Research Paper

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Working Paper #970926R

BY
Stephen E. Chick, Tava Olsen,
Kannan Sethuraman,
Kathryn E. Stecke, and Chelsea C. White III
University of Michigan Business School

University of Michigan Business School
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Research Support
•
Ann Arbor, Michigan 48109-1234

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STEPHEN E. CHICK, TAVA OLSEN,
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UNIVERSITY OF MICHIGAN BUSINESS SCHOOL

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University of Michigan, Ann Arbor

Abstract: We present a model of the machining system selection process that is focused on capital intensive, complex machining systems that are intended to provide service over a long time horizon. This model was developed based on interviews with both machine tool suppliers and buyers. The systems considered here increasingly face potentially conflicting demands such as (a) the ability to be quickly and inexpensively upgraded and reconfigured in order to have quick new product change-over and ramp-up time; and (b) high product variety at close to mass production costs. This new "reconfigurability" capability increases the importance of supplier base quality as well as the supplier-buyer relationship after the machining system has been selected, issues that are considered in the machining system selection process presented here.

I. Motivation

Over the past two decades, many industries worldwide have witnessed the emergence of intense international competition, the creation of fragmented markets populated with demanding customers, and diverse market-shifting technological changes (Clark and Fujimoto, 1991). In order to be competitive in this environment, companies need the capability to meet the fast-changing demands of the marketplace quickly and cost-effectively. Pine (1993) emphasizes the need for shedding the old paradigm of mass production, whose focus was efficiency through stability and control, and embrace a new paradigm of mass customization, which stresses creating variety and customization through flexibility and quick responsiveness.

This emphasis on high product variety at close to mass production cost requires manufacturers to (a) customize products; (b) be flexible enough to produce a variety of products on the same system; and (c) be agile so that the shift of production from one product to another is fast, smooth, and efficient. The reconfigurable manufacturing system (RMS) presented in Koren (1996) proposes a new type of manufacturing system in response to these challenges and is characterized as follows:

> These challenges can be addressed to a significant degree by a new type of manufacturing system, the *reconfigurable manufacturing system* (RMS). Such a system can be created using basic process modules - hardware and software - that can be rearranged quickly and reliably. This type of system will be open-ended, so that it can be improved, upgraded, and reconfigured rather than replaced. Future RMSs are expected to possess the following five essential characteristics: modularity, convertibility, customization, integratibility, and diagnosability. A system that exhibits these characteristics will i) allow dramatic reduction in

launch time of both new systems and rebuilt systems, and ii) achieve system upgrading relatively quickly and inexpensively by upgrading one or more modules at a time rather than replacing the entire system.

In this report, we present a descriptive model of the machining system selection process that is focused on capital intensive, complex systems that are intended to provide service over a long time horizon. This model is based on interviews with both machine tool suppliers (Giddings & Lewis, Lamb Technicon, and R&B Machine Tool) and buyers (GM Powertrain Division and Eaton Truck Components Division). As mentioned previously, the modern manufacturing environment is increasingly stressing high product variety at close to mass production costs. Therefore the selection of machining systems must consider a variety of possibly conflicting objectives. These objectives include low production costs and the ability for systems to be quickly and inexpensively upgraded and reconfigured (resulting in short new product change-over and ramp-up time). Such "reconfigurability" capability increases the importance of supplier base quality and the supplier-buyer relationship after the machining system has been selected, issues that are considered in the machining system selection process presented here.

This paper is organized as follows. In Section II, we present a status report of the U.S. machine tool industry and argue that it is not possible to have world-class manufacturing without a world-class machine tool industry. In Section III, we compare and contrast the capabilities of different types of machine tool systems and highlight the tradeoffs between objectives that are typically faced while selecting a system from the choices available. Our descriptive model of the machining system selection process is presented in Section IV. There we highlight the multi-objective nature of the decision-process and the need for buyer-supplier coordination. This descriptive model is applied to two different companies in Section V. The potential impact of RMSs on the machining system selection process and the need for closer buyer-supplier relationships is presented in Section VI, where we also suggest a framework for modeling the RMS alternative. We conclude our report by presenting directions for further research in Section VII.

II. Status of the U.S. Machine Tool Industry

The U.S. machine tool industry is considered to be a high leverage industry because, although it is relatively small in size, it impacts the entire industrial economy in a very significant way (Dertouzos, Lester, and Solow, 1989). Thus, it is of considerable concern that the U.S. share of worldwide machine tool production dropped from 19.3% to less than 7% in a decade (Schiller, 1992). Dertouzos et al. (1989) state their concerns as follows:

The entire industrial economy suffers if a nation's machine tools are too slow,

> cannot hold tight tolerances, break down often, or cost too much. If American manufacturers must turn to foreign sources for machine tools (or other basic processing systems), they can hardly hope to be leaders in their industries, because overseas competition will often get the latest advances sooner.

A similar sentiment is also expressed in a recent report by the RAND corporation (RAND report, 1994): "Without a healthy domestic machine-tool industry, manufacturers may face a one- to two-year time lag in obtaining the latest production technology from foreign sources."

Also, the U.S. machine tool industry often faces extremely volatile demands. Figure 1 (Anderson, 1997) captures this volatility in U.S. machine tool orders and shipments. It also illustrates the propagation of demand volatility in that the standard deviation of year-to-year changes in machine tool shipments is roughly twice that of automotive sales and a hundred times that of GDP. Recent studies (Lee, Padmanabhan, and Whang, 1997 and Sterman, 1989) focus on minimizing inventory costs when faced with variance amplification in product distribution chains (also known as the "bullwhip effect"). Figure 1 shows that an analogous bullwhip effect is occurring at the machine tool order level, indicating that the machine tool industry is very vulnerable to market swings. We believe that strong supplier-buyer relationships and long term contracts can diminish the variance amplification in the machine tool industry by providing better, more timely information (see also Lee et al., 1997) and reduce the development time of new or reconfigurable equipment.

Dertouzos et al. (1989) observe the growing American dependence on foreign machine tool vendors and highlight some of the principal causes for this trend. Also see RAND (1994) for a more recent confirmation of this trend. The primary reason cited for this trend has been the technological superiority of products from overseas, in particular those from Japan and Germany. The industry's response to business cycles was also highlighted as another reason for the decline of the U.S. machine tool industry's competitiveness. Up until the mid-1970s, the industry employed a level strategy to production: backlogging during boom times and working on this backlog during slower periods. However, with the advent of quickly responding competitors from Japan, American machine tool suppliers lost this option and much of their hold on the US and international markets. Also, Dertouzos et al. (1989) state that innovation has lagged in U.S. machine tools because of the lack of exchange of ideas among the American suppliers and due to the complacent nature of buyer firms.

During our interviews with both machine tool suppliers and buyers, both suppliers and buyers have expressed a desire to work closely with each other (see also Schriefer, 1995). This cooperative action is viewed by the buyers and suppliers as important for the health of the domestic machine tool industry.

III. Alternate Machining System Configurations: Capabilities and Limitations

Several recent texts provide extended histories of process automation technologies and their capabilities (Cohen and Apte, 1997 and Buzacott and Shanthikumar, 1993). In this section, we provide a shorter description of the different technologies and discuss their capabilities and limitations. These range from stand-alone machine tools to transfer lines.

Fixed automation is characterized by high-investment, special purpose equipment, where the sequence of manufacturing operations and the equipment configuration is kept fixed. A good example of this type of automation is the traditional dedicated transfer line. These dedicated systems typically make a very limited variety of parts (often a single standardized product) in very large volumes (in excess of a million parts a year). The primary disadvantage of a transfer line is its inflexibility in accommodating changes in product design.

Stand-alone machining centers, on the other hand, are designed to produce a wide range of products. The requirements for adding a new product to a machine's repertoire only consist of writing a suitable control program and possibly adding some tooling. A job shop acquires its flexibility through these high-investment, general-purpose machines that are capable of producing a wide variety of low-volume products economically and with a high degree of precision. These machines can have a high setup time, unless they are computer numerically controlled (CNC).

Flexible automation is aimed at combining the efficiencies of a transfer line with the flexibility of a job shop. It is best suited for a large range of mid-volume and mid-variety production environments. Browne et al. (1984) provide a detailed discussion on the classification of flexible manufacturing systems (FMSs). In summary, a flexible machining cell (FMC) is the simplest and the most flexible type of flexible manufacturing system and consists of one general-purpose CNC machine tool, interfaced with automated material handling. A general FMS allows several routes for parts, with small volume production of each, and consists of two or more FMCs or CNCs of possibly different types and of general-purpose, metal-removing machine tools. It also can have real time, on-line control of part production. A flexible transfer line operates similar to a dedicated transfer line. For all part types, each operation is assigned to, and performed on, only one machine. This results in a fixed route for each part through the system. The benefits come from the possibility to process several part types.

Stand-alone CNCs are said to attain about 60-65% utilization, whereas FMSs tend to be able to reach 90-95% utilization. This is because of the manufacturing discipline required from management in order to run in the integrated manner required by an FMS (Kegg, 1997).

In today's market environments, companies must constantly adapt to the changing needs of the customers to succeed and prosper. This dynamically changing business environment poses new challenges for manufacturing and imposes new demands on machining systems. In our interviews with machine tool buyers we found that, in general, companies are currently responding to these demand by buying as much flexibility as they can afford (in terms of cost and volume requirements). Koren and Ulsoy (1997) envision a new generation of manufacturing systems, called reconfigurable manufacturing systems (RMSs), that provide exactly the right amount (no more and no less) of functionality and capability exactly when it is needed. These systems will be able to be improved, upgraded, and reconfigured rather than be replaced. A good analogy for these types of systems is the personal computer. Today's personal computers obtain additional capabilities or functionality through the addition or upgradation of software, memory, or graphics cards.

The more complicated systems described above suggest a more complicated decision process for machining system selection. The intent of this paper is to contribute to the development of this process.

IV. Machining System Selection Process

Sprovieri (1997) provides some up front questions to be answered about the products that are to be manufactured or assembled. One important consideration is the potential future market for the products. "Accurate market forecasting is one of many details that manufacturers may overlook."

We now present a descriptive model of a machining system selection process. This process is based on interviews with both buyers and suppliers. The model is comprised of six stages.

1. Strategic goal setting
2. Selection-process stage
3. The pre-bid stage
4. The post-bid, pre-'best-and-final' stage
5. The option selection stage
6. The post-selection stage

We discuss the details of the six different stages below. Figure 2 presents the flow chart that illustrates this decision making process model.

1. Strategic Goal Setting. In any organization, market needs and competitive forces typically drive the decision to procure new technologies or to automate processes. We assume throughout that corporate strategic goals have been set relative to introducing new products or increasing market share, the need to get products to market more rapidly with greater quality and reduced costs, the need for greater capacity, etc. Further, we also assume that the potential machine tool buyer has defined the characteristics of the products, their expected annual volumes, and the quality requirements to be manufactured by the machining system and understands the possible machining system investment in light of the corporate strategic goals. As manufacturers make critical decisions about the acquisition of sophisticated machine tool systems, they must carefully evaluate the benefits and costs of such systems and be highly sensitive to the realities and special attributes of these systems. Kaplan (1986) highlights the pitfalls of using outdated and inappropriate procedures for investment analysis and proposes new ways for the justification of the investment in such sophisticated automated systems.

2. The Selection-Process Stage. Choosing a selection process (such as the level of internal pre-bid specification of the request-for-quote organization) significantly impacts the buyer-supplier relationship and the quality of the machine-tool system eventually selected. Available processes for machining system selection range from totally intuitive processes that are based on individual judgment to processes that are based on an organized set of decision-making principles and procedures. The former processes may be appropriate for simple decisions that have little long-term effect on the firm. The latter processes, which are the focus of this paper, are typically appropriate for problems that have potentially significant strategic impact on the firm. Factors that would influence the choice of process for the selection of a most preferred machining system include:

- Decision impact. A simple purchase of a relatively inexpensive or commodity machining system does not require an executive.
- Amount of resources (e.g., knowledge, time, workforce size, money) available for alternative selection.
- Need for, and/or desirability of, internal consensus. The process of selection can provide an opportunity for needed education and employee empowerment, both useful if continuous learning is being promoted in the organization and/or if the new system will require organizational change and concomitant employee support/acceptance.
- Amount of justification needed for the selection; the amount of scrutiny that the decision may face.
- Other objectives that may need to be considered include the development of a positive relationship with the supplier of the selected system and/or the enhancement of supplier base quality.

This stage also sets the template for decisions made in stages 3-6 below.

3. The Pre-Bid Stage. There are several steps that need to take place prior to publishing the request for proposal (RFP) or request for quote (RFQ).

i. <u>*Formation of the Selection Team*</u>. A major purchase decision offers the opportunity for internal consensus, ownership building, and organizational learning throughout the corporation. A good leader for the selection team typically has excellent personal, communication, and facilitation skills, a good overview of the various corporate functions, and is high enough in the organization to be able to facilitate communication between executive officers at important points during the selection process. More effective selection teams are cross-functional and are composed of representatives from all affected organizational units within the firm, i.e., the internal stakeholders. Such organizational units are likely to include finance, manufacturing, marketing and sales, engineering, quality, and the plant(s) that will be responsible for setting up, operating, and maintaining the system once it is in place. There may be significant value in at least informally consulting with trusted and knowledgeable suppliers and others in the industry throughout the machine tool selection process. Although the objective of the selection team is to determine the best option, the successful selection team may become the project team (the group of individuals who will be involved with the system throughout its lifetime) and the effective selection team leader may become the project manager.

ii. *Options Definition*. A careful definition of what constitutes an option is critical to the selection of a most preferred machine tool system. Possible types of options include:

- Candidate machine tool systems.
- Candidate supplier-partners with whom to develop the machining system.
- Some combination of the above.

The type of option that can be under consideration depends on the nature of the supplier base. If the supplier base is design-capable, then any of the above three options can be considered. However, if the supplier base is composed of companies without design capability, then the second and third options may not be possibilities.

We have identified three canonical states that the buyer may be in when putting out an RFP or RFQ. These states correspond to points in the following matrix:

	Few Process Specifications	Total Process Specifications
Few Product Specifications	c	b
Total Product Specifications	b	a

a. *Total Product and Process Specifications by the Customer Up Front.* In this situation the only remaining decision will be which specific supplier and machine to choose. In the subsequent decision process, value is likely to be a major deciding factor.

b. *Supplier Competitively Provides Engineering Resources to Define Product or Process.* This process may be done in several rounds of bidding. Eight to ten suppliers are often involved in bidding, although it may be as few as three or four. The process typically takes four to eight weeks.

c. *"Blank Sheet" Commitment to Supplier.* Under this process, the customer and supplier work together to fully specify the product and its machining process. This may be a multiple-year process. The supplier is selected on the basis of more general attributes than those used for types (a) and (b). In particular, the customer may consider company culture and a supplier's past performance. Cost is much less likely to be a major factor.

iii. Objectives Hierarchy Construction. The objectives hierarchy lists the primary and secondary objectives under consideration and how they interrelate. For example, total life cycle cost can be decomposed into an initial capital cost, maintenance cost, salvage value (a future negative cost), etc. Lowest level objectives should be measurable in the sense that a numerical value, or range of values, can be assigned to each option for each lowest level objective. A lowest level objective is sometimes referred to as an *attribute*. Various sub-hierarchies in the objectives hierarchy will often be associated naturally with various parts of the firm's organizational structure. In particular, accounting and finance, marketing, and engineering will naturally be linked to separate sub-hierarchies. Clearly, the type of option under consideration affects the list of objectives under consideration. As the original equipment manufacturers set out to select a particular machining system for their factories, a number of attributes will be considered relevant. However, the degrees of importance for each attribute may differ between firms as well as between factories within the same firm. Some of these attributes are quantifiable and some are non-quantifiable. Some of the key quantifiable attributes for a machining system are: throughput capabilities, reliability and maintainability, quality of output (repeatability), inventory reduction, system efficiency, and flexibility (in terms of the number of part types that can be handled and the setup times required). Examples of potentially desirable but non-quantifiable attributes include the reduction of non-value-added activity, increased plant safety, and the ergonomic design of machines. Table 1 provides an extensive list of attributes that may be considered by a buyer while evaluating alternate machining systems. In addition to these attributes, the supplier is also evaluated on the level of after-sale services provided to the buyer, including factory-floor equipment education and quality and maintenance improvement assistance. Some suppliers indicate an interest in expanding such after-sale services for their clients.

We remark that some objectives lead to more easily measured attributes than others. AMT (1996) classifies attributes into four categories, based on whether they are (i) quantifiable versus non-quantifiable, and (ii) tangible versus intangible. Difficult-to-quantify objectives may be very important to consider in a decision-making situation, and the urge to ignore such objectives because of this difficulty is therefore important to resist. We remark that decision aiding processes have been specifically designed to help decision makers deal with such difficult-to-quantify objectives, e.g., ISMAUT (White and Anandalingam, 1993).

iv. _Compile a List of Potential Suppliers_. Once an option has been defined (step (ii)) and important attributes for the system to contain have been identified (step (iii)) potential suppliers must be identified. While some companies will allow any supplier to submit bids, most buyers do some prescreening. This prescreening may be based on prior experiences with the suppliers or may be according to company policy about potential suppliers.

v. _Compose the RFP/RFQ._ The RFP/RFQ must be developed and released to the suppliers identified in step (iv), with a timeline for each bidder's conference and proposal/quote submission. The development of the RFP/RFQ is frequently an iterative process with input furnished by one or more suppliers.

4. The Post-Bid, Pre-Best-and-Final Stage. At this stage, all of the proposals have been received and are under evaluation. Each RFP/RFQ response represents an option for consideration. If the set of options is insufficiently rich, then new options are sought, perhaps with a delay of the RFP/RFQ due date. Tasks undertaken during this period are as follows:

i. _Options Scoring_. During this task, attribute scores for each of the options are determined. We remark that a carefully crafted RFP/RFQ can result in easily scored options. The process of generating attribute scores represents an opportunity for internal stakeholder involvement. The part of the organization that developed a particular sub-structure for the objectives hierarchy is likely to be that part of the organization most appropriately involved in scoring those attributes associated with that sub-structure.

ii. _Options Reduction_. It may be possible to eliminate options, for example, on the basis of infeasibility (e.g., removing options that fail to satisfy minimal requirements for any given objective). Sometimes an option can be revised to conform with needs.

iii. _Information Sharing_. This task involves determining the amount of information to be shared with the remaining bidders and more broadly with the supplier base. Broad principles that may be considered include:

- The buyer's competitive advantage in the industry should not be compromised.
- A bidder's competitive advantage should not be compromised.
- Shared information should help to produce an excellent set of 'best and final' bids.
- Shared information should support the development of a positive partnership with the winning bidder.
- Shared information should have a positive impact on long-term supplier base quality and competitiveness, reflecting the desire to maintain a strong supplier base for the future.

5. The Option Selection Stage. The deliverable of this stage is the identification of a most preferred option. Recall that an option is a candidate machine tool system, a candidate supplier partner, or some combination of the two. At this point, options are well-defined and attribute scores are understood as well as possible, given the nature of the individual attributes. The selection of the most preferred option involves trading off objectives, usually at a high level in the objectives hierarchy, in light of the options under consideration. The ideal alternative selection environment that we envision involves executive officers providing preferential information in an interactive setting, based on scoring information that was provided earlier by various parts of the organization. The actual options selection process could employ decision support tools based on any one of a variety of analytic methodologies, e.g., multi-attribute utility theory (MAUT) or the analytical hierarchy process. We note that each analytic method, used in an interactive setting, is associated with a need for facilitation, and that some methods require more complicated facilitation procedures than others. We found that, in practice, the method of option selection differed widely between companies and even differed from decision-maker to decision-maker within a company.

6. The Post-Selection Stage. There are several issues that may be addressed in the post-selection stage. If the intent of the option selection stage was to select a partner for system design and construction, then the selection of a most preferred machining system is a task that needs completion. At this point, an abbreviated list of the above procedures may be used to select a most preferred machining system:

- Identify several machining system options.
- Determine the associated objectives hierarchy.
- Score the hierarchy.
- Trade off the objectives, presumably with the buyer providing the preferential information.
- Select a most preferred machining system.

Other issues that may be addressed during the post-selection stage include:

i. *Post Option Selection Communication*. After the most preferred option is selected and the decision is announced, the next important issue is to determine what information should be communicated to the bidders, and perhaps to the entire supplier community, in order to help strengthen the capabilities of the supplier base.

ii. *Relationship with the Winning Bidder.* Another issue to be addressed is to determine what 'next steps' should be taken in order to insure that the decision made will result in a high quality machining system and/or partnership. These include constructing the contract; monitoring the project; training; runoff and acceptance at the supplier; installation, final acceptance, and production startup; and post installation audit for continuous improvement (for further discussion, see AMT, 1996). If the system selected is to be reconfigurable then this relationship is especially important.

iii. *Selection and Selection Process Evaluation.* Questions that arise in evaluating the option selection process and the final decision include:

- Was the best system selected?
- Does the organization support the decision and is it stronger (e.g., more knowledgeable, more team oriented) after having participated in the process?
- Did the supplier community, or a portion of this community, learn from the process in such a way that it was strengthened (i.e., improved its ability to deliver a higher quality product in the future)?
- Did the process contribute to an effective post selection relationship with the winning bidder? For example, was the supplier provided an incentive to continuously improve the system and reduce cost after winning the bid, rather than look for ways of increasing cost (through, for example, future change orders)?

Our interviews indicate that post-selection evaluation is infrequently undertaken. However, such an evaluation may present a valuable learning opportunity.

V. Two Examples of the Machining System Selection Process

This section shows how the model described in Section IV applies to two machine tool system purchasing decisions. In particular, we describe one specific purchasing decision made at Eaton Truck Components Division and a more general process that is used by the GM Powertrain Division.

1. Decision Process for the Eaton Truck Components Division. This section describes how in 1992 Eaton selected a supplier to install a system for one of their facilities at Shenandoah.

1. Strategic goal setting. The manufacturing strategy that was crafted by the Eaton team in 1989 was given the code name Concept 2000 and was aimed at providing the firm with greater manufacturing agility. Some of the major objectives behind the program were as follows:

1) Expand torque and ratio coverage for emerging engines.
2) Develop new design features to dramatically improve customer satisfaction and improve durability and performance.
3) Develop a modular family of product features for use in both synchromesh and non-synchromesh applications worldwide.
4) Create a modern manufacturing facility to improve productivity, flexibility, and reduce time to market.
5) Develop worldwide suppliers and use their technical input for product design and cost reduction worldwide.

Concept 2000 was geared towards integrating the worldwide product families into a common set of product platforms. In 1990, the transmission manufacturing equipment at Shenandoah, Shelbyville, and Kings Mountain, Tennessee, was quite outdated. Eaton performed a worldwide benchmark analysis of the state of the technology in case and shift cover machining and determined that they had the oldest equipment in the market: 60% of the equipment had no book value and the average age of the equipment was 17 years. Also, they found that Eaton was using conventional equipment whereas its competitors were using flexible manufacturing systems and were well equipped for the changing needs of the customers. With a desire to be more competitive, Eaton decided to procure the state-of-the-art in machining systems.

2. Selection-process stage. Since the decision to be made was a major one, a detailed decision process involving many different company employees was selected. This process is described further below.

3. The pre-bid stage.

i. *Formation of the Selection Team*. A selection team was formed consisting of employees from many different divisions.
ii. *Options Definition*. Eaton had a fairly well defined idea of what type of machining system was required. Therefore an option in this case was both a specific supplier and a specific set of machines.

iii. *Objectives Hierarchy Construction.* The list of selection criteria developed by Eaton for ranking the suppliers is contained in Table 2.

iv. *Compile a List of Potential Suppliers.* An initial list of ten suppliers was compiled.

v. *Compose the RFP/RFQ.* The ten suppliers were invited to submit quotes by December 1, 1991. The selection criteria developed in step (iii) were provided to each supplier.

4. The post-bid, pre-'best-and-final' stage. Of the ten suppliers chosen only six proposals were submitted. These six were further narrowed to three suppliers using the criterion in step 3(iii). These suppliers were given feedback on the strengths and weaknesses of their proposal and invited to resubmit their proposals.

5. The option selection stage. The final selection was made by a team of 30 people who were involved in ranking the choices based on features, functions, price, and service. The final selection was a day and a half long process. By that time, the three quotes were quite similar with respect to cost, and so other, more subjective criteria, such as service, were carefully considered. The final decision was made by a facilitated group consensus process.

6. The post-selection stage. At this point the machining system was completely decided so no extra design was necessary. The purchase was a multi-year phased purchase. Eaton negotiated a four year pricing schedule so that renegotiation was not necessary. Much of the relevant information on what factors affected the final selection was shared back with the original bidders.

2. GM Powertrain Division's Decision Process.

This section describes the general process used by GM Powertrain to select a machining system.

1. Strategic goal setting. GM managers usually set the goals for manufacturing the parts for which they are responsible.

2. Selection-process stage. The method of selecting the most preferred system is chosen by the staff based on program capacity requirements. What follows is the method used by our GM contact.

3. The pre-bid stage.

i. *Formation of the Selection Team*. A selection team is formed consisting of engineers from a number of different manufacturing facilities.

ii. *Options Definition*. GM does most engineering in-house. Therefore, a machining system is usually very well defined when the buying decision is to be made. An option therefore is both a specific supplier and a specific set of machines.

iii. *Objectives Hierarchy Construction.* Price is usually used as the final deciding factor for choosing a supplier. However, before price is considered, suppliers must meet a minimum standard for quality, etc. These standards are defined ahead of time.

iv. *Compile a List of Potential Suppliers*. Only suppliers who are believed to meet the standards defined in (iii) are invited to submit proposals.

v. *Compose the RFP/RFQ*. The proposal request is usually very specific with respect to what is required of the desired machining system.

4. The post-bid, pre-'best-and-final' stage. The suppliers are given a target price based on previous purchases and other bids and are asked to match them. Also, innovations by other suppliers on more efficient ways to machine the parts may be shared.

5. The option selection stage. Because the suppliers have been chosen to meet the necessary standards, the lowest price supplier is chosen.

6. The post-selection stage. Some fine tuning of the system design, particularly with respect to material handling, product design changes, and design for manufacture improvements, may be needed before the system is actually installed. Teams of engineers from both the supplier and GM work together during this stage.

Table 3 summarizes the machining system decision-making process for these examples from Eaton Truck and General Motors. In addition, we summarize the new aspects of this decision-making process that would arise with the future consideration of a reconfigurable option.

VI. Toward RMS Model Development and Evaluation

The description of the machine tool system selection process that we presented in Section IV was developed through interviews with various industry stakeholders, and is based on past experience and current trends in machine selection. In this section, we describe how the inclusion of future RMSs as system options may affect the decision process. We describe two features of RMSs in particular.

1. *System Reconfigurability*: Consideration of the ability to rapidly reconfigure the

manufacturing system, to alter the product flow in order to affect throughput, quality, and other attributes.

2. *Equipment Reconfigurability*: The use of contracts to permit functionality and/or capacity to be added, and paid for, at a time or times in the future determined by the buyer.

Both of these issues support the RMS objective of permitting buyers to have available a preferred level of functionality and/or capacity exactly when it is needed and both of them can easily be incorporated in the above alternative machine tool selection process. We now discuss how these two issues could be effectively considered in the machine tool selection process.

1. Reconfiguration of Machines to Alter Product Flow. One type of RMS seeks to provide production systems that can adapt their configuration of system flow. Machine configuration (series, parallel, hybrid) affects system throughput, equipment reliability, workpiece quality, work-in-process, and a number of other attributes. Each configuration can be considered as a different system option, even if precisely the same equipment is used in each. Two important issues for RMS science are (1) the selection of a relatively small set of feasible configurations (the number of possible configurations grows combinatorially with the number of machines in the system) and (2) a mechanism for evaluating the attributes of each configuration, so that a good system configuration can be selected.

Typically it is difficult to provide analytical results that precisely quantify the performance of complex machining systems with buffers and equipment subject to random downtimes. Analytical models may provide bounds which prove useful for addressing the issue of selecting a subset of feasible configurations which is much smaller than the set of all possible configurations. Simulation is then a natural tool for estimating the performance of various configurations. The integration of simulation output with multi-attribute decision-making processes has not yet formally been done, and leads to some interesting practical and research challenges, as discussed in Section VII.

2. Equipment Modularity and Customization. Our interviews have indicated that usually the machine tool system alternative offered to buyers is the purchase of a machine tool system with or without various options associated with the basic system. For example, consider a modular drilling machine which can be purchased with or without a custom tool. The alternatives that would be considered are:

A. Purchase the drill now, without the custom tool.
B. Purchase both the drill and the custom tool now.

Although the custom tool initially may not be needed, it may be required later to effectively respond to possible future demands of a new product. Typically, selection of A or B would be based on the relative importance to the firm of minimizing cost versus maximizing the likelihood of being able to meet future uncertain customer demand, where this likelihood would be based on customer demand forecasts.

During one of our interviews, we learned that machine tool system makers may offer to potential customers machine tool systems that allow functionality and/or capacity to be added after the initial sale, at a future time to be selected by the purchaser. We refer to such an alternative as an RMS alternative. In the context of our example, this alternative is:

C. Purchase the drill now, with the possibility of adding, and paying for, the custom tool at a time selected in the future by the buyer.

Alternative C should cost less than B. In evaluating alternative C, there are many ways that customer demand can evolve over time, and for each possibility there may be many decision points over time where the option to purchase the custom tool can be exercised. We have found that a decision tree, with chance nodes and decision nodes, where the decision nodes represent the decision points, can often provide an effective representation of simple forms of this type of situation, as we illustrate below. Evaluating alternative C requires an understanding of whether or not the option should be exercised at each of these decision points. Let a *policy* be a rule that determines whether or not the option will be exercised for each decision point. Clearly, there may be many possible policies. Fully evaluating alternative C is equivalent to considering all possible policies, a task significantly more complex than the evaluation of alternatives A and B. Examples, one of which is presented below, indicate that some of these policies may be superior, and many may be decidedly inferior, to both alternatives A and B. We remark that alternative C would tend to heighten the need for a longer term buyer-supplier relationship.

Example. We now briefly illustrate several of the concepts discussed above with a hypothetical purchasing situation. We make the following assumptions:

- The buyer is to select one of the three possible alternative machining systems, A, B, or C, as defined above.

- There are three periods of production. If the buyer selects the RMS alternative, then the buyer can exercise the option to add the custom tool at the end of period 1 or at the end of period 2. If the option is exercised at the end of period 1, then the drill with the custom tool is ready for production at the beginning of period 2.

- Selection of the alternatives is based on two attributes, cost and satisfaction. 'Satisfaction' is the ability to effectively satisfy customer requirements. We discount both cost and satisfaction with discount factor β, which we set equal to 0.95 in the numerical analysis presented below.

- The buyer can decide at the beginning of each period to make either one of the two products, P1 or P2. We assume that the buyer always decides which product to produce solely on the basis of customer preference.

- Forecasts indicate that the customer will prefer P1 (P2) during the first period with probability 0.75 (0.25). Forecasts also indicate that customer preference does not tend to change from period to period and that if the customers currently prefer P1, then during the next period the customers will prefer P1 with probability 0.75. This conditional probability is identical for product P2.

- Assume that alternative A costs $500,000 and alternative B costs $535,000. The drill with the option to reconfigure costs $510,000 up front. Reconfiguration costs $25,000 which is charged when the option is exercised. Thus, alternative C costs $\$(510{,}000+\beta*25{,}000)$, $\$(510{,}000+\beta^2*25{,}000)$, or $510,000, if the option is exercised at the end of period 1, is exercised at the end of period 2, or if the option is not exercised, respectively.

- The production of either product using the drill with the custom tool satisfies customer requirements. The production of product P1 using the drill without the custom tool also satisfies customer requirements. However, the production of product P2 using the drill without the custom tool does not satisfy customer requirements. We measure customer satisfaction as follows. If customer requirements are met during a period, then the buyer receives a unit of value. If customer requirements are not met during a period, then the buyer receives no unit of value. Thus, the buyer receives a unit of value during a period if the drill has the custom tool attached and either product is produced or if the drill does not have the custom tool attached and product P1 is produced. If the drill does not have the custom tool attached and product P2 is produced, then the buyer receives no unit of value.

Consider the following scenario. Assume alternative C is selected, customers prefer P2 in period 1, and the buyer decides to exercise the option of adding the custom tool at the end of period 1. Then the cost accrued is $\$510{,}000+\beta*\$25{,}000$ and the satisfaction value is $\beta + \beta^2$.

Figure 3 is a decision tree that depicts all three alternatives. There are seven (7) square decision nodes, d(1), d(21), d(22), d(31), d(32), d(33), and d(34), representing opportunities for exercising the option to add the custom tool. The circles represent chance nodes and indicate whether P1 or P2 is preferred in a given period. An 'up' arrow from a chance node means P1 is produced; a 'down' arrow from a chance node means P2 is produced.

A policy is a rule that states whether or not the option to purchase the custom tool will be exercised at each of the decision nodes. For example, consider the policy d(1) = N, d(21) = N, d(22) = Y, d(31) = N, and d(32) = N, where 'Y' means exercise the option and 'N' means do not exercise the option. (Note for this policy, which is policy 10 in Table 3, it is unnecessary for d(33) and d(34) to be defined.) This policy indicates that the option will be exercised only if P2 is produced in period 1.

We note that for this example there are 27 distinct policies. The expected total discounted cost and satisfaction measure for each of these policies is presented in Table 4. Policy 1, i.e., d(1) = Y, is equivalent to selecting alternative B. Policy 26, i.e., d(1) = N, d(21) = N, d(22) = N, d(31) = N, d(32) = N, d(33) = N, and d(34) = N, is equivalent to buying the option and never exercising. Policy 27 is alternative A, which clearly dominates policy 26. Each of the other 24 policies represents one way of interpreting alternative C. An expected cost versus customer satisfaction graph is presented in Figure 4. We observe from this figure that there are several nondominated policies, i.e., candidates for the most preferred policy. These nondominated policies include policies 1, 9, 10, and 27, two of which, 9 and 10, are possible interpretations of alternative C. We also observe that many of the policies that could be possible interpretations of alternative C are clearly dominated, i.e., less desirable on both attributes than some other policy.

In summary, we have considered a hypothetical purchasing situation and have added an RMS alternative to the set of alternatives. We showed that the RMS alternative can have many interpretations, which we called policies, suggesting that such an alternative can be relatively complex to fully analyze. The value of considering the RMS alternative is that for several of its associated policies, the RMS alternative may be a candidate for the most preferred alternative.

From the perspective of the machine tool maker, the type of RMS alternative considered above represents a contractual innovation that requires no R&D investment and that justifiably might be considered by the potential buyer as a superior product. Thus, there appears to be good reason for sellers to offer the RMS alternative as a product. From the perspective of the buyer, the RMS alternative may be the most preferred alternative, so there is clear reason for the buyer to request that an RMS alternative be offered, if it is not offered initially, and consider it seriously, even though the level of evaluative analysis may be significantly more complex for an RMS alternative than for a non-RMS alternative. This additional complexity suggests the need for new forms of decision support for machine tool system selection, a topic of ongoing research by the authors.

VII. Conclusions and Future Research Directions

Interviews with several buyers and suppliers of machine tools during a year-long span provided background for a general, descriptive model for selecting complex machining systems. The model reflects the importance of considering multiple and potentially conflicting attributes, as well as the powerful impact of the buyer-supplier relationship on the health of the machine tool industry. RMSs, being particularly complex, seem to entail particularly strong buyer-supplier relationships. Our industrial contacts also indicate that research in the following areas would be helpful to improve the decision-making process.

One intent is to identify those parts of the process that can be supported by decision support systems (DSSs) and to begin the process of DSS construction. We anticipate that there would be at least two parts of the process that will be amenable to decision support based on MAUT. First, a DSS such as ISMAUT (White and Anandalingam, 1993) appears to be well suited for the portion of the process described in Section IV.5. Second, if Section IV.5 has been used for supplier selection rather than machine tool system selection, then either ISMAUT or an extension of ISMAUT such as ISMAUT$^+$ (Stewart et al., 1990) might be useful in Section IV.6 for supporting machine tool system selection. ISMAUT$^+$ particularly appears to be of potential use for situations where there are a large number of machine tool system options, e.g., when machine tool system configuration is under consideration.

Another important research direction is the connection of analytical tools with ISMAUT. Complex systems are often best analyzed with systems analysis methodologies such as discrete-event simulation and queueing analysis. At present, a methodology for integrating simulation analysis with ISMAUT has not yet been formally developed and investigated, in part due to the stochastic character of the value scores for attributes. When the value scores are stochastic, as is the case when values are obtained with simulation, one can only speak of the probability that a given system dominates another system. Some research (Mareschal, 1986; Czogola and Roubens, 1986) has accounted for stochastic value scores in MAUT and ISMAUT. However, a full analysis of value scores that are correlated between systems (e.g., via common random numbers) and between attributes (e.g., WIP and throughput) remains to be explored. Two issues, then, that need research to permit the integration of simulation analysis with multi-attribute decision-making processes are (1) how to allocate additional simulation replications to improve the understanding of the probability that one system dominates another; and (2) whether a simulation analysis needs to be done at all, given that other value information and trade-off weights have been provided.

ACKNOWLEDGMENTS

We greatly appreciate the time and information provided by representatives Cargill Detroit Cincinnati Milacron, Eaton Truck Components Division, GM Powertrain Division, Giddings & Lewis, Lamb Technicon, and R&B Machine Tool. In addition, this work would not have been possible without the support of the NSF and the Engineering Research Center for Reconfigurable Machining Systems at the University of Michigan. Lastly, the diligent efforts of Ms. Kimberly Stauffer, graduate student at the University of Michigan, helped bring this paper to its current form.

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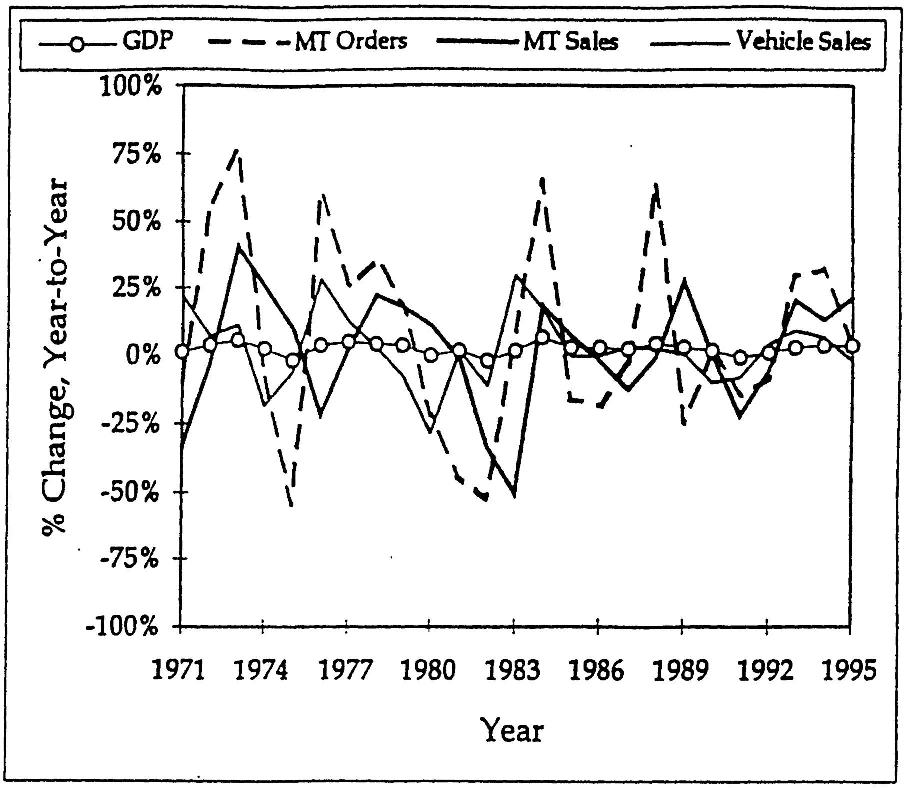

GDP change	*σ=.2%*
MT Orders change	*σ= 37%*
MT Shipments change	*σ= 22%*
Vehicle Sales change	*σ= 13%*

Data Sources:
GDP: 1997 Federal Budget; Machine Tools: The Economic Handbook of the Machine Tool Industry; Vehicles: Bureau of the Census (SIC Code 3711).

Figure 1: Volitility in U.S. Machine Tool Orders

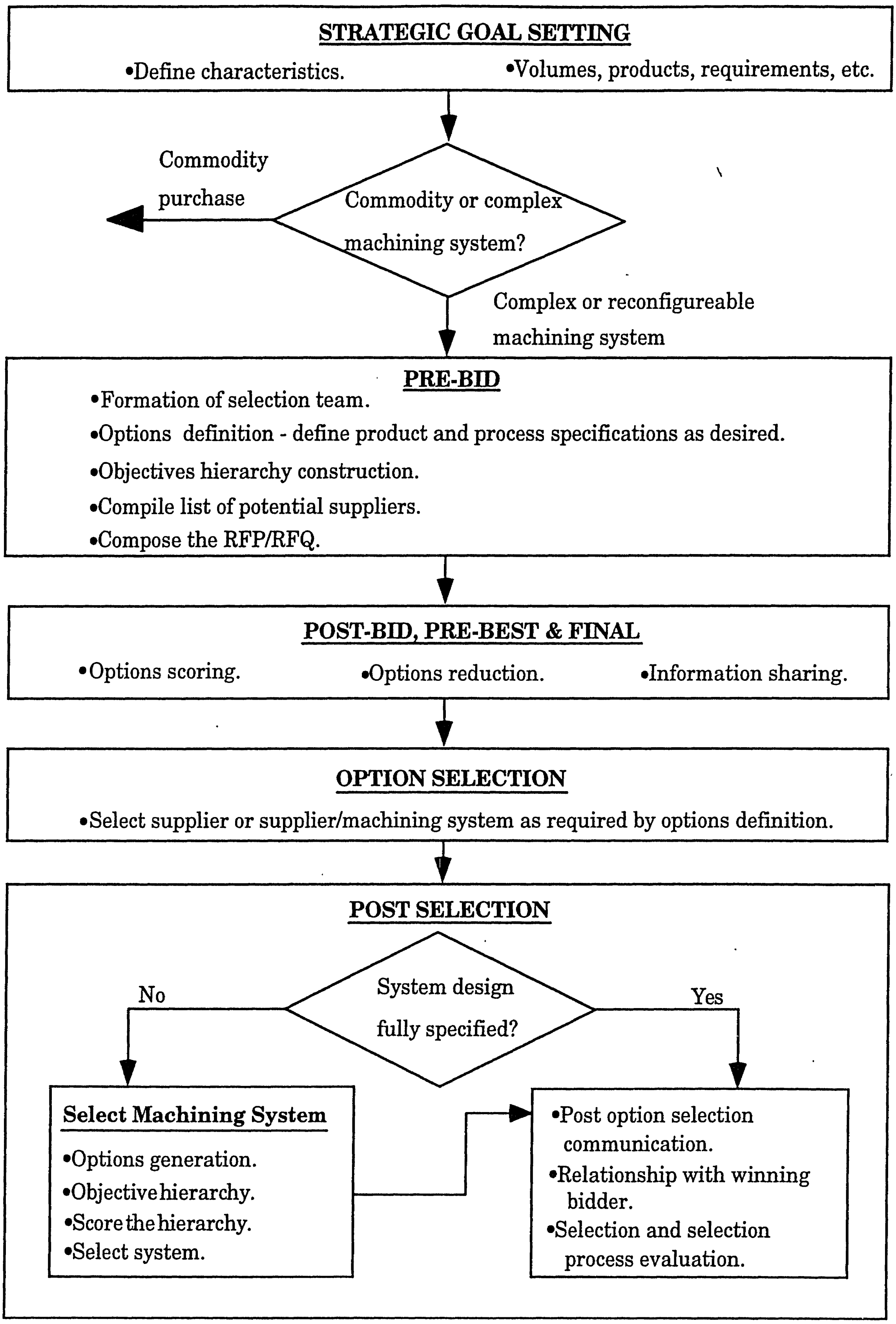

Figure 2: Decision Flow Chart

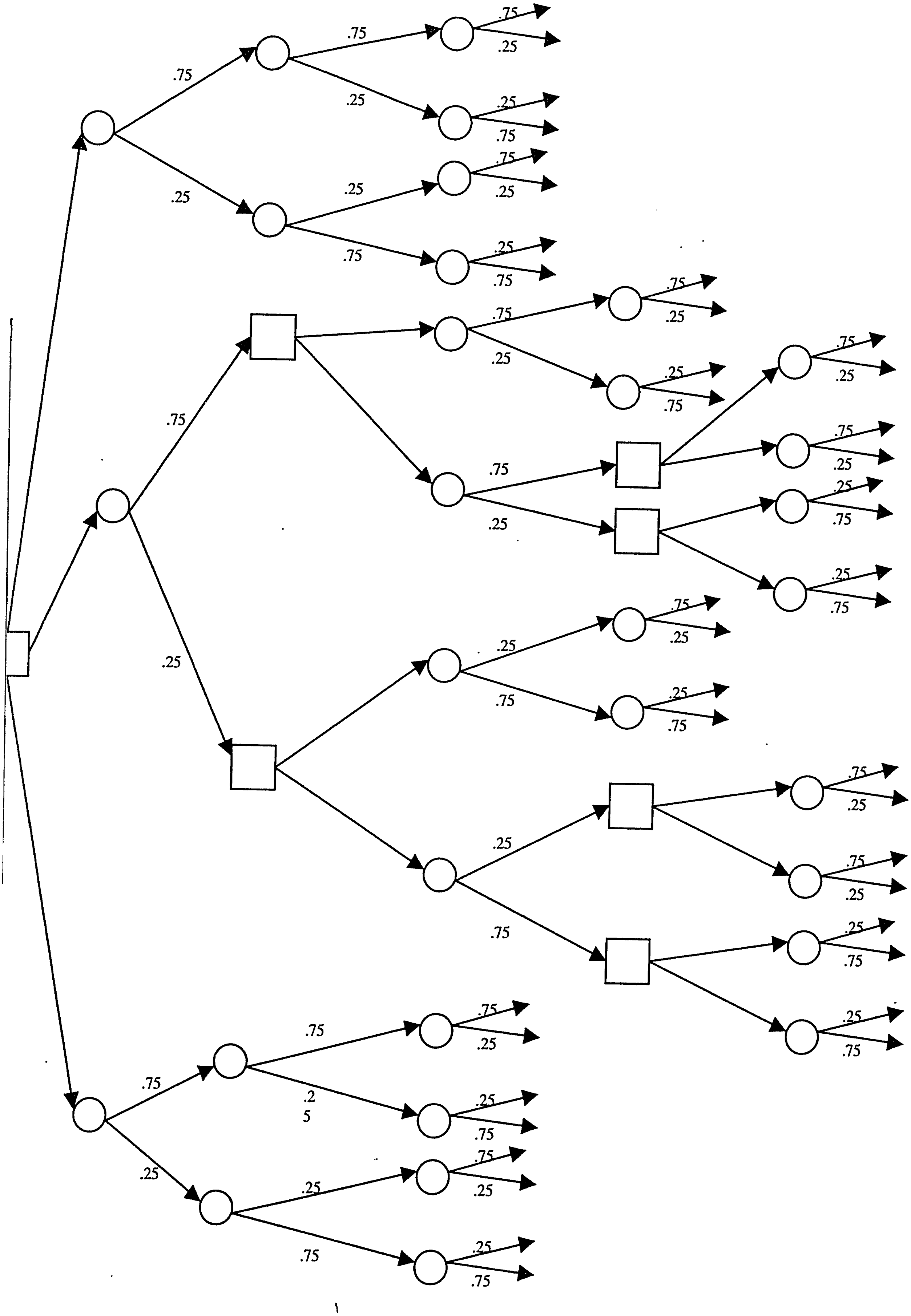

Figure 3: Decision Tree for the RMS Example

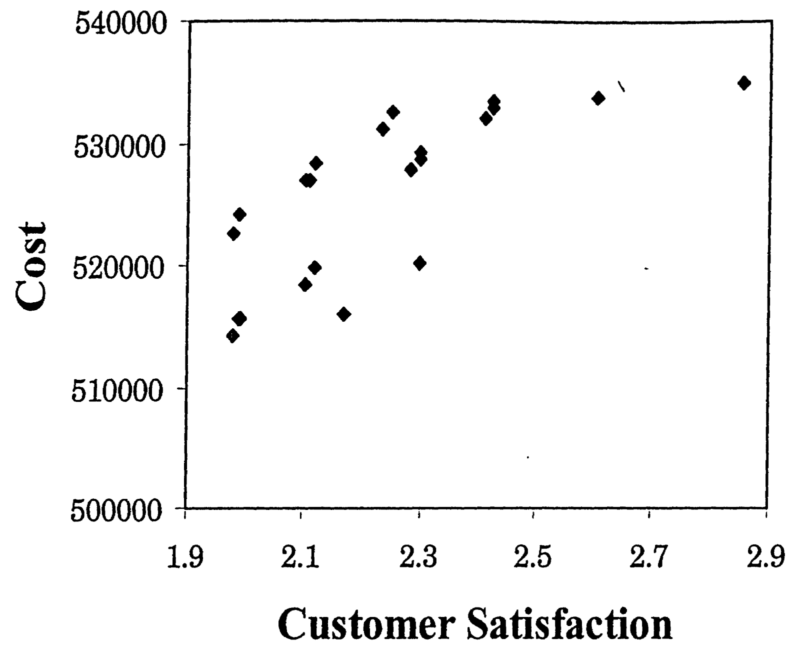

Figure 4: Expected Cost versus Customer Satisfaction Graph for the RMS Example

Table 1: Some Machining System Attributes Mentioned in Industry Interviews

Cost issues:
- initial capital outlay
- operations and maintenance
- engineering & lead time
- labor
- equipment life-cycle cost
- product life cycle/demand

Performance:
- throughput
- quality
- system efficiency
- WIP
- setup reduction
- availability
- material and tool management

Human factors:
- education of work force
- maintainability
- ergonomic design
- safety

Machine and system characteristics:
- floor space
- reliability
- compatibility
- workpiece flexibility

Supplier support:
- program management
- maintenance
- installation

Comprehensive and prompt quotation:
- meticulous report
- recommendations
- features
- options

Marketplace acceptance:
- past experience
- price and delivery
- warranty

Other intangibles:
- courtesy
- reputation
- follow-up
- personal contact

Table 2: Machine Tool Selection Criteria and Importance for a 1992 Eaton Decision

<u>Quotation Completeness and Timeliness:</u> (10%)

- Quote submission date
- Detailed machine times per operation
- Standard equipment features and options
- Quoted quality capabilities
- Recommendations for purchase
- Customer user lists and recommendations

<u>Proposal's Technical Merit:</u> (25%)

- System solution for Eaton
- Material management system
- Tool management system
- Fixturing and processing utilization
- Equipment capabilities
- System performance (output and throughput)
- Quality capability (Cp and Cpk index)
- Special installation requirements

<u>Supplier System Support:</u> (25%)

- Overall program management
- Training (operators, maintenance, engineering)
- Tooling and fixturing design and build
- Run-off of system (at supplier and plant)
- Maintenance requirements
- CNC programming requirements (CAD interface)
- Simulation study results
- Installation support

<u>Commercial Acceptance:</u> (30%)

- Price and delivery
- Payment terms
- Warranty coverage
- System experience
- Eaton experience

<u>Subjective Measures:</u> (10%)

- Confidentiality
- Courtesy and promptness
- Follow up of proposal
- Reputation of company
- Personal representation

Table 5: A Comparison of the Machining Selection Process Between Several Buyers and with the RMS Option

Stage	Eaton	General Motors	RMS
1. Strategic Goal Setting:	Market niche is a wide variety of medium volume products that tend to need flexible production systems.	Market niche is high volume products that tend to need dedicated machining systems.	Strategic goals must include strategies for rapid new product introduction.
2. Selection Process Stage:	Selection process eliminates cost by getting similar quotes and focuses on more subjective criteria.	Selection process eliminates subjective criteria by selecting "acceptable" suppliers and then focuses on cost.	Selection process must include a plan for rewarding a consideration of long-term cost.
3. Pre-Bid Stage			
(i) Formation of Selection Team:	Team must contain experts on the product family to be produced.	Team must contain experts on specific product to be produced.	Team must contain experts on reconfigurability and its options.
(ii) Options Definition:	System description will sometimes be vague in the initial stages.	Machine tool system will usually be very well-specified.	Must include options for reconfiguration and policies on how and when to possibly exercise the reconfiguration option (see Section 6).
(iii) Objectives Hierarchy Construction:	Maximize subjective measures subject to acceptable cost.	Minimize cost subject to acceptable subjective measures.	Must include valuation of different options for possible reconfiguration or not.
(iv) Compile List of Potential Suppliers:	Must have acceptable cost and "behavior".	Must have acceptable quality.	Must be acceptable for a *long term* relationship.
(v) Compose RFP/RFQ:	May leave room for further refinement.	Very detailed and specific.	Must outline a reconfiguration option plan.
4. The Post-Bid, Pre-Best-and-Final Stage:	Lots of feedback given to suppliers on the strengths and weaknesses of their proposals.	Feedback on cost and an opportunity to match is given. Innovations on efficiencies may be shared.	Discuss feasibility and practicality of reconfiguration options with suppliers.
5. Option Selection Stage:	Team consensus is used.	Lowest cost option (among acceptable options) is selected.	Involves the selection of a policy for reconfiguration as well as a supplier/machining system.
6. Post-Selection Stage:	Relevant information on factors affecting the final selection is shared with suppliers.	Fine tuning of the system may take place.	Contact must be maintained with the supplier for possible future reconfiguration. Future cost savings should be noted and the decision making team appropriately

Table 4: Expected Total Discounted Cost and Satisfaction Measures

	d(1)	d(21)	d(22)	d(31)	d(32)	d(33)	d(34)	-----Expected----- Cost	Customer Satisfaction
1	Y							535000	2.85
2	N	Y	Y					533750	2.60
3	N	Y	N			Y	Y	533453	2.42
4	N	Y	N			Y	N	529223	2.30
5	N	Y	N			N	Y	532043	2.41
6	N	Y	N			N	N	527813	2.28
7	N	N	Y	Y	Y			532859	2.42
8	N	N	Y	Y	N			528629	2.30
9	N	N	Y	N	Y			520168	2.30
10	N	N	Y	N	N			515938	2.17
11	N	N	N	Y	Y	Y	Y	532563	2.25
12	N	N	N	Y	Y	Y	N	528332	2.12
13	N	N	N	Y	Y	N	Y	531152	2.23
14	N	N	N	Y	Y	N	N	526922	2.11
15	N	N	N	Y	N	Y	Y	528332	2.12
16	N	N	N	Y	N	N	N	522691	1.98
17	N	N	N	Y	N	N	Y	526922	2.11
18	N	N	N	Y	N	Y	N	524102	1.99
19	N	N	N	N	Y	Y	Y	519871	2.12
20	N	N	N	N	Y	Y	N	515641	1.99
21	N	N	N	N	Y	N	Y	518461	2.11
22	N	N	N	N	Y	N	N	514230	1.98
23	N	N	N	N	N	Y	Y	515641	1.99
24	N	N	N	N	N	Y	N	511410	1.87
25	N	N	N	N	N	N	Y	514230	1.98
26	N	N	N	N	N	N	N	510000	1.85
27	N	N	N	N	N	N	N	500000	1.85