, offers endless improvement and enhancement opportunities. Items listed below concentrate specifically on research opportunities instead of computer model enhancements.

- Incorporate multiple part analysis. Accumulate the results for each part, determine which factors are affected and how.
- Incorporate resource sharing methodologies.
- Integrate RCM methodology with product functional analysis tools, such as Ashby's material properties and process selection charts and methodology.
- Develop optimization methods to select best design parameters for specific production objective functions.
- Integrate or incorporate RCM into product design standards currently underdevelopment (such as STEP), or develop the integration of RCM and CAD.
- Integrate RCM with quality assurance methodologies.
- Integrate RCM with scheduling algorithms, MRP, and other operations management tools and techniques.
- Investigate how RCM can be used for machine replacement analysis.
- Develop additional repeat cost functions, such as quantity discounts.
- Develop advanced resource parameter relationships, such as that mentioned above between salvage value and age.

- Develop a more advanced batch resource analysis?

APPENDIX A

SUMMARY OF MODEL PARAMETERS

$\lceil\ \rceil$	Ceiling function (i.e., integer rounded up).
a_r	Hours in a day that resource r is available, where $0 \le a_r \le 24$.
b_r	Unit or batch level resource. b_r = False for unit level resource, b_r = True for batch level resources. For batch resources, p_r is used to design lot size.
c_r	Resource cost.
C_r	Net resource cost, $c_r - s_r$.
CA_r	Average cost per part for resource r.
CT_r	Total cost for resource r at a particular production volume Q.
g_r	Resource group number.
G	Total number of groups.
h_r	Time delay, in hours, before cost is incurred for resource r.
k_r	Resource function type identifier. 0 = no growth. 1 = linear growth, 2 = exponential growth.
l_r	Life of resource r in hours (i.e., shelf life).
N_r	Number of resources required at a particular production volume.
o_r	For sequential resources, the overlap of its production time, t_r, with other resources, expressed as a percent, where $0 \le o_r \le 1$.
p_r	Number of parts produced in time t_r for a resource. This is an integer which is usually 1, but it can be larger when more than one part gets produced with every individual resource usage.
q_r	Maximum number of parts that can be produced from resource r.
Q	Production volume.
r	A particular resource.

R Total number of resources.

s_r Resource salvage value.

t_r Production time for resource r in hours.

TT_r Total production time for production quantity Q for resource r.

TA_r Average production time for production quantity Q for resource r.

U_r Resource utilization at a particular production volume.

$v1_r$ User defined variable for resource repeat cost.

$v2_r$ Second user defined variable for resource repeat cost.

w_r Quantity delay in pieces before expenditure for r is incurred.

APPENDIX B

RCM SUMMARY TABLES

Note: The summary tables, generated by RCM's computer model, contain one hundred calculations and require three printed pages. For this Appendix, only one or two pages are provided to illustrate the type of results that RCM produces.

Table 4. Summary Calculations for Current Selected Resource

Table 5. Summary Calculations for All Selected Resources

Table 6. Summary Calculations for Current Selected Alternative

Table 7. Summary Calculations for All Selected Alternatives

Table 8. Resource Results for a Liner Resource

Table 9. Resource Results for a Labor Resource

Table 10. Resource Results for a Setup Labor Resource

Table 11. Single and Tandem Torch Welding Comparison

Table 12. Total Cost, Time, and Utilization for Welding Alternatives

Table 13. Results with an Operations Plan Change

Table 14. Manual Welding and Robotic Welding Comparison

APPENDIX C

ACRONYMS

ABC	Activity-based costing
AEM	Assemblability evaluation method
AI	Artificial intelligence
BOM	Bill of material
CAD	Computer aided design
CAM	Computer aided manufacturing
CAPP	Computer aided process planning
CIM	Computer integrated manufacturing
CNC	Computer numerical control
CPM	Critical path method
DFA	Design for assembly
DFM	Design for manufacture
EOQ	Economic order quantity
FMS	Flexible manufacturing systems
FV	Future value
GT	Group technology
IRR	Internal rate of return
JIT	Just-in-Time
MRP	Material requirements planning
NC	Numerical control

