

Development of a QFD-based expert system for CNC turning centre selection

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Abstract Computer numerical control (CNC) machine tools are automated devices capable of generating complicated and intricate product shapes in shorter time. Selection of the best CNC machine tool is a critical, complex and time-consuming task due to availability of a wide range of alternatives and conflicting nature of several evaluation criteria. Although, the past researchers had attempted to select the appropriate machining centres using different knowledge-based systems, mathematical models and multi-criteria decision-making methods, none of those approaches has given due importance to the voice of customers. The aforesaid limitation can be overcome using quality function deployment (QFD) technique, which is a systematic approach for integrating customers' needs and designing the product to meet those needs first time and every time. In this paper, the adopted QFD-based methodology helps in selecting CNC turning centres for a manufacturing organization, providing due importance to the voice of customers to meet their requirements. An expert system based on QFD technique is developed in Visual BASIC 6.0 to automate the CNC turning centre selection procedure for different production plans. Three illustrative examples are demonstrated to explain the real-time applicability of the developed expert system.

Keywords CNC turning centre · Expert system · Multi-criteria decision-making · Quality function deployment

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Introduction

Machine tools have been around since the industrial revolution, extensively used to manufacture parts/components of machines, which is a process of selectively removing material to create a desired shape. They are capable of producing parts/components of different shapes and sizes, having simple to complex contours. These days' products are becoming much more complex, and difficult to design and manufacture. Hence, the manufacturing organizations are forced to develop and adopt new technologies to avoid long design and machining time for complex products. So, machine tools have been gradually evolved out over the past few decades to meet the increasing demand of manufacturing complicated components with high degree of accuracy in large volume. The computer numerical control (CNC) machine tools are now being extensively applied for automated machining operations to help in achieving faster production rate with decreased human involvement and effort. Development of CNC machine tools is a great contribution to the manufacturing domain as automation of the machining process with flexibility to handle small to medium batch quantities in part production now becomes possible. This CNC technology can be applied to milling, turning, grinding, boring, drilling machines, flame cutters, etc. The CNC as the name suggests is equipped with computers that help in organizing and restoring information to attain high accuracy and speed in part production. Its basic aim is to achieve the desired objectives of the manufacturing organizations within the limited available budget. In an industrial setting, CNC machine tools can be combined into entire cells of tooling machines that can operate independently of each other. They are often driven by completely digital designs, which eliminate the need for design blueprints to be physically drawn up. All the CNC

machines are able to accurately control motions in multiple directions, and hence, can generate complex contours and shapes on the workpieces with higher dimensional accuracy and precision. Many of them are capable of running for several days without human intervention. These automated features of CNC machine tools make it possible to produce thousands of identical parts/components with minimal supervision, and allow the operators to perform other tasks thus saving a lot of time. Besides this, they can also produce parts/components with a level of accuracy that can be nearly impossible to attain using the older tools. This improved accuracy can help eliminate waste due to production of less defective parts. Features, like automatic tool and job change, etc. substantially reduce the machining time, thereby trimming down the total production cost at the end. The CNC machine tools, capable of performing repetitive complicated and unsafe machining operations, become highly productive and cost effective, thus gaining wide acceptance in manufacturing industries. A manufacturing organizations' productivity is directly related to the proper choice of its CNC machine tools as their proper use can increase the overall production while effectively utilizing the available resources and reducing the chance of human injury. Although CNC machine tools are highly productive and flexible, they are also quite expensive to procure, install and maintain. However, their ability to enhance productivity can easily offset the huge initial investment if they are properly evaluated and selected. Hence, it is an important decision for the production planners to choose the most appropriate CNC machine tool among various available alternatives to fulfil the organizational requirements.

The CNC machine tool selection process is focussed on fulfilment of two basic requirements, i.e. (a) boundary (fixed) conditions, and (b) performance expectations (desired results). For a CNC machine tool, the boundary conditions include spatial constraints, range of spindle speed, etc. whereas, performance expectations comprise positional accuracy, repeatability, capability to generate complicated parts, etc. Once these conditions and expectations are identified and prioritized, the most appropriate CNC machine tool that meets the basic application requirements can be easily selected. Choosing the best suited CNC machine tool from a wide range of similar alternatives is a complex and time-consuming task as it involves consideration of a large number of qualitative and quantitative factors, such as capital cost, table area, three axes movement, power, spindle speed range, machining diameter and length, tool capacity, flexibility, safety, etc. which are sometimes interrelated to each other. Technical brochures can effectively convey various machine features/specifications and some level of technical performance data, but they do not provide true comparisons with the

other competing machines. So, lack of accurate information is another problem faced by the production planners while selecting a CNC machine tool for a specific application. The production planners also need to analyse huge amount of raw data consisting of many interrelated factors for proper and effective evaluation of available CNC machine tool alternatives, which involves human expertise in a particular domain. But, human expertise is scarce, and it may not be always possible to analyse a large amount of data and crucial details of a problem. Moreover, it has limited working memory, and hence, cannot comprehend the data quickly. These shortcomings can be overcome while developing a database containing the technical specifications of various CNC machine tools, which can be updated from time to time. The database can then be integrated with an expert system to ease out and automate the CNC machine tool selection process. A selection procedure is not a simple task, but rather a sequence of interdependent activities that must take into consideration the customers' requirements, manufacturing economics, design expectations and above all, human safety. Thus, there is a need for a systematic and rational approach that can aid in solving the CNC machine tool selection problem, avoiding human intervention and expertise. In this paper, an expert system based on quality function deployment (QFD) technique is developed in Visual BASIC 6.0 to automate the CNC turning centre selection procedure for three different production plans, i.e. flexible, mass and tailor made (customer specific). The database containing the technical specifications of more than 200 CNC turning centres is developed in MS-Access. The QFD technique is augmented to systematically integrate the needs of customers with various engineering or technical characteristics and derive the priority weights for different technical requirements while evaluating the feasible CNC turning centres. Three numerical examples are illustrated to demonstrate the applicability of the developed QFD-based expert system for CNC turning centre selection.

The rest of the paper is organized as follows. A literature review on the past researches is provided in Sect. 2 and QFD methodology is explained in Sect. 3. Section 4 describes the development procedure of QFD-based expert system for CNC turning centre selection. Three illustrative examples are provided in Sect. 5, and in Sect. 6, final conclusions are drawn.

Literature review in machine tool selection

Till date, many studies have been reported in the literature on solving machine tool selection problems using diverse multi-criteria decision-making (MCDM) methods, mathematical models and knowledge-based systems. Sun (2002)

applied data envelopment analysis (DEA) to assess 21 CNC machines with respect to their technical and cost factors. Sensitivity analysis with variable variation and weight restrictions identified six CNC lathes as ‘good buys’ to be subsequently recommended for further consideration. Yurdakul (2004) presented a new strategic justification tool employing analytic hierarchy process (AHP) and analytic network process (ANP) which were applied to calculate the contribution of machine tool alternatives to manufacturing strategy and rank them based on the developed hierarchical structures. Ayağ and Özdemir (2006) introduced triangular fuzzy numbers in pair-wise comparison of the AHP matrix to overcome the vagueness and uncertainties in judgments of the decision makers in the conventional AHP method while evaluating machine tool alternatives. Ayağ (2007) integrated AHP method with simulation technique to determine the best machine tool satisfying the needs and expectations of a manufacturing organization. The AHP method was adopted to narrow down the list of feasible machine tool alternatives and a simulation generator was then used to automatically model the manufacturing organization. Durán and Aguilo (2008) developed a fuzzy AHP-based software for evaluation and justification of machine tools. Önüt et al. (2008) proposed a combined fuzzy AHP and fuzzy technique for order preference by similarity to ideal solution (TOPSIS) for machine tool selection, while incorporating triangular fuzzy numbers in the traditional AHP and TOPSIS methods. Dağdeviren (2008) integrated AHP and preference ranking organization method for enrichment evaluation (PROMETHEE) for equipment selection. The AHP method was applied to analyse the structure of the selection problem and determine the criteria weights, whereas, PROMETHEE method was employed to obtain the final ranking of the alternatives. Yurdakul and İç (2009) discussed about the benefits of using fuzzy numbers instead of crisp numbers in a TOPSIS method-based machine tool selection model. İç and Yurdakul (2009) developed a decision support system (DSS) using extended versions of MCDM approaches, like fuzzy AHP and fuzzy TOPSIS to help the decision makers in machining centre selection decisions. Qi (2010) developed a comprehensive evaluation model for machine tool selection and applied fuzzy integral approach for aggregation of performance scores of the alternatives with respect to different criteria. Ayağ and Özdemir (2011) proposed an intelligent approach for machine tool selection using fuzzy ANP to consider the vagueness and uncertainty existing in the importance attributed to judgment of the decision maker. Özgen et al. (2011) presented a combined application of modified DELPHI method, AHP and PROMETHEE approaches with fuzzy set theory for solving machine tool selection problems. İç (2012) applied an integrated TOPSIS and design of experiments approach to

solve a CNC machine tool selection problem in a real-time industrial environment. İç et al. (2012) developed a component-based machining centre selection model based on AHP, which would use only the technical specifications while evaluating the machining centre components. Ilangkumaran et al. (2012) developed an evaluation model based on AHP and VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) methods under fuzzy environment for selection of the best machine tool among various alternatives. Taha and Rostam (2012) developed a DSS to select the best alternative machine tool using a hybrid approach of fuzzy AHP and PROMETHEE methods. Ayağ and Özdemir (2012) applied ANP together with the modified TOPSIS method for performance analysis on machine tools. Furthermore, a fuzzy ANP approach was adopted to deal with the imprecise and uncertain human comparison judgments. Samvedi et al. (2012) integrated fuzzy AHP and grey relational analysis (GRA) approaches for selection of a machine tool from a given set of candidate alternatives. Fuzzy AHP was applied to calculate the criteria weights followed by GRA method to rank the alternatives. Aghdaie et al. (2013) applied step-wise weight assessment ratio analysis (SWARA) and complex proportional assessment of alternatives with grey relations (COPRAS-G) methods for machine tool evaluation and selection. Dawal et al. (2013) presented a simple approach for multi-attribute-based selection of machine tools using fuzzy AHP and TOPSIS methods. Tho et al. (2013) integrated intuitionistic fuzzy entropy and TOPSIS method to deal with the vague information in the decision-making process for machine tool selection. Nguyen et al. (2014) presented a hybrid approach integrating fuzzy ANP and COPRAS-G methods for evaluating machine tools with consideration of interactions between the considered attributes. Xin et al. (2014) proposed an optimal machine tool selection approach based on interval-valued fuzzy C-means clustering algorithm. Sahu et al. (2015) applied VIKOR method for determining a compromise ranking list of five alternative CNC machine tools while considering 21 subjective evaluation criteria.

