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An Expert System Framework for Economic Evaluation of Machining Operation Planning

by G. Zhang and S.C-Y. Lu

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Guangming Zhang

Department of Mechanical Engineering and Systems Research Center
University of Maryland
College Park, Maryland 20742

Stephen C-Y. Lu

Knowledge-Based Engineering Systems Research Laboratory
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

Abstract

Recognizing the importance to combine the manufacturing system and the management system for machining operation planning, a new methodology is proposed in this paper to evaluate the economic aspect of an operation plan. To assure the quality of a machined part satisfying the required specifications, the manufacturing system acts as an alternative generator to provide meaningful and practical plans. Through costing analysis, the variable, fixed, and total costs associated with the machining operation are quantitatively determined. The management system, which functions as an evaluative mechanism, selects the optimal plan based on the defined goal. This proposed methodology has been used as a framework in designing an expert system. The system establishes the sequence of machining operation planning and search the optimal plan which integrates the considerations from both production engineers and managers, and balances their needs for a quality and productive operation.

1 Introduction

Machining operation planning is an activity of economically choosing cutting conditions capable of producing parts that meet the required specifications such as tolerance and surface finish. In addition, the chosen plan must meet the production schedule on the shop floor. Generally speaking, an operation plan is created by a production engineer, who examines the engineering drawing of, and the demand for, the part, finds machine tools available, and then determines the appropriate cutting data such as feed, depth of cut, and cutting speed to produce the part. During such a decision-making process, the production engineer has two types of concerns, i.e., technical and economic concerns.

In order to aid production engineers in their planning efforts, data relevant to machining operation planning have been accumulated and published for reference [1,2]. On the other hand, research work related to the machining operation planning has received much attention over the years. 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, which can be effectively used for the planning purpose [3-4]. In the research of machining economics, quantitative models have been proposed to evaluate costs related to the machining operation [5-6]. Costing analysis revealed that the parameter of cutting speed is an important factor in determining the costs directly related to the labor, overhead, and tooling required during machining. 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 the machining operation [7]. Attempts to develop powerful computer systems, or expert systems, have been made to assist production engineers and managers during the process of making an operation plan [8-9].

However, the progress in applying scientific methods of machining operation planning on the shop floor has been slow. Production engineers still prepare their plans mainly based on their previous experience, not on the optimization methods. The main hurdle is that these methods suffer from a serious drawback, i.e., they fail to incorporate the basic factors in the economic study of machining operation planning, making them inapplicable on the shop floor. For example, the adoption of high speed machining, which requires new tool materials and/or equipment that are expensive, is hardly justified by the previous approaches. This is because the fixed cost, especially the fixed cost of discrete type, associated with the machining operation was ignored in the previous approaches. This ignorance makes it difficult to objectively assess the effect of using the high fixed cost equipment on the evaluation of the total machining cost. In fact, the costly equipment very often permits low variable production costs to achieve an economic plan for the machining operation.

In this paper, a new methodology is proposed to combine the manufacturing system and the management system together, and thus to form a comprehensive environment for performing machining operation planning. In section 2 of this paper, the structure of the new methodology is outlined. Section 3 describes how the manufacturing system functions as a generator to provide alternative plans. Section 4 focuses on costing analysis. Methods to evaluate variable costs and fixed costs associated with the machining operation are given. Through a case study, the procedure to perform the costing analysis is demonstrated. The necessity of having the fixed cost included in the costing analysis is indicated. Two application examples are provided in Section 5. The insight and usefulness of the proposed methodology are discussed. In Section 6, the framework of an expert system which is based on the above proposed methodology is presented, and the architecture of a prototype system is illustrated.

2 Structure of Machining Operation Planning

From the viewpoint of manufacturing systems engineering, manufacturing operation planning might seem to be a matter of selecting the cutting parameters such as cutting speed, feed, and depth of cut to machine a designed part. However, the planning is a decision-making process to fully and economically utilize the manufacturing environment to fabricate the designed part.

As a human thinking process, the decision maker usually starts with identifying feasible regions of system parameters when he/she attempts to make any possible plans. The first priority is often given to the determination of feasible regions of the three cutting parameters, i.e., cutting speed, feed, depth of cut to assure the quality of a machined part. Afterward, alternative plans can be formed within the identified feasible regions to guarantee that these alternative plans are meaningful and practical. The final plan selected for a given part to be machined is a function of the goal to be achieved. For example, company managers may be interested in keeping the cost related to the machining operation as low as possible, or in seeking the maximum profit attainable from the machining operation. Because of this, costing analysis to evaluate the variable and fixed costs associated with the machining operation is critical in making a good plan. As new machining technologies become available such as high speed machining and laser machining, the machining operation planning is not alone a matter of selecting cutting data, it should be related to making an appraisal for the justification of possible technical and economical benefits from adopting the new machining technologies.

Figure 1 depicts the basic structure of the methodology proposed in this paper. The structure consists of five elements. The first element is the alternative generator, which is built on the manufacturing system to provide qualified plans. The second element is the costing analyzer to identify and evaluate components of the variable and fixed costs. The third element is the 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 the 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 Cutting Parameters

In the manufacturing system, machining operation planning is technically referred to as the activity of determining the cutting conditions for the transformation of a part from its given form to a final form according to design specifications. The focus of this activity, with regard to a single point cutting process such as turning or boring, is on selecting the three cutting parameters, i.e., depth of cut, feed, and cutting speed.

3.1 Depth of Cut and Feed

It has been well established that a large depth of cut and/or a large feed can easily introduce a considerable cutting force, which causes the workpiece to deflect and vibrate during machining, leading to substantial dimensional errors after machining. Sometimes, the machining process becomes unstable, causing tool breakage. On the other hand, small depth of cut and feed require increased number of passes or revolutions of the workpiece, to remove material from the part being machined, leading to low productivity. In addition, the cutting parameter feed 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. Machining data handbooks provide reliable information that has been accumulated from experience. Besides, mechanistic models that describe the machining operations 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 machining operation, the maximum deflection of workpiece during machining, and the surface finish after machining.