NPV	Net present value
PC	Personal computer
RCM	Resource consumption model
ROI	Return on investment analysis
STEP	Standard for transfer and exchange of product model data
TOC	Theory of constraints
VA	Value analysis
WBS	Work breakdown structure

APPENDIX D

COMPUTER PROGRAM LISTING

The RCM computer model contains many supporting programs. The program (technically called a method) provided below, named RCMCALCULATIONS, implements the analyses and methodology from Chapter III. It is provided so that the reader can better understand how the equations are converted into program code. The code runs in Microsoft's Visual Foxpro®, version 3.0b.

```
*      Author : Rick Jerz
* Application : RCMCALCULATIONS
* Create Date : 97/02/03
* Last Modify : 97/10/11
* Description : Calculations for RCM

*********************************************************************************
* Recalculates a single resource costs
*    Includes: Quantity, Time, Consumption, and System Constraints
*
*  Puts the results of the calculations into gnSummary[] array.
* Note: Must be careful to adjust for difference in array starting point.
*      PEGraph starts at 0, VFP starts at 1.


DIMENSION lnCost[3]           && Array that holds the cost for the 3 constraints.
DIMENSION lnTime[3]           && Array that holds the time for 3 constraints.
DIMENSION lnUtilization[3]    && Array that holds the utilization for the 3 constraints.
DIMENSION lnNumPur[3]         && Array that holds the number of resource purchases for the 3 constraints.
DIMENSION aAltCost[100]
DIMENSION aAltTime[100]
DIMENSION aAltUtilization[100]

*  Force data type
   lnNumPur = 0.0000000000
   lnCost = 0.0000000000
   lnTime = 0.0000000000
   lnUtilization= 0.0000000000
   aAltCost = 0.0000000000
   aAltTime = 0.0000000000
   aAltUtilization = 0.0000000000

*  Clear the Summary Array
   thisform.gnSummary = 0.0000000000


* Calculate the production volume increment for 100 values.
```

```
lnIncrement = ceiling((val(thisform.pgfMain.Page2.txtXAxisMax.value)  -
val(thisform.pgfMain.Page2.txtXAxisMin.value))/100)


***********************************************************************************
* Must do all of the following for each alternative, when nUserSelect = 4
lnTotalAlternatives = iif(thisform.nUserSelect = 4, alen(thisform.aSelAlternatives,1),1)

for n = 1 to lnTotalAlternatives
   lcCurrentProjectID = alltrim(thisform.pgfMain.page1.txtProject.value)
   lcCurrentAlternativeID = alltrim(thisform.pgfMain.page1.txtAlternative.value)


***********************************************************************************
***********************************************************************************
* Determine how many subsets of data are being considered.

DO CASE
CASE thisform.nUserSelect = 1
   lnSubsets = 1
CASE thisform.nUserSelect = 2
   lnSubsets = alen(thisform.aAltResources,1)
   lnSubsetCount = -1                          && Reset subset counter, make it -1 for PEGRAPH
CASE thisform.nUserSelect = 3
   lnSubsets = alen(thisform.aSelResources,1)
CASE thisform.nUserSelect = 4
*   Must recreate the A.AltResources array for each alternative.
lcCurrentAlternativeID = alltrim(thisform.aSelAlternatives[n, 2])
   SELECT *;
    FROM rcm!resources;
    WHERE Resources.cprojid = lcCurrentProjectID;
      AND Resources.caltid = lcCurrentAlternativeID;
   Into Array thisform.aAltResources
   lnSubsets = alen(thisform.aAltResources,1)
   lnSubsetCount = -1                          && Reset subset counter, make it -1 for PEGRAPH