A comparative study between various MCDM techniques that had been used in the past and the developed QFD-based model to solve the machine tool selection problems is provided in Table 1. It can be observed from the literature that the earlier MCDM methods as applied for machine tool selection are unable to take into account the voice of customers in the evaluation process. But, the customers’ requirements have an immense importance in the present-day manufacturing scenario where there is an enormous competition to capture every single percentage of market share available, which is primarily driven by an organization’s ability to satisfy its customers. Further, it is also realized that till date, no



Table 1 Comparative study between different MCDM methods used for machine tool selection

Method	Flexibility	Operational approach	Computational time	Complexity	Decision maker's involvement	Compensatory nature	Type of data
AHP	High	Pair-wise comparison	Very high	Very high	Very high	Yes	Ordinal
ANP	High	Pair-wise comparison	Very high	Very high	Very high	Yes	Ordinal
PROMETHEE	Moderate	Pair-wise comparison	High	High	Very high	No	Mixed
GRA	High	Grey system	Moderate	Moderate	Moderate	Yes	Mixed
DEA	Very low	Efficiency measurement	Very high	High	No	No	Cardinal
TOPSIS	Low	Euclidean distance	Moderate	Moderate	Moderate	No	Cardinal
VIKOR	Low	Euclidean distance	High	Moderate	Moderate	No	Cardinal
QFD-based expert system	High	Pair-wise comparison	Very low	Moderate	Low	Yes	Mixed

attempt has been made to interrelate the technical requirements of various machine tools with the corresponding customers' requirements. Moreover, the MCDM methods that had been previously applied to select machine tools have one or more inherent drawbacks. Like, in AHP and ANP methods, huge mathematical calculations are involved, and if there is any ambiguity or uncertainty in the pair-wise comparison matrix, the reliability of the derived solutions is itself questionable. Similarly, TOPSIS method introduces two reference points, i.e. positive ideal and negative ideal solutions, but it does not consider the relative importance of the distances of the alternatives from those two points. It signifies that the selected alternative may not always be the best solution (i.e. closest to the ideal solution). PROMETHEE method is based on some preference functions and in most of the real-time situations, the decision maker faces a problem in selecting the most appropriate preference function. VIKOR method is more time consuming as the final decision is to be compromised taking into consideration two other factors as acceptable advantage and acceptable stability of the decision. On the other hand, DEA comprises of too many lengthy computations and cannot often be solved manually. The decision maker needs to have some soft skills in computer programming for performing such calculations. These drawbacks of MCDM methods previously adopted for machine tools selection can be effectively addressed while developing a QFD-based expert system, which can not only incorporate the customers' requirements into the selection process but also interrelate them with the technical requirements. It is

also supposed to be superior to other MCDM methods on its ability to deal with the dynamic nature of the decision-making problems. Hence, in this paper, a user-friendly software prototype with graphical interface in Visual BASIC 6.0 is developed to help the production planners in selecting the best CNC turning centre to meet the dynamic requirements of a specific production system and accomplish the managerial benefits of an automated selection procedure.

QFD methodology

In this era of global competition, the success of any organization depends on its ability to understand and meet the ever changing needs of the customers. QFD methodology is now being recognized as an efficient technique to deal with the voice of customers which includes the customers' needs for a product, customers' perceptions on the relative importance of those needs, and the relative performance of the manufacturing organization and its main competitors on those needs. QFD basically consists of two components, i.e. quality and function, which are deployed in the design process. The quality deployment brings customer's voice into the design phase, whereas, function deployment links different organizational functions and technical requirements in the design to manufacturing. It is a focused methodology for carefully listening to the voice of customers, and then effectively responding to those needs and expectations, thereby attaining the highest customer satisfaction. It is employed to translate the customers' requirements, in terms of engineering or technical

characteristics, that can be deployed through product planning, process planning, service design and part development.

This quality improvement tool was developed in late 1960s in Japan by Akao who is regarded as the father of QFD and was first implemented at the Mitsubishi Heavy Industries Kobe Shipyard in 1972 under the guidance of Shigeru Mizuno and Yasushi Furukawa (Akao 1990). Ford Motor Company, Toyota, Procter and Gamble, Mitsubishi, Campbell's soup, Hewlett-Packard, Kodak, IBM, Xerox and 3M Corporation were among the early adopters of QFD methodology. Chan and Wu (2002) reviewed the implementation of QFD technique in different organizations, such as shipbuilding, automobiles, electronics, software, banking and accounting, health care, education and research, retail outlets, apartment layouts, airline services, office equipment, consumer products, financial services, telephone services, gas and electrical services, distribution networks, traffic management, food industry, fishing industry, chocolate industry, online gaming, hot bar soldering, etc. It is observed that the above-mentioned applications are for product and process development, but lately, QFD has also been applied for selection of suppliers (Bevilacqua et al. 2006; Bhattacharya et al. 2010; Shad et al. 2014), non-traditional machining processes (Chakraborty and Dey 2007), industrial robots (Karsak 2008), product design and development (Liu 2011; Soota et al. 2011) and materials (Mayyas et al. 2011; Prasad and Chakraborty 2013). QFD is such a systematic, robust and practical quality improvement tool that apart from the above-cited domains, it has also been applied in some unconventional fields, like game of soccer (Partovi and Corredoira 2002).

QFD understands how the customers or users become interested and satisfied with the end products. Customers' requirements and their relationships with the design characteristics are the driving force behind QFD methodology (Dursan and Karsak 2013). It can be used to translate subjective quality criteria into objective ones that can be quantified and measured. It is a complimentary method for determining how and where priorities are to be assigned in product or process development, and intelligently links the needs of the customers with the design and development of a product. There are three basic steps in implementing QFD methodology. At first, the spoken and unspoken wants or needs of the customers are prioritized. In the next step, those needs are translated into technical characteristics and specifications, and in the final step, a quality product or service is developed and delivered focusing everybody towards customer satisfaction.

QFD methodology can be adopted to process both qualitative and quantitative data. Its main merit over the other MCDM approaches is that it provides flexibility to

the decision makers to correlate both customer needs and engineering metrics through assigning scores and weights to them, and at the same time, it defines the direction of improvement for each metric which may be directly or inversely proportional to each other (Mayyas et al. 2011). QFD for a product is developed through brainstorming of a team, which comprises of six to eight persons, consisting of representatives from various cross-functional departments, like marketing, design, production, quality assurance, testing, purchasing, vendor, etc. The representatives from those cross-functional departments are collectively known as the QFD team, as shown in Fig. 1. The main advantage of this cross-functional group decision-making approach is that it takes opinions from the representatives of various departments and incorporates them into the product, leading to a better quality product and higher customer satisfaction. This also avoids any biasness and partiality in the decision-making process.

QFD employs a matrix format to capture a number of issues vital for the planning process. According to Dai and Blackhurst (2012), the overall process of QFD is based on its core matrix framework, called house of quality (HoQ), which is used to intertwine customers' needs, service design or management requirements, target design goals and competitive product or service evaluations (Sharma and Rawani 2008). Although, HoQ is the primary tool in QFD method, the statements or demands of the customers may not always be clear or comprehensible, therefore, some other tools are also required which can interpret and explain the voice of customers clearly. Thus, along with HoQ, seven other management and planning tools are used to identify and prioritize customers' expectations quickly

