University of Stellenbosch
Department of Industrial Engineering

Attributes and Multi-Criteria Decision Analysis in Machine Selection for Process Chains

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Declaration

I, the undersigned, hereby declare that the work contained in this assignment is my own original work and that I have not previously in its entirety or in part been submitted it at any university for a degree.

Ek, die ondergetekende, verklaar hiermee dat die werk gedoen in hierdie werkstuk vervat, my eie oorspronklike werk en dat ek dit nie vantevore in die geheel of gedeeltelik by enige universiteit ter verkryging van 'n graad voorgelê het nie.

Synopsis

The purpose of this project is to find a means to evaluate a number of machines to optimise a process chain. Firstly seven machine types were identified to be included in the study. These machine types include: broach machines, EDM machines, CNC lathes, engine lathes, drilling machines, milling machines and grinders.

The information requirements for these machines in terms of attributes for three areas were identified. Functionality, economical and reliability and availability attributes were identified. These attributes were subsequently incorporated into a MS-Access database to provide a database of machine information.

Several methods for comparing machines were studied and the decision then fell on one existing method to be used for machine evaluation. A new method was developed to use for evaluating machines. The existing method is the Analytic Hierarchy Process, whereas the new method developed, is called the Quotient Exponential Method.

These methods were implemented in the MS-Access database to enable the user to evaluate machines by means of both methods.

The results indicate that these methods provide the correct answers according to test values used. It should be noted that the decision methods should, however, only serve as an aid towards an answer and do not necessarily provide the final answer. The AHP process is very time-consuming for this project because of the large number of criteria evaluated.

Opsomming

Die doel van hierdie projek is om 'n manier te vind om masjiene te evalueer om sodoende 'n proses-ketting te optimeer. Eerstens is besluit op die soorte masjiene wat ingesluit gaan word in die projek. Sewe soorte masjiene is gekies en sluit in: RNB draaibanke, masjiendraaibanke, boormasjiene, skuurders, elektriese ontladings masjiene, veelvuldige punt snymasjiene en rubeitelmasjiene.

Die inligting-vereistes van die sewe masjiene, in terme van hul attribute vir drie areas, is vervolgens geïdentifiseer. Hierdie drie areas is funksionaliteit, koste, asook beskikbaarheid en betroubaarheid. Hierdie attribute word in 'n MS-Access databasis gebruik om 'n databasis van masjien-inligting te skep.

Verskeie metodes vir die vergelyking en evaluasie van masjiene is bestudeer en daar is op een bestaande metode besluit vir die evaluering van 'n aantal masjiene. Daarbenewens is ook 'n nuwe metode ontwikkel vir die evaluering van masjiene. Die bestaande metode is die Analitiese Hiërargiese Proses, terwyl die nuwe metode die Kwosiënt Eksponensiële Metode genoem word.

Altwee hierdie metodes is in MS-Access geïmplemeteer om die gebruiker in staat te stel om masjiene met albei metodes te vergelyk.

Die resultate verkry toon aan dat die korrekte resultaat verkry word volgens die toetsdata wat ingevoer is ten opsigte van die twee metodes. Dit moet in gedagte gehou word dat hierdie metodes egter slegs as 'n hulpmiddel tot besluitneming gebruik behoort te word en nie noodwendig die finale antwoord lewer nie. AHP is baie tydsaam gevind, aangesien die masjiene in die projek baie attribute bevat het.

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To Michael, thanks for supporting me in everything I did and tried to do.

Terms of reference

The purpose of this study is to evaluate methods of comparing machines in order to optimise the process chain.

The information requirements of a number of machine tools need to be identified. Subsequently multi-criteria decision-making methods have to be found that are applicable on this problem and the information requirements, together with the decision-making methods, should be used to evaluate a number of machines in order to decide on the best machine for the particular application.

The requirements of the thesis are as follows:

- The thesis should add to the academic development of the student.
- The thesis should add to the body of knowledge in the University's Industrial Engineering Department.

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Glossary

VBA	Visual Basic
EDM	Electrical Discharge Machining
AHP	Analytical Hierarchy Process
CNC	Computer Numerically Controlled
RI	Random Index
CI	Consistency Index
MIT	Massachusetts Institute of Technology
Alternatives	The different choices available to the decision maker, also referred to as goals or decision criteria

1. Introduction

One of the core areas of industrial engineering practice and research is that of decision-making, in particular multi-criteria decision-making. In many engineering applications decisions depend on the evaluation of a set of alternatives in terms of a number of criteria. In a manufacturing process there are many decisions to be made, for example production sequencing. The main objectives for sequencing of production machines are to minimise the in-process inventory, minimising idle time and labour cost, and to maximise production flexibility. Scheduling of production in a way to minimise tool wear and subsequent tooling replacement is another objective, but these have not been researched to any great extend as yet.

1.1 Project Motivation

A process chain is concerned with the processes through which a tool or workpiece physically passes. The process chain should be as short as possible.

This project is aimed at searching for a means to evaluate machines in order to optimise the process chain. There are various methods already available to achieve this.

In this project the well-known Analytic Hierarchy Process will be evaluated, in addition to which a new method was devised, called the Quotient Exponential Method, which will also be evaluated. Both these methods will be evaluated to determine whether or not they could be used to decide on the best machine from a collection of machines for a particular purpose.

Seven machine types will be evaluated.

A project plan is given in Appendix I.

1.2 Scope of Report

The purpose of this project is to determine the information requirements of machine tools and evaluate methods for deciding among different machines of a specific machine type.

Section 2 will give an overview of the seven machine types. In section 3 the machine attributes, as determined, will be described. An overview of multi criteria analysis and some of its methods will be given in section 4. It will also include a detailed description of the steps in the Analytic Hierarchy Process and QE method. Section 5 will discuss the MS-Access database created, as well as the implementation of the two methods. The results for the two methods applied in MS-Access will be given in Section 6. Finally a conclusion will be made in section 7.

2. Machine Types

Machining is a cutting process where a cutting tool is used to remove excess material from a workpiece, so that that the remaining material is in the desired shape. This is one of the most important manufacturing processes.

Most of the conventional lathes, milling machines, planers and drill presses, etc. that are used today have the same basic designs as earlier versions. Through constant improvements, modern machine tools have, however, become more accurate and efficient.

The manufacture of tools and dies has become a more difficult task than ever before, since the dies are nowadays more intricate, larger and the production quantities more demanding of the toolmaker.

Seven machines were chosen for this project, assuming that they could form part of a process chain in tool and die manufacturing. These machines are as follows:

- Broach machine
- CNC Lathe
- Engine Lathe
- CNC Milling Machine
- Electronic discharge machines (EDM)
- Drill press
- Grinders

In the previous section an introduction and the project motivation were given. This section will give a brief overview of the tool and die industry, as well as the seven machines mentioned above.

2.1 Tool And Die Industry

It is well-known that tools and dies are the essence of industrial manufacturing, because they play a supportive role to other industries, such as the automobile, electrical appliances, electronics industry and so on.

The die and mould industry is also one of the most prominent industries. It forms part of the overall tool and die industry.

Material removal as a means of manufacturing objects date back to the prehistoric times when people learned to carve wood and chip stones to remove excess material until the required tool was made. When the art of joining objects together was developed, toolmakers made tools with handles for hunting and for farming, such as spears and axes (22).

In the 1950' s, tools were made by nesting inserts into a holder block. With the advent of the EDM and mills, man returned to the original method of making tools by removing excess material. Today it is just a little more difficult to throw away a modern tool, as one was previously able to do. The modern technology in tool making is advancing very quickly. As new materials and techniques are developed, research is done on new processes to meet ever evolving customer demands.

Tool and die makers produce tools, dies and special guiding and holding devices that enable machines to produce a variety of products. To perform these functions, tool and die makers employ many types of machine tools and precision measuring systems.

Within the tool and die industry the machine tool industry is recognised as a provider of low-cost high quality lean manufacturing solutions (19). Industrialised-advanced countries have created market niches on the back of a well-developed and supportive machine tool sector. Current efforts within the industry are to improve the features of CNC machines, and provide further added value at lower and lower costs, to meet the specific requirements of users.

Industrial mould manufacturing industry comprises establishments engaged in the manufacture of extrusion moulds, metal casting moulds, industrial moulds and metal products machinery (20).

Dies are made for die casting, which is a centuries old process of injecting molten metal into a steel die under high pressure. At the same time die casting is one of the most promising processes of the future. Few other processes add as much value to raw material in such a short time, or as cost effectively. The increased use of lighter weight metal components, such as aluminium die castings, has spurred a marked growth in the automotive sector.

The relevant seven machine types will now be described.

2.2 Broaching Machines

Broaching is a machining process where a cutting tool called a broach is pushed or pulled over a surface that is being machined or through an opening in a surface. This is done to enlarge or change the shape of the hole or to form the outside to a desire shape (Krar et al. [2]).

Broaches are referred to as multiple–point cutting tools that produce flat, circular and irregular profiles.

The broaching machining process could be tracked back to the 1850s. At first it was used for producing internal shapes, such as keyways and splines in pulleys and gears. In the 1930s its application was extended to exterior surfaces and its costs became competitive with other machining processes. Currently, almost every type of form and material could be broached (27).

This high-productive metal removal process is often required to produce one-of-a-kind parts.