*   * Must force Time high in order to find minimum
*   for x = 1 to 100
*       thisform.gnSummary[x,4]=1000.000000
*   next x
ENDCASE

***********************************************************************************
***********************************************************************************
* Calculate the overall controlling cycle time accounting for all overlaps.
*  (to be used for system constraint calculations.

* First, get the overall time for groups in series without overlap
SELECT MAX(nresprodtime*(1-nrespcntover)/nresprodpcs) as ControlTime;
 FROM rcm!resources;
 WHERE Resources.cprojid = lcCurrentProjectID;
   AND Resources.caltid = lcCurrentAlternativeID;
 GROUP BY Resources.ngroup;
 into cursor lnControlTime
* Combine the controlling sequence time and the largest individual resource time for an alternative.
select sum(controlTime);
 from lnControlTime;
 union;
 SELECT  MAX(Resources.nresprodtime/nresprodpcs);
 FROM rcm!resources;
 WHERE Resources.cprojid = lcCurrentProjectID;
   AND Resources.caltid = lcCurrentAlternativeID;
 into cursor lnControlTime

* Select the largest time between the sequential resource times and the largest individual
*  resource time.  This become the controlling cycle time.
select max(sum_controltime) as CycleTime;
```

```
 from lnControlTime;
 into array lnControlTime

* Now get the minimum resource availability for unit costs (not batch).
SELECT MIN(Resources.nresavail) as MinAvail;
 FROM rcm!resources;
 WHERE Resources.cprojid = lcCurrentProjectID;
   AND Resources.caltid = lcCurrentAlternativeID ;
   AND Resources.lbatch = .F.;
   INTO array lnMinAvailability


********************************************************************************
********************************************************************************
* For the number of resources
for m = 1 to lnSubsets

DO CASE
CASE thisform.nUserSelect = 1
   for i = 1 to alen(thisform.aProjResources,1)
      if alltrim(thisform.aProjResources[i ,4])= alltrim(thisform.pgfMain.Page1.txtResource.value) ;
         and alltrim(thisform.aProjResources[i ,3])= lcCurrentAlternativeID then
         lnRes = i
         exit
      else
      endif
   next i
CASE thisform.nUserSelect = 2
   * Find the resource under investigation in the aProjResources array.
   for i = 1 to alen(thisform.aProjResources,1)
      if alltrim(thisform.aProjResources[i ,4])= alltrim(thisform.aAltResources[m,4]) ;
         and alltrim(thisform.aProjResources[i ,3])= alltrim(thisform.aAltResources[m,3]) then
         lnRes = i
         exit
      else
      endif
   next i
   * Is the current resource under investigation in the aSelResources array?
   lnResFound = 0
   for i = 1 to alen(thisform.aSelResources,1)
      if alltrim(thisform.aSelResources[i ,4])= alltrim(thisform.aAltResources[m,4]) ;
         and alltrim(thisform.aSelResources[i ,3])= alltrim(thisform.aAltResources[m,3]) then
         lnResFound = 1
         lnSubsetCount = lnSubsetCount + 1
         exit
      else
      endif
   next i
CASE thisform.nUserSelect = 3
   for i = 1 to alen(thisform.aProjResources,1)
      if alltrim(thisform.aProjResources[i ,4])= alltrim(thisform.aSelResources[m,4]) ;
         and alltrim(thisform.aProjResources[i ,3])= alltrim(thisform.aSelResources[m,3]) then
         lnRes = i
         exit
      else
      endif
   next i
CASE thisform.nUserSelect = 4
   * Find the resource under investigation in the aProjResources array.