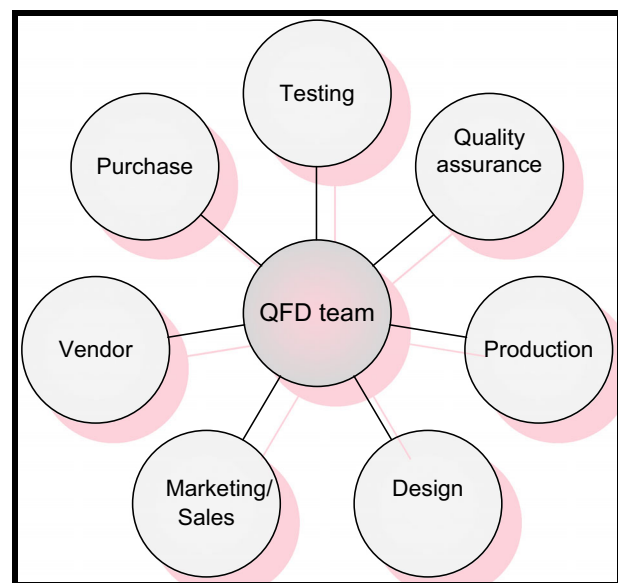


Fig. 1 A QFD team

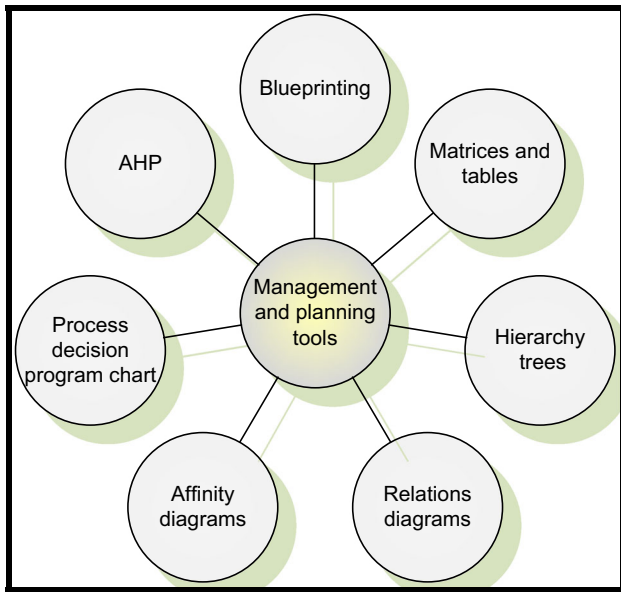


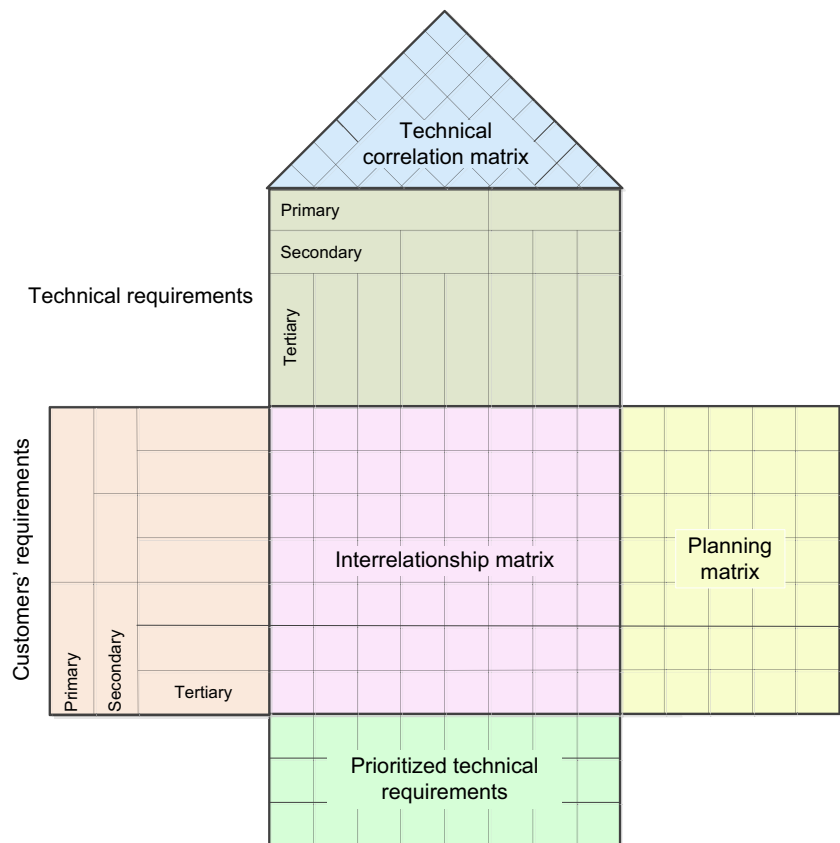
Fig. 2 Management and planning tools

and effectively. Figure 2 presents those seven management and planning tools, while the basic structure of HoQ matrix is shown in Fig. 3. HoQ translates the customers' requirements, based on marketing research and

benchmarking data, into an appropriate number of engineering targets to be met by a new product design. Basically, HoQ is the nerve centre and the engine that drives the entire QFD process (Raissi et al. 2012). The procedural steps involved in the development of HoQ matrix are described as below:

Step I In the first step, various market segments are determined and subsequently analysed to identify the potential customers. The QFD team then conducts customer surveys to accumulate the relevant information about customers' requirements or expectations from the product/service. The seven management and quality tools, i.e. affinity diagrams, tree diagrams, relations diagrams, matrices and tables, process decision program charts, AHP, and blueprinting are employed to analyse and categorise those information as primary, secondary and tertiary. The customers' requirements are then prioritized based on customers' choice and its relative importance to them using a 1–5 rating scale, where 1 having the least priority and 5 having the maximum priority. These customers'

Fig. 3 House of quality matrix



- requirements are placed on the left wall of HoQ matrix along the rows.
- Step II** In this step, the key performance indicators in an organization to achieve customer satisfaction are recognized. Additionally, regulatory standards and technical requirements dictated by the management are also identified. Further, these technical requirements are organized as primary, secondary and tertiary using different management and quality tools, and are arranged at the top of HoQ matrix along the columns.
- Step III** The interrelationship matrix, which shows the relationship between customers' requirements and technical requirements is now established and positioned at the centre of HoQ matrix. The relationship between pairs of customers' requirement and technical requirement is portrayed using symbols or numbers, termed as correlation index, as shown in Table 2.
- Step IV** The performance measures in the existing designs usually conflict with each other. The technical correlation matrix, which is more often referred to as roof matrix, shows the relationship between various technical requirements. This roof matrix also helps in establishing the interrelationship matrix, and identifies where the technical requirements must work together to avoid any design conflict.
- Step V** Once the roof matrix is constructed, the planning matrix measuring the performance of the organization with respect to its benchmarked competitive organization is developed. The performance of the organization is then ranked on a scale of 1–5, 1 being the least satisfying and 5 being the excellent performance. This matrix is set on the right side of the interrelationship matrix.

- Step VI** Finally, the priorities assigned to the technical requirements are recorded and compared to those of the benchmarked competitor according to the relative weight of each relationship. Then, these values are linked back to the customers' requirements to meet the new design requirements and are positioned at the bottom of HoQ matrix as prioritized technical requirements.

Development of a QFD-based expert system for CNC turning centre selection

The developed QFD-based expert system relates the dynamic requirements of the customers with technical specifications of CNC turning centres and then selects the most suitable machine based on the considered evaluation criteria. The basic framework for design and development of the QFD-based expert system is exhibited in Fig. 4. It has five basic modules, e.g. recognition of customers' requirements, identification of technical requirements, creation of the database, development of the expert system and evaluation of the alternatives to select the best CNC turning centre.

Based on a market survey using questionnaires and customers' feedback, the wants and needs of the customers related to CNC turning centres are first accumulated. These customers' voices are then prioritized using different management and planning tools. The 12 most important customers' requirements associated with the selection of CNC turning centres are detailed out as follows:

- (a) Allocated fund—It is associated with the initial acquisition cost and investment needed to procure and set up a CNC turning centre in a manufacturing organization. It also includes the expenditure made on installation of the said machine tool. An organization's objective is always to reduce the allocated fund and keep it as minimum as possible.
- (b) Availability of space—It is related to the total space occupied by a CNC turning centre with respect to its length, width and height dimensions. There are always some spatial constraints within the shop floor because of which machine tools having smaller overall dimensions are always preferred.
- (c) Capacity—This characteristic of a CNC turning centre deals with the maximum dimension, i.e. length, diameter and weight of the workpiece that can be machined. It is always better to have a CNC machining centre with higher capacity.
- (d) Productivity—It can be defined as the volume of workpieces machined by a CNC turning centre per

Table 2 Correlation index for interrelationship matrix

Number	Symbol	Relation
1		Very weak relation
3		Weak relation
5		Moderate relation
7		Strong relation
9		Very strong relation

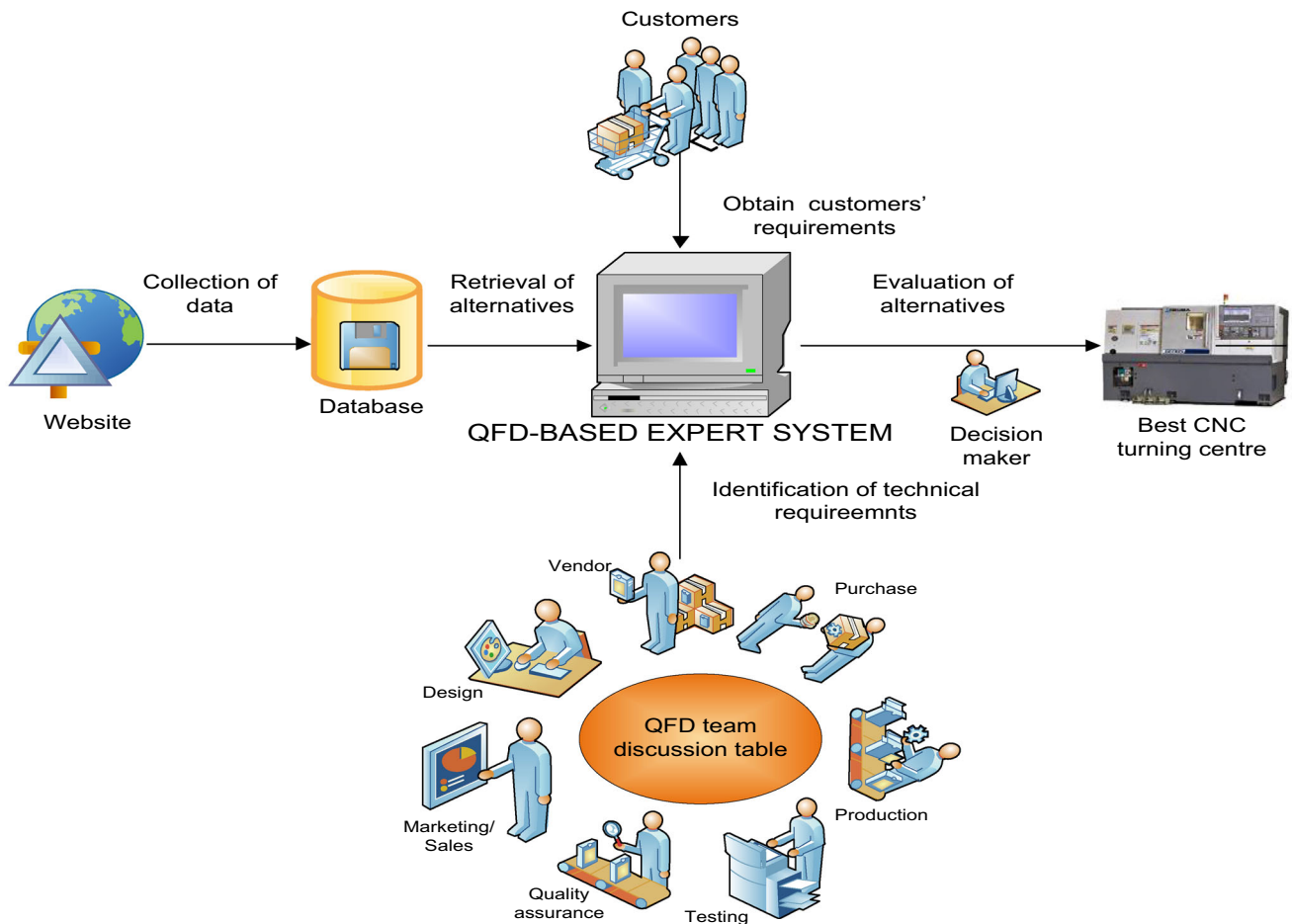


Fig. 4 Basic framework for development of QFD-based expert system

unit time. As productivity is directly proportional to a manufacturing organization's profit, it is always preferred to have highly productive CNC turning centres.