As a demonstration example, Fig. 2 presents a boring operation where a hole is being machined. Due to the slenderness of a boring bar, the depth of cut used during machining while maintaining the process stability is 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 upper limit posed on feed, 0.2 mm/rev as indicated in Fig. 2, is determined by the surface finish requirement such as AA $= 2.5\ \mu m$ shown in Fig. 2 [5].

3.2 Cutting Speed

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

$$\mathrm{MT} = \frac{\pi(D_{final} + D_{initial})}{2} \frac{1}{1000v} [\frac{\frac{(D_{final}-D_{initial})}{2}}{d_{limit}}] \frac{l}{f} \tag{1}$$

where D_{final} = diameter after machining in mm,

D_{final} = diameter after machining in mm,

l = cutting length in mm,

f = feed in mm/rev,

v = cutting speed to be selected in m/min,

d_{limit} = upper limit of depth of cut in mm, and

$[\frac{\frac{(D_{final}-D_{initial})}{2}}{d_{limit}}]$ = number of passes needed to obtain D_{final}.

Examining Eq. (1), it seems that a high cutting speed is associated with a high productivity because of a short machining time resulted. However, using high cutting speeds may, on many occasions, not be advised because of the tool life - cutting speed relationship, which is given by

$$\mathrm{TL} = (\frac{v_r}{v})^{1/n} \cdot t_r \tag{2}$$

where t_r = measured tool life under a reference cutting speed v_r,

TL = tool life associated with the selected cutting speed, and

n = tool life exponent, mainly depending on tool and part material. For example, n ranges from 0.20 to 0.30 for carbide tool materials with steel materials being machined, 0.40 to 0.60 for diamond coating tool when machining steel materials.

Based on Eq. (2), the higher the cutting speed, the shorter the tool life. Therefore, The time needed for replacing a dull cutting tool by a new cutting tool could offset the time saved from a reduction of the required machining time when using a high speed to machine. Furthermore, the cost of tools that are used on 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 Costing Analysis

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

4.1 Evaluation of Variable Costs

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

1. Cost related to the machining activity such as the total labor and utility cost, and the company facility cost (or the Overhead of operation). Equation (3) presents a quantitative evaluation of this cost for machining a part.

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

2. Cost related to the tooling. Usually, a single cutting tool or edge can be used for machining a few parts. An operator will not change the tool until it becomes dull. In addition, replacing a new tool or sharp edge 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 a cutting tool or edge. The other is the cost

of the physical tool replacement process. Equation (4) presents such a quantitative evaluation.

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

3. Cost related to auxiliary activities such as loading and unloading the part being machined, and returning the tool to the beginning position of the cut. The cost associated with this nonproductive time is given by

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

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

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

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

   (b) market demand.

   (c) capacity hours devoted to the machining operation.

The following equation represents a quantitative evaluation of the inventory cost which is on a monthly basis.

$$\text{Inventory Cost} = \text{Holding Cost} \cdot [\frac{(\text{Capacity Hours}) \cdot 60}{\text{PT}} - \text{Monthly Demand}] \tag{7}$$

where the ratio term represents the number of parts produced monthly, and the difference between the two terms in brackets denotes the inventory level, namely, a surplus of production over demand. Therefore, the inventory cost per part, or the unit inventory cost, is given by

$$\text{Unit Inventory Cost} = \frac{\text{Holding Cost} \cdot [\frac{(\text{Capacity Hours}) \cdot 60}{\text{PT}} - \text{Monthly Demand}]}{\frac{(\text{Capacity Hours}) \cdot 60}{\text{PT}}} \quad (8)$$

The total variable cost associated with the machining operation, or the unit variable cost, is equal to the sum of all the variable costs evaluated above.

$$\begin{aligned} \text{Unit Variable Cost} &= \text{Machining Cost} + \text{Tooling Cost} + \\ &\quad \text{Auxiliary Cost} + \text{Unit Inventory Cost} \end{aligned} \quad (9)$$

4.2 Evaluation of Fixed Cost

Fixed costs, which arise from making preparation for the future, are mainly made up of depreciation of the machining equipment used, maintenance disbursements, and administrative expenses. It is the part of the 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 involved in the machining operation becomes evident if a balance between the production and the market demand is being 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 is limited, for example, 175 hours per month. Therefore, in order to manufacture 4000 pieces per month, we need, at least, three machine tools. When the production time is reduced to 5 min/piece, say using a higher cutting speed to machine, two machine tools may be sufficient to machine 4000 pieces during a month. If the fixed cost is determined on a machine-tool basis, say $4000 per machine tool, using the high cutting speed to machine means to decrease the fixed cost from $12000 to $8000, indicating a significant saving because of the nature of discrete type.

Because the fixed cost is, in general, not subject to rapid change, the fixed cost per unit can easily get out of hand by knowing the total amount of products being manufactured. In the present work, the following equation is used for the evaluation of the unit fixed cost.

$$\text{Unit Fixed Cost} = \frac{(\text{Fixed Cost per Machine Tool}) \cdot (\text{Number of Machine Tools})}{\frac{(\text{Capacity Hours per Machine Tool}) \cdot (\text{Number of Machine Tools})}{\text{PT}}} \tag{10}$$

where the numerator represents the total investment 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, i.e.,

$$\text{Total Unit Cost} = \text{Unit Variable Cost} + \text{Unit Fixed Cost} \tag{11}$$

4.3 Case Study

As pointed out previously, cutting speed plays a big role in both the quality of a machined part and the machining economics. In the case study presented below, we assume that a part, as shown in Fig. 2, is being machined and study how the productivity of machining operation is affected, and how the unit variable cost, unit fixed cost, and total unit cost vary when the machining operation runs under different cutting speeds. In the present study, the following parameter settings are used.