   for i = 1 to alen(thisform.aProjResources,1)
      if alltrim(thisform.aProjResources[i ,4])= alltrim(thisform.aAltResources[m,4]) ;
         and alltrim(thisform.aProjResources[i ,3])= alltrim(thisform.aAltResources[m,3]) then
         lnRes = i
         exit
      else
      endif
```

```
   next i
   * Is the current resource under investigation in the aSelResources array?
   lnResFound = 0
   for i = 1 to alen(thisform.aSelResources,1)
      if alltrim(thisform.aSelResources[i ,4])= alltrim(thisform.aAltResources[m,4]) ;
         and alltrim(thisform.aSelResources[i ,3])= alltrim(thisform.aAltResources[m,3]) then
         lnResFound = 1
         lnSubsetCount = lnSubsetCount + 1
         exit
      else
      endif
   next i
ENDCASE


* Variable assignment to aid the reader.
lnResCost = thisform.aProjResources[lnRes ,6]                              && cr
lnResSalvage = thisform.aProjResources[lnRes ,7]                    && sr
lnNetCost = lnResCost - lnResSalvage                                              && Cr
lnResLifePcs = thisform.aProjResources[lnRes ,8]                    && qr
lnResLifeTime = thisform.aProjResources[lnRes ,9]                   && lr
lnResProdTime = thisform.aProjResources[lnRes ,10]                         && tr
lnResProdPcs = thisform.aProjResources[lnRes ,11]                          && pr
lnIsBatchResource = thisform.aProjResources[lnRes ,12]
* For batch resources, RCM assumes 100% availability
lnResAvailability = iif(lnIsBatchResource = .f., thisform.aProjResources[lnRes ,15],24)          && ar
lnResTimeDelay = thisform.aProjResources[lnRes ,16]                        && hr
lnResPieceDelay = thisform.aProjResources[lnRes ,17]                && wr
lnResDecayType = thisform.aProjResources[lnRes ,18]                        && kr
lnResDecayValue = thisform.aProjResources[lnRes ,19]                && v1r
lnResDecayValue2 = thisform.aProjResources[lnRes ,20]               && v2r


*********************************************************************************
*********************************************************************************
*********************************************************************************
* Curve calculations for Y Data
For i = 1 To 100

*********************************************************************************
*  Step 1) Determine the production volume(x-axis values) for all curves.
   lnProdVolume  = val(thisform.pgfMain.Page2.txtXAxisMin.value) + (lnIncrement * (i-1))

*  Adjustment for average versus total calculations
   lnVolume = iif( thisform.pgfMain.Page2.opgCalculate.value = 1, lnProdVolume, 1)


*********************************************************************************
*  Step 2) Calculate quantity contrained costs, Y-axis values.

*  Adjustment for a production quantity delay.       Applies to all three constraint conditions.
   lnQPrime = iif(lnProdVolume < lnResPieceDelay , 0 ,lnProdVolume - lnResPieceDelay )

   lnNumPur[1] = ceiling((lnQPrime + .0000000000) / lnResLifePcs) && Number of purchases
* (Note: must add .0000000000 to force proper data precision)

*  Calculate repeat cost.
   lnTotalResCost = thisform.rcmRepeatCost(lnNumPur[1], lnResDecayType , lnResDecayValue, lnResDecayValue2 )
   lnCost[1] = lnTotalResCost /lnVolume

*  Time calculations are not applicable.

*  Calculate Utilization
   lnUtilization[1]= (lnProdVolume *100)/( lnNumPur[1]*lnResLifePcs)
```

```