- (e) **Machining time**—It is the time taken by a CNC turning centre to machine a workpiece having the desired dimensions and shape. Less machining time reduces the lead time to market a product. So, a CNC turning centre which has less machining time is more beneficial for a manufacturing organization.
- (f) **Power requirement**—It deals with the power rating of a CNC turning centre, i.e. amount of power required to operate it. It is always beneficial to have machines which consume less power.
- (g) **Flexibility**—Flexibility of a CNC turning centre relates to its ability to deal with the changing part configurations to allow variations in part assembly and process sequence, and changes in production volume and product design. A manufacturing organization must be proficient to produce reasonably priced customized parts/components of higher

dimensional accuracy that can be quickly delivered to the customers.

- (h) **Ease of machine tool handling**—The CNC machine tool handling and changing task should be easy as it requires frequent human intervention. Easy machine tool handling makes it simple to respond to any change in the production plan.
- (i) **Auxiliary attachments**—These are the additional attachments provided with CNC turning centres to enhance their overall machining performance. For example, guards are added to increase operator safety, automatic tool and job changers are often provided to reduce human interference and total machining time, and turret may be equipped with multiple tool holders so that a range of different machining operations can be performed simultaneously.
- (j) **Surface finish**—It relates to the dimensional accuracy and smoothness of the workpiece surface machined by a CNC turning centre. This is also crucial from the aesthetics viewpoint of the product.



- (k) Generation of complicated parts—The CNC turning centres are able to accurately control motions in multiple directions, and hence, can generate complex shape contours on the workpieces with higher precision and accuracy. Therefore, a CNC turning centre which can easily machine complicated part geometries has an added advantage over the others.
- (l) Adaptability—It is associated with a CNC turning centre’s ability to adapt to new machining conditions. The CNC machines having this feature are favoured over the others to satisfy diverse customer requirements.

Next, an expert panel comprising of members from various departments of a manufacturing organization, like purchasing, production, testing, quality assurance, marketing, design, etc. is interviewed to obtain their opinions regarding the technical specifications of CNC turning centres. After critically analysing those specifications, 13 technical requirements are finally shortlisted based on their impact on the selection procedure, as enlisted below:

- (a) Area (mm²)—This specification of a CNC turning centre denotes the total space occupied by it on the shop floor. It is an important consideration in case of any spatial constraint within the shop floor.
- (b) Cost—It relates to the capital investment required to procure and install a CNC turning centre. A CNC turning centre having less initial capital investment is always preferred to that requiring higher capital outflow.
- (c) Height (mm)—It is one of the dimensions of a CNC turning centre. It actually measures the spread of the machine in vertical direction.
- (d) Maximum length (mm)—It refers to the maximum length of a workpiece that can be accommodated and machined on a CNC turning centre. This specification is related to the capacity of a CNC turning centre.
- (e) Maximum diameter (mm)—It is related to the maximum diameter of a workpiece that can be machined on a CNC turning centre. Like maximum length, it is also related to the capacity of the machine.
- (f) Maximum spindle speed (min⁻¹)—Rotations of the spindle of a CNC turning centre per minute is its spindle speed. It can be correlated to overall productivity and attainable surface finish.
- (g) Travel X-axis (mm)—It signifies the maximum length that the tool can move in X-direction.
- (h) Travel Z-axis (mm)—It indicates the maximum length that the tool can travel in Z-direction.

- (i) Rapid traverse X-axis (m/min)—It expresses the movement of the tool turret at the fastest rate in X-axis, requiring only an end point for this movement.
- (j) Rapid traverse Z-axis (m/min)—Similarly, rapid traverse Z-axis is the movement of the tool turret at the fastest rate in Z-axis direction.
- (k) Spindle motor power (kW)—It is the power rating of a CNC turning centre. It is directly related to the consumption of electrical power while running the machine.
- (l) Number of tools—It is the maximum number of tools that can be accommodated in a tool holding device of a CNC turning centre. More number of tools facilitates in generating complicated shapes on the workpieces and also reduces the total machining time.
- (m) Weight (kg)—It is another specification of a CNC turning centre indicating its overall weight. Machine weight is quite critical when a load limit exists on the shop floor.

Among all these technical specifications, cost of a CNC turning centre is expressed using a qualitative scale of 1–9. The actual range of cost (in USD) along with its scale values and interpretations is given in Table 3.

The detailed information and relevant data regarding the technical specifications of various CNC turning centres are accumulated from the brochures of different manufacturers available online. Then, these collected data for CNC turning centres are stored into MS-Access option of Visual BASIC 6.0. An exhaustive database containing technical specifications of more than 200 CNC turning centres is thus created.

The next stage involves in the development of the QFD-based expert system, which can be broadly divided into two phases. At first, the related HoQ matrix is constructed and the feasible alternatives satisfying the set criteria values are extracted from the database. The HoQ matrix developed here is a simplified one where technical correlation and

Table 3 Scale indicating range of cost for CNC turning centres

Cost (in USD)	Scale	Interpretation
25,000–30,000	1	Lowest
30,001–45,000	2	Very very low
45,001–60,000	3	Very low
60,001–70,000	4	Low
70,001–85,000	5	Medium
85,001–105,000	6	High
105,001–130,000	7	Very high
130,001–155,000	8	Very very high
155,001–180,000	9	Highest

planning matrices are not considered. Only the prioritized technical requirements are taken into account at the bottom of HoQ matrix. The customers' requirements and technical requirements are already identified, and they are placed on the left wall of HoQ matrix along the rows and at the top of HoQ matrix along the columns, respectively.

Once the customers' requirements and technical requirements are placed in HoQ matrix, the corresponding interrelationship matrix is developed. Three production plans, i.e. 'Flexible Production', 'Mass Production' and 'Custom' are provided to the production planners to choose the kind of interrelationship matrix to be developed to accommodate the dynamic demands of the customers. Flexibility is the measure of how fast a setup can convert its process(es) from making an old line of products to a new set of items. A flexible production plan is often required to permit low cost switching from one product line to another. This type of production plan can efficiently produce highly customized and unique products in varying volumes while utilizing CNC technology. Its use can reduce the need for human intervention and provide an infrastructure which can react quickly to deviations in the production plan. Consistent and better quality products, with lower cost can be produced using the same manpower while adopting a flexible production plan. While, mass production is the manufacturing of large volumes of standardized products, making many copies of the products very quickly, using assembly line techniques. It is often characterized by mechanization to achieve high volume output, efficient flow of materials through various stages of manufacturing, careful supervision of quality standards and minute division of labour. As there is a continuous flow of materials, there is no queuing at any stage of the production process. Supervision is also easy in case of mass production because only few instructions are necessary.

If any of the first two options is chosen, i.e. 'Flexible Production' and 'Mass Production', an automatically filled up interrelationship matrix with default values appears. On the other hand, if 'Custom' option is selected, the end user needs to fill up the interrelationship matrix based on the subjective judgments. The customers' requirements can be either beneficial (higher the better) or non-beneficial (lower the better), and are attributed by the value of the corresponding improvement driver (+1 for beneficial criteria and -1 for non-beneficial criteria). The next stage comprises of assigning priority weights to the requirements of the customers. For assigning priority values to customers' requirements, a scale of 1–5 is set, where 1—not important, 2—important, 3—much more important, 4—very important and 5—most important. After critically analyzing the relationship between customers' requirements and technical specifications of CNC turning centres, it is observed

that productivity is highly correlated to spindle speed, motor power and rapid traverse speed; whereas, area, height and weight of CNC turning centre have the least relationship with it. Similarly, it is also found that flexibility is strongly related to spindle speed and number of tools, while availability of space is highly interrelated with area and height. Furthermore, it is revealed that the allocated fund is greatly associated with cost of the CNC turning centre; whereas, machining time is strongly related to spindle speed, and rapid traverse in X- and Z-axes. Moreover, it is also noticed that power requirement is positively related to spindle motor power, but it is least influenced by maximum length and diameter of the work-piece, and travel in X- and Z-axes. Additionally, it is observed that number of tools considerably influences the capability of a CNC turning centre to generate complicated parts. The interrelationships between the remaining customers' requirements and technical requirements are subsequently developed similarly with values from an appropriate scale of 1–9, where 1—very very weak, 2—very weak 3—weaker, 4—weak, 5—moderate, 6—strong, 7—stronger, 8—very strong and 9—very very strong.

Once the HoQ matrix is filled up with all the necessary data, the 'Weight' functional key is pressed to obtain the priority weights of all the technical requirements, using the following equation:

$$w_j = \sum_{i=1}^n Pr_i \times ID_i \times \text{correlation index} \quad (1)$$

where w_j is the weight for j th technical requirement, n is the number of customers' requirements, ID_i is the value of improvement driver for i th customer requirement, Pr_i is the priority assigned to i th customer requirement and correlation index is the relative importance of j th technical requirement with respect to i th customer requirement. These weights are subsequently used for calculation of the performance scores of the feasible CNC turning centres.

The second phase of QFD-based expert system embarks with identifying the most important technical requirements based on which the end user wants to evaluate the candidate CNC turning centres. Once the desirable technical requirements are shortlisted by the end user, the range for each selected technical requirement needs to be specified. Depending on the given ranges of values for the shortlisted technical requirements, a list of feasible CNC turning centres is then extracted.

The final stage of the expert system consists of evaluating the feasible candidate alternatives to select the best CNC turning centre. In this stage, a final set of CNC turning centres that needs to be evaluated based on the set criteria is chosen from the list of feasible alternatives. A decision matrix comprising of the selected technical

specifications with respect to each chosen CNC turning centre is then developed. This decision matrix now needs to be normalized to make it dimensionless so that the performance of all the alternatives can be compared with respect to the set criteria. The following linear normalization procedure is adopted here.

For beneficial criteria (technical requirements for which weights are positive)

$$\text{Normalized value} = \frac{\text{Property value} - \text{Smallest value}}{\text{Highest value} - \text{Smallest value}} \quad (2)$$

For non-beneficial criteria (technical requirements for which weights are negative)

$$\text{Normalized value} = \frac{\text{Smallest value} - \text{Property value}}{\text{Highest value} - \text{Smallest value}} + 1 \quad (3)$$

The performance score for each CNC turning centre is now computed using the following equation:

$$\text{Performance score (PS}_i) = \sum_{j=1}^n w_j \times (\text{Normalized value})_{ij} \quad (4)$$

$(i = 1, 2, \dots, m; j = 1, 2, \dots, n)$

where m is the number of alternatives and n is the number of technical requirements. The weights for the selected technical requirements are automatically retrieved from the HoQ matrix. Based on these performance scores, the feasible CNC turning centres are ranked and a graphical representation showing the performance score of each CNC turning centre is automatically generated. The best performing CNC turning centre is finally identified and its detailed technical specifications are displayed along with its actual photograph.