1. Workpiece:

Material:	SAE 1035 steel	
Diameters:	46 mm	(initial)
	50 mm	(final)
Length:	200 mm	

2. Tooling:

material:	Carbide
(t_r, v_r):	(100 min, 80 m/min)
Exponent n :	0.25
Tool Cost:	25 $/piece
Changing Time:	15 min

3. Machine Tool:

Capacity:	175 hours/month
Fixed Cost:	4000 $/month

4. Cutting Data:

d_{limit}:	2 mm
Feed:	0.2 mm/rev
Auxiliary Time:	25% · (Machining Time)

5. Managerial Data:

Monthly Demand:	4000 pieces
Wage Rate:	12 $/hour
Overhead:	6 $/hour
Holding Cost:	1 $/piece
Revenue:	9 $/piece

Table 1 lists the numerical data calculated during the decision making for machining operation planning. Each row of Table 1 corresponds to a specific cutting speed setting. For example, Row 1 represents the information derived from setting cutting speed to 80 m/min. The first part of Table 1 (the first five columns) relates to the calculation of the production time. The second part of Table 1 relates to the calculation of costs where each column represents a specific cost item. The last three columns represent the unit variable cost, the unit fixed cost, and the total unit cost which is the sum of the unit variable and fixed costs. As indicated in Table 1, the numerical value listed in the column marked as Unit Variable Cost is equal to the sum of the numerical values listed in the four preceding columns representing the machining cost, the tooling cost, the auxiliary cost, and the unit inventory cost, respectively.

4.3.1 Relation between Production Time and Cutting Speed

Examining the fifth column of Table 1 carefully, the production time fluctuates as cutting speed varies from 40 m/min to 140 m/min. It reaches its minimum value of 4.86 min/piece at cutting speed = 100 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 becomes high. However, the fractional tool changing time needed for maintaining a workable cutting edge during machining increases accordingly as the cutting speed becomes high. This is due to a short tool life as a result of 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 a function of the cutting speed [5].

4.3.2 Relation between Total Unit Cost and Cutting Speed

Examining the last column of Table 1, the total unit cost varies as the cutting speed increases from 40 m/min to 140 m/min. It reaches its minimum value of $4.79/piece at cutting speed = 90 m/min. This is due to the following reasons.

1. A lower unit fixed cost if comparing with those resulted at cutting speed settings lower than 90 m/min. This cost is listed as $1.90/piece. Referring to Eq. (10), the unit fixed cost mainly comes from the investment needed to carry out the machining operation. Examining the integer numbers listed in the column marked as Number of Machine Tools in Table 1, they represent the number of machine tools which are needed to manufacture a volume requested by the market demand. Evidently, such a number is a function of market demand, available capacity hours per machine tool, and production time which is a function of cutting speed. 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. As indicated in Table 1, two machine tools would be sufficient when the cutting speed

used is in a range from 90 m/min to 120 m/min. If comparing the total fixed costs under two different cutting speed settings, say 80m/min and 90 m/min, the total fixed cost would be \$12000 (\$4000 · 3) for cutting speed = 80 m/min, but only \$8000 for cutting speed = 90 m/min. Hence, there is a significant difference in the evaluation of the unit fixed cost between them. One is \$2.01/piece, and the other is \$1.90/piece.

2. A lower unit variable cost if comparing with those resulted at cutting speed settings higher than 90 m/min. This cost is listed as \$2.89/piece. Such a low unit variable cost is mainly due to a low tooling cost, which is \$1.58/piece as listed. If comparing this tooling cost with \$2.17 at cutting speed = 100 m/min, there is a clear distinction between the two tooling costs.

3. The lowest unit inventory cost among all the cutting speed settings. This unit inventory cost is listed as \$0.05/piece. It is due to the fact that the current production time is so well determined that the number of total parts machined (4200 pieces/month) just matches the market demand (4000 pieces/month). Therefore, on a monthly basis, there are only 200 pieces which will be stored for later use or sell, resulting a minimum holding cost for the inventory activity.

Figure 4 graphically presents the costing analysis associated with the machining operation for 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. It points out the importance to evaluate the unit fixed cost in the study of machining economics. As indicated in Fig. 4, at the optimal cutting speed setting which minimizes the total unit cost, the unit fixed cost accounts for 39.7% of the total unit cost. This makes the importance of controlling the fixed cost involved in the machining operation very apparent. It is evident that ignorance of the unit fixed cost evaluation in either the machining economics or the management science could easily violate the validity of applying the costing analysis to the machining operation.

Another observation from Fig. 4 is that the fixed cost stops decreasing and remains almost at a constant level at high cutting speeds. On the other hand, the unit variable cost increases dramatically due to the frequent tool changes. Therefore, using high speed machining is not recommended from the economic perspective when using carbide tool materials during machining.

Note the numerical values listed in Table 1, and the curve shown in Fig. 2, to represent the auxiliary cost. Because the auxiliary time associated with a machining operation, to a certain degree, is factory-dependent. For example, a specialized fixture for the machining operation could reduce the auxiliary time needed to load and unload a part substantially. In the present work, we approximate the auxiliary time as a percentage of machining time needed, which is an assumption made for the case study.

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 for 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 to be selected for the machining operation. For breaking even, the received revenue must be, at least, equal to the sum of the indirect and direct costs.

The evaluation of operation profit can be difficult because of the complicated relation between price and demand for the part in market. In the present work, only for the purpose of demonstration, we assume that the revenue function is a product of price and the number of parts manufactured. The operation profit is given by

$$\text{Operation Profit} = (\text{Unit Price - Total Unit Cost}) \cdot$$

$$\frac{\text{(Capacity Hours per Machine Tool)} \cdot \text{(Number of Machine Tools)}}{\text{PT}} \tag{12}$$

Based on Eq. (12), the operation profit on a monthly basis for cutting speed = 90 m/min, 93 m/min, and 100 m/min can be calculated as \$42882, \$42945, and \$42250, respectively, where the unit price equal to \$15 is assumed. It is apparent that the machining operation plan to gain better profit is associated with the cutting speed set at 93 m/min. Note that the cutting speed set at 90 m/min would be planned for achieving the minimum total unit cost, and a cutting speed equal to 100 m/min would be the best setting for achieving 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 costing analysis, but also marketing analysis such as the study of price-demand relation. Further research in this direction is pressingly 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 the present work is to combine the manufacturing considerations and the managerial considerations together 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

High speed machining due to its surprising finish quality as well as high productivity has attracted production engineers on the shop floor and the managers of manufacturing companies as well. On the other hand, a short tool life associated with machining at a high cutting speed requires frequent changes of the cutting tool is an obvious obstacle to adopting high speed machining on the shop floor. Thanks to the appearance of new tool materials such as silicon nitride or diamond-coated tools, the 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]

$$\begin{aligned} \text{TL} &= (\frac{v_r}{v})^{1/n} \cdot t_r \\ &= (\frac{300}{v})^{1/0.42} \cdot 56 \end{aligned} \qquad (13)$$