********************************************************************************
*  Step 3) Calculate time constrained costs, Y-axis values.

*  Adjustment for a production "time" delay.            Applies to only time and system constraint conditions.
   lnQ2Prime = lnResTimeDelay*lnResProdPcs/lnResProdTime
   lnQPrime = iif( lnQ2Prime < lnResPieceDelay, lnResPieceDelay, lnQ2Prime)
   lnQPrime = iif(lnProdVolume < lnQPrime  , 0 ,lnProdVolume - lnQPrime )

   lnTotalProductionTime = ceiling((lnQPrime + .0000000000) / lnResProdPcs ) * ((lnResProdTime * 24)/lnResAvailability)
   lnNumPur[2] = ceiling((lnTotalProductionTime + .0000000000)/lnResLifeTime)

*  Calculate repeat cost.
   lnTotalResCost = thisform.rcmRepeatCost(lnNumPur[2], lnResDecayType , lnResDecayValue, lnResDecayValue2 )
   lnCost[2] = lnTotalResCost /lnVolume

*  Time calculatons.
   lnTime[2] = lnTotalProductionTime  / lnVolume

*  Utilization calculations
   lnUtilization[2]= (lnTotalProductionTime*100)/( lnNumPur[2]*lnResLifeTime)        && Temporary value


********************************************************************************
*  Step 4) Calculate capacity constrained costs.
*  Adjustment for a production "time" delay.            Applies to only time and system constraint conditions.
   lnQ2Prime = lnResTimeDelay*lnResProdPcs/lnControlTime
   lnQPrime = iif( lnQ2Prime < lnResPieceDelay, lnResPieceDelay, lnQ2Prime)
   lnQPrime = iif(lnProdVolume < lnQPrime  , 0 ,lnProdVolume - lnQPrime )

   lnTotalProductionTime = ceiling((lnQPrime + .0000000000) / lnResProdPcs ) * ((lnControlTime * 24)/lnMinAvailability)
   lnNumPur[3] = ceiling((lnTotalProductionTime + .0000000000)/lnResLifeTime)

*  Calculate repeat cost.
   lnTotalResCost = thisform.rcmRepeatCost(lnNumPur[3], lnResDecayType , lnResDecayValue, lnResDecayValue2 )
   lnCost[3] = lnTotalResCost /lnVolume

*  Time calculatons.
   lnTime[3] = lnTotalProductionTime  / lnVolume

*  Utilization calculations
   lnUtilization[3]= (lnTime[2]/lnTime[3])*(lnTotalProductionTime   *100)/( lnNumPur[3]*lnResLifeTime)    && Temporary
value

*  For Batch resource, system = time
   if lnIsBatchResource = .t. then
      lnNumPur[3] = lnNumPur[2]
      lnCost[3] = lnCost[2]
      lnTime[3] = lnTime[2]
      lnUtilization[3] = lnUtilization[2]
   endif

********************************************************************************
********************************************************************************
*  Step 5) Put calculations into objects

DO CASE
********************************************************************************
* Current Resource
CASE thisform.nUserSelect = 1

*  Send the production volume to PEGRAPH's XData.
   for k = 0 to 3
   thisform.pgfMain.Page3.olegphCost.XData[k, i-1] = lnProdVolume
   thisform.pgfMain.Page4.olegphTime.XData[k, i-1] = lnProdVolume
   thisform.pgfMain.Page5.olegphUtilization.XData[k, i-1] = lnProdVolume
   next k
```

```
*   Send information to PEGRAPH's YData
*   Cost
    thisform.pgfMain.Page3.olegphCost.YData[0, i-1] =  iif(thisform.pgfMain.page2.chkQuantityConstraint.value = 1,lnCost[1],0)
    thisform.pgfMain.Page3.olegphCost.YData[1, i-1] = iif(thisform.pgfMain.page2.chkTimeConstraint.value = 1, lnCost[2],0)
    thisform.pgfMain.Page3.olegphCost.YData[2, i-1] = iif(thisform.pgfMain.page2.chkSystemConstraint.value = 1, lnCost[3],0)
*   Time
    thisform.pgfMain.Page4.olegphTime.YData[0, i-1] = lnTime[1]            && Time doesn't make sense
    thisform.pgfMain.Page4.olegphTime.YData[0, i-1] = iif(thisform.pgfMain.page2.chkTimeConstraint.value = 1, lnTime[2],0)
    thisform.pgfMain.Page4.olegphTime.YData[1, i-1] = iif(thisform.pgfMain.page2.chkSystemConstraint.value = 1, lnTime[3],0)
*   Utilization
    thisform.pgfMain.Page5.olegphUtilization.YData[0, i-1] = iif(thisform.pgfMain.page2.chkQuantityConstraint.value =
1,lnUtilization[1],0)
    thisform.pgfMain.Page5.olegphUtilization.YData[1, i-1] = iif(thisform.pgfMain.page2.chkTimeConstraint.value = 1,
lnUtilization[2],0)
    thisform.pgfMain.Page5.olegphUtilization.YData[2, i-1] = iif(thisform.pgfMain.page2.chkSystemConstraint.value = 1, lnUtilization[3],0)

*   Send information to the Summary cursor
    thisform.gnSummary[i,1] = lnProdVolume
    thisform.gnSummary[i,2] = lnCost[1]
    thisform.gnSummary[i,3] = lnCost[2]
    thisform.gnSummary[i,4] = lnCost[3]
    thisform.gnSummary[i,5] = max (lnCost[1], lnCost[2], lnCost[3])        && Controlling cost
    thisform.gnSummary[i,6] = max (lnNumPur[1], lnNumPur[2], lnNumPur[3])
                        && Replenishments
    thisform.gnSummary[i,7] = max (lnTime[1], lnTime[2], lnTime[3])
                                && Controlling Time
    thisform.gnSummary[i,8] = lnUtilization[3]                                                  && Controlling Utilization
                                                        && Replenishments
*   thisform.gnSummary[i,8] = min (lnUtilization[1], lnUtilization[2], lnUtilization[3])
    && Controlling Utilization
    && Replenishments


*********************************************************************************
* Current Alternative
CASE thisform.nUserSelect = 2
* Must also do the "m" assignment if it is a selected resource
if lnResFound = 1 then
    *   Send information to PEGRAPH's YData
    *   Cost
        thisform.pgfMain.Page3.olegphCost.XData[lnSubsetCount , i-1] = lnProdVolume
        thisform.pgfMain.Page3.olegphCost.YData[lnSubsetCount , i-1] =  max (lnCost[1], lnCost[2], lnCost[3])
    *   Time
    thisform.pgfMain.Page4.olegphTime.XData[lnSubsetCount , i-1] = lnProdVolume
        thisform.pgfMain.Page4.olegphTime.YData[lnSubsetCount , i-1] = max (lnTime[1], lnTime[2], lnTime[3])
    *   Utilization
    thisform.pgfMain.Page5.olegphUtilization.XData[lnSubsetCount , i-1] = lnProdVolume
        thisform.pgfMain.Page5.olegphUtilization.YData[lnSubsetCount , i-1] = lnUtilization[3]
    else
endif

*   Send information to the Summary cursor (This is identical to CASE 3, except it includes all resources)
    thisform.gnSummary[i,1] = lnProdVolume
    thisform.gnSummary[i,2] = thisform.gnSummary[i,2]+ max (lnCost[1], lnCost[2], lnCost[3])
    thisform.gnSummary[i,3] = max (lnTime[1], lnTime[2], lnTime[3])
*   thisform.gnSummary[i,4] = thisform.gnSummary[i,4]+ (lnUtilization[3]/lnSubsets)
    thisform.gnSummary[i,4] = thisform.gnSummary[i,4]+ lnUtilization[3]

* Need to accumulate the summary information into the summary plot
*   Cost
    thisform.pgfMain.Page3.olegphCost.XData[lnSubsetCount +1, i-1] = lnProdVolume
    thisform.pgfMain.Page3.olegphCost.YData[lnSubsetCount +1 , i-1] =  thisform.gnSummary[i,2]
*   Time
    thisform.pgfMain.Page4.olegphTime.XData[lnSubsetCount+1, i-1] = lnProdVolume
    thisform.pgfMain.Page4.olegphTime.YData[lnSubsetCount+1  , i-1] = thisform.gnSummary[i,3]
*   Utilization
```

```
    thisform.pgfMain.Page5.olegphUtilization.XData[lnSubsetCount +1, i-1] = lnProdVolume
    thisform.pgfMain.Page5.olegphUtilization.YData[lnSubsetCount +1 , i-1] = thisform.gnSummary[i,4]


******************************************************************************
* All Selected Resources
CASE thisform.nUserSelect = 3
*   Send information to PEGRAPH's XData and YData
*   Cost
    thisform.pgfMain.Page3.olegphCost.XData[m-1, i-1] = lnProdVolume
    thisform.pgfMain.Page3.olegphCost.YData[m-1, i-1] =  max (lnCost[1], lnCost[2], lnCost[3])
*   Time
    thisform.pgfMain.Page4.olegphTime.XData[m-1, i-1] = lnProdVolume
    thisform.pgfMain.Page4.olegphTime.YData[m-1, i-1] = max (lnTime[1], lnTime[2], lnTime[3])
*   Utilization
    thisform.pgfMain.Page5.olegphUtilization.XData[m-1, i-1] = lnProdVolume
    thisform.pgfMain.Page5.olegphUtilization.YData[m-1, i-1] = min (lnUtilization[1], lnUtilization[2], lnUtilization[3])


*   Send information to the Summary cursor
*   Production volume
    thisform.gnSummary[i,1] = lnProdVolume
*   Cost
    thisform.gnSummary[i,2] = thisform.gnSummary[i,2]+ max (lnCost[1], lnCost[2], lnCost[3])
*   Time is simply the maximum time (it is not additive).
    thisform.gnSummary[i,3] = max (lnTime[1], lnTime[2], lnTime[3])
*   Calculate average utilization.
    thisform.gnSummary[i,4] = thisform.gnSummary[i,4]+ (lnUtilization[3]/lnSubsets)

******************************************************************************
* All Selected Alternatives
CASE thisform.nUserSelect = 4

*   Send information to the Summary cursor
    aAltCost[i] = aAltCost[i]+ max (lnCost[1], lnCost[2], lnCost[3])
    aAltTime[i] = max (lnTime[1], lnTime[2], lnTime[3])
    aAltUtilization[i] = aAltUtilization[i] +  ( lnUtilization[3]/lnSubsets )

*   Cost
    thisform.pgfMain.Page3.olegphCost.XData[n-1, i-1] = lnProdVolume
*   Time
    thisform.pgfMain.Page4.olegphTime.XData[n-1, i-1] = lnProdVolume
*   Utilization
    thisform.pgfMain.Page5.olegphUtilization.xData[n-1, i-1] = lnProdVolume

    thisform.gnSummary[i,1] = lnProdVolume


ENDCASE

Next i

Nex t m

* Put Alternative summary information into plots
IF thisform.nUserSelect = 4 THEN
for x = 1 to 100
*   Cost
    thisform.pgfMain.Page3.olegphCost.YData[n-1 , x -1] =  aAltCost[x]
*   Time
    thisform.pgfMain.Page4.olegphTime.YData[n-1  , x -1] = aAltTime[x]
*   Utilization
    thisform.pgfMain.Page5.olegphUtilization.YData[n-1 , x -1] = aAltUtilization[x]
    if n = 1 then
        thisform.gnSummary[x,2] = aAltCost[x]
```

```
        thisform.gnSummary[x,3] = thisform.aSelAlternatives[n, 2]
        thisform.gnSummary[x,4] = aAltTime[x]
        thisform.gnSummary[x,5] = thisform.aSelAlternatives[n, 2]
        thisform.gnSummary[x,6] = aAltUtilization[x]
        thisform.gnSummary[x,7] = thisform.aSelAlternatives[n, 2]
    else
        thisform.gnSummary[x,3] = iif(thisform.gnSummary[x,2]<= aAltCost[x], thisform.gnSummary[x,3],
thisform.aSelAlternatives[n, 2])
        thisform.gnSummary[x,2] = min(thisform.gnSummary[x,2], aAltCost[x])
        thisform.gnSummary[x,5] = iif(thisform.gnSummary[x,4]<= aAltTime[x], thisform.gnSummary[x,5],
thisform.aSelAlternatives[n, 2])
        thisform.gnSummary[x,4] = min(thisform.gnSummary[x,4], aAltTime[x])
        thisform.gnSummary[x,7] = iif(thisform.gnSummary[x,6]<= aAltUtilization[x], thisform.gnSummary[x,7],
thisform.aSelAlternatives[n, 2])
        thisform.gnSummary[x,6] =  min(thisform.gnSummary[x,6], aAltUtilization[x])
    endif
next x
* Reset accumulators.
aAltCost = 0.0000
aAltTime = 0.0000
aAltUtilization = 0.0000
ENDIF

Next n
```

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