Figure 5 exhibits a flowchart for the developed QFD-based expert system to help the end user to navigate through it properly. The procedural steps for running this software prototype are enlisted as below:

- Step I An opening window containing the guidelines to be followed by the end user for running the QFD-based expert system appears at first.
- Step II Once the guidelines are understood, the end user selects an option from the type of production plans and presses the ‘Next’ key. A HoQ matrix depending on the type of the production plan appears in a new window.
- Step III The customers’ requirements are identified as beneficial or non-beneficial while assigning appropriate improvement driver values.

- Step IV A priority value between 1 and 5 is assigned to each customer requirement.
- Step V Based on the type of production plan, an interrelationship matrix, either filled up or blank, appears. If it is blank, it needs to be filled up with necessary values, else proceed to the next step.
- Step VI The ‘Weight’ functional key is pressed to obtain the priority weights of all the technical requirements in the HoQ matrix.
- Step VII A set of evaluation criteria is chosen from the list of available technical requirements to finalize the selection decision.
- Step VIII The ‘Input Range’ functional key is pressed to generate empty cells to capture ranges of the selected criteria values within which the specifications of CNC turning centres should lie.
- Step IX All the feasible alternatives satisfying the given ranges of specifications are extracted by pressing ‘Feasible Alternatives’ key.
- Step X The end user then shortlists the final set of alternatives to be evaluated.
- Step XI The ‘Next’ key is pressed to automatically develop the corresponding decision matrix with the technical specifications of the finally selected alternatives with respect to the set evaluation criteria in a new window.
- Step XII The performance scores and ranks of the finally selected alternatives are computed after pressing the ‘Calculate Rank’ key.
- Step XIII The ‘Rank Analysis’ key is pressed to graphically display the performance score of each alternative.
- Step XIV The ‘Machine Details’ key is pressed to display the detailed technical specifications of the most appropriate CNC turning centre along with its actual photograph.

The interrelationship matrices for flexible and mass production plans are slightly different from each other. For example, presence of auxiliary attachments in a CNC turning centre makes it more flexible. This affects the overall cost of the machine more strongly in flexible production than mass production. In flexible production plan, the correlation indices between flexibility and all other technical requirements are high due to greater impact of these requirements on flexibility. Moreover, a large volume of finished products is required in mass production and hence, if the number of tools is more in a CNC turning centre, its productivity will also be high. Therefore, there exists a stronger relationship between productivity and number of tools in mass production than flexible

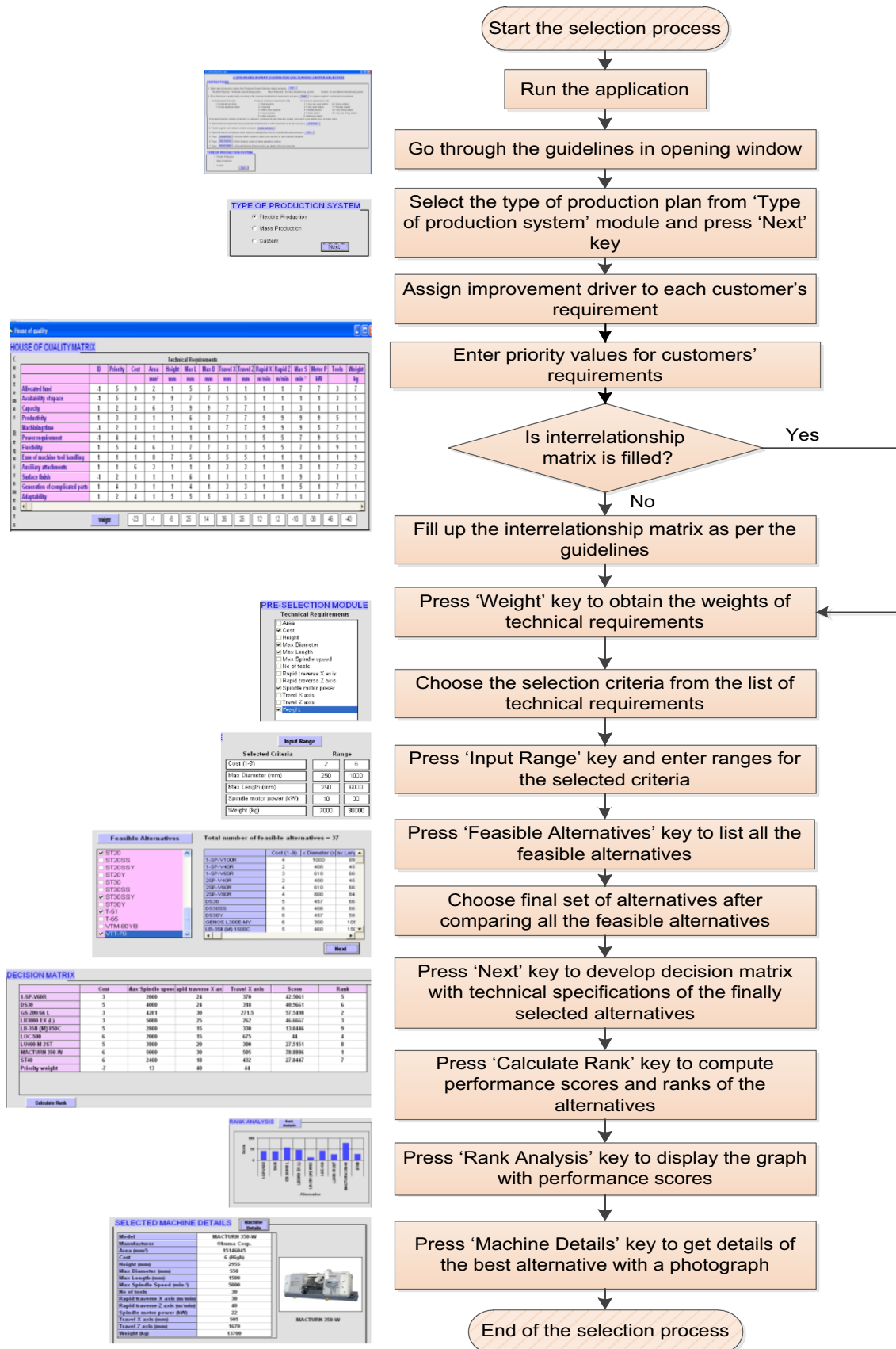


Fig. 5 Flowchart of the QFD-based expert system

production. Similarly, the capacity of a CNC turning centre for mass production should be such that it can accommodate more number of tools so that several machining operations can be performed simultaneously. Hence, capacity of the machine and number of tools are more strongly related in mass production than flexible production.

Illustrative examples

An Intel® Core™ i5-2034M CPU with 2.50 GHz, 4.00 GB RAM operating platform is required to run this QFD-based expert system. Three illustrative examples are provided to demonstrate its applicability. Figure 6 displays the instruction sheet, which first appears on the screen when this software prototype is run to assist the end user to get acquainted with it.

Example 1

In this example, the end user desires to select an appropriate CNC turning centre for a manufacturing system which is subjected to change in the type and volume of parts produced. A flexible production plan can only offer a variety of parts/products with rapidly changing production level as demanded by the customers. Taking this feature of

flexible production into account, ‘Flexible Production’ option is chosen from ‘Type of Production System’ module. On pressing the ‘Next’ key, the corresponding HoQ matrix with the filled up interrelationship matrix according to flexible production plan now appears in a new window, as shown in Fig. 7. The improvement driver and priority values for each customer’s requirement are then entered in their respective columns. The improvement driver value of –1 for ‘Allocated fund’, ‘Availability of space’, ‘Machining time’, ‘Power requirement’ and ‘Surface finish’ reveal that they are the non-beneficial attributes requiring minimum values. A priority value of 5 assigned to ‘Allocated fund’, ‘Availability of space’ and ‘Flexibility’ signifies that these customers’ requirements have the highest importance. On the other hand, a priority value of 1 for ‘Ease of machine tool handling’ and ‘Auxiliary attachments’ shows that they are not so much important to the customers in this case. The ‘Weight’ key is then pressed to derive the priority weight of each technical requirement present in the HoQ matrix. Next, depending on the end requirements of the final product, cost, maximum diameter, maximum length, spindle motor power and weight are shortlisted to finalize the CNC turning centre selection decision.

In the HoQ matrix, among the five criteria chosen for evaluation of CNC turning centres, negative priority weights for cost, spindle motor power and weight identify

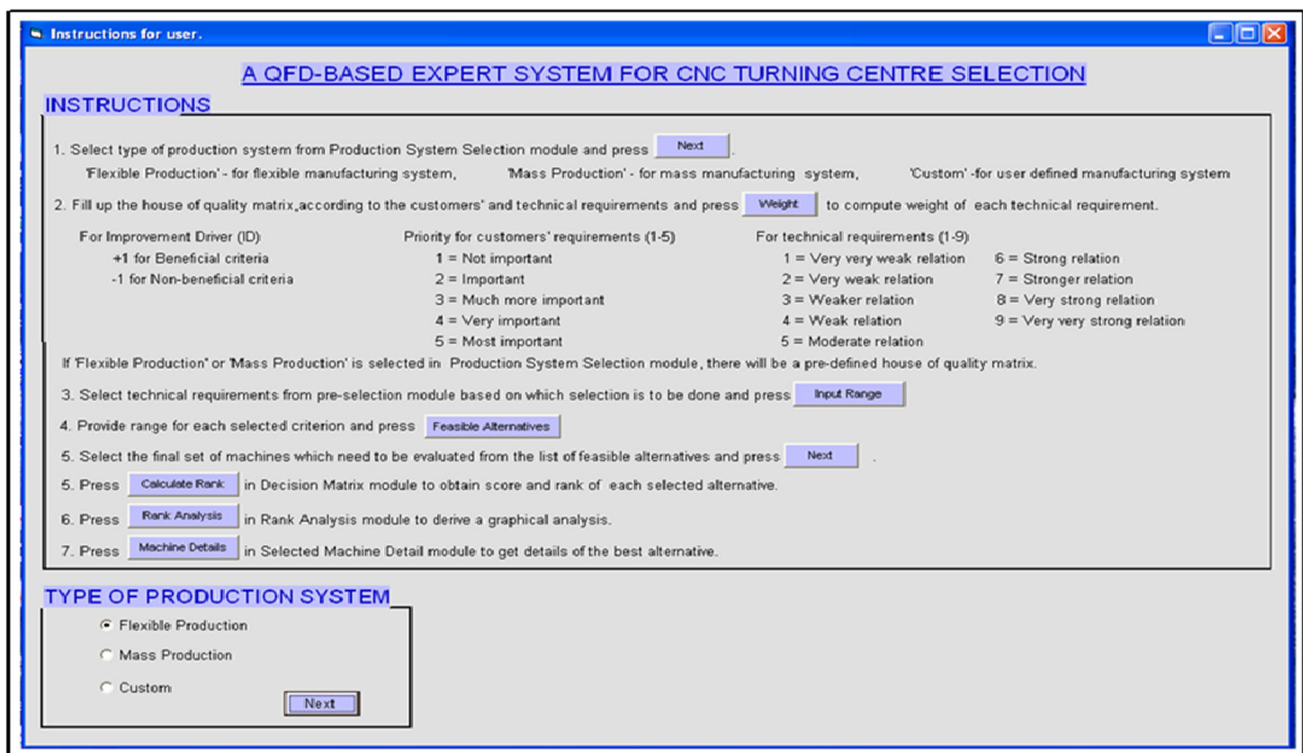


Fig. 6 Opening window having guidelines for the end user

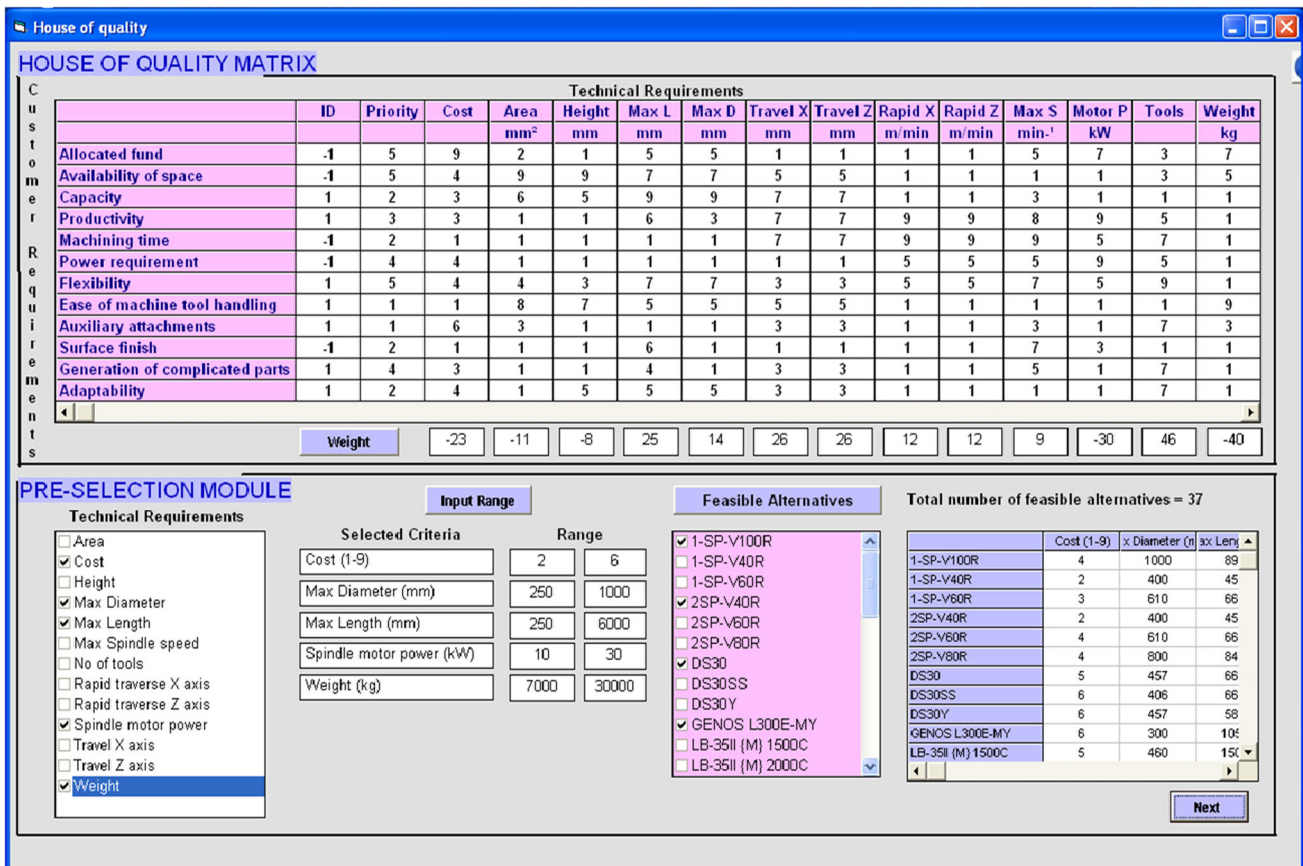


Fig. 7 HoQ matrix for flexible production plan

them as non-beneficial technical requirements. Now, pressing of the ‘Input Range’ key generates the necessary empty cells, where the ranges of values for the selected technical requirements are entered. Then, the functional key ‘Feasible Alternatives’ is then pressed to display a list of feasible CNC turning centres satisfying all the set criteria values. A final set of 12 alternatives to be evaluated is chosen from this list of feasible alternatives for ultimate selection of the most appropriate CNC turning centre for the given application.

In Fig. 8, the final decision matrix for the CNC turning centre selection problem is developed from the database on pressing the ‘Next’ functional key. Pressing of the ‘Calculate Rank’ key then normalizes the decision matrix, computes the performance scores and displays the ranking preorder of the considered CNC turning centres. Additionally, their relative performances are graphically displayed when the end user presses the ‘Rank Analysis’ button. Finally, the ‘Machine Details’ key is pressed to retrieve the detailed technical specifications and an actual photograph of the best suited CNC turning centre. Here, model ST20 manufactured by Haas Automation Inc. is identified as the best CNC turning centre, followed by

GENOS L 300E-MY. On the other hand, LOC-500 is indicated as the least preferable choice for the given application. It can be noticed from the specifications of model ST20 that it can simultaneously satisfy all the shortlisted technical requirements, i.e. its cost, weight and spindle motor power are low; and maximum diameter and maximum length are high.

Example 2

In this example, a CNC turning centre for producing a large volume of standardized parts/components needs to be selected from a wide range of available alternatives. Mass production is the suitable approach for producing parts in large volume at low unit cost. Keeping this in mind, the end user selects ‘Mass Production’ option from ‘Type of Production System’ module. A HoQ matrix with already filled up interrelationship data for mass production plan now appears, as shown in Fig. 9. Similar to the earlier example, after identifying the beneficial and non-beneficial attributes, and entering the priority for each customer’s requirement, the ‘Weight’ button is pressed to obtain the priority weights for the technical requirements. A priority

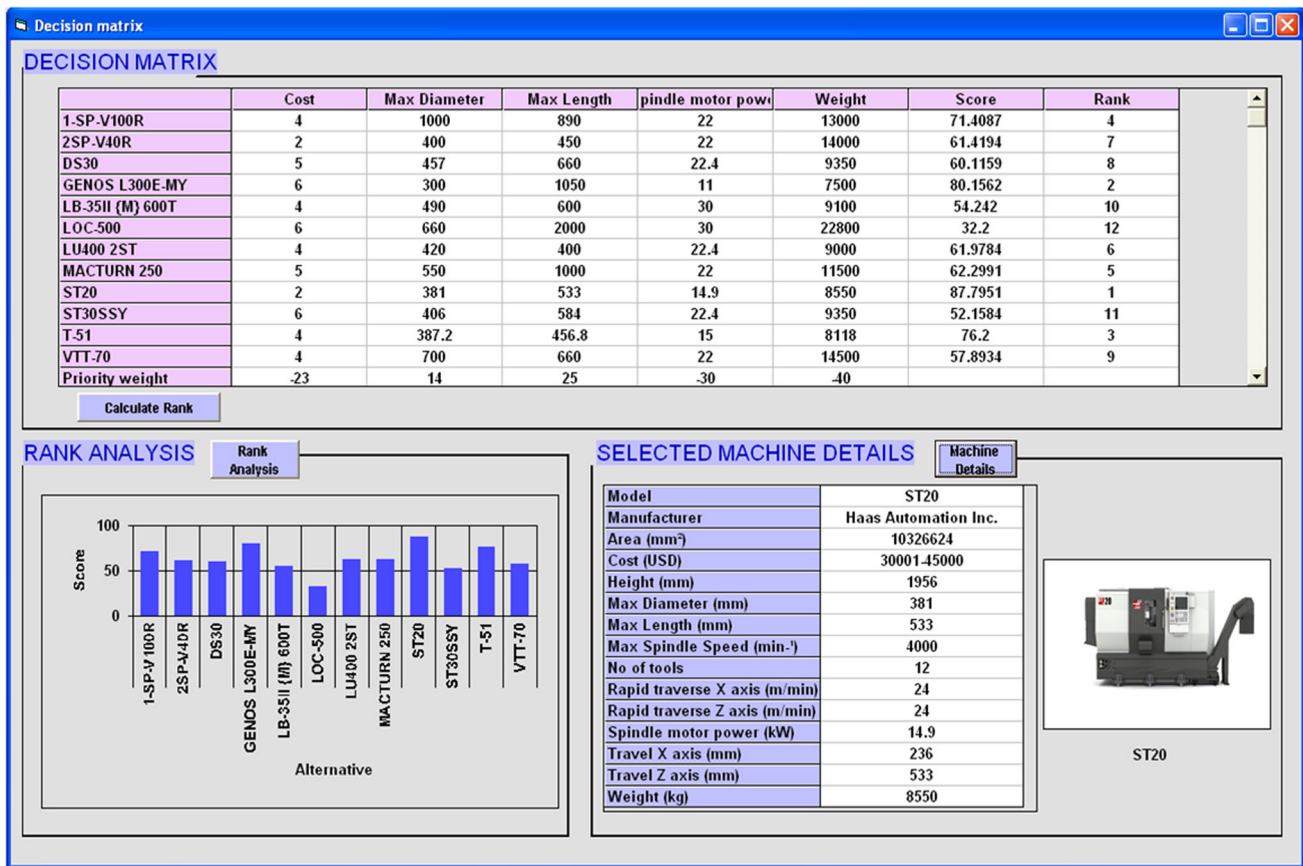


Fig. 8 Output of the expert system for flexible production plan

value of 5 assigned to ‘Allocated fund’ shows that it is the most important criterion for the customers. ‘Productivity’ and ‘Generation of complicated parts’ are also important for this particular CNC turning centre selection problem and hence, a priority value of 4 is assigned to them. In this case, ‘Availability of space’ and ‘Power requirement’ is not the constraints for the customers; therefore, they are allotted a priority value of 1 signifying their least importance. Four technical requirements, i.e. cost, rapid traverse X-axis, travel X-axis and maximum spindle speed are identified here as the governing requirements. A negative priority weight of cost implies that it is a non-beneficial criterion, whereas, for the other three criteria, it is always better to have their higher values. Then, the ranges of values for these selected criteria are entered in their respective cells and the functional key ‘Feasible Alternatives’ is pressed to retrieve all the feasible alternatives fulfilling the set criteria values. From the list of feasible alternatives, the end user selects a set of nine alternatives for final assessment.

The decision matrix for this problem with all the selected technical specifications for the finally chosen alternatives is shown in Fig. 10. In the next step, their

performance scores and ranking preorder are determined after pressing the ‘Calculate Rank’ key. MACTURN 350-W manufactured by Okuma Corporation is identified as the most appropriate choice for this application, while LB-35II (M) 850-C emerges out as the least suitable CNC turning centre under the given conditions. To retrieve all the technical details of MACTURN 350-W along with its photograph, the ‘Machine Details’ key is then pressed. A close review of the details of MACTURN 350-W reveals that although its cost is slightly high (85001-105000 USD), but it has comparatively higher values for the other three technical parameters, i.e. maximum spindle speed, rapid traverse X-axis and travel X-axis. Hence, its selection can be justified with respect to the considered criteria.

Example 3

This example illustrates the selection of a CNC turning centre when the end user has the flexibility to fill up the interrelationship matrix based on the association between customers’ requirements and technical requirements. After selecting the ‘Custom’ option, when the end user presses the ‘Next’ key, a blank HoQ matrix is automatically

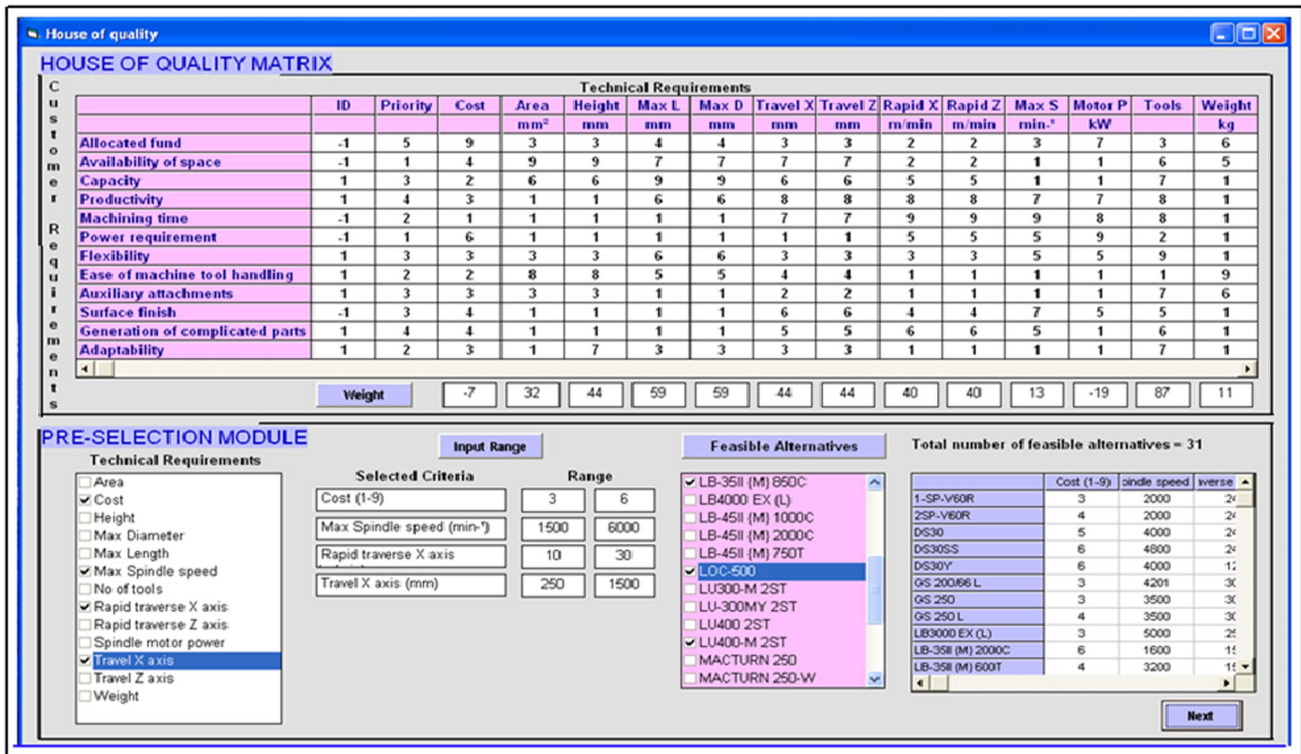


Fig. 9 HoQ matrix for mass production plan

generated. After identifying the appropriate beneficial and non-beneficial attributes, +1 or -1 value is assigned to them. For this example, ‘Allocated fund’ and ‘Capacity’ are the most important customers’ requirements, having a priority value of 5 assigned to them. ‘Availability of space’ and ‘Productivity’ have been assigned a priority value of 4. On the other hand, a priority value of 1 implying least importance to the customers is allotted to ‘Ease of machine tool handling’ and ‘Adaptability’. Figure 11 exhibits the HoQ matrix filled up based on the opinions and judgments of the end user showing the relationship between customers’ requirements and technical requirements. The weight of each technical requirement is then derived. The end user now shortlists area, cost, height, maximum diameter and maximum spindle speed from the technical requirements list, based on which the CNC turning centres are to be evaluated. In the next step, the ‘Feasible Alternatives’ key is pressed to obtain a list of candidate alternatives satisfying all the set criteria values.

A decision matrix containing the selected technical specifications for the final set of alternatives is developed in a new window, as displayed in Fig. 12, when the user presses the ‘Next’ key. This QFD-based expert system identifies MACTURN 250 manufactured by Okuma Corp. as the best CNC turning centre, whereas, GENOS L 300-W is the least suitable choice for the given application. It is observed that the performance scores of MACTURN 250

and MACTURN 550-W are almost same. A closer look at the technical specifications of these two machines reveals that the former has lower values for area, cost and height which are the non-beneficial attributes. The maximum spindle speed for MACTURN 250 is also higher, which is a beneficial criterion. Therefore, its selection as the best turning centre is justified.

Real-time implementation of the developed expert system

A specific machine shop of a manufacturing organization is considered here for real-time application of the developed expert system. The identity of this organization is not disclosed for confidentiality and anonymity purpose, and hereafter, it is referred to as XYZ Limited. It is noticed that the said organization used to practice the conventional (manual) technique for selection of CNC turning centres for various machining applications. This manual approach of short listing the appropriate CNC turning centres for a specific application is often a costly and time-consuming task due to various activities involved, like creating and receiving records, record keeping and maintenance, retrieving data for comparison and identification of a suitable CNC turning centre, and disaster prevention and recovery planning of vital records. Those activities require scarce resources, like manpower, office space, operating

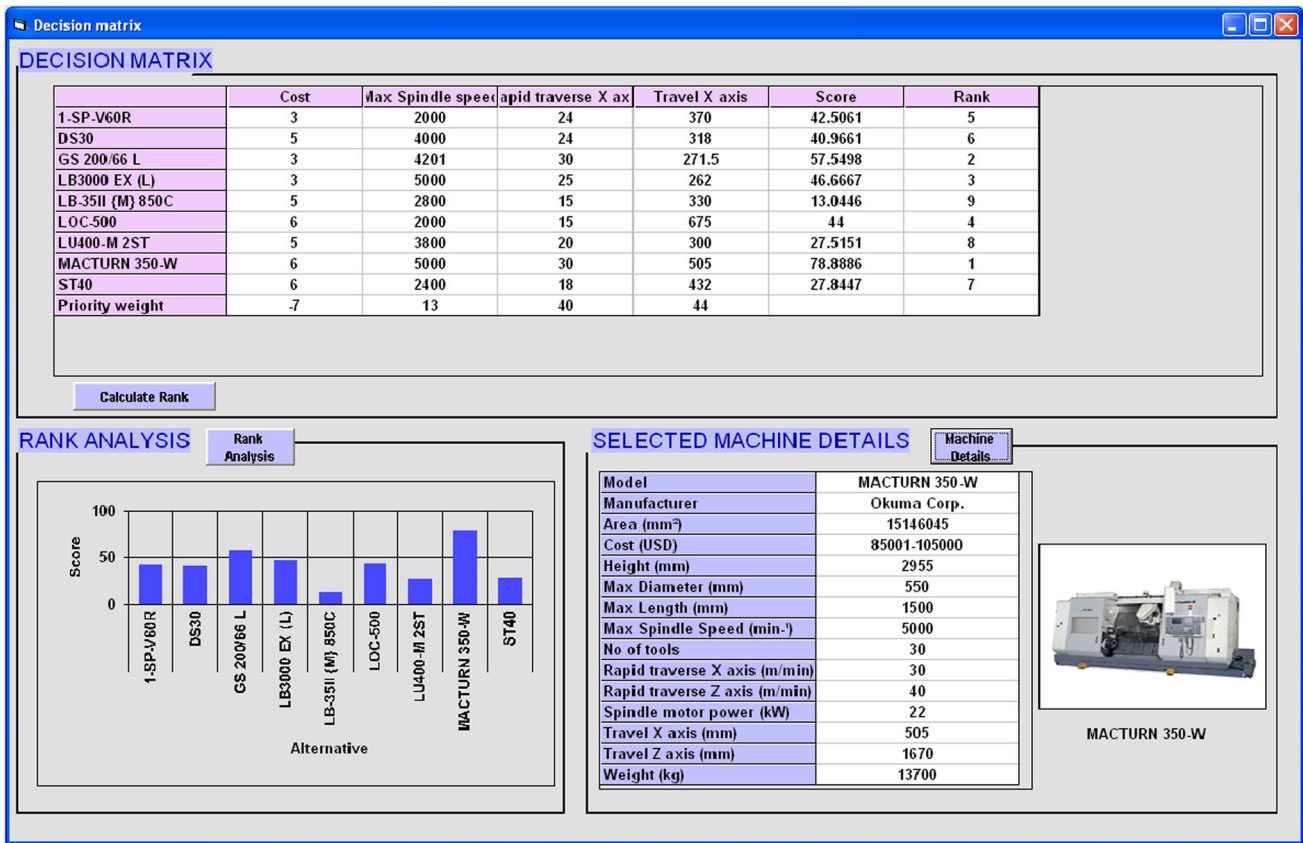


Fig. 10 Output of the expert system for mass production plan

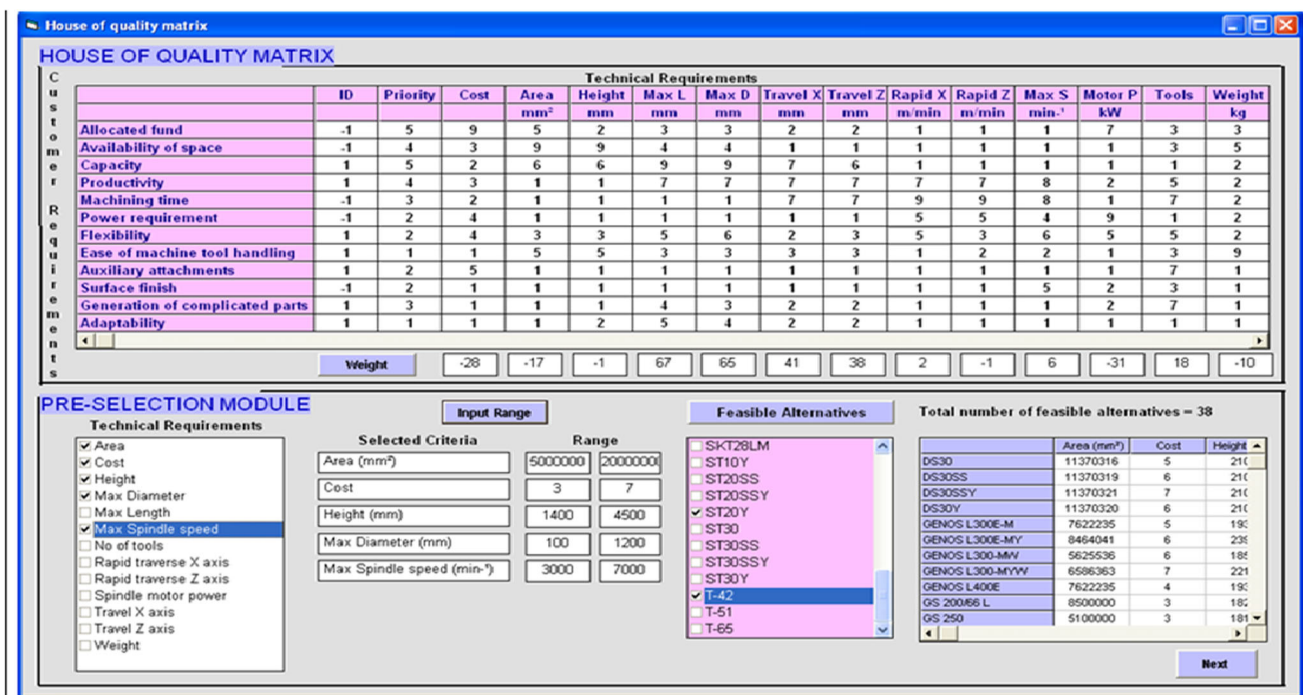


Fig. 11 HoQ matrix for custom option plan

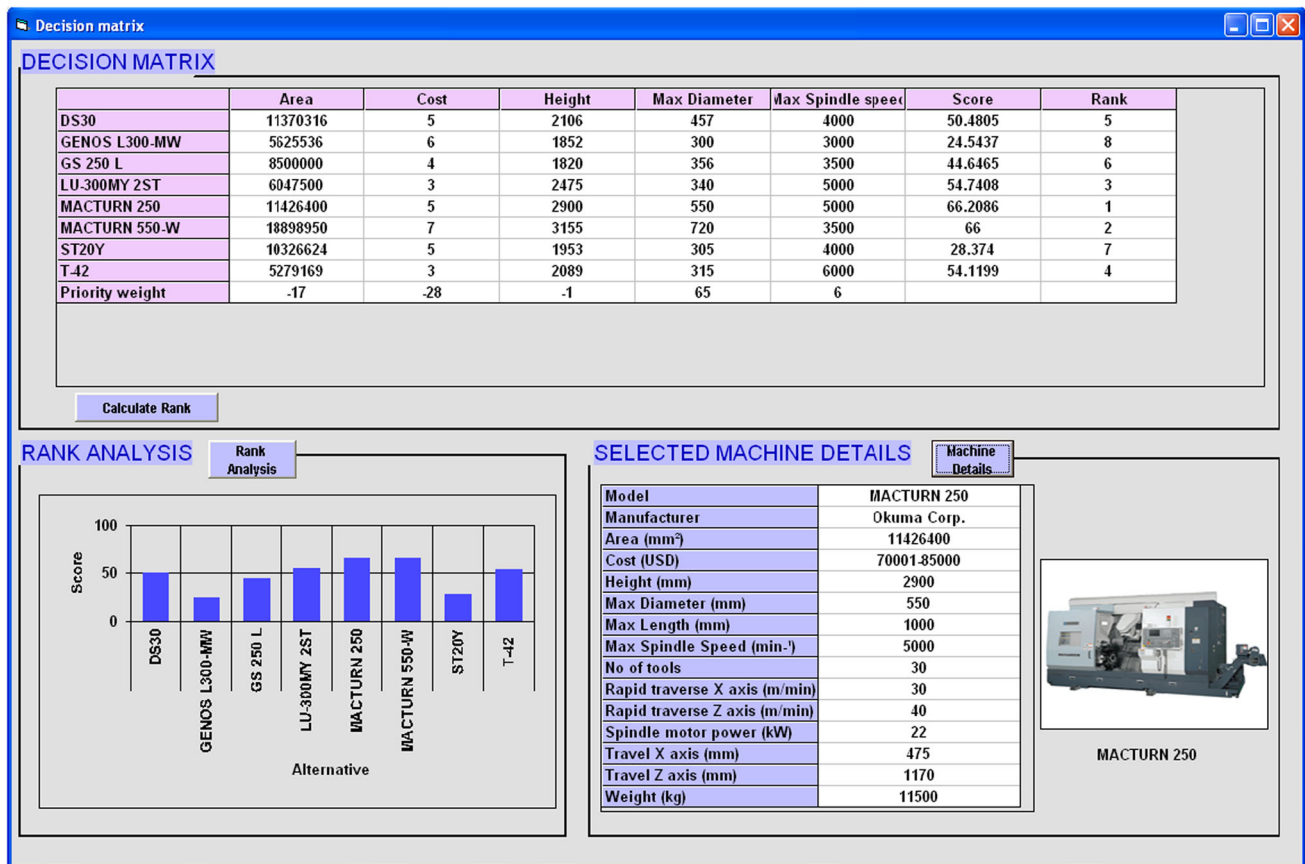


Fig. 12 Output of the expert system for 'Custom' option

supplies, etc. But, it is observed that once this expert system is implemented in the said organization for the selection of CNC turning centre, many of the activities utilized earlier in the manual method are either removed from the selection process or required in meagre amount. This implies that with the implementation of the developed expert system, there is a considerable reduction in manpower and time for upkeepng of records, and smaller office space is required due to comparatively less number of documents. Additionally, in the current automated environment, fewer operating supplies are consumed because of computerization of the selection process. A cost-benefit analysis is carried out to find out the monetary benefits of implementing this expert system in the considered organization, which is estimated to be in the range of 3600–4000 USD per month. This derived cost-benefit can be attributed to savings under various cost heads due to automation of the selection procedure, like 3000–3100 USD per month is spared because of reduction in manpower requirement, 400–500 USD per month is saved due to reduced office space utilization, 100–200 USD per month is cut down on account of decreased consumption of operating supplies and 100–200 USD per month is curtailed owing to cloud computing-based disaster planning.

Although the development and subsequent implementation of the expert system in the said organization require an initial investment, it is often offset by the derived saving. Moreover, once it is successfully installed, there is no recurring maintenance cost. It is also noticed that managers of the said organization can derive a plethora of benefits from application of this expert system, such as (a) reduction in costs related to the selection process, (b) better utilization of workforce associated with decreased number of employees and increased personnel efficiency, (c) enhancement of managerial efficiency with better decision-making, (d) effective utilization of information in the organizational environment, (e) strengthening of management information system for timeliness of CNC turning centre selection decision, and (f) accuracy in the decision-making process leading to higher production rate.

Conclusions

In today's competitive manufacturing environment, the need for quality products is of utmost importance. Therefore, achieving cost-efficient, consistent machining results through automation is attractive to the manufacturing

organizations. In this paper, an expert system based on QFD methodology is designed and developed to help the process planners in CNC turning centre selection, where a large number of available alternatives need to be evaluated based on several conflicting criteria. It eases out and automates the entire selection procedure, while eliminating rigorous calculations involved, thereby reducing the time taken to arrive at the best decisive action. The level of human intervention is also minimized and the end users do not need to have an in-depth technical knowledge regarding various CNC machine tools. It ensures an error-free computation of CNC turning centre selection decision. Moreover, as discussed earlier, it encompasses both customers' requirements and technical requirements in the selection procedure, thus providing the end users with a competitive edge over the previously adopted methodologies. It can also work in a group decision-making environment where opinions from different individuals can be sought. It can be employed for selection of CNC turning centre for any type of production system depending on the requirements of the end users. The database for CNC turning centres can be upgraded from time to time to make it more dynamic. It can also be applied for selection of various other CNC machine tools, such as milling, grinding, etc. while creating a new module and database within the same system.

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