There are two types of broaching procedures: internal broaching and external broaching (also called surface broaching). For external broaching the broach tool may be pushed or pulled across a workpiece surface. The surface may also move over the tool. For internal broaching a starting opening or hole is required so as to insert the tool at the beginning of the broaching stroke. The tool or workpiece will then be pushed or pulled to force the tool through the hole.

Broaching is very similar to planing, turning, milling and other metal cutting operations in that each tooth removes a small amount of material.

The basic function of a broaching machine is to provide a linear motion of the tool past a stationary work position. This could be done in different ways. The most important factor in deciding on the type of broaching machine is the type of broach cutting tool required for a given job.

2.2.1 Broaching Machine Types

Most broaching machines are classified as either horizontal or vertical broaching machines, (Krar et al. [2]).

A ***vertical broaching machine*** moves the broach tool along a vertical path, either up or down. About 60% of all existing broaching machines are vertical broaching machines and almost all these machine are hydraulically driven. Internal vertical machines are either pull-up or pull-down machines. The first to be introduced was the pull-up type. With this machine the workpiece is placed below the worktable. It is used for broaching round and irregular shaped holes. The more sophisticated pull-down machines, in which the workpiece is placed on top of the worktable, were developed later than the pull-up type. These pull-down machines are capable of holding internal shapes to closer tolerances by means of locating fixtures on top of the worktable. The ***vertical surface or combination broaching machine*** could be powered by hydraulic or electromechanical drive and is produced in single- and double-ram versions. This type is found mainly in the automotive and hand tool industry.

Horizontal broaching machines are designed to move the broach tool in a horizontal plane. This type was among the first used after the advent of powered broaching. The machines are both hydraulically and mechanically driven and have very long strokes without the limitation of ceiling height placed on vertical machines. About 40% of all broaching machines are now horizontals. They are used exclusively for specific types of work, such as roughing and finishing automotive engine blocks.

These machines pull the broach past the workpiece.

In contrast the ***broaching press*** or vertical push-down machine pushes the tool through the workpiece. It is often nothing else than a general-purpose hydraulic press with special fixtures and is only used for internal broaching.

The ***continuous broaching*** machine is a high production machine where the workpieces are carried through the machine on fixtures mounted on a chain conveyor moving past a series of stationary broaches. Alternatively the parts may remain stationary and the broaches are moved across them. This machine is only used for surface broaching. The operator loads the parts at the one end and it drops out of the fixtures at the other end. It thus eliminates the return stroke. This has been the most popular type of machine produced for high-production surface broaching. A machine with the workpiece held stationary and cutting tools mounted on a chain for a horizontal instead of vertical configuration, is a recent innovation. This machine has the advantage of low floor space requirements, as well as eliminating the problem of high ceiling clearance for the vertical machine.

The ***rotary broaching machine*** is another high productive machine that uses both milling and broaching techniques. The broaches are mounted in broach holding columns at the periphery of the machine. The workpieces are then carried on a rotary table past the broaches. The process has been used to produce small, high quality parts such as computer parts.

When it is impossible to bring the workpiece to the machine ***portable broaching machines*** are used. These machines are lightweight units that have found a special success in broaching with good accuracy irregular, square or circular shaped holes in large industrial equipment.

2.2.2 Benefits

The advantages for broaching are as follows (26):

- *Complex and Irregular Shapes*: Complicated irregular shapes could be cut as long as all surfaces of the section remain parallel to the direction of the broach travel.
- *Superior Finished Surfaces*: Roughing and finishing cuts are generally combined in the same operation.
- *Reduced Cycle Times:* Total cycle time is greatly reduced because a feature could be roughed and finished in a single quick stroke.
- *Increased Dimensional Repeatability*: The number of process variables is reduced and the repeatability improved because the machine only has a single moving part. Close tolerances are also usually held.
- *Simplified Operator Interface and Training*: The broaching machine requires less manpower because of its simplicity and thus eliminates the need for highly skilled machine operators.
- *Reduced Maintenance*: With only one moving part, there is practically no maintenance.
- Stable process accuracy.
- Economical.

2.2.3 Limitations

Limitations for broaching are as follows (Van De Motter [30]):

- Tooling is more expensive than for other metal cutting operations.
- Large machine space requirements.
- Broaching is not suitable for every situation. The workpiece surface must be parallel to the direction the workpiece or tool travels otherwise broaching may be inappropriate.
- The broached workpiece must have sufficient strength to resist the forces exerted by the broach.
- Forces exerted by the broach demand that machines and fixtures must be rigid.

2.3 Lathe Machines

Turning is the process where a single point tool removes material from the surface of a rotating cylindrical workpiece and the tool is fed linearly in a direction parallel to the axis of rotation (Groover [3]).

The machine tool used for this process is called a *lathe*. The purpose of a lathe is to rotate a part against a tool whose position it controls. The lathe provides power to feed the tool at a specified rate and depth of cut. The workpiece is held between two centres and rotated on its axis while the cutting tool is advanced along the lines of a desired cut. As mentioned above, the cutting tool is fed either in parallel or at right angles to the axis of the workpiece. It may also be fed at an angle relative to the axis of the workpiece.

In addition to turning many other kinds of operations could be performed with the lathe tool and this makes it a very versatile machine tool. These operations include: facing, taper turning, form turning, chamfering, cut-off, threading, boring and drilling.

The basic lathe used for turning is called an *engine lathe,* because in earlier days these machines were driven by steam engines.

2.3.1 Engine lathe

The engine lathe is versatile and usually used in low to medium production. The lathes could be classified as tool room, heavy-duty and gap-bed lathes (Krar et al. [2]). A British subject, Henry Maudslay, developed the first engine lathe. The basic engine lathe consists of many parts (Krar et al. [2]).

The distance between the centres, as well as the swing, usually determines the size of a lathe. Swing could be defined as the maximum workpiece diameter that could be rotated in the spindle (Groover [3]).

Some principal components are the headstock, tailstock, carriage and bed. The *headstock* is mounted on the left-hand side of the bed and holds the drive unit that rotates the main spindle, which in turn rotates the workpiece. A chuck may be fitted to the spindle nose to hold and drive the workpiece. The headstock spindle is driven either by a cone pulley and belt (belt-driven lathe) or by transmission of gears (gear-head lathe) in the headstock.

The converse of the headstock is the *tailstock*. It consists of upper and lower tailstock castings and holds a dead or live centre that supports the right-hand end of the workpiece. It could be adjusted in position along the ways to accommodate different lengths of workpieces and then locked in the position by a tailstock clamp.

The *carriage* consists of three parts: the saddle, cross-slide and apron. The carriage slides along the *ways* of the lathe so as to move the cutting tool along the lathe bed parallel to the axis of motion. The *saddle* is mounted on top of the lathe ways. These ways are similar to tracks on which the carriage rides and are built into the bed of the lathe. A tool post or compound rest mounted on the *cross-slide* is used for supporting the cutting tool. This cross-slide is mounted on the saddle, which again is part of the carriage. The cross-slide provides cross movement for the cutting tool and moves perpendicular to the carriage movement, thus towards or away from the operator. Moving the cross-slide will enable the tool to be fed radially into the workpiece for operations such as facing, form turning and cut-off. In turn moving the carriage enables the tool to be fed parallel to the workpiece axis for straight turning. The *apron* is mounted on the saddle to provide carriage and cross-slide movement controls.

The workpiece should be held in place for machining and this may be done in various ways. It could be held between two centres, one in the headstock and one in the tailstock. The headstock centre is used to drive the rotation of the work. The tailstock centre could either be a dead or live centre. The live centre rotates in a bearing in the tailstock and a dead centre is fixed to the tailstock so that it does not rotate. The workpiece could also be held by a chuck with three of four jaws on its outside diameter. The chucks could be used with or without the tailstock centre. A collet or faceplate may also be used. A collet is used to hold cylindrical shaped work such as a bar stock. One end of the collet could be squeezed to reduce its diameter and thus giving secure grasping pressure against the workpiece.

A faceplate fastens to the lathe spindle and is used to grasp irregular shapes. It has custom-designed clamps for the specific workpiece being machined.

2.3.2 Other lathe machines

Modern production has led to the development of a large number of special types of lathes. Some of these lathes will be discussed briefly.

Tool room Lathe

This is a smaller lathe and has a wider range of speeds and feeds. The machine has a single-tooth clutch arrangement and lead-screw reverse control at the apron.

Turret lathe

This lathe differs from an engine lathe in two respects. The first difference is that this lathe is manually operated and a turret that could hold up to six tools replaces the tailstock. The turret is pivoted about a vertical axis so that the tool on each side could be brought into the cutting position by rotating the turret. Secondly, a square four-sided turret that is capable of indexing four tools into position, replaces the tool post (compound rest). The turret lathe is used for high-production work because of its ability to quickly change from one tool to the next.

Bar machines

This machine is similar to a chucking machine except that a collet is used for holding the workpiece. Long bar stock could be fed through the headstock into position. At the end of each machining operation a cut-off operation separates the new part. The bar of stock is then indexed forwards to provide the stock for the next part. This is all done automatically. These machines could be classified as *single- or multiple-spindle bar machines*. Single spindle machines have only one spindle thus allowing only one cutting tool to be used at a time on a workpiece.

Multiple-spindle machines increase tool utilisation by simultaneously machining multiple parts by multiple tools. With the single-spindle machine the time to complete one workpiece is the sum of all the turret operations. For the multiple-spindle machine the time of the multiple machining cycle is the time needed for the longest single cut. This multiple-spindle machine thus has the highest production rate of any turning machines, but because of longer set-up times and increased tooling cost the machine is less economical on short runs and more economical on long-run production.

