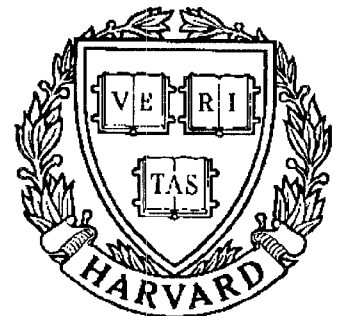


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An Expert System Approach for Economic Evaluation of Machining Operation Planning

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Abstract

A comprehensive understanding of machining operation planning, which covers both the machining domain and the managerial domain, is essential to assure a practical and satisfactory decision-making process. This paper presents an expert system approach to integrating economic and manufacturing systems during the evaluation of machining operation planning. The manufacturing system functions as an alternative generator that provides meaningful and practical plans to ensure product quality. The management system performs cost analysis for the alternatives and makes the decision in selecting the optimal plan based on the defined goal. A simulation-based inductive learning process is adopted to acquire the engineering knowledge for machining operations. The modularity architecture of the reasoning system illustrates the information flow between the manufacturing and management systems, which balances their needs for efficient machining of a quality product.

1 Introduction

Computer automation has been seen in production lines during the past two decades. It greatly improves the engineering productivity and product quality. In machining industries, computer-aided process planning has been a research focus to replace conventional planning systems.

In a conventional production system, an operation plan is usually created by a production engineer, who examines the engineering drawing of the part, acquires the appropriate machine tools, and determines proper cutting parameters for production. In general, the

created operation plan is submitted to a production management for approval. The management staff review the technical aspect and evaluate the economic aspect before finalizing the operation plan proposed by the production engineer. It is evident that the decision-making process is knowledge processing which balances the needs for both technical and managerial considerations.

In order to aid production engineers in their planning efforts, reference data relevant to machining operation planning has been published ^{1,2}. Additionally, research work related to machining operation planning has received much attention. The development of mechanistic model approaches provides a quantitative mapping function between the control space of cutting parameters and the performance space comprising machining accuracy and surface finish, and thus can be extremely useful for planning purposes ^{3,4}. In the research of machining economics, quantitative models have been proposed to evaluate costs related to machining operations ^{5,6}. Cost analysis has revealed that the cutting speed parameter is an important factor in determining the costs directly related to labor, overhead, and tooling. Optimization techniques have been applied to these quantitative models to seek the cutting speed which minimizes the variable cost, or maximizes the production rate and profit rate, associated with machining operations ⁷. Attempts to develop expert systems have been made to assist production engineers and managers during the process of making an operation plan ^{8,9}.

Progress in application of scientific methods of machining operation planning on the shop-floor has been slow. Both production engineers and managers still prepare and review plans based mainly on their previous experience, not on optimization methods. The main obstacle in these methods is lack of the information flow. Such lack prevents an effective communication between the manufacturing and management systems. In most cases, these methods fail to incorporate the basic factors of the economic study in the process of machining operation planning. Therefore, these methods are inapplicable on the shop floor. For example, the adoption of high-speed machining, which requires expensive, new equipment and/or tool materials, is hardly justified by conventional planning methods. This is because the fixed cost, especially of discrete type, associated with the machining operation, was pre-

viously ignored. This indifference makes it difficult to objectively assess the effect of using high fixed cost equipment on the evaluation of total machining cost. In fact, the costly equipment very often permits for low variable production costs to achieve an economic plan for the machining operations. This paper proposes a concurrent engineering approach, namely, integrating the technical and economic considerations in the initial stage of machining operation planning. Using an expert system as a tool, the proposed methodology combines manufacturing and management systems and creates a comprehensive environment for the study of machining operation planning.

2 Structure of Machining Operation Planning

Machining operation planning involves economically choosing machining conditions to meet required specifications. It may seem to be simply a matter of selection. However, this planning is a decision-making process to fully and economically utilize the manufacturing environment and available resources in production.

The decision maker usually starts by identifying feasible ranges of system parameters. The first priority is usually given to the determination of feasible ranges of three cutting parameters, i.e., cutting speed, feed, depth of cut, to assure the product quality. Afterward, alternative plans may be formed within the identified feasible ranges to guarantee that these alternative plans are meaningful and practical. The final plan selected for a given part is a function of a preset goal. Cost analysis to evaluate the variable and fixed costs associated with the machining operation is critical to a good plan. As new machining technologies become available, such as high speed machining and laser machining, the machining operation planning is not only a matter of selecting cutting data. The planning should also be related to making an appraisal for the justification of possible technical and economical benefits from adopting new machining technologies.

Figure 1 depicts the basic structure of the methodology proposed in this paper. The first element is an alternative generator, which is built on the manufacturing system to provide qualified plans. The second element is a cost analyzer to identify and evaluate components of variable and fixed costs. The third element is an optimizer to select the optimal plan

based on a prescribed criterion from the management. The fourth element is the comparator to test the optimality and to assess the validity of adopting new and advanced machining operations from an economic perspective. The feedback path from the comparator to the alternative generator determines the direction and amount of change in the three cutting parameters for improvement, and thus closes the optimizing loop. The whole loop interacts with its surrounding environment mainly through the market which reflects the demand and price of the part to be machined.

3 Consideration of Machining Parameters

In the manufacturing system, machining operation planning is technically referred to as the determination of machining conditions for transformation of a workpiece, according to design specifications. The focus of this activity, with regard to a single point cutting process, is on selecting the significant cutting parameters.

3.1 Depth of Cut and Feed

It has been well established that a large depth of cut and/or feed can easily introduce a considerable cutting force, thus causing considerable workpiece deflection and vibration, leading to substantial dimensional errors. The machining process may become unstable, causing tool breakage. Small depth of cut and feed require increased number of passes or revolutions of the workpiece, leading to low productivity. The feed cutting parameter also directly relates to the surface finish. A large feed leaves a significant amount of uncut areas on the machined surface, deteriorating the finish quality.

Therefore, a function that defines the relation between the two cutting parameters and the performance measures of interest is needed. Mechanistic models that describe the machining operations, as well as machining data handbooks, have also been used to serve this purpose. For given values of depth of cut and feed, a mechanistic model predicts the performance measures of interest such as stability of the operation, deflection of the workpiece, and surface finish.

Figure 2 presents an internal thread machining operation. Due to stability concerns and

the slenderness of the threading tool, the depths of cut which may be used are considerably limited. The 1.0 mm indicated in Fig. 2, which serves as the upper limit, is based on the prediction given by a developed mechanistic model ³. The feed, 0.25 mm/rev as indicated in Fig. 2, is determined by the required thread pitch.

3.2 Cutting Speed

Great attention has been given to the criteria of choosing the cutting speed for machining operations. The reason to machine at high cutting speed is not merely to seek high productivity, but also to achieve good product quality, such as surface finish. Cutting speed plays an important role in the determination of machining time, and thus productivity. For a given depth of cut and feed, with regard to Fig. 2, the machining time is given by

$$\text{Machining Time} = \text{MT} = \frac{\pi(D_{final} + D_{initial})}{2} \frac{1}{1000v} \left[\frac{(D_{final} - D_{initial})}{2d_{limit}} \right] \frac{l}{f} \quad (1)$$

where $D_{initial}$ and D_{final} are the diameters in mm before and after machining, l is the cutting length in mm, f is feed in mm/rev, v is cutting speed to be chosen, and d_{limit} is the upper limit of depth of cut in mm. Note that $\left[\frac{(D_{final} - D_{initial})}{2d_{limit}} \right]$ is the number of passes needed to obtain D_{final} .

Equation (1) seems to imply that high cutting speeds are associated with high productivity due to short required machining times. However, using high cutting speeds may not be advised due to the tool life - cutting speed relationship, which is given by

$$\text{Tool Life} = \text{TL} = \left(\frac{v_r}{v} \right)^{1/n} \cdot t_r \quad (2)$$

where t_r is the measured tool life under a reference cutting speed v_r , and n is the tool life exponent, mainly depending on tool and part material. For example, n ranges from 0.15 to 0.30 for carbide tool materials with steel materials being machined, 0.35 to 0.55 for diamond coating tools when machining steel materials.

Equation (2) clearly depicts the inverse relationship between tool life and cutting speed. The time needed for tool replacement could offset the time saved due to reduced machining time. Furthermore, the cost of tools which are used in a given operation represents a major

part of the machining cost. Thus, the tool life - cutting speed relationship has a considerable effect on the evaluation of machining economics.

4 Cost Analysis

Aside from assuring the quality of machined parts, the ultimate objective of machining operation planning is to develop the least cost plan while maintaining a satisfactory level of productivity. The total cost of the machining operation consists of two components, namely, fixed and variable costs. Both costs serve as a basis for economic evaluation of machining operation planning.

4.1 Evaluation of Variable Costs

In general, variable cost of a production activity consists of those costs which vary proportionally with the level of production activity. With regard to the machining operation, variable cost comes from the following items:

1. Cost related to the machining activity such as the total labor and utility cost, and the overhead of operation cost. Equation (3) presents a quantitative evaluation of this cost.

$$\text{Machining Cost} = (\text{Wage Rate} + \text{Overhead}) \cdot \text{MT} \quad (3)$$

2. Cost related to tooling. Usually, a tool can be used to machine several parts. In addition, tool replacement takes time and interrupts the machining operation. Therefore, the tooling cost for machining a single part consists of two terms. One is a fraction of the cost of tool. The other is the cost of the physical tool replacement process. Equation (4) presents such a quantitative evaluation.

$$\text{Tooling Cost} = \frac{\text{MT}}{\text{TL}} \cdot (\text{Tool Cost}) + \frac{\text{MT}}{\text{TL}} \cdot (\text{Changing Time}) \cdot (\text{Wage Rate} + \text{Overhead}) \quad (4)$$

3. Cost related to auxiliary activities such as loading and unloading the part being machined, and returning the tool to its initial position. The cost associated with this

nonproductive time is given by

$$\text{Auxiliary Cost} = (\text{Wage Rate} + \text{Overhead}) \cdot (\text{Auxiliary Time}) \quad (5)$$

4. Cost related to inventory. Keeping a certain level of inventory is essential to manufacturing systems. The cost of handling parts in and out of inventory and storage costs become unavoidable parts of the variable cost associated with machining operations. Important factors involved in inventory cost are

(a) production time, i.e., the time needed to produce one part. This value is equal to the sum of machining time, fractional tool changing time, and auxiliary time, i.e.,

$$\text{Production Time} = \text{PT} = \text{MT} + \frac{\text{MT}}{\text{TL}} \cdot (\text{Changing Time}) + \text{Auxiliary Time} \quad (6)$$

(b) market demand, and

(c) capacity hours devoted to the machining operation.

The following equation presents a quantitative evaluation of inventory cost, on a monthly basis.

$$\text{Inventory Cost} = \text{Holding Cost} \cdot \left[\frac{(\text{No of Machines})(\text{Capacity Hours}) \cdot 60}{\text{PT}} - \text{Monthly Demand} \right] \quad (7)$$

The ratio term represents the number of parts produced monthly. The difference between the two terms in brackets denotes the inventory level, namely, a surplus of production over demand. Note that the inventory cost evaluated based on Eq. (7) is a discrete type of variable because the number of machines used during the operation has to be an integer. Consequently, the inventory cost per part, or the unit inventory cost, is also a discrete type of variable, indicating its importance in balancing the variable and fixed costs in machining operation planning. The unit inventory cost evaluated in the present work is based on

$$\text{Unit Inventory Cost} = \frac{\text{Inventory Cost}}{\frac{(\text{No of Machines})(\text{Capacity Hours}) \cdot 60}{\text{PT}}} \quad (8)$$

The total variable cost, or the unit variable cost, is equal to the sum of the machining cost, tooling cost, auxiliary cost, and unit inventory cost, which are evaluated above.

4.2 Evaluation of Fixed Cost

Fixed costs, which arise from making preparation for the future, consist mainly of depreciation of machining equipment, maintenance disbursements, and administrative expenses. Fixed cost is the part of total cost which remains at a constant level even when the volume of part being machined fluctuates widely and rapidly.

The need for evaluating the fixed costs becomes evident if a balance between production and market demand is considered during the decision-making process. Referring to Fig. 2, assume that a monthly demand of the part is 4000 pieces, the production time is 6 min/piece, and the capacity hours available for a single machine tool are limited, for example, 175 hours per month. Therefore, in order to manufacture 4000 pieces per month, at least, three machine tools will be required. If the production time is reduced to 5 min/piece, say using a higher cutting speed to machine, two machine tools may suffice. If the fixed cost is determined on a machine-tool basis, say \$6000 per month, using the high cutting speed to machine implies a decreased fixed cost from \$18000 to \$12000 due to the nature of discrete type.

The discontinuity in cost evaluation comes from the introduction of integer variable for the number of machine tools to be used during machining. In the present work, it is accounted in the evaluation of inventory cost, as indicated in Eq. (8). The fixed cost per unit can be obtained with knowledge of the total amount of products being manufactured. The following equation is used for the evaluation of the unit fixed cost.

$$\text{Unit Fixed Cost} = \frac{(\text{Fixed Cost per Machine Tool})}{\frac{(\text{Capacity Hours per Machine Tool}) \cdot 60}{PT}} \quad (9)$$

where the numerator represents the investment of an individual machine tool and the denominator represents the number of parts manufactured based on the available machining capacity.

The total unit cost to produce a part is the sum of the unit fixed cost and the unit variable cost associated with the machining operation.

4.3 Case Study

As pointed out previously, cutting speed plays a major role in both quality of a machined part and machining cost. In the case study, as shown in Fig. 2, we investigate the cost and productivity of machining operation run under different cutting speeds. The following parameter settings are used in the present study.

1. Workpiece:

Material: AISI 1035 steel
Diameters: 56 mm (initial)
60 mm (final)
Length: 250 mm

2. Tooling:

material: Carbide
(t_r, v_r): (100 min, 80 m/min)
Exponent n : 0.20
Tool Cost: \$25/piece
Changing Time: 15 min

3. Machine Tool:

Capacity: 175 hours/month
Fixed Cost: \$6000/month

4. Cutting Data:

d_{limit} : 2 mm
Feed: 0.25 mm/rev
Auxiliary Time: 25% · (Machining Time)

5. Managerial Data:

Monthly Demand: 4000 pieces
Wage Rate: \$15/hour
Overhead: \$10/hour
Holding Cost: \$1/piece
Revenue: \$9/piece

4.3.1 Relation between Production Time and Cutting Speed

Upon careful examination of Table 1, the production time is found to fluctuate as the cutting speed varies from 30 m/min to 145 m/min. It reaches its minimum value of 3.08 min/piece

at a cutting speed of 95 m/min. If the data listed in the first five columns of Table 1 are plotted, as shown in Fig. 3, the machining time decreases significantly as the cutting speed used grows large. However, with the same increase in cutting speed, the fractional tool changing time needed for maintaining a workable cutting edge during machining increases accordingly. This is due to a short tool life resulting from machining at a high cutting speed. In fact, the minimum production time is a compromise between the machining time and the fractional tool changing time, both of which are functions of cutting speed ⁵.

4.3.2 Relation between Total Unit Cost and Cutting Speed

Upon examination of Table 1, the total unit cost is also found to vary as the cutting speed increases from 30 m/min to 145 m/min. It reaches its minimum value of \$4.07/piece at cutting speed = 75 m/min. This is as a result of the following.

1. A lower unit fixed cost as compared to those produced at cutting speeds lower than 75 m/min. This cost is listed as \$1.89/piece. Referring to Eq. (9), the unit fixed cost comes mainly from the investment required to carry out the machining operation. The integer numbers listed in the column entitled 'Number of Machine Tools,' in Table 1, represent the number of machine tools which are needed to manufacture a volume requested by the market demand. In the present case study, the market demand and capacity hours per machine tool are kept as constants. A short production time will result in a smaller number of machine tools needed. Two machine tools would be sufficient when the cutting speed used is in a range from 45 m/min to 140 m/min. If comparing the total fixed costs under two different cutting speed settings, say 40m/min and 50 m/min, the total fixed cost would be \$18000 ($\$6000 \cdot 3$) for cutting speed = 40 m/min, but only \$12000 for cutting speed = 50 m/min. Hence, there can be a significant difference between the two unit fixed costs.
2. A lower unit variable cost as compared to those produced at cutting speeds higher than 75 m/min. This cost is listed as \$2.19/piece. Such a low unit variable cost is mainly due to a low tooling cost, \$0.55/piece. If comparing this tooling cost with

\$1.74 at a cutting speed of 100 m/min, a clear distinction is demonstrated.

Figure 4 graphically presents the cost analysis of the case study. The three curves represent the total unit cost, unit variable cost, and unit fixed cost, respectively. Figure 4 offers a clear picture, and provides an explicit explanation, about the cost structure of the machining operation under consideration. At the optimal cutting speed setting which minimizes the total unit cost, the unit fixed cost accounts for 46.3% of the total unit cost. Thus the importance of controlling the fixed cost involved in the machining operation is apparent. It is evident that ignorance of the unit fixed cost evaluation, in either machining economics or management science, could easily violate the validity of application of the cost analysis. Another observation is that the unit variable cost increases dramatically due to frequent tool changes when machining at high cutting speeds. Meanwhile, the unit fixed cost remains almost at a constant level at high cutting speeds. This explains the reason why high speed machining is not recommended from the economic perspective when carbide tool materials are used.

Note the numerical values listed in Table 1, and the auxiliary cost representative curve shown in Fig. 2. The auxiliary time associated with machining operations is factory-dependent. For example, a specialized fixture for the machining operation could substantially reduce the auxiliary time needed to load and unload a part. In this research, the auxiliary time is approximated as a percentage of machining time required.

4.3.3 Relation between Operation Profit and Cutting Speed

One major goal of carrying out any machining operation is to gain profit to make new capital available for the production in the future. Figure 5 clearly depicts the role of profit during the planning of machining operations. The operation profit is equal to the difference between the revenue and the sum of the direct and indirect costs. It is obvious that the operation profit is a function of the cutting speed of machining operation.

The evaluation of operation profit can be difficult as a result of the complicated relation between price and demand for the part in market. For the purpose of demonstration only,

in this research, the revenue function is assumed to be a product of price and the number of parts manufactured. The operation profit is given by

$$\text{Profit} = \frac{(\text{Unit Price} - \text{Total Unit Cost}) \cdot (\text{Capacity Hours per Machine Tool}) \cdot (\text{No of Machines}) \cdot 60}{\text{PT}} \quad (10)$$

Based on Eq. (10), the operation profits on a monthly basis for cutting speeds of 75 m/min, 85 m/min, and 95 m/min can be calculated as \$31360, \$32285, and \$30094, respectively, where a unit price of \$9 is assumed. It is apparent that the machining operation plan for increased profit is associated with a cutting speed of 85 m/min. Note that a cutting speed of 75 m/min would be planned for achieving the minimum total unit cost, and a cutting speed of 95 m/min would be the best to achieve the maximum production rate. Thus, the condition for maximum operation profit is the compromise between the minimum total unit cost and the maximum production rate. However, in reality, the evaluation of operation profit is much more complicated. As indicated in Fig. 5, it involves not only cost analysis, but also marketing analysis such as the study of the price-demand relation. Further study in this direction is urgently needed to search for a systematic approach and a better solution for the evaluation of the operation profit.

5 Applications and Discussion

The main emphasis of this research is to combine manufacturing and managerial considerations during the decision-making process for machining operation planning. An insight into the usefulness of the proposed methodology is further demonstrated with the following two application examples.

5.1 Justification for Adopting High Speed Machining

Due to its surprising finish quality and high productivity, high speed machining has attracted production engineers, as well as, managers of manufacturing companies. Short tool life associated with high speed machining is an obvious obstacle to adopting high speed

machining. Thanks to the appearance of new tool materials such as silicon nitride and diamond-coated tools, tool life at high cutting speeds has been substantially elongated. For example, the tool life - cutting speed relation of a TIC-coated tool is given by, according to Venkatesh's experimental work ¹⁰.

$$TL = \left(\frac{300}{v}\right)^{1/0.38} \cdot 56 \quad (11)$$

It is evident that at high cutting speeds the new coated tool material can maintain a longer tool life than carbide tool materials. For example, the tool life would be 292 minutes at a cutting speed of 160 m/min based on Eq. (11). However, a major disadvantage of these new coated or composition tool materials is that they are expensive; a diamond-coated tool can easily cost \$300.

Referring to the previous case study, we assume that a TIC-coated tool is used to replace the carbide tool. The tooling cost is \$200/piece. In addition to applying the new tool life - cutting speed relation, namely, Eq. (11), in the cost analysis, a new Wage Rate (\$24/hour) and Overhead (\$12/hour) are used in the cost analysis since operating a machine tool running at a high rotating speed requires a more skillful operator and special attention to maintaining the routine operation. Table 2 presents the calculated results which indicate that, at a cutting speed of 160 m/min, the minimum total unit cost is \$3.17/piece. This value is lower than \$4.07/piece at a cutting speed of 75 m/min, as in the previous case study. The operation profit, on a monthly basis, is \$34642. This is higher than \$32285 at a cutting speed of 85 m/min, as in the previous case study. Examining the two corresponding rows of Table 1 and Table 2 carefully, an important observation can be made. This observation is that a significant reduction of the machining time, in the case of high speed machining, leads to a shorter production time and a higher productivity of the machining operation. In addition, the high productivity requires only one machine tool to manufacture the parts. The output, 5942 pieces/month, as listed in Table 2, will meet the market demand on a monthly basis. Thus, the reduction of required machine tools contributes additional savings from the fixed cost associated with the machining operation. As indicated in Table 2, the unit fixed cost drops to \$1.01/piece from \$1.89/piece, as in the previous case. Therefore,

adopting high speed machining using new tool materials in manufacturing can be justified not only for providing higher quality products and higher productivity, but also for offering an opportunity to further reduce the production cost.

It is certain that the reluctance of adopting high speed machining, as we have witnessed in practice, aside from not recognizing the possible economic benefit, comes from some other facts.

- High speed machining fits the need of mass production best. The high tooling cost can well be distributed to each part quantitatively manufactured. For productions in small batches, long auxiliary time and high cost related to setting up a new production line can easily offset the savings gained from reducing the machining time.
- The new tool materials usually have high hardness, low coefficient of friction, and high wear resistance. However, these materials are brittle. In general, it is not economical to use expensive cutting tools during those machining operations in which the vibratory motion of the tool is severe. This is especially true during intermittent machining operations. The impact between the tool and workpiece leads to premature tool failure, thus increasing the tooling cost dramatically.
- A new and advanced machine tool may be needed to carry out high speed machining¹¹. For example, using a cutting speed of 160 m/min to machine a part with a diameter of 60 mm may require that the machine tool be able to reach a spindle speed of 849 rpm, which is available for most universal lathes, or threading machines, at the present time. However, if the workpiece diameter is equal to 25 mm, the machine tool should have a spindle speed equal to 2038 rpm, which is not available for present universal lathes, or threading machines. A new and advanced lathe, or threading machine, which can meet this spindle speed requirement may need to be purchased. Under such circumstances, more investment is needed. This could overturn the previous justification of adopting high speed machining from the economical perspective.

5.2 Economic Review of New Investment

The present approach can also be used to appraise new investments for the machining operation. This example determines whether it is appropriate to buy a new machine tool in order to adopt high speed machining for the production of the part shown in Fig. 2.

With reference to the previous case study and the first application example, the difference of the operation profit on a monthly basis is equal to $(\$34642 - \$32285) = \$2357$, which is equivalent to \$28284 per year. This difference represents the gain from adoption of the new technique of high speed machining to manufacture the part. Assume that the time duration of this production is a five-year term. The following list provides net cash flows, at three different interest rates, regarding the additional annual profit.

End of Year	Additional Gain annual	Present Value interest: 10%	Present Value interest: 15%	Present Value Interest: 20%
1	\$28284.00	\$25712.73	\$24594.78	\$23570.00
2	\$28284.00	\$23375.21	\$21386.77	\$19641.67
3	\$28284.00	\$21250.19	\$18597.19	\$16368.06
4	\$28284.00	\$19318.36	\$16171.47	\$13640.05
5	\$28284.00	\$17562.14	\$14062.15	\$11366.71
Total:		\$107218.63	\$94812.36	\$84586.49

Through examination of these values, the fundamental meaning of net cash flow at a specific interest rate is clear. For example, when the cost of purchasing a new machine tool for use in high speed machining is equal to, or less than, \$107218 and if such an amount of money may be borrowed at an interest rate of 10%, this investment represents the purchase of a productive asset. This asset will yield a rate of profit of 10% during its five-year lifetime. Similarly, if the interest paid for the money borrowed increases, say to a rate of 20%, the investment should be kept below \$84586.49.

6 Framework of an Expert System

Decision makers of machining operation planning, both production engineers and shop managers, are confronted with constraints from two important environments, i.e., the physical and economic environments. These two environments are independent of each other, but strongly interconnected. Production engineers have the knowledge of how to physically manufacture the part. Shop managers have their focus on the economic merit to gain operation profit while manufacturing the part. A comprehensive understanding of machining operation planning, which covers both the machining domain and the managerial domain, is essential to assure a practical and satisfactory decision-making process. Knowledge of both physical and economic aspects of machining operations is critical, and a good method to make this knowledge explicit and usable is important to manufacturing practice. Knowledge-based expert system approaches from artificial intelligence research are among the most promising new techniques. If properly designed, these systems are able to capture knowledge of machining operation planning combined with inference mechanisms which enable them to use this knowledge effectively in the process of making an operation plan. The methodology proposed in this research has been used as a framework in the development of an expert system for machining operation planning.

Figure 6 illustrates the architecture of a prototype expert system developed in this research. This prototype expert system is divided into two parts, the knowledge base and the reasoning system. The knowledge base consists of a large set of causal rules and a database also called working memory. The causal rules are acquired through a simulation-based inductive learning process, instead of interviewing manufacturing experts for personal experience, which is usually biased^{12,13,14}. The simulator, which is a mathematical model to describe the machining operation, generates the training examples for given cutting conditions. An ordered array of the numerical values of input and output variables of the simulator constitutes a training example. The generated training examples are fed into an AI-based inductive learning program, the output of which is the synthesized rules. Table 3 provides a typical set of rules, which indicates, for example, that the workpiece deflection

during machining will be within 0.20 and 0.52 mm if the range of cutting speed is from 75 to 144 m/min, and feed is kept below 0.18 mm/rev, ..., and the workpiece diameter is between 98 and 129 mm. These rules form a basis to guide the evaluation of Eqs. (1-6). The elements in the working memory, mainly numerical data, are designed to vary dynamically in size at run time. For example, the attribute-value elements for the evaluation of inventory cost only have unit holding cost, ordering cost, and transportation cost prior to the running time. Upon these elements being activated during the decision-making process, a mathematical expression of the required inventory model can be generated in the working memory through a designed inference procedure to supply model-based information related to the inventory. It is understandable that it would be unrealistic to store specific information related to the inventory without knowing the production time, facility capability, and market demand. The structure of the knowledge base developed has been proven effective during the decision-making process because all the provided knowledge has its roots in the physics of the manufacturing and managerial domains. The knowledge is much more reliable and consistent than that obtained through traditional interview processes.

The reasoning system is built on six independent modules. As illustrated in Fig. 6, specifications given in the blue-print become a set of premises through the user input module first. Based on these premises, the primary cutting data selection module performs the rule matching to retrieve the relevant rules and data from the knowledge base. Meaningful and practical plans are generated within a confined feasible space in the manufacturing domain. The production management module integrates managerial considerations with the decision-making process by adding financial constraints through cost analysis, defining the objective function by directly talking to the user (decision-maker) through the user input module, and finally setting up an optimization model. The optimization module performs the function of an inference engine and also acts as a blackboard for recording intermediate results during the search process for the optimal machining operation plan. Recognizing the fact that not all operation planners are experienced, a frame-based representation is applied in the modification module to provide a standard format for the optimal machining operation plan by presetting default values. By outputting the default values used during

the decision-making process, this prototype system reminds the operation planner of those system parameters which have not been considered. Whenever a request for modification is made, the modification module will initiate the search process again. Hence, it controls the decision-making process, especially the determination of ending or interrupting the operation planning process. Following the thinking logics of human decision-makers, these modules function independently and interactively to integrate the knowledge in both the manufacturing domain and the managerial domain and to finally reach a satisfied operation plan.

The appropriateness and effectiveness of using this proposed methodology in the framework design of an expert system has been witnessed since the prototype expert system was put into use for industrial consultation. It successfully assists both production engineers and managers during the decision-making process^{12,13,14}. By augmenting the knowledge base with so-called unreliable data, such as statistical data, human heuristics, and personal experience, and by integrating the power of reasoning with uncertainty, the second generation of this expert system is being developed^{15,16}.

7 Conclusions

This paper discussed an expert system approach for economic evaluation of machining operation planning. A new methodology has been developed and applied in the implementation of a prototype expert system. Through integration of the manufacturing and management systems, the derived operation plan technically assures the satisfaction of required specifications, and economically utilizes labor, material, and working capacity.

Cost analysis plays a central role in the economic evaluation. The unit variable cost reflects the spending distribution between labor and tooling. The unit fixed cost indicates the primary investment to initiate the machining operation. The relation between the variable and fixed costs gives evidence of the need for carefully setting machining parameters.

The economic benefit of adopting high speed machining has been studied. Emphasis has been given to the evaluation of fixed cost of discrete type. The results indicate that a high tooling cost could be compensated by a low machining cost, and the reduction in

the fixed cost could offer a great opportunity for additional profit. A method of economic review of new investment when adopting new and advanced technology has been proposed and its applicability is demonstrated through a practical example.

The implementation of an expert system has to rely on such science-based methodology as proposed in this paper. It is the integrated knowledge which assures a rational operation plan in reality. This indicates that there is an urgent need to incorporate the efforts of the manufacturing, management, and artificial intelligence research. Such collaborative efforts will certainly promote the evolution of production automation to improve product quality and productivity for the entire manufacturing community, and certainly make artificial intelligence real in the engineering domain.

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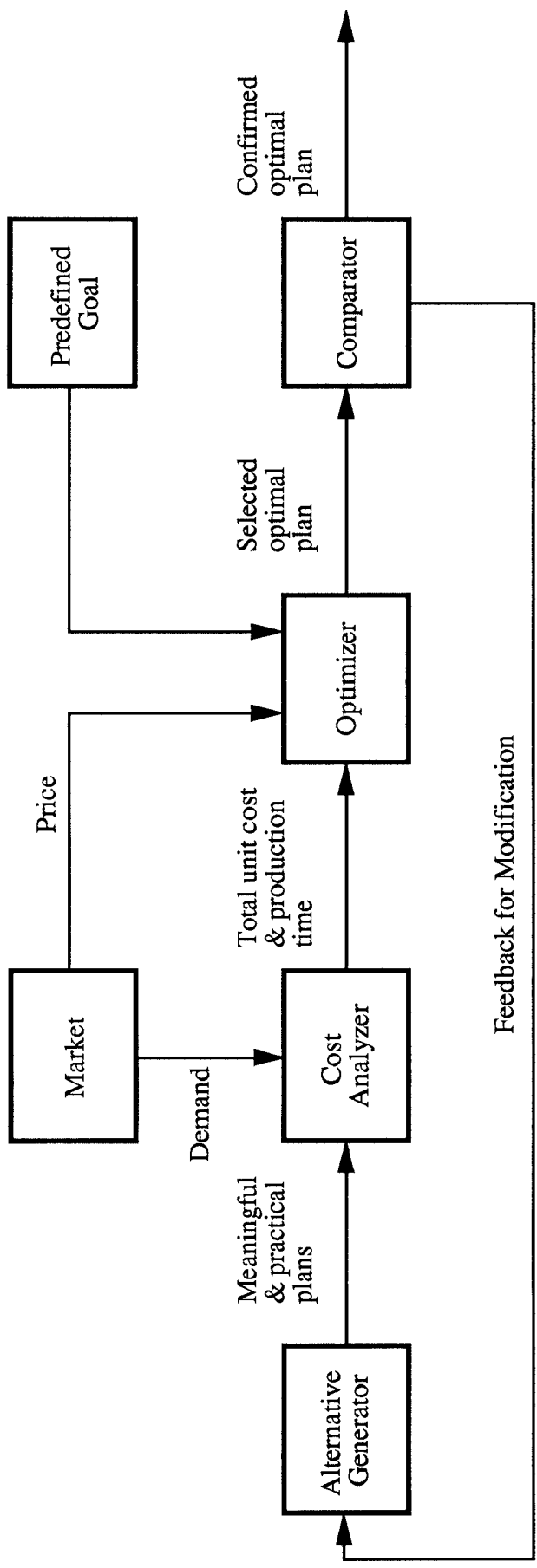


Figure 1 Basic structure of machining operation planning

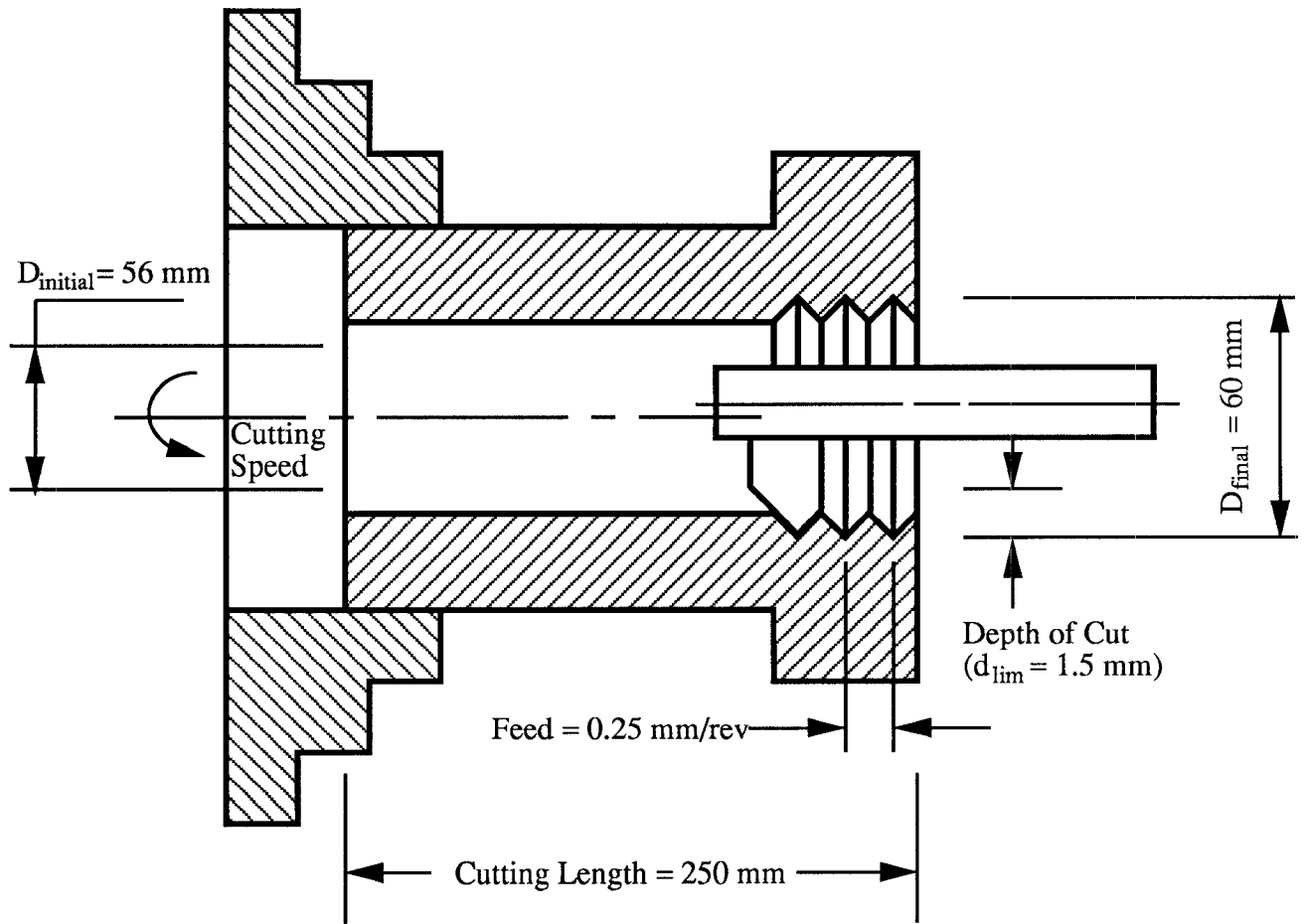


Figure 2 Demenstration Example - An Internal Thread Machining Operation

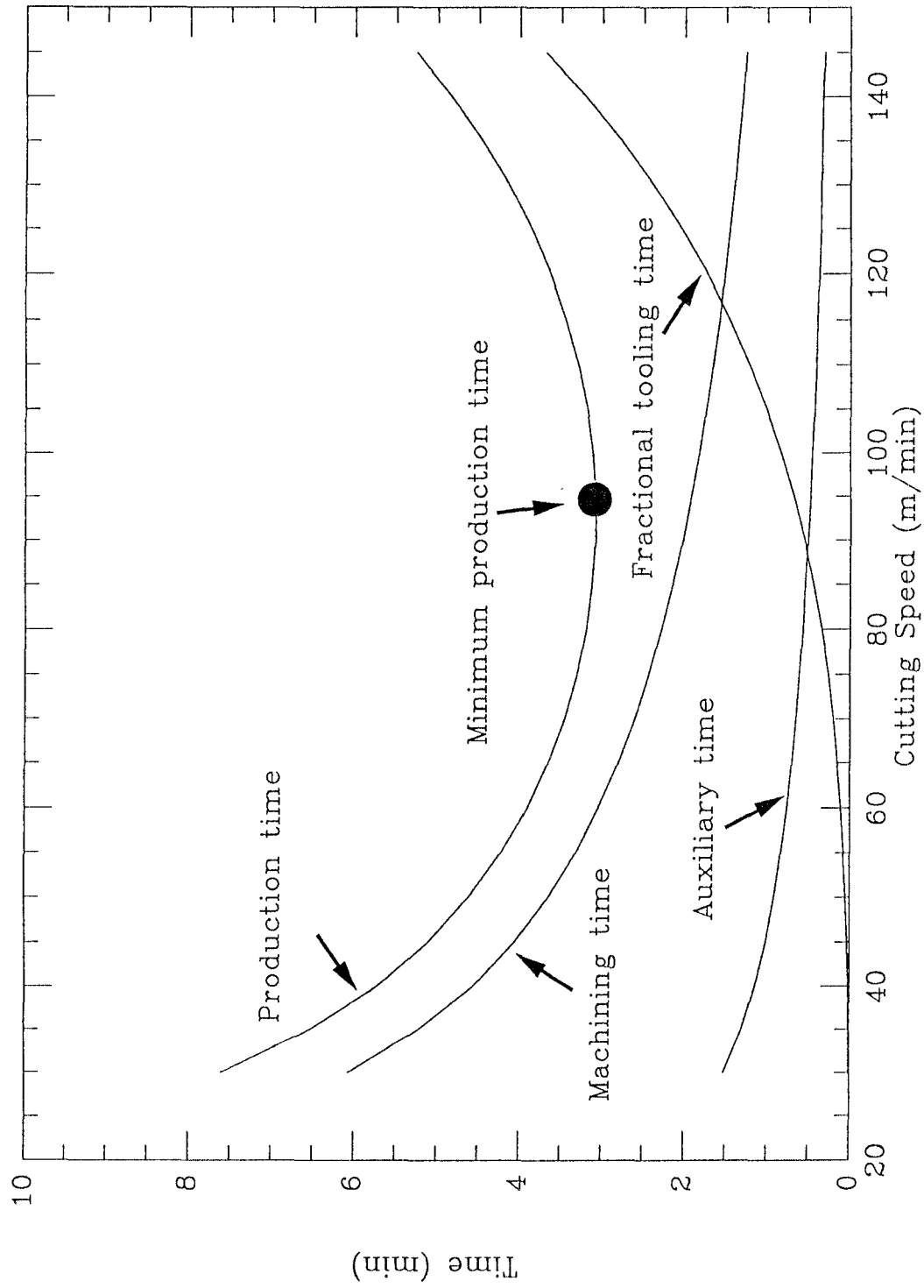


Figure 3 Production time as a function of machining time, fractional tooling time, and auxiliary time

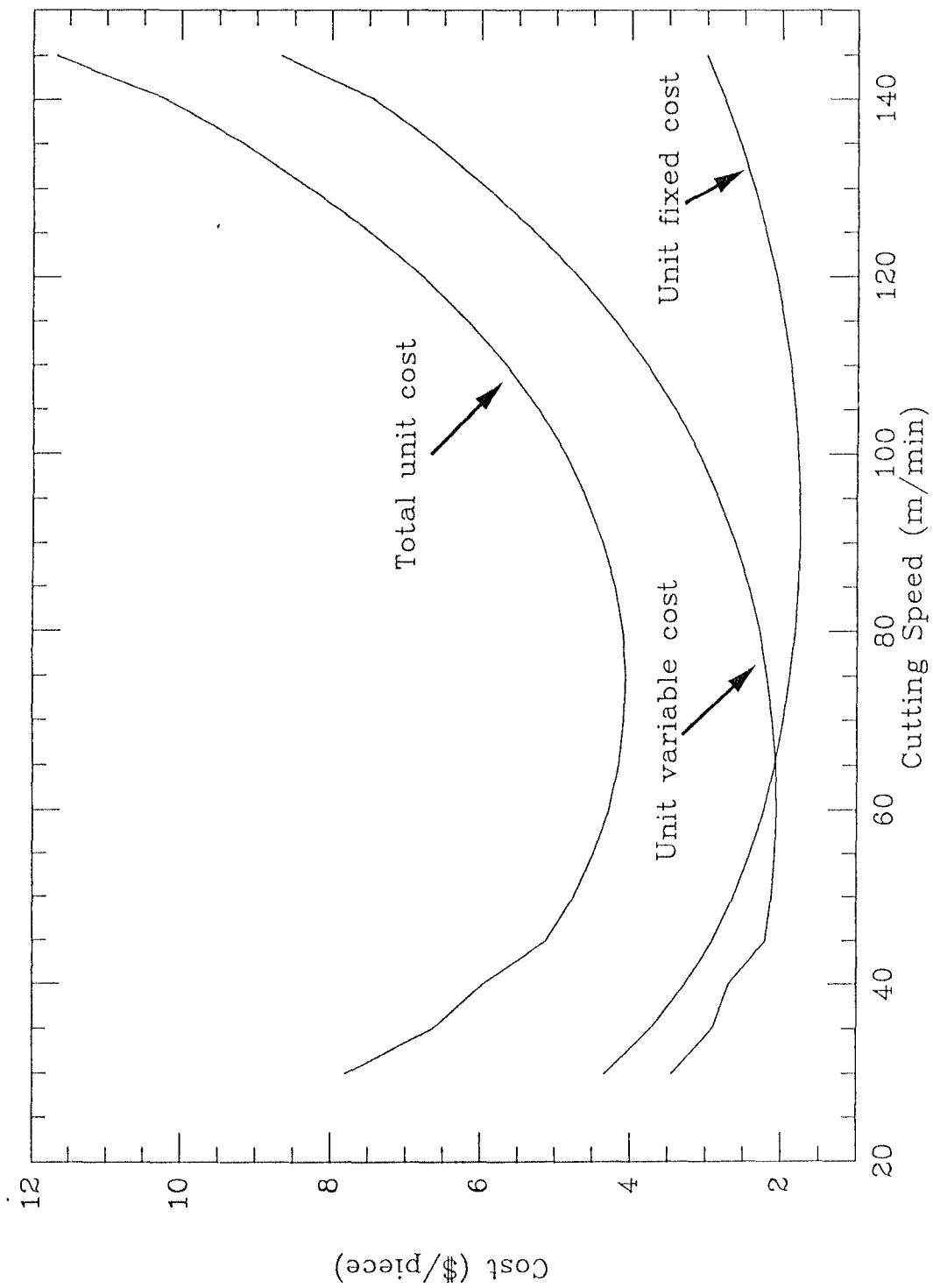


Figure 4 Costing analysis of the machining operation

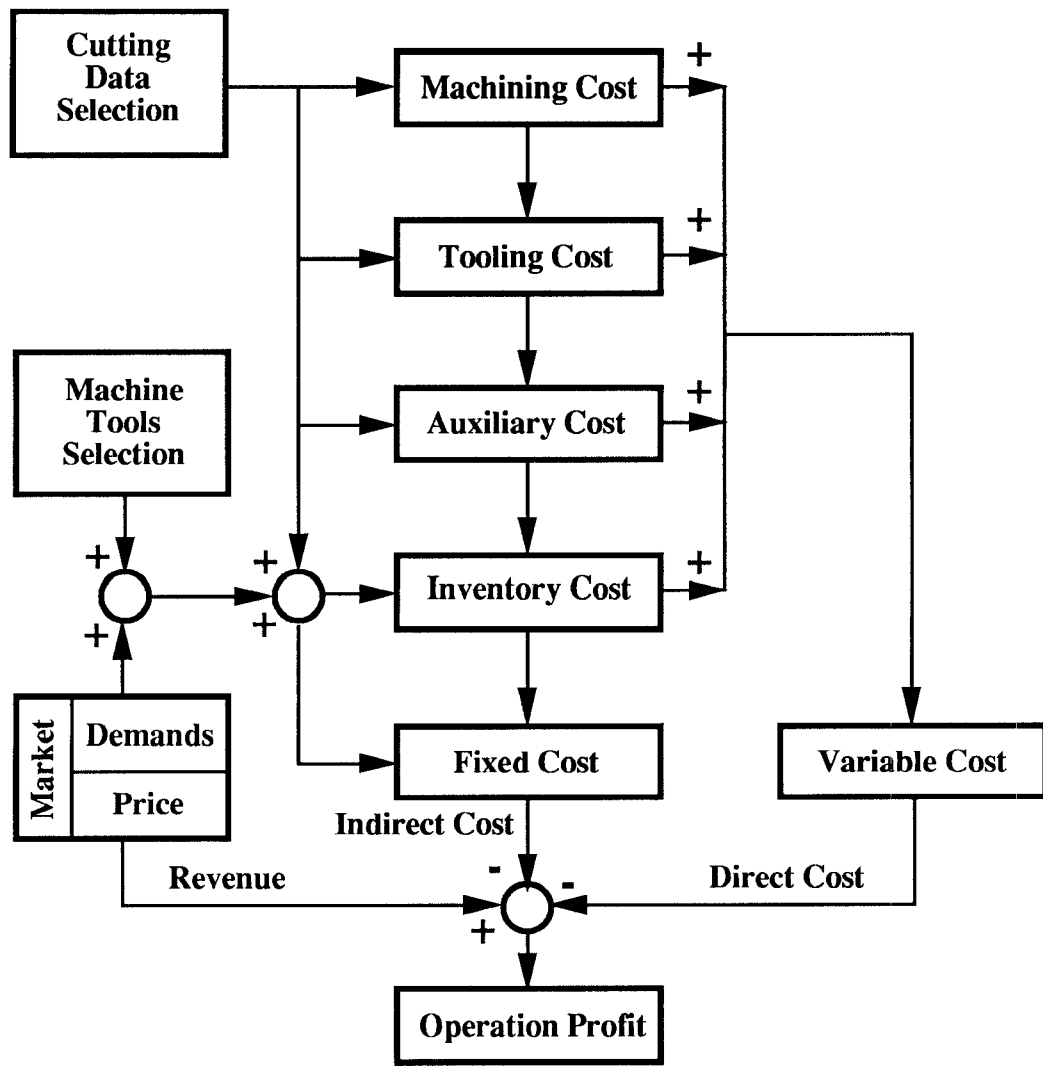


Figure 5 Profit as function of revenue and cost for the machining operation

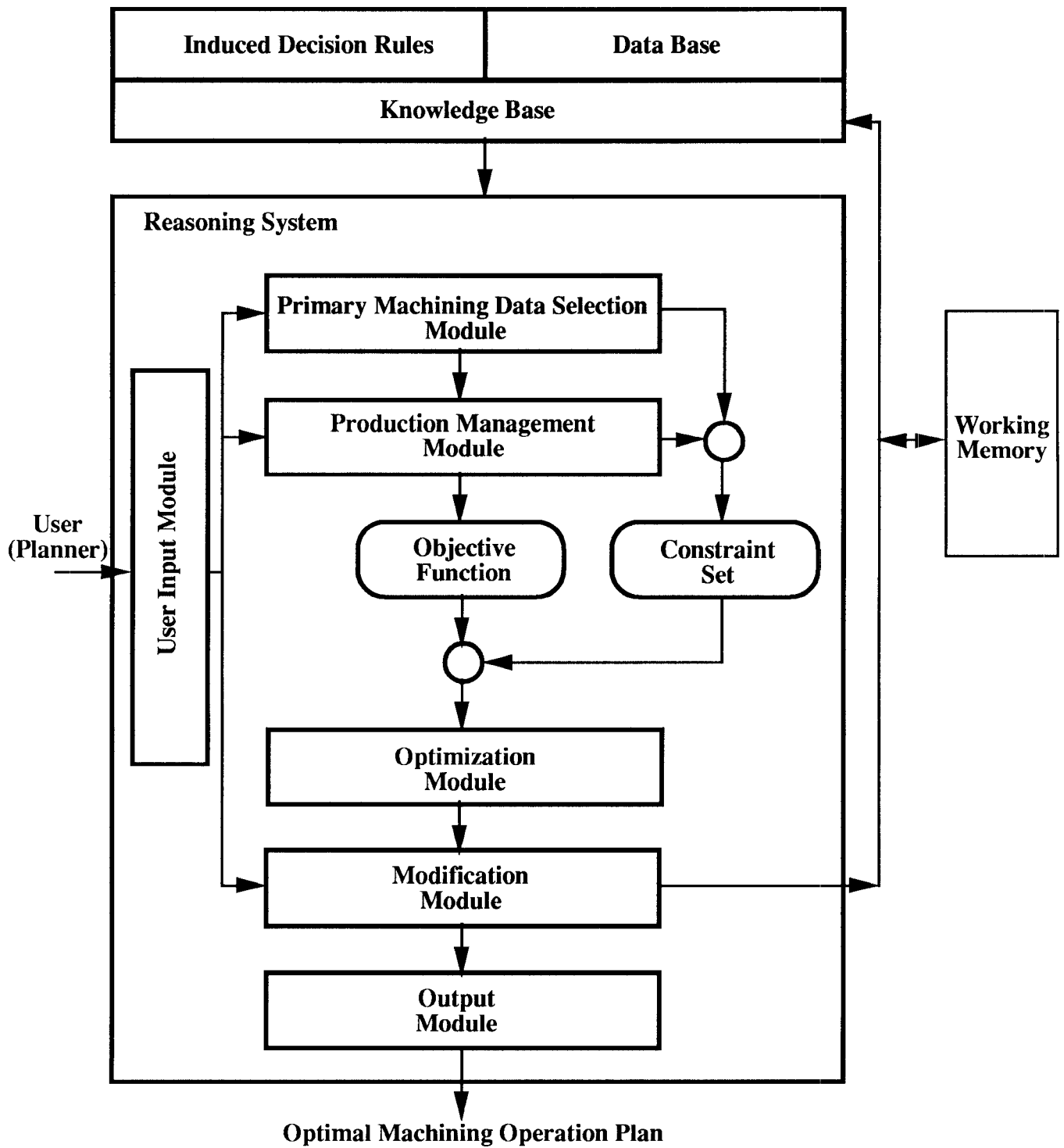


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Table 1 Evaluation of the production time and total unit cost for the case study (carbide tool)

Cutting speed (m/min)	Machining time (min)	Fractional changing time (min)	Auxiliary time (min)	Production time (min)	Number of machine tools	Products manufactured	Machining cost (dollars)	Tooling cost (dollars)	Auxiliary cost (dollars)	Unit Inventory cost (dollars)	Unit Variable cost (dollars)	Unit fixed cost (dollars)	Total unit cost (dollars)
30	6.07	0.01	1.52	7.60	4	5526	2.53	0.01	0.63	0.28	3.45	4.34	7.80
35	5.21	0.01	1.30	6.52	3	4830	2.17	0.03	0.54	0.17	2.91	3.73	6.64
40	4.56	0.02	1.14	5.72	3	5510	1.90	0.04	0.47	0.27	2.69	3.27	5.96
45	4.05	0.03	1.01	5.10	2	4120	1.69	0.07	0.42	0.03	2.21	2.91	5.12
50	3.64	0.05	0.91	4.61	2	4557	1.52	0.11	0.38	0.12	2.13	2.63	4.76
55	3.31	0.08	0.83	4.22	2	4978	1.38	0.16	0.35	0.20	2.08	2.41	4.49
60	3.04	0.11	0.76	3.90	2	5378	1.27	0.23	0.32	0.26	2.06	2.23	4.29
65	2.80	0.15	0.70	3.65	2	5747	1.17	0.31	0.29	0.30	2.07	2.09	4.16
70	2.60	0.20	0.65	3.45	2	6079	1.08	0.42	0.27	0.34	2.12	1.97	4.09
75	2.43	0.26	0.61	3.30	2	6361	1.01	0.55	0.25	0.37	2.19	1.89	4.07
80	2.28	0.34	0.57	3.19	2	6584	0.95	0.71	0.24	0.39	2.29	1.82	4.11
85	2.14	0.44	0.54	3.12	2	6740	0.89	0.91	0.22	0.41	2.43	1.78	4.21
90	2.02	0.55	0.51	3.08	2	6821	0.84	1.14	0.21	0.41	2.61	1.76	4.37
95	1.92	0.68	0.48	3.08	2	6824	0.80	1.42	0.20	0.41	2.83	1.76	4.59
100	1.82	0.83	0.46	3.11	2	6747	0.76	1.74	0.19	0.41	3.09	1.78	4.87
105	1.74	1.01	0.43	3.18	2	6596	0.72	2.11	0.18	0.39	3.41	1.82	5.23
110	1.66	1.22	0.41	3.29	2	6378	0.69	2.54	0.17	0.37	3.78	1.88	5.66
115	1.58	1.46	0.40	3.44	2	6104	0.66	3.04	0.17	0.34	4.21	1.97	6.18
120	1.52	1.73	0.38	3.63	2	5788	0.63	3.60	0.16	0.31	4.70	2.07	6.78
125	1.46	2.04	0.36	3.86	2	5441	0.61	4.24	0.15	0.26	5.27	2.21	7.47
130	1.40	2.38	0.35	4.13	2	5078	0.58	4.96	0.15	0.21	5.91	2.36	8.27
135	1.35	2.77	0.34	4.46	2	4710	0.56	5.77	0.14	0.15	6.63	2.55	9.17
140	1.30	3.20	0.33	4.83	2	4346	0.54	6.68	0.14	0.08	7.43	2.76	10.20
145	1.26	3.69	0.31	5.26	3	5990	0.52	7.68	0.13	0.33	8.67	3.00	11.67

Table 2 Evaluation of the production time and total cost for the comparison (TIC -coated tool)

Cutting speed (m/min)	Machining time (min)	Fractional changing time (min)	Auxiliary time (min)	Production time (min)	Number of machine tools	Products manufactured	Machining cost (dollars)	Tooling cost (dollars)	Auxiliary cost (dollars)	Inventory cost (dollars)	Unit Variable cost (dollars)	Unit fixed cost (dollars)	Total unit cost (dollars)
100	1.82	0.03	0.91	2.76	2	7606	1.09	0.38	0.55	0.47	2.49	1.58	4.07
105	1.74	0.03	0.87	2.63	2	7976	1.04	0.41	0.52	0.50	2.47	1.50	3.97
110	1.66	0.03	0.83	2.52	1	4172	0.99	0.44	0.50	0.04	1.97	1.44	3.41
115	1.58	0.03	0.79	2.41	1	4354	0.95	0.47	0.48	0.08	1.98	1.38	3.36
120	1.52	0.04	0.76	2.31	1	4536	0.91	0.51	0.46	0.12	1.99	1.32	3.32
125	1.46	0.04	0.73	2.23	1	4717	0.87	0.54	0.44	0.15	2.01	1.27	3.28
130	1.40	0.04	0.70	2.14	1	4896	0.84	0.58	0.42	0.18	2.02	1.23	3.25
135	1.35	0.04	0.67	2.07	1	5074	0.81	0.62	0.40	0.21	2.04	1.18	3.23
140	1.30	0.05	0.65	2.00	1	5251	0.78	0.65	0.39	0.24	2.06	1.14	3.21
145	1.26	0.05	0.63	1.93	1	5426	0.75	0.69	0.38	0.26	2.09	1.11	3.19
150	1.21	0.05	0.61	1.87	1	5600	0.73	0.73	0.36	0.29	2.11	1.07	3.18
155	1.18	0.06	0.59	1.82	1	5772	0.71	0.77	0.35	0.31	2.14	1.04	3.18
160	1.14	0.06	0.57	1.77	1	5942	0.68	0.81	0.34	0.33	2.16	1.01	3.17
165	1.10	0.06	0.55	1.72	1	6111	0.66	0.85	0.33	0.35	2.19	0.98	3.18
170	1.07	0.06	0.54	1.67	1	6278	0.64	0.90	0.32	0.36	2.23	0.96	3.18
175	1.04	0.07	0.52	1.63	1	6443	0.62	0.94	0.31	0.38	2.26	0.93	3.19
180	1.01	0.07	0.51	1.59	1	6606	0.61	0.99	0.30	0.39	2.29	0.91	3.20

Table 3 Induced decision rules for rough operation (A mathematical model to describe the internal thread operation used as the simulator to generate training examples)

IF	[SPEED	= 75 v 104 v 144	(m/min)]
	[FEED	= 0.18	(mm/rev)]
	[DEPTH OF CUT	= 2.03	(mm)]
	[RAKE ANGLE	= -5 v 0 v 5	(degree)]
	[NOSE RADIUS	= 0.41 v 0.79 v 1.60	(mm)]
	[DIAMETER	= 98 v 120	(mm)]
			OR
	[SPEED	= 75 v 104 v 144	(m/min)]
	[FEED	= 0.38	(mm/rev)]
	[DEPTH OF CUT	= 1.02	(mm)]
	[RAKE ANGLE	= -5 v 0 v 5	(degree)]
	[NOSE RADIUS	= 0.41 v 0.79 v 1.60	(mm)]
	[DIAMETER	= 98 v 120	(mm)]
THEN	[TANGENTIAL FORCE	= 700 ... 840	(Newton)]
	[NORMAL FORCE	= 350 ... 490	(Newton)]
	[MAX DEFLECTION	= 0.20 ... 0.52	(mm)]
	[ROUGHNESS	= 1.27 ... 2.95	(μm)]
	[METAL REMOVAL RATE	= 27.4 ... 55.8	(cm^3/min)]