It is evident that the new coated tool material can maintain a tool life longer than carbide tool materials at a high cutting speed. For example, the tool life would be 253 minutes at cutting speed = 160 m/min based on Eq. (13). However, one of the major disadvantages of these new coated or composition tool materials is that they are expensive, say 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. (13), in the costing analysis, we also assume that a new Wage Rate ($24/hour) and a new Overhead ($12/hour) be used in the costing analysis because 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 and indicates that, at cutting speed = 160 m/min, the minimum total unit cost is $4.43/piece, which is lower than $4.79/piece at cutting speed = 90 m/min in the previous case study, and the operation profit on a monthly basis is $45007, which is higher than $42882 at cutting speed = 90 m/min in the previous case study. Examining the two corresponding rows in Table 1 and Table 2 carefully, an important observation is that a significant reduction of the machining time in the case of high speed machining, leading 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, 4258 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 \$1.41/piece from \$1.90/piece in the previous case. Therefore, adopting high speed machining using new tool materials in manufacturing can be justified not only for providing high quality products and high productivity, but also for offering an opportunity to further reduce the production cost and to gain more operation profit.

It is certain that the reluctance of adopting high speed machining as we have witnessed on the shop floor, besides 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 massively manufactured. For productions in small batches, a long auxiliary time and the 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, but they are brittle. In general, it is not economical to use expensive cutting tools during those machining operations where the vibratory motion of tool during machining is severe. Especially, during intermittent machining operations, the impact between the tool and workpiece leads to premature tool failure, increasing the tooling cost dramatically.

- A new and advanced machine tool may be needed to carry out high speed machining [11]. For example, setting cutting speed at 160 m/min for a part with diameter equal to 50 mm may require that the machine tool be able to reach a spindle speed equal to 1019 rpm, which is available for most universal lathes 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 the present universal lathes. We may need to purchase a new and advanced lathe which can meet this spindle speed requirement. 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 application example studies if a new investment is appropriate to buy a new machine tool to adopt high speed machining for the production of the part shown in Fig. 2.

With reference to th previous case study and the first application example, the difference of the operation profit on a monthly basis between the two operation plans is equal to ($45007 - $42882) = $2125, which is equivalent to $25500 on a yearly basis. This difference represents the gain from adopting the new technique of high speed machining to manufacture the part. Assume that the time duration of this production is on a five-year term. The following list provides net cash flows, at three different interest rates, regarding the additional profit gained annually.

End of Year	Additional Gain annual	Present Value interest: 10%	Present Value interest: 15%	Present Value Interest: 20%
1	$25500.00	$23181.82	$22173.91	$21250.00
2	$25500.00	$21074.38	$20158.10	$17708.33
3	$25500.00	$19158.53	$18325.55	$14756.94
4	$25500.00	$17416.84	$16659.59	$12297.45
5	$25500.00	$15833.49	$15145.08	$10247.88
	Total:	$96665.06	$92462.23	$76260.60

By examining the calculations displayed above, the fundamental meaning of the net cash flow at a specific interest rate is clear. For example, when the cost of purchasing a new machine tool for using high speed machining is equal to, or less than, the amount of $96665.06 and if such an amount of money can be borrowed at an interest rate 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 at a rate of 20%, the investment should be kept below $76260.60 in order to maintain the profitability of using high speed machining.

6 Framework of an Expert System

The decision makers of machining operation planning today, both production engineers and shop managers, are confronted with constraints from both 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 about both physical and economic aspects of machining operations is critical, and a good method to make this knowledge explict and useful are important to manufacturing practice. Knowledge-based expert system approach from artificial intelligence research is among the most promissing new techniques in this research area. 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 paper has been used as a framework in the development of an expert system for the machining operation planning.

Figure 6 illustrates the architecture of a prototype system developed in this research. This prototype system is divided into three parts, the knowledge base, the reasoning system, and a working memory. The knowledge base consists of a large set of decision rules and a database which contains relevant domain facts. The decision rules in our system are acquired through a combined simulation and inductive learning process, instead of interviewing manufacturing experts for personal experience, which is usually biased [12-13]. 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 induced decision rules. Table 3 provides a typical set of induced 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 information posted in the working memory, which contains mainly numerical data retrieved from the database, will vary dynamically in size at run time. For example, the attribute-value elements for the evaluation of inventory cost stored in the database only have unit holding cost, ordering cost, and transportation cost prior to the running time. Upon these elements being actuated during the decision-making process, a mathematical expression of the required inventory model can be generated in the working memory through the inference procedure in our system 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 knowledge base developed in this research has been proven effective during the decision-making process because all the provided knowledge has its root on the physics of the manufacturing and managerial domains. The knowledge is much reliable and consistent than those obtained through traditional interview processes.

The reasoning system consists of six independent modules which operate cooperatively under proper control during problem solving. 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. As a result, meaningful and practical plans are generated within a confined feasible space in the manufacturing domain. The production management module integrates managerial considerations to the decision-making process by adding financial constraints through costing 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 by him or her. 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 cooperatively 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 as a framework for designing an expert system has been witnessed since the prototype system put into use for industrial consultation. It successfully assists both production engineers and managers during the decision-making process [12-13]. By augmenting the knowledge base with so-called experience-based 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[14-15].

7 Conclusions

A new methodology for the economic evaluation of machining operation planning has been developed and applied in an expert system development. By integrating the manufacturing system and the management system together, the derived operation plan not only technically assures the satisfaction of required specifications for the machined part, but also economically utilizes the labor, material, and working capacity to manufacture the part.

Costing analysis plays a central role in the economic evaluation. The unit variable cost reflects the spending distribution between the 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 setting cutting parameters with great care.

The economic benefit of adopting high speed machining has been studied. Emphasis has been given to the evaluation of the fix 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 to gain additional profit. A method of economic review of a new investment when adopting new and advanced technology into the machining operation has been proposed and its applicability is demonstrated through a practical example.

The framework design of an expert system has to be relied on a 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 Intelligent research. Such collaborative efforts will certainly promote the evolution of production automation to improve the product quality and productivity for the entire manufacturing community.

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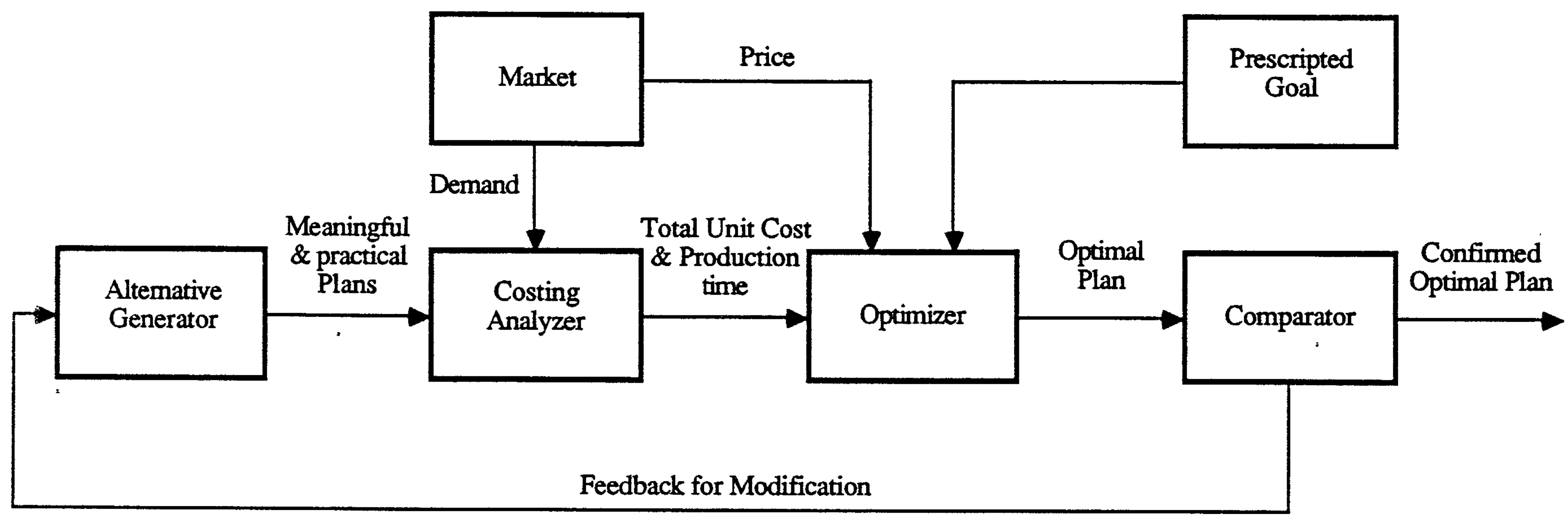

Figure 1 Basic Structure of Machining Operation Planning

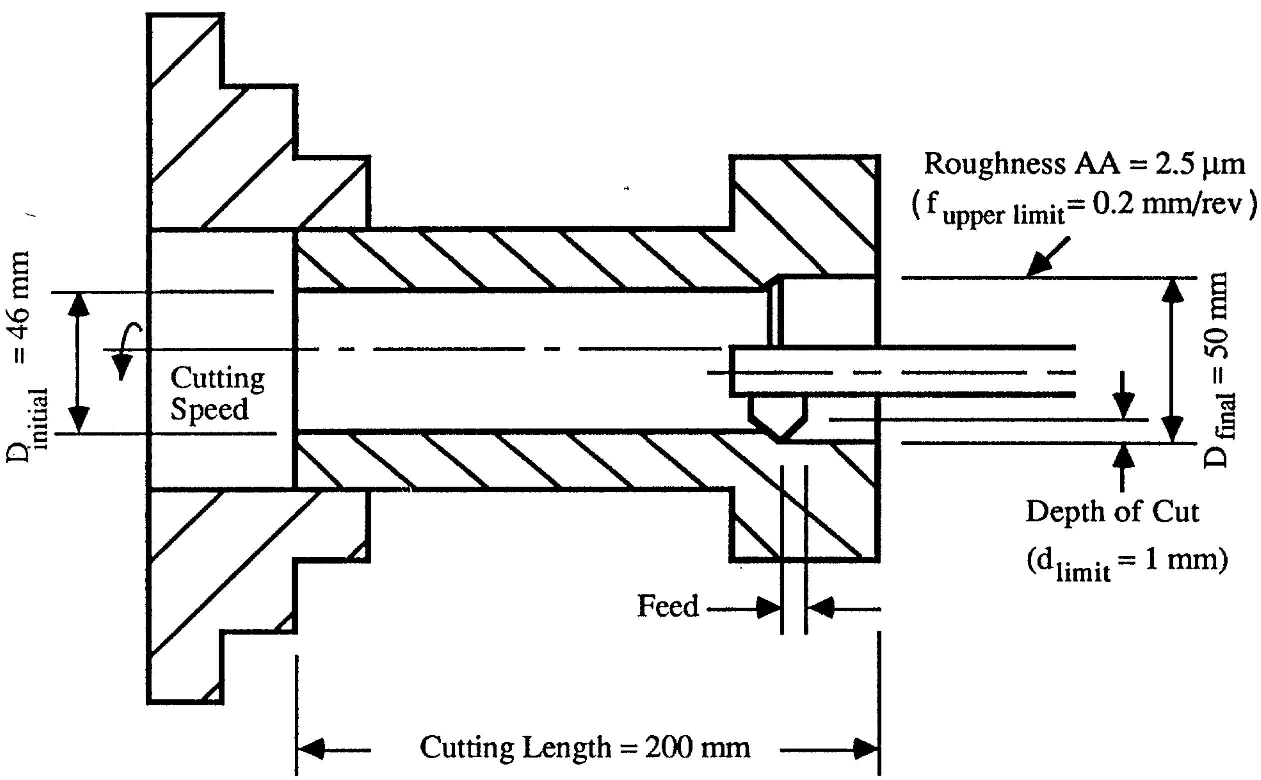

Figure 2 Demonstration Example - A Boring Machining Operation

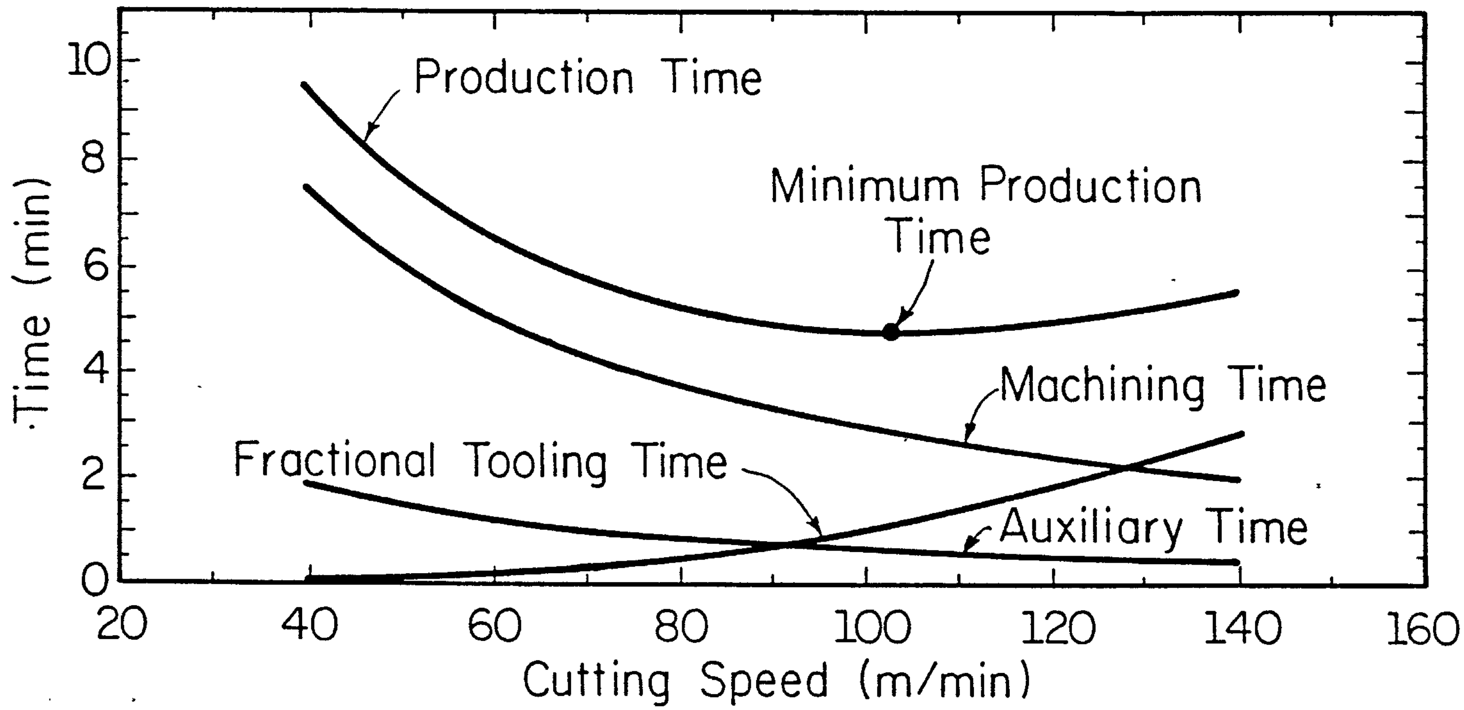

Figure 3 Production Time as a Function of Machining Time, Fractional Tooling Time, and Auxiliary Time

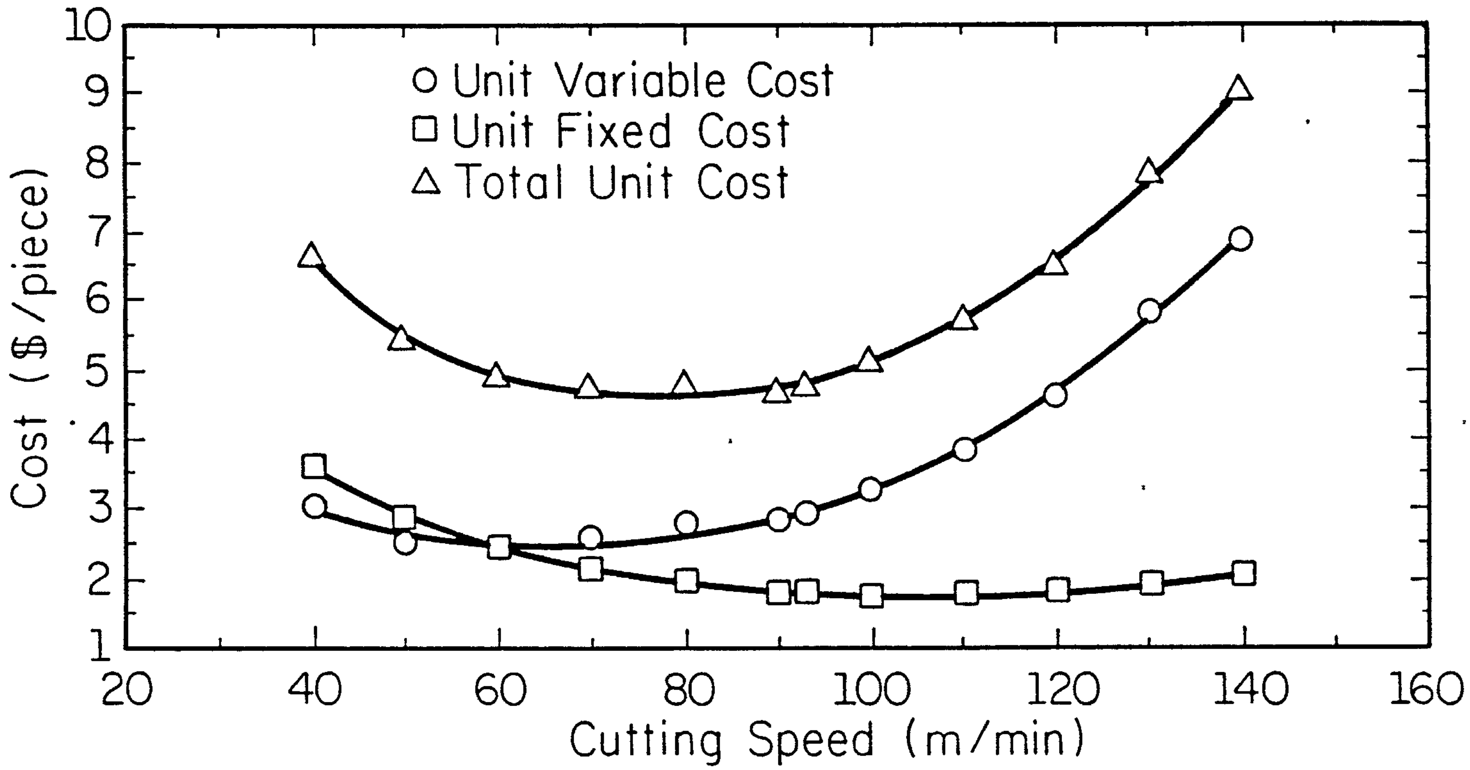

Figure 4 Costing Analysis of the Machining Operation

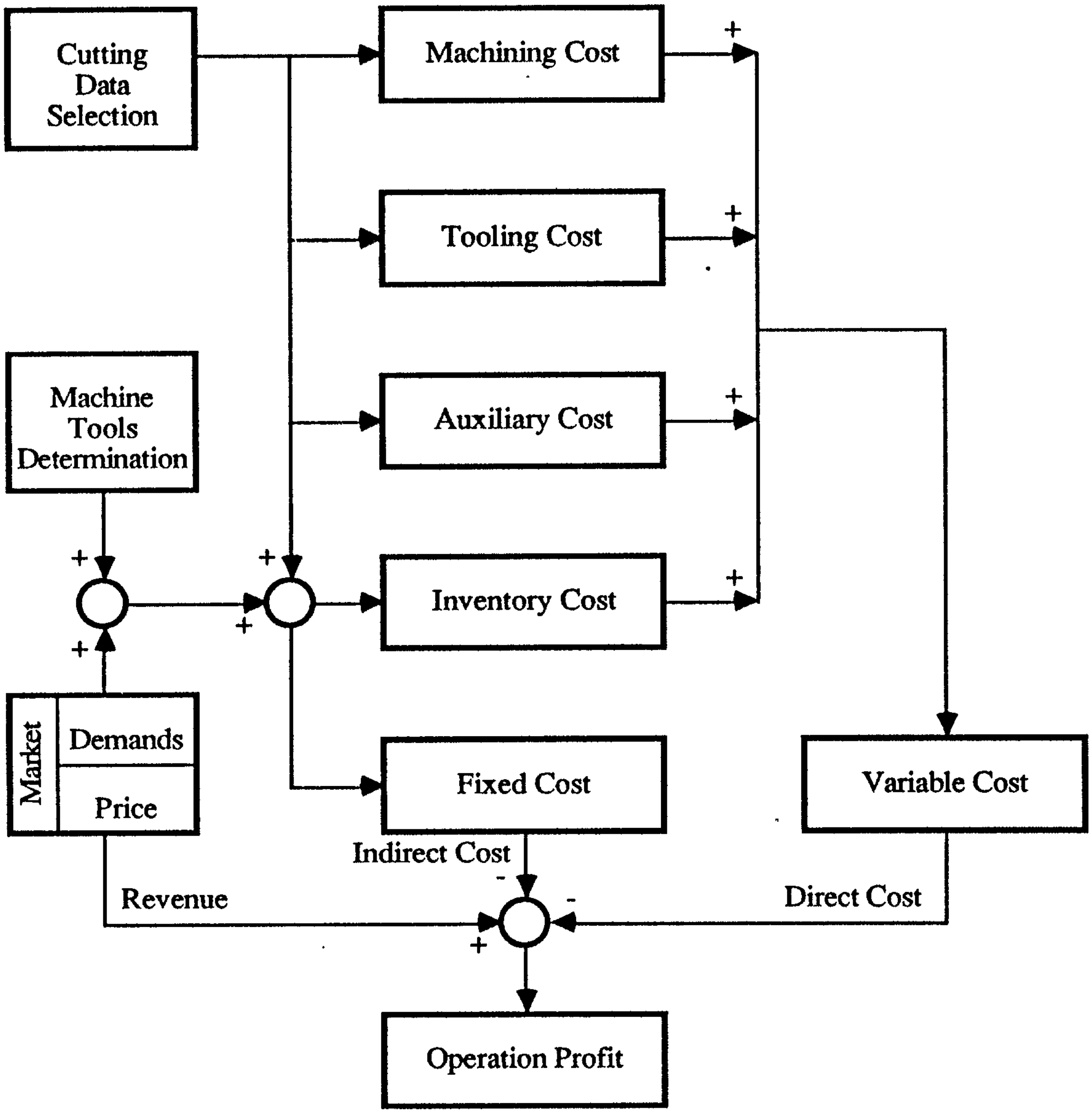

Figure 5 Profit as a Function of Revenue and Cost for the Machining Operation

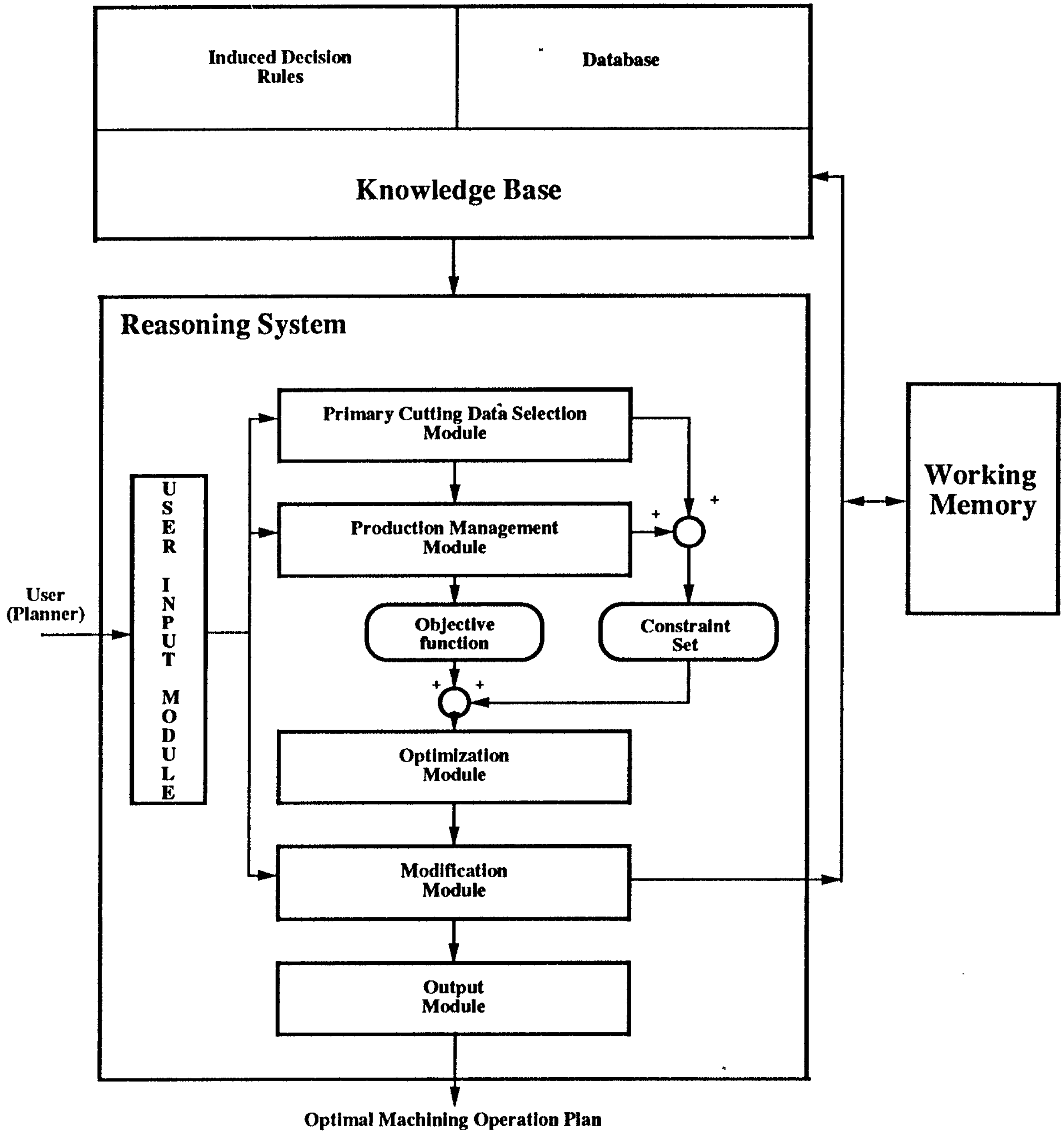

Figure 6 Framework for Designing the Prototype Expert System

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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)	Fra. Chan. 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)
40	7.54	0.07	1.89	9.50	4	4420	2.26	0.14	0.57	0.10	3.07	3.62	6.69
50	6.03	0.13	1.51	7.67	3	4104	1.81	0.27	0.45	0.03	2.56	2.92	5.48
60	5.02	0.24	1.26	6.52	3	4830	1.51	0.46	0.38	0.17	2.52	2.48	5.00
70	4.30	0.38	1.08	5.76	3	5466	1.29	0.75	0.32	0.27	2.63	2.19	4.82
80	3.77	0.57	0.94	5.28	3	5964	1.13	1.11	0.28	0.33	2.85	2.01	4.86
90	3.35	0.81	0.84	5.00	2	4200	1.01	1.58	0.25	0.05	2.89	1.90	4.79
100	3.01	1.10	0.75	4.86	2	4320	0.90	2.17	0.23	0.07	3.37	1.85	5.22
110	2.74	1.47	0.69	4.90	2	4284	0.82	2.89	0.21	0.07	3.93	1.87	5.86
120	2.51	1.91	0.63	5.05	2	4158	0.75	3.75	0.19	0.04	4.73	1.92	6.65
130	2.32	2.43	0.58	5.33	3	5907	0.70	4.77	0.17	0.32	5.96	2.03	7.99
140	2.15	3.03	0.54	5.72	3	5505	0.65	5.90	0.16	0.27	6.98	2.18	9.16

Table 2 Evaluation of the Production Time and Total Unit Cost for the Comparison (TIC-Coated Tool)

Cutting Speed (m/min)	Machining Time (min)	Fra. Chan. Time (min)	Auxiliary Time (min)	Production Time (min)	Number of Machine Tools	Products Manufac-tured	Machining Cost (Dollars)	Tooling Cost (Dollars)	Auxiliary Cost (Dollars)	Unit Inven-tory Cost (Dollars)	Unit Varia-ble Cost (Dollars)	Unit Fixed Cost (Dollars)	Total Unit Cost (Dollars)
140	2.15	0.09	0.54	2.78	2	3773	1.29	1.29	0.32	0.47	3.37	1.59	4.96
150	2.01	0.10	0.50	2.61	1	4017	1.21	1.42	0.30	0.01	3.03	1.49	4.52
160	1.88	0.11	0.47	2.46	1	4258	1.13	1.55	0.28	0.06	3.02	1.41	4.43
170	1.77	0.12	0.44	2.33	1	4492	1.06	1.69	0.26	0.11	3.12	1.34	4.46
180	1.67	0.13	0.42	2.22	1	4729	1.00	1.83	0.25	0.15	3.23	1.27	4.50
190	1.59	0.14	0.40	2.13	1	4953	0.95	1.98	0.24	0.19	3.36	1.21	4.57
200	1.51	0.15	0.38	2.04	1	5172	0.91	2.09	0.23	0.23	3.46	1.16	4.62

Table 3 Induced Decision Rules for Rough Machining Operations (a mathematical model to describe the boring operation was 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	=	.41 v .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	=	.41 v .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)]
	[RAKE ANGLE	=	-5 v 0 v 5	(degree)]
	[ROUGHNESS AA	=	1.27 .. 2.95	(μm)]
	[METAL REMOVAL RATE	=	27.4 ..55.8	(cm^3/min)]