Chucking machines

The chucking machine uses a chuck in its spindle to hold the workpiece. There is no tailstock, meaning that parts cannot be held between two centres. Chucking machines may be fitted with any type of work holding fixture within the capacity of the machine and they usually have manually controlled power-operated chucking mechanisms. Thus the feeding actions of the cutting tools are controlled automatically. Only short lightweight parts may be used.

2.3.3 CNC Lathe

CNC or computer numerical control refers to an NC machine system that utilises programmable configuration control in which a special-purpose mini computer is dedicated to the operation of a machine tool. The first prototype of a numerically controlled machine was designed by MIT in 1952, (28). This machine was capable of vertical, two-axis milling.

CNC machine tools have become commonly available from 1960 onwards. CNC has led to the development of machine tools capable of more complex machining cycles and higher level of automated operation.

A CNC lathe consists of the mechanical part and CNC system, as the heart of a lathe. The basic and optional functions of this CNC system are linear and circular interpolation, backlash compensation, automatic co-ordinate system setting, tools offset, cutter compensation, background edit, self-diagnosis and canned cycles.

With CNC, the machine motions are not controlled by an operator, but rather by stored numerical data. Usually the *z*-axis and *x*-axis are controlled as to position and speed, as well as turret index and spindle speed selection by numerical command. A CNC machine requires a program in order to run. This is a series of numbers and coded letter symbols that define machine movements. Machine programs define the axis position according to the Cartesian coordinate system.

An automatic and programmable tool changing mechanism is an essential feature on any turning centre and is usually of the indexable turret type. To give the machine more versatility, machines could be equipped with a *driven/live spindle* for most of the turret positions. The programmer is then able to specify drilling and turning operations on the component using a rotating tool station. Some advantages tool changers provide is the ability to maintain tooling without machine downtime, simplified programming and tooling layout, increased machine utilization, and permit additional operations. Such tool changers, however, require a higher equipment investment and may add to the machining cycle time.

The CNC lathe can perform any operation that would be performed on conventional machines. The CNC lathe is especially used for contour turning operations and close tolerance work.

Modern CNC machines are able to perform various milling operations and automatic tool indexing under computer control. The more sophisticated machine may perform workpiece gauging (checking the key dimensions after machining), tool monitoring (sensor indicates when tools are worn), automatic tool changing when tools become worn and even automatic workpiece changing after completion of the work cycle (Groover [3]).

The advantages of CNC are the reduction in workpiece cost and an increase of part quality. It is also capable to produce parts that would be extremely difficult by means of a conventional machine. CNC machines have much lower set-up times when compared with conventional machines, but compared with machining time, there is no significant improvement over conventional machines. Other factors to consider in CNC turning are shortened lead times, decreased tooling and tooling lead-time, and increased design flexibility.

2.3.4 Benefits

- Provides a way to make accurate radially symmetrical objects.
- Complex parts with high detail could be produced.
- For CNC lathes the multiple tool capability is a significant time savers and eliminate operator errors.
- For CNC lathes less operator skill is needed and the operator is able to spend more time on other tasks in the work area.
- Very high accuracy could be achieved.
- Short run production parts could be machined.
- Turning treatment could be done of workpieces with a rectilinear, stepped, and curved profile in the chuck and centres.
- The range of the control of the spindle speed and feeds enables one to machine workpieces from both ordinary ferrous and non-ferrous metals as well as of alloyed steel. Virtually any material may be machined with a proper cutter.

2.3.5 Limitations

- A reduced set of features is possible, while certain features are not possible at all.
- There is higher materials waste than with the casting type processes.
- There is a high initial cost of equipment for the CNC lathe.
- The cost for programming and computer time is an added factor.
- Special maintenance is needed for CNC lathes.

2.4 Milling Machines

Milling is an operation in which the workpiece is fed past a rotating cylindrical tool with multiple cutting edges to generate the required surfaces. The cutting tool in milling is called a *milling cutter* and the cutting edges are called teeth (Krar et al. [2]). Each milling cutter tooth takes a small individual chip from the stock. There are four types of cutters: plain, form, face and end milling cutters.

The machine tool that performs the milling operation is a milling machine. The first milling machine was developed in 1818 by Eli Whitney in the United States (Groover [3]). Modern machining centres were introduced in the late 1950s after numerical control had been developed.

Milling machines are used to accurately produce a machined surface on a workpiece. This is done by using the rotating milling cutters as mentioned earlier. In some machines the workpiece is held stationary and the rotating cutter is moved past it at a given feed rate, or both the workpiece and the cutter are moved in relation to each other. More frequently than not the workpiece is advanced at a slow feed rate and the cutter rotates at a very high speed.

The milling machine is probably the most versatile machine tool, because it is able to handle a variety of operations normally performed by other machine tools. Apart from machining flat surfaces, it could also be used for thread and gear cutting, drilling, boring, reaming and slotting.

Milling machines are made in different types, sizes and power capacities.

Most milling machines are equipped with power feed for one or more axes. Power feed is smoother than manual feed and could thus produce a better surface finish. Power feed also reduces operator fatigue on long cuts.

The machines could firstly be classified as horizontal or vertical. The horizontal machine has a horizontal spindle and is well suited for peripheral milling. Vertical milling machines have a vertical spindle and are suited for face milling, end milling, surface milling and die sinking on flat workpieces.

Milling machines are classified into knee and column type, bed type, planar type, tracer mills, and CNC milling machines (Dallas [1]).

2.4.1 Types of milling machines

A number of milling machine types will now be described briefly.

Knee and column type

This machine is the basic machine tool for milling. The spindle is mounted on a column for support and a knee supports the worktable. The horizontal type has the capability of positioning three sliding motions. Some cutters could be centred and held in place by a draw-in-bolt, but for horizontal machines intermediate holding devices or arbors are needed to support the cutter. Arbors may be defined as a shaft that holds the milling cutter and is driven by the spindle (Groover [3]). The vertical spindle is usually moveable towards and away from the tabletop, manually or by power. No provision is made for the support of a cutter. The cutter could be mounted directly in the spindle.

In both machines all three or four motions could be used to feed a workpiece during a cut, although table motion is usually preferred. The worktable may be moved in the *x* direction, the saddle in the *y* direction and the knee moved vertically in the *z* direction.

There are two special knee and column milling machines. The *universal milling machine* permits the worktable to be swivelled in a horizontal plane to any required angle. Angular surfaces may be cut without moving the table. The other machine is the *ram mill* that has a ram moveable by hand or power in a direction parallel to the saddle movement. The tool head is located on the end of the horizontal ram. This ram could be moved in or out over the worktable to place the cutter relative to the workpiece and it could also be swivelled.

Bed type Mill

These machines are designed for mass production. The bed type mill has a rectangular shaped bed casting. The worktable is mounted directly to the bed of the machine tool, but this construction limits the possible motions of the table. Heavy cutting loads on large or heavy workpieces are allowed. The cutter is mounted on a spindle that could be adjusted vertically along the machine column. These machines may be further classified as horizontal, vertical, planar type etc. When a machine has only one spindle bed, it is called a *simplex* mill (Dallas [1]). Machines with two spindle heads are *duplex* and the head are placed horizontally on opposite sides of the bed. Machines with a third spindle mounted vertically over the bed for increased machining capability are called *triplex* machines and thus have three spindle heads.

Planar type

This is the largest milling machine. They are built to mill very large parts. The worktable and bed are heavy and very low to the ground. A rigid cross rail/bridge is mounted upright from the floor on each side of the bed-table unit. The worktable rides on this bedway and is powered in the *x*-axis direction by a hydraulic cylinder drive system. The major advantage is the machine's inherent static rigidity, allowing for heavy cuts with minimum structural deflections. A limitation is that removing the chips from the workpiece surface could be difficult.

Gantry type

A gantry type machine is a common type that is used in the aerospace industry. It is very similar to a planar type milling machine except that the entire gantry moves in the *x*-axis direction. The gantry is made of a cross-rail mounted upright and supports the cross saddle and spindle carriers. The gantry is driven by a ball screw drive system. This machine presents a stationary work surface that facilitates double loading. It also offers the option of extending the bed for additional *x*-axis travel. The limitation of removing chips and coolant is a bigger problem than with the planar type machine.

Computer numerically controlled (CNC) milling machines

Milling could be performed under computer control. Such mills are called Computer Numerical Control or Numerical Control mills and are becoming increasingly common in machine shops.

CNC milling machines are milling machines where the cutter path is controlled by numerical data, rather than by a physical template (Groover [3]). Thus the machine tool is driven by a computer to produce a desired shape.

The CNC computer is programmed to drive the motors attached to each of the machine's moving axes in a discrete manner to create the cutting action, which would produce the desired shape in a workpiece. Electronic measuring devices are attached to each moving axis and monitored by the CNC to assure accurate movement according to the program. In this way a CNC machine could produce the same part as a human operator, but much faster and with greater precision. An operator is, however, needed to change cutters and load and unload workpieces.

For operations, such as profile milling, surface contouring etc. where two or three axes have to be simultaneously controlled to achieve the required cutter path, CNC milling is very effective. The CNC system provides simultaneous control of all axes, accurate positioning of the table or workpiece, built-in canned cycles for the depth axis, as well as continuous path capabilities for machining operations where a curve or contour shape is required.

Automatic tool changers provide the capability to change from one machine operation to another by using the NC program to control the exchange cutters between the machine tool and a tool storage drum (magazine).

Some milling machines also have two or more pallet shuttles. This gives the milling machine the capability to continue with machining the current part, while the operator unloads the previous part and loads the next part. This reduces the non-productive time of the machine.

Modern CNC machines are able to perform various milling operations and automatic tool indexing under computer control. The more sophisticated machines could perform workpiece gauging (checking the key dimensions after machining), tool monitoring (sensors indicate when tools are worn), automatic tool changing when tools become worn and even automatic workpiece changing after completion of the work cycle (Groover [3]).

The CNC mill-turn centre is a machine that has the configuration of a turning centre but could also position a cylindrical workpiece at a required angle. This enables machining features onto the outside surface of the workpiece by a rotating tool such as a milling cutter.

2.5 Benefits

Benefits of the milling machines are as follows:

- Very good for one-off objects.
- Virtually any material may be milled with a proper cutter.
- Complex parts with high detail could be produced.
- Close tolerances are possible.
- Weights may vary from a few grams to heavy workpieces.
- High long-term precision and reliability may be achieved.
- A high quantity of metal is removed.

2.6 Limitations

- A more reduced set of features are possible, while certain features are not possible at all.
- There is more materials waste than the casting type processes.
- It is quite slow.
- The material to be machined should be secured on the moveable table with clamps or a vice.

2.7 Electronic Discharge Machines

Electrical discharge machining is one of the most widely used non-traditional processes.

Electrical discharge machining (EDM) is a process used to remove metal through the action of an electrical discharge of short duration and high current density between the tool and the workpiece. Stated differently it is a non-traditional method of removing metal by a series of rapidly recurring electrical discharges between an electrode (the cutting tool) and the workpiece in the presence of a liquid (usually a hydrocarbon dielectric) (Dallas [1]). The process is sometimes also referred to as spark erosion or machining.

The origin of electrical discharge machining goes back to 1770, when the English scientist, Joseph Priestly, discovered the erosive effect of electrical discharges. In 1943, Soviet scientists B. Lazarenko and N. Lazarenko had the idea of exploiting the destructive effect of an electrical discharge and developing a controlled process for machining materials that are conductors of electricity (Moser [29]). Already in 1889, Paschen explained this process and devised a formula that predicted the arcing capability in various materials.

Since the 1950s EDM has been a growing force in North American tool, die and mould making shops.

EDM has rapidly earned its place alongside milling and grinding equipment as a proactive, mainstream technology. EDM has proved valuable in machining materials in complex shapes, regardless of their hardness or toughness.

EDM has its greatest application in tool making, such as the manufacturing of press tools, extrusion dies, forging dies and moulds. It is also increasingly applied to make prototype and production parts, especially in the aerospace and electronics industries in which production requirements are relatively low (Dallas [1]).

The workpiece has to be electrically conductive. The electrode (tool) should also be electrically conductive and held in close proximity, but not in contact with the workpiece during machining. A wide variety of materials are used for electrodes, such as graphite, copper, brass, copper tungsten, silver tungsten, carbide and zinc alloys. Graphite is preferred for many applications because of its melting characteristics.

An electrical spark is used to cut the workpiece and it takes a shape opposite to that of the cutting electrode. Both the electrode and workpiece are submerged in a dielectric fluid during machining. The dielectric is usually a lubricating oil and a non-conductor of electricity. It helps to initiate the spark between the electrode and the workpiece, serves as an insulator between the tool and workpiece and also acts as a coolant. A discharge occurs where the gap between the two parts are the smallest. The dielectric fluid then ionises here to create a path for the discharge. The discharge region is heated to a very high temperature and this causes minute metal chips of the workpiece surface to melt and vaporize. These are then washed away by the continuously flushing of dielectric fluid so to prevent shorting. The high temperatures, however, also melt away the tool, causing small cavities in the surface opposite to the cavities in the workpiece. This is called electrode (tool) wear ratio and usually ranges between 1 and 100 percent (Groover [3]).

There are different types of systems for filling the work tank, forcing the dielectric fluid through the spark gap to remove metal particles and for circulating the dielectric fluid.

One system used to fill the work tank is to apply air pressure to the fluid in the base reservoir. The level of fluid is maintained by maintaining the pressure on the reservoir fluid and the tank is then drained using gravity. When the air is released, the fluid drains into the base. Another system for filling the tank is using a centrifugal pump. With this system the fluid is pumped into the work tank through a hose and when the desired level is reached the pump is shut off and a valve closes on the hose that maintains the fluid level. The fluid is drained by opening the valve and letting gravity make the fluid return to the base reservoir.

The dielectric fluid of an EDM has to be circulated under constant pressure to ensure that it will flush away the metal particles efficiently, in addition to which filters and bypass valves are also used in their systems. The pressure system circulates the fluid from the work tank through a pressure pump and then forces the fluid through a fine filter, usually made of paper. The fluid then flows to the electrode or via a bypass valve to the work tank in a parallel path. This ensures a stable cutting condition by regulating the volume of fluid going through the arc gap. With the vacuum system the fluid flows from the electrode and bypass valve through the filter and pump, which is thus just the opposite of the pressure system. Clean fluid is then returned to the work tank.

There are also different methods to circulating the fluids. These methods include: normal flow, jet flow, reverse flow and immersion flushing.

A power supply is connected to the workpiece and the tool and is used to control the timing and intensity of the electrical charges and the movement of the electrode in relation to the workpiece. There are different types of power supply, such as resistance capacitance, pulse type, rotary impulse generator and static impulse generator.

The power supply also holds electronic circuits that automatically advance the electrode towards the workpiece by using a machine-tool servosystem. This servo is generally a hydraulic cylinder operated by an electro hydraulic valve. This servomechanism automatically maintains a gap of approximately 0.02mm between the electrode and the workpiece.

This is done by comparing the voltage between the workpiece and the electrode by means of a preselected reference voltage. The servo head then feeds the electrode towards the workpiece until the reference voltage is reached. This position is held until the voltage becomes higher than the reference voltage and the head then again moves towards the workpiece. When the voltage becomes less than the reference voltage, the head will move away from the workpiece until the reference voltage is reached.

2.7.1 Advantages

- Any electrically conductive material may be cut.
- No stress is created in the workpiece material because the electrode never comes into contact with the workpiece.
- One person is able to operate several EDM machines at a time.
- Better dies and moulds could be produced at lower costs.
- The process is automatic, because the servomechanism advances the electrode into the workpiece as the metal is removed.
- EDM is a no-contact and no-force process and is well suited for making frail or fragile parts that may not take the stress of machining.

2.7.2 Limitations

- Metal removal rates are low.
- Material for the workpiece and tool have to be electrically conductive.
- Electrode wear could become costly.
- Electrodes are impractical when they are smaller than 0.07mm in diameter.

- The accuracy of an EDM is limited to about ±0.00254mm for wire and ram EDMs.

2.8 Drill Machine or Press

The drill is probably one of the first mechanical devices developed historically. Around 1846 James Nasmyth developed the powered drill press, which permitted the drilling of accurate holes in metal.

The drill press is the standard machine tool for drilling and an essential machine for any workshop. It is primarily used to create a round hole in metal, but related operations such as spot facing, tapping, reaming, counterboring and countersinking are also possible for the drilling machine (Groover [3]). The most common drill operation is drilling with a twist drill that produces internal cylindrical surfaces.

Reaming is used to slightly enlarge an existing hole to provide better tolerances and surface finish.

Tapping is the operation of cutting internal threads in an existing hole with a tool, called a tap.

Counterboring produces a stepped hole where a larger diameter follows a smaller diameter somewhat into the hole.

Countersinking produces a tapered or cone-shaped enlargement to the end of a hole. This is similar to counterboring, except that the step is cone-shaped.

The *spot facing* operation provides a flat-machined surface on a workpiece by smoothing and squaring the surface around a hole. This usually provides a seat for the head of a cap screw.

The drilling machine mainly consists of a spindle that turns the drill and advances it into the work, as well as a worktable that holds the workpiece in position while the hole is being drilled. On many drill presses both the worktable and the head could be raised or lowered to accommodate various heights of workpieces.

2.8.1 Types of drilling machines

A few general types of drilling machines will be described next.

Sensitive drill press

This drill is a light, high-speed machine used for drilling small parts as well as other operations. It is manually fed and available in bench and floor models. The main parts are the base that provides stability for the machine and also a mounting for the column (Krar et al. [2]). The column is a cylindrical post fixed to the base. The worktable is fitted to the column and supports the workpiece to be machined with hold down clamps. The worktable may be moved up or down between the column and the head. It could also be tilted or swivelled out of the way to allow tall work to be supported. The drill head holds a motor that is used to revolve the spindle at a speed controlled by a variable speed control dial. The spindle holds a drill chuck that holds the cutting tools.

Upright drill

This drill is similar to the sensitive drill. However, the upright drill is larger and suitable for heavier work. It stands on the floor and consists of a worktable for holding the part, a drilling head with a powered spindle for the drill bit and a bed and column for support. The spindle may be fed by a hand lever, hand wheel or automatically by a feed mechanism. It has a gear-box providing various speeds and the worktable may be raised or lowered. The controlled power feed results in a better finish, tool life and accuracy than the sensitive drill press. The *bench drill* is similar, but is mounted on a bench instead of the floor.

Radial drill

This is a large drill press used to cut holes in large and heavy workpieces. The radial arm has a drilling head that could be moved and clamped along the arm. Drilling operations are rapid because positioning the drill head takes less time and effort than shifting the workpiece for each hole operation. The drill head may be moved quickly to any location while the workpiece remains stationary. This permits better production. In some models the head may also be swivelled so that holes could be drilled on an angle (Krar et al. [2]).

Gang drill

This is a drill equipped with two or more independently powered and operated drill heads, mounted on a single table. Usually it consists of a series of two to six upright drills connected together in a line arrangement. The drill permits that a series of operations could be accomplished simultaneously by moving the workpiece on the worktable form one spindle to the next. The drill heads could have fixed locations or may be repositioned on the table.

Multiple spindle drill

This drill is related to the gang drill. Any number, from 2 to over 60 drill spindles, are connected on a single head and driven by a common drive. It could be used to perform multiple operations in a single hole, one operation in multiple holes or multiple operations in multiple holes. Thus one may drill multiple holes simultaneously into the workpiece. A typical application of this type of drilling is in the automotive industry to drill engine blocks.

Numerically controlled (NC) drill press

The positioning of the holes in the workpieces could be controlled with NC drill presses. These drills use turrets to hold multiple tools that may be indexed and controlled by the NC program. They are used for high production. Minimal set-up, reduced point-to-point time, optimised drilling speed and extended drill life all combine to increase productivity.

2.8.2 Advantages

- Some worktables are designed to tilt, swivel and rotate around the column, which allows easy positioning of the stock for any drilling operation.
- Simple, easy operation.
- Rapid drilling of many holes is possible.
- Structural compactness and good rigidity are noticeable features.
- Most machines have a wide range of speed changes, as well as quick gear changing.

2.8.3 Limitations

- The accuracy of the hole location depends on many factors, particularly the experience of the operator.
- Set up time may be long.

- Too much pressure when using the drill press may break the drill bit, while too little permits the cutting lip to slide over the work and thus dulls the drill bit by abrasion.

2.9 Grinders

In the early 19th century the first solid bonded grinding wheels were produced in India. The technology was exported to Europe and America. Other bonding materials were introduced throughout the years. The U.S.A firm of Brown & Sharpe manufactured the first grinding machine in the 1860's for grinding parts for sewing machines (Groover [3]). Grinding machines also contributed to the development of the bicycle industry in the 1890s and later in the automotive industry in the U.S.

Grinding is traditionally used to finish parts whose geometries have already been created by other operations.

In the grinding process the workpiece is brought into contact with a revolving grinding wheel that operates at high surface speeds. The grinding wheel consists of abrasive particles and bonding material. The abrasive particles act as cutting teeth and the bonding material keeps the particles in place. The wheel is in a disk shape and precisely balanced for high rotational speeds.

As the abrasive particles become dull, the pressure and the heat created between the wheel and the workpiece causes the dull face to break away and new sharp cutting edges are left behind.

A magnetic chuck that is clamped on to the worktable of the grinder, holds most workpieces ground on a surface grinder. There are two types of magnetic chucks: an electromagnetic chuck and permanent magnetic chuck. The electromagnetic chuck uses electromagnets to provide holding power and it may be varied to suit the areas of contact and thickness of the workpiece. The permanent magnetic chuck, however, uses permanent magnets to hold the workpieces. This is a very convenient way to hold a workpiece.

Grinding fluids are sometimes used during grinding for reduction of grinding heat, lubrication, removing small metal chips and abrasive particles as well as controlling of the grinding dust (Krar et al. [2]). The grinding fluid could be applied in three ways. *Flood grinding* floods the wheel and operates with a stream of fluid through a nozzle. This is the most common form of fluid application.

A mixture of grinding fluid and air is called a *mist application*. This is used when the machine does not make provision for grinding fluid application. The mixture is fed through a nozzle that is directed to the point of contact between the workpiece and the wheel. The cooling action is caused by the air and vapour.

The third way is to apply *grinding fluid under pressure*. The fluid under pressure breaks the air stream around the wheel and the fluid may then flow between the workpiece and wheel.

2.9.1 Types of Grinders

Many types of grinders are available, and some of these types will now be described briefly.

Surface grinders

Plain flat surfaces are produced with this surface grinding. The workpiece is passed against the periphery of the grinding wheel or the flat face of the wheel. For peripheral grinding the wheel is rotated about a horizontal axis and rotating the wheel about the vertical axis performs face grinding. There are four types of surface grinding machines:

Horizontal spindle with reciprocating worktable: This machine is the most common surface grinder. The workpiece is reciprocated longitudinally under the grinding wheel and the wheel is fed transversely into the work a certain distance between strokes (Groover [3]). By using a formed grinding wheel, special contoured surfaces may be formed.

Horizontal spindle with rotating worktable: The workpiece is held on a magnetic chuck of a rotating table and then passed under the grinding wheel. The machine allows faster grinding of circular parts because the wheel is always in contact with the workpiece.

Vertical spindle with reciprocating worktable: This machine is set up so that the wheel diameter is larger than the workpiece width. It grinds on the face of the wheel while the work is moved back and forward under the wheel. The machine is capable of heavy cuts. Most of the machine is able to tilt the wheel head a few degrees.

Vertical spindle with rotating worktable: Grinding is done with the face of the wheel. The large surface contact area between the wheel and the workpiece causes high metal removal rate when equipped with appropriate grinding wheels.

Cylindrical grinders

A cylindrical grinder is used when the diameter of the workpiece has to be ground accurately to size and to a surface finish. The cylindrical workpiece is rotated between centres. There are two types of feed, traverse feed and plunge cut. In the first type the wheel is fed parallel to the axis of rotation of the workpiece. With plunge cut the grinding wheel is fed radially into the work.

Internal grinders

Internal grinding is defined as the accurate finishing of holes in a workpiece by a grinding wheel (Krar et al. [2]). With internal grinders the wheel is automatically fed into the workpiece until the desired diameter for the hole is reached. The wheel is then withdrawn from the hole and before the next hole is ground it is automatically dressed. The workpiece is usually held in a chuck and rotated to provide high surface speeds. The wheel diameter has to be smaller than the original hole. The machine has a horizontal work head spindle on the left side and a wheel head that drives the grinding wheel on the right side. Internal grinding machines could be vertical or planetary.

Centreless grinders

As the name suggests, the workpiece is not physically held in place between centres while it is being ground. Two wheels are required for centreless grinding: the regulating wheel and the grinding wheel. The workpiece thus rests on a work rest blade that is equipped with suitable guides for the type of workpiece and backed up by a regulating wheel. The rotation of the grinder forces the workpiece into the work rest blade and against the regulating wheel, while the regulating wheel controls the speed of the work. The regulating and grinding wheels rotate in the same direction and the centre heights of the machines are fixed. This results in the workpiece being controlled by the distance between the wheels and the height of the work rest blade. It is effective on workpieces that cannot be held in a chuck or accept centres,

The process is often used for high production work. The grinding wheel does the cutting and the regulating wheel at a lower speed and an angle so to control the throughfeed of the work. It is frequently used for the production of cylindrical, tapered and multi-diameter workpieces.

Cutter and tool grinder

The sharpening of machine tools is very important. The cutter and tool grinder is designed for grinding and cutting tools, such as milling cutters, reamers, lathe tools, taps, etc. The general-purpose type of tool and cutter grinder is the most popular because of its capacity and capability. This machine is designed to sharpen most types of cutting tools. Some other grinding operations are also possible, such as surface, internal and cylindrical grinding operations. The only limitation for this machine is the size of the workpiece it can handle.

CNC Grinding

The use of CNC capability on grinding machines has made complex contour grinding a practical reality. Complex forms may be produced to remarkable degrees of precision by form grinding, giving high surface finish with constant material integrity. It also has a wheel head that could be rotated to the most precise degree of accuracy (23).

The CNC machine panel combines machine, programming and setup functions in one easy-to-use module. The grinding machine has CNC-rotation for the spindle-holder turret. This enables the automatic change of wheels. The benefits are reduced cycle times and regrinding of complex cutters is becoming inexpensive and routine.

2.9.2 Advantages

- Produces good surface finishes.
- The machine structure has a high general static and dynamic stiffness.
- It allows for safe, easy operation.

- It serves small or large production lots equally well.
- It is able to grind plain surfaces, external and internal cylinders and contour shapes.

2.9.3 Limitations

- Soft materials and aluminium may not be worked with the grinder.
- It requires high driving power.
- It creates a high noise level.
- The typical grinding process generates heat at the point of the cut. High amounts of energy are converted into heat, resulting in high temperatures where the cutting takes place. Damage to the workpiece is demonstrated by burn marks and cracks that often do not show up until later inspections.

This concludes the discussion of the seven types of machines. In the following section the machine attributes identified for each machine type will be discussed.

3. Machine Attributes

In the previous section seven different machine types were discussed. In this section attributes for each of these machines will be given, described and comments will be made. After specifying the machine types for the project, various attributes for each machine were identified. This was done to determine what information would be needed when selecting a machine for a task in a process chain. Attributes were identified for three categories, namely functionality, economy and reliability-availability. The information for identifying the relevant attributes was found from searching the Internet, product catalogues, textbooks and research papers. Machine specifications for the machines were studied and from the above a list of attributes was compiled.

Some of the functionality attributes are common to all the machines. However for some of the machines the attributes are influenced by different factors. The economical and reliability attributes are also common to all the machine types.

For each machine first a broad range of attributes were found (superset of attributes) and this was then scaled down to those attributes found to be most important that would be used in the evaluation. These attributes that are included in the project are indicated in bold at the beginning of the following tables.

3.1 Broach Functionality Attributes

The following table provides the functionality attributes for a broaching machine.

Table 1 Broach Functionality Attributes

Attribute	Unit	Description/Comments
Max Stroke	mm	The maximum distance in which the tool could move. This defines the workpiece size that could be machined, as well as the type of operation.
Broaching/Cutting speed	m/min	The speed at which the tool is pushed or pulled over or through the surface being machined.
Return stroke speed	m/min	The movement where the broach tool is pulled back out of or over the workpiece.
Broaching / Cutting force	kg	The actual amount of force necessary to operate a broach. The force is in the direction of the broach tool travel. Proper fixtures are needed to stop vibration occurring because vibration leads to tool break.
Max Broach diameter	mm	The maximum width capacity of the broach tool used to machine the workpiece.
Max Broach length	mm	The maximum length of the broach tool used to machine the workpiece. The length is determined by the amount of stock removed and limited by the machine stroke, stiffness and accuracy.
Surface finish	μm	Surface finish describes the deviation from the ideal flat surface. It helps determine whether a pull-up or a pull-down broach should be used. Increases in depth of cut may then cause chatter and/or poor surface quality.
Clearance between guideways	mm	The amount of clearance between the guideways of the machine.
Pull Head to tabletop bottom	mm	The distance from the head to the tabletop.
Machine mass	kg	The total mass of the machine unit.
Max width of broach tool	mm	The designed maximum width the broach tool.
Tool life	min	Failure of the broach cutting tool occurs when it is no longer capable of producing parts within the required specifications. The total length of time over which it is able to produce parts to specification, is called its tool life.

Attribute	Unit	Description/Comments
Tool wear ratio	%	Gives the wear ratio of a specific broach tool. The contact and rubbing at high temperatures and at high pressures will change the original tool contour over a period of time. The most important factor influencing tool wear is the cutting temperature.
Wear type		Wear may occur on the face and on the flank. With broaches the most wear occurs at the flank. The wear causes surface finish to suffer and dimensional accuracy is reduced. Types of wear include: abrasive wear, plastic deformation, chemical distortion, diffusive wear and attrition wear.
Depth of cut	mm	The depth of cut and the feed directly influence the performance and tool life of an insert. An increase in depth of cut widens the area of contact on the tooth face and changes the force. If the depth of cut is too large for the width of an insert, or the feed too high, the insert may be overloaded and cutting forces too high, causing immediate breakage. It also results in greater chip distortion and reduced tool life, although increased depths reduce the machining cycle.
Cutting temperature	°C	The temperature that the process reaches during machining. The high temperatures at broach edges are responsible for rapid tool wear.
Hydraulic unit mass	kg	The mass of the hydraulic unit used to power the machine.
Cutting fluid required (approx)	ϑ	The amount of cutting fluid needed to reduce cutting temperature, lubricate the tool, improve surface finish, increase tool life, and remove chips.
Cutting fluid type		This is the type of cutting fluid used during machining. Testing several fluids to determine which ones give the best result, provides the selection. It also helps to determine whether a pull-up or a pull-down broach should be used. A cutting fluid with a high specific heat and a high thermal-conductivity, that provides good surface contact, could increase tool life simply by reducing the tool temperature a few degrees.

Attribute	**Unit**	**Description/Comments**
Oil reservoir capacity	ϑ	The amount of oil the base tank is able to handle.
Electrical unit mass	kg	The mass of the electric unit.

3.2 Lathe Functionality Attributes

The functionality attributes for the lathe are provided in the following table.

Table 2 Lathe Functionality Attributes

Attribute	**Unit**	**Description/Comments**
Longitudinal travel (Z-axis)	mm	The distance the machine could travel in the upward direction.
Cross travel (X-axis)	mm	The distance the machine could travel in the *x* direction.
Distance between centres	mm	The distance between the live centre on the headstock and the dead centre on the tailstock of the lathe. The live centre is fitted on the spindle nose to hold and drive the work. The live centre has a 60-degree point that provides a bearing for the work to turn between centres. The headstock is clamped on the left-hand side of the bed. The tailstock is on the right-hand side of the lathe bed. These attributes designate the size of the lathe.
Axes traverse rates – x	m/min	Rapid traverse is the rapidly returning of the carriage or cross slide to the starting point when turning any workpiece.
Axes traverse rates - z	m/min	Rapid traverse is the rapidly returning of the carriage or cross slide to the starting point when turning any workpiece.
Chuck size	mm	Some workpieces cannot be held and machined because of their size. Lathe chucks are then used for holding workpieces in machining operations. Most common lathes are: three-jaw, four-jaw or collet

Attribute	Unit	Description/Comments
		chuck. Their characteristics prescribe the size/diameter of the chuck to be used. Chuck size influences the speed of spindle.
Number of tools	#	The number of tools the turret is able to hold. The more tools, the shorter the machining time.
Spindle speed	rpm	The spindle speed, S, is the rotation speed of the spindle/chuck holding the workpiece, defined in revolutions per minute (rpm). This is how fast the tool spins as it cuts. A faster spindle speed will create a smoother cut, and could generally take a higher feed rate, but will create greater heat from friction in some materials (aluminium, brass, etc.). Too high speed makes the cutting tool edge break down rapidly. A too low cutting speed will result in low production rates.
Bed length	mm	The length of the bed on which the carriage could be moved. This attribute is sometimes used to designate the lathe size.
Bed width	mm	The width of the bed on which the carriage is moved.
Swing over bed	mm	As defined in Par 2.3.1 (on page 10), this is the maximum workpiece diameter that could be rotated in the spindle over the bed.
Swing over carriage	mm	The maximum workpiece diameter that could be rotated in the spindle over the carriage.
Swing over cross slide	mm	The maximum workpiece diameter that could be rotated in the spindle over the cross slide.
Width of cross slide	mm	This is the width of the cross slide used to hold the workpiece and thus designates the workpiece size that could be machined.
Spindle nose radius	mm	A small nose radius reduces cutting forces and a large nose radius makes the tool stronger. The spindle nose could hold a live centre or faceplate.
Tailstock Spindle Taper		The tailstock spindle has an internal taper that receives the dead centre, which supports the right-hand end of the workpiece. A taper is defined as a uniform

Attribute	Unit	Description/Comments
		change in the diameter of a workpiece measured along its axis (Krar et al. [2]). It provides a rapid and accurate method of aligning a workpiece and an easy method of holding tools.
Headstock spindle diameter	mm	The diameter of the headstock spindle (cylindrical shaft supported by bearings) that drive the work. This also influences the workpiece size.
Cutting temperature	°C	The temperature at which the machining process occurs.
Turret type		The type of turret the machine uses.
Tailstock centre diameter	mm	The diameter of the centre holding the right-hand end of the workpiece.
Hydraulic motor	kW	The power of the hydraulic motor driving the spindle.
Coolant pump	kW	The power of the pump circulating the coolant fluid.

3.3 Milling Machine Functionality Attributes

The following table gives the functionality attributes for the milling machine.

Table 3 Milling Machine Functionality Attributes

Attribute	Unit	Description/Comments
X travel	mm	The distance the tool is designed to move in the *x* direction. This affects the maximum workpiece size.
Y travel	mm	The distance the tool can move in the *y* direction. It affects the maximum workpiece size.
Z travel	mm	The distance the tool can move in the *z* direction. It affects the maximum workpiece size.

Attribute	Unit	Description/Comments
A travel	mm	The distance the tool can move in the *a* direction. It affects the maximum workpiece size.
B travel	mm	The distance the tool can move in the *b* direction. It affects the maximum workpiece size.
Max Spindle speed	rpm	The rotating speed of the cutting tool is defined in revolutions per minute (rpm). This is how fast the milling tool spins as it cuts. The cutter needs to be revolved at a specified number of revolutions per minute to achieve its proper cutting speed. If a cutter is run too fast the cutter will have to be replaced and regrinded which causes a loss of time. A faster spindle speed will create a smoother cut, and may generally take a higher feed rate but would create greater heat from friction in some materials (aluminium, brass, etc.). The diameter of the cutter affects its speed.
Rapid traverse feed	m/min	Rapid traverse is the rapidly returning to the starting point when machining any workpiece.
Tool magazine capacity	#	The number of tools the machine magazine could hold. It enables the machine to maintain tooling without machine downtime. It also shortens machining time.
Tool change time, average	sec	The time it takes to change from one tool to another.
Work table size	mm^2	Gives the measurements of the worktable that supports the workpiece to be machined. This also influences the workpiece size.
Surface finish	µm	Surface finish describes the deviation from the ideal flat surface. For a fine finish the feed should be reduced.
Ram travel	mm	For ram-type machines. Refers to the distance the ram could move parallel to the saddle movement.

Attribute	Unit	Description/Comments
Knee travel	mm	For knee and column type machines. The distance the knee could move up and down the stationary column.
Quill travel	mm	For vertical machines. The distance the quill could move toward and away from the tabletop.
Spindle nose to table distance	mm	As the name indicates.
Spindle centre to column distance	mm	As the name indicates.
Spindle diameter	mm	The diameter of the spindle that holds and drives the cutter. This influences the tool size.
Head tilt	deg	With vertical machines angular surfaces could be achieved by swinging the head. The attribute gives the angle in degrees to which the head is tilted.
Max tool length	mm	The maximum tool length the machine can accommodate.
Max tool diameter	mm	The maximum tool diameter the machine can handle.
Max tool weight	kg	The maximum weight for a tool the machine is able to accommodate.
Tool changer type		The type of tool changer used.
Taper		The type of taper used to hold the tool or chuck.
Coolant capacity	ℓ	The average amount of the coolant needed during machining.
Machine mass	kg	The total mass of the machine.
Distance, tabletop to floor	mm	The distance from the tabletop to the floor.
Number of T slots	#	T-slots are supplied on the work surface of the gantry type machine for holding the workpiece or workpiece fixtures. This attribute gives the number of T-slots on the surface.
T slots size	mm	The size or diameter of the T-slots.

Attribute	Unit	Description/Comments
Cutting fluid type		The type of fluid used for cooling, lubrication and washing away minute metal chips.
Cutting temperature	°C	The temperature of the process during machining.
Number of teeth on cutter	#	This indicates the number of teeth on a cutter. The operator should be able to determine the proper spindle speed for any cutter.
Diameter of cutter	mm	This provides the diameter of the cutter tool.

3.4 EDM Functionality Attributes

The following table reflects the functionality attributes for the Electrical Discharge Machining.

Table 4 EDM Functionality Attributes

Attribute	Unit	Description/Comments
X travel	mm	The distance the tool could travel in the *x* direction. This influences the workpiece size.
Y travel	mm	The distance the tool could travel in the *Y* direction. This influences the workpiece size.
Z travel	mm	The distance the tool could travel in the *Z* direction. This influences the workpiece size.
U travel	mm	The distance the tool could travel in the *U* direction. This influences the workpiece size.
V travel	mm	The distance the tool could travel in the *V* direction. This influences the workpiece size.
Best surface roughness	µm	Lower removal rate resulting in improved or more smooth surface finish. Low feed = good surface finish. The surface finish is proportional to the number of discharges per second. The type of surface finish required determines the amperes used, capacitance,

Attribute	Unit	Description/Comments
		frequency and voltage settings. For slow metal removal and good surface finish low amperage, high frequency, low capacitance and highest gap voltage are required.
Electrode wear ratio	%	Is equal to the volume of metal lost from the tool divided by the volume of metal removed from the workpiece. It varies with the tool and workpiece materials used. The higher the melting point of the tool material the lower the wear.
Dielectrical tank capacity	ϑ	The amount of dielectric fluid the work tank could hold.
Work table size	mm^2	Gives the measurements of the worktable that support the workpiece to be machined. This also influences the workpiece size.
Max Electrode mass	kg	The maximum mass for which the electrode was designed.
Max cutting speed	mm^2/min	The instantaneous velocity of the primary motion of the selected point on the cutting edge relative to the workpiece.
Max machining current	A	This refers to the direct current supplied by the power supply for the electrical discharges, which occurs between the tool and the workpiece. If current is maintained and the frequency increases a smooth surface finish will be achieved.
Electrode/Cutting tool material		The cutting tool (electrode) is made from electrically conductive material and may be materials such as carbon, graphite, copper tungsten and yellow brass. It has to be a good conductor, easily machined to shape at low cost, produce efficient metal removal from workpiece and have low electrode wear. The melting point of the material affects the metal removal rate and the tool wear.
Dielectrical fluid type		The dielectric fluid should be a non-conductor of electricity. It could be petroleum products, such as light lubricating oils, transformer oils, and kerosene. The fluid should have a low viscosity to flow easily and remove metal

Attribute	Unit	Description/Comments
		chips effectively. The dielectric fluid affects the electrode wear and metal removal rate.
Cutting temperature	°C	The temperature the electrical discharging process reaches while machining.
Sparkgap	mm	Gap between electrode and workpiece to prevent them from coming in contact with each other.
Power supply type	kW	There are various power supply types: resistance capacitance, pulse-type, rotary impulse generator, and static impulse generator. The power supply provides pulsating direct current to the EDM.
Rate at which direct current is applied.	Hz	Gives the number of discharges per second.
Spark length	mm	Electrical energy impulses become sparks that jump the gap between the electrode and the workpiece through the dielectric fluid. This attribute gives the length of the spark that cuts the workpiece.
Capacitance of cutting current	C	Provides the capacitance of the cutting current. It is influenced by the surface finish.
Overcut around electrode	mm	It refers to the amount the cavity in the workpiece is cut bigger than the electrode used. Thus it is the distance between the surface of the workpiece and the surface of the electrode. The overcut could be varied to suit the metal removal rate and the surface finish required. It is dependent on the amount of gap voltage and chip size, which vary with the amperage used.
Level to which dielectric fluid is filled	ϑ	Gives the level to which work tank is filled to submerge the electrode and workpiece in dielectric fluid.
Circulating method of dielectric fluid		There are different methods for circulating the dielectric fluid. These include pressure and vacuum systems. Too much dielectric fluid will remove the chip

Attribute	Unit	Description/Comments
		before it is able to assist in the cutting action and thus results in a slower machining rate. Too little pressure will not remove the chips fast enough, causing short circuits.
Pressure used to circulate dielectric fluid	kPa	The dielectric fluid is circulated under constant pressure to ensure that metal particles are flushed away efficiently.
Dielectric tank weight	kg	The weight of the tank in which the electrode and workpiece are submerged under dielectric fluid.
Filter element type		The element through which the dielectric fluid is filtered to remove metal particles. It is usually made of paper.
Filter unit	μ	This refers to a replaceable filter unit that is supplied with the machine. A 5μ unit is used for general work and 2 μ unit for very fine detail work.
Mass of machine unit	kg	This is the total mass of the machine unit.

3.5 Drill Machine Functionality Attributes

The attributes for drilling machines appear in the following table.

Table 5 Drill Functionality Attributes

Attribute	Unit	Description/Comments
X travel	mm	The distance the drill head could travel in the *x* direction.
Y travel	Mm	The distance the drill head could travel in the *y* direction.
Chuck size	mm	The size of chuck used to hold straight drills. It is either tightened by hand or key. On large drills the chuck is held on the spindle by a self-holding taper.

Attribute	Unit	Description/Comments
Max Spindle speed / cutting speed	rpm	The spindle speed, S, is the rotation speed of the spindle/chuck holding the workpiece. This is the most important factor, which determines the life of the tool. Too fast cutting speed results in the cutting edges of the drill dulling rapidly and this requires frequent regrinding. Too slow a cutting speed results in a broken drill. Drilling speed depends on the type and hardness of the material, the diameter of the drill, the type and condition of the drill press, the efficiency of the cutting fluid used, the depth of the hole and the accuracy and quality of the hole required.
Table work size	mm^2	Provides the measurements of the worktable. The worktable is fitted to the column and it may be adjusted to any place between the base and the head, which is fitted near the top of the column. It is either round or square and supports the workpiece to be machined. Its surface is 90 degrees to the column.
Quill travel	mm	The quill holds the spindle. It does not revolve, but slides up and down the inside of the drill head to provide a downfeed for the cutting tool. This attribute gives the distance the quill could move up and down in the drill head.
Quill diameter	mm	Gives the diameter of the quill that houses the spindle.
Edge of column to spindle centre	mm	This is the distance from the edge of the column to the centre of the spindle. This designates the size of the drill press.
Column diameter	mm	The column is an accurate cylindrical post, which fits into the base of the drilling machine. The worktable is fitted to the column. This attribute gives the diameter of the column.
Column length	mm	The length of the column on which the table could be moved up or down.
Drill diameter	mm	The diameter of the cutting tool used will depend on the diameter of the hole required.
Depth of cut	mm	The distance from the work surface to the end point of the hole.
Drill head tilt	deg	The drill head is used to revolve the cutting tool

Attribute	Unit	Description/Comments
		and advance it into the workpiece. In some machines the drill head could be tilted to an angle.
Work table tilt	deg	The worktable could be raised, lowered or swivelled around the column. The table could also be tilted in either direction for the drilling of holes on an angle. This attribute gives the angle to which the table is tilted.
Machine mass	kg	This is the total mass of the drill machine.
Number of spindle speeds	#	It provides the number of different spindle speeds the drill press provides.
Cutting fluid type		The proper cutting fluid type will improve tool life, surface finish and dimensional accuracy of the workpieces produced.
Cutting temperature	°C	The temperature of the process when machining a workpiece.

3.6 Grinder Functionality Attributes

The attributes for grinders are given in the following table.

Table 6 Grinder Functionality Attributes

Attribute	Unit	Description/Comments
Max grinding length	mm	The maximum length that the machine is designed to grind. This influences the work envelope of the machine.
Max grinding width	mm	The maximum width that the machine can grind influences the work envelope of the machine.
Chuck size	mm	The size of the magnetic chuck that holds the workpiece. It is clamped to the table of the grinder, and could be electromagnetic or permanent magnetic.

Attribute	Unit	Description/Comments
Table work size	mm^2	The area that the workpiece could be set on for machining. This influences the work envelope of the machine.
Cutting speed	mm^2/min	Cutting speed is defined as the rate at which a point on the work circumference travels past the cutting tool. The cutting speed is how fast the tool edge moves through the workpiece.
Surface finish	µm	Surface finish describes the deviation from the ideal flat surface. Factors affecting the surface finish are the material to be ground, the amount of material to be removed, the grinding wheel selection, the condition of the machine and the feed rate.
Internal grinding depth	mm	For internal grinders the depth the machine grinds to reach the required diameter for the workpiece.
Max table to spindle centre	mm	The distance from the table to the spindle centre.
Center height	mm	The height to the centre of the grinding wheel.
Wheelhead swivel range	deg	The range of degrees in which the head could be swivelled.
Grinding wheel / disc diameter	mm	The diameter of the wheel used for grinding a workpiece.
Cutting force	N	If the power requirements are increased, the cutting force is increased.
Grinding wear ratio	%	The grinding ratio is the volume of material removed from the work per unit volume of wheel wear. It is used to measure the grindability of materials. The higher the grinding ratio, the easier to grind a workpiece material. It is affected by speed, feed grinding fluids etc.
Worktable tilt	deg	The angle to which the worktable can be tilted.
Machine mass	kg	The total machine mass.

Attribute	Unit	Description/Comments
Cutting temperature	°C	The temperature reached during the grinding process.
Grinding fluid amount	ϑ	The amount of grinding fluid needed to act as a coolant, lubricant and remove metal chips.
Wheel speed	mm/min	The wheel speed affects the choice of wheel bond. As wheel speed increases the wheel wear decreases. Increase in wheel speed allows power to be utilised in grinding and this produces increased productivity.
Cross-feed	mm/min	This is the rate at which the workpiece is moved across the wheel face. High cross-feeds increase wheel wear and produce rougher finishes. Slower cross-feeds improve the finish; reduces wheel wear, but results in lower productivity.

3.7 CNC Attributes

The CNC attributes that are identified for both the CNC lathe and CNC milling machines are summarised in the table below.

Table 7 CNC Attributes

Attribute	Unit	Description/Comments
Number of controlled axes	#	The number of axes controlled by computer.
Number of simultaneously controlled axes	#	The number of axes that can be controlled simultaneously to produce a certain contour.
Self-diagnosis	1 for yes 2 for no	If a machine has this function the machine tool will monitor and optimise itself. It monitors error sources and then compensates for these. Additionally, some machines will have components that could sense impending failure,

Attribute	Unit	Description/Comments
		request maintenance, and could be diagnosed remotely (25).
Subprogram nesting levels	#	The number of subprograms that may be programmed.

In the following tables, common attributes per category (functionality, economy and reliability-availability (see page 36)) are listed.

3.8 Common Functionality Attributes

The following attributes are common functionality attributes for all the machine types. Some of the machine types have different comments for these attributes. If a machine has a particular comment regarding an attribute it is indicated in the description/comments column of Table 8.

Table 8 Common Functionality Attributes

Attribute	Unit	Description/Comments
Number of axes	#	Gives the number of axis of a machine.
Max workpiece height	mm	The part size is important in order to determine the work envelope of the machine. **Grinding machine**: It is important to use the largest wheel that is consistent with the operation because using small wheels on large workpieces will result in inefficient production.
Max workpiece length	mm	Same as above.
Max workpiece width	mm	Same as above.
Max workpiece mass	mm	The maximum mass that the machine is able to handle. Machines can handle only a certain amount of mass, which in turn also limits the work envelope.
Feed rate	mm/min	The feed rate is defined as the distance the cutting tool advances along the length of the work for every revolution of the spindle.

Attribute	Unit	Description/Comments
		Lathe: For the engine lathe the feed is dependant on the speed of the feed rod and is controlled by gears. For CNC lathe the feed is dependant on the type of feed drive used. It could be open-loop or closed-loop drives and should provide accurate control of position and velocity at low feed rate so that precise contouring movements could occur. Material of the tool, rigidity of the workpiece, size and condition of the lathe, and depth of cut should be considered when choosing the feed, which determines the surface finish, power requirements, and material removal rate. **Mill:** The feed is dependant on the spindle speed as well as on the depth and width of cut, the type of cutter, the workpiece material, the sharpness of the cutter, the power and rigidity of the machine. The feed per tooth and the number of teeth on the cutter form the basis of determining the feed rate. The production rate is directly related to the feed that could be used. The feed per tooth should be reduced when the depth of cut is considerable large and the cutter or workpiece is fragile. **Drill**: Feed is the determining factor in the production rate and life of the drill. The diameter of the drill, the material of the workpiece and the condition of the drilling machine influence the feed rate. Usually the feed rate increases as the drill diameter increases. Too high a feed may break the drill, whereas too light a feed will quickly dull the edges of the cutting tool.
Positioning accuracy	μm	Defined as the degree of agreement between a measured value and the standard or accepted value for that measurement. For any given input this is the maximum difference between the commanded (ideal) position and the actual position. Accuracy affects how closely parts are made to specifications. **EDM**: Accuracy is related to the spark gap width. The smaller the gap, the higher the accuracy. But a smaller gap means lower

Attribute	Unit	Description/Comments
		working voltage and lower removal rate. It is also affected by the electrode accuracy and the allowance made for spark gap. If the discharge time is too small the wear on the tool becomes excessive and reduces the accuracy of the process.
Repeatability accuracy (Precision)	μm	Repeatability is defined as the degree to which repetitive measurements on a single system are in agreement. Another way of stating this definition, is that repeatability is how close a system returns to a desired location or locations time after time under repeated cycling. There is a direct relationship between system cost, accuracy and repeatability. Precision is defined as the repeatability of a result and relates to how variable the results are compared to the average. This is often expressed as a 95% confidence limit or variance. Precision is a measurement of how closely the analytical results could be duplicated.
Metal removal rate	mm^3/min	The total volume of metal removed per unit of time. **EDM**: Each discharge removes a minute amount of metal. The amount of metal removed will be proportional to the amount of charge between electrode and workpiece. For high MRR (metal removal rate) high amounts of current have to be delivered rapidly so as to melt the maximum amount of metal. But this leads to a rough surface finish. A smoother surface finish could be achieved with smaller charges but results in lower MRR. The MRR depends mainly on the electrical parameters. Including the amount of current in each discharge, the frequency of the discharge, the electrode material, workpiece material and dielectric flushing conditions. The rate is affected by the duration of the individual sparks for a given quantity of electrical energy.

Attribute	Unit	Description/Comments
Main motor power	kW	Power, P, consumed in the machining process is the rate of energy dissipation. The amount is equal to the power required to remove a unit volume of material times the volume of material removed per unit time. **Mill**: The power for milling should include the power losses and the power actually used by the cutter. Efficient use of the power is influenced by cutter speed, design, material as well as workpiece material. **Grinding machine**: It is a critical factor for good grinding performance. When adequate power is not available, then the selection of the grinding wheel is made to permit overcoming the lack in power. Inadequate powered machines will not operate efficiently and thus be less reliable.

3.9 Common Economical Attributes

Table 9 gives the economical attributes that are common to all the machine types.

Table 9 Common Economical Attributes

Attribute	Unit	Description/Motivation
Machine price	R	The acquisition price of the machine, as bought when new, or second hand.
Tool cost	R	This is the cost of the tools used for the machining process of a part.
Electricity cost	R	The cost of electricity for operating the machine at a certain power for the duration of a process.
Labour cost	R	The cost of the operator operating the machine.
Maintenance cost	R	This is the cost to maintain the machine.
Depreciation cost	R	The cost to write off the value of the machine as it deteriorates.

Attribute	Unit	Description/Motivation
Floor space required	R	This relates to the total floor space needed for the machine to fill.
Floor space cost	R	The cost for the total floor space needed.
Downtime cost	R	This is the cost when the machine breaks down.
Cutting Fluid cost	R	This refers to the cost of the cutting fluid needed for the machining process.

3.10 Common Reliability and Availability Attributes

Two attributes were identified for machines to determine their reliability and availability.

Table 10 Common Reliability Attributes

Attribute	Unit	Description/Motivation
Mean time between failures (MTBF)	min	This refers to the average time between successive failures. This is important to determine in order to establish the regular pattern of the failures.
Mean time to repair (MTTR)	min	This is the expected value of the time to repair a machine. It is important to determine to evaluate the maintainability of machines. It is determined in order to find out the regular pattern of repair time. The repair time of all machines is taken as random variables to analyse the distribution of repair time.

This concludes the machine attribute definitions. In the following section an overview of multi-criteria decision analysis and some of its methods are given.

4. Multi-Criteria Decision Analysis

Decision is one of the most central and pervasive human activities. Everybody makes decisions all the time. In the previous section the attributes identified for each machine type were given. These criteria will be used to select the best number form a group of candidate machines to realize processes in a process chain. Since this is a multi-criteria decision-making process this section will report on some multi-criteria analysis methods. Thereafter the Analytic Hierarchy Process (AHP) as well as a new method for multi-criteria decision-making will be described.

Most realistic engineering optimisation problems, particularly those in design, require the simultaneous optimisation of more than one objective function. This multi-objective problem is almost always solved by combining the multiple objectives into one scalar objective whose solution is a Pareto optimal point for the original multiple objective problem.

Multi-criteria analysis (MCA) establishes preferences between options by reference to an explicit set of objectives that the decision-making body has identified, and for which it has established measurable criteria to assess the extent to which the objectives have been achieved (11). In other words, it uses mathematical programming techniques to select options based on objective functions, including weighted goals of decision-makers with explicit considerations of constraints and costs. The key feature in MCA is its emphasis on the judgement of the decision-making groups in determining the objectives and criteria, and estimating the importance of the weights.

Multi-criteria decision analysis (MCDA) is a form of multi-criteria analysis used in both public and private sector organisations. It is an approach and a set of techniques, which result in an overall ordering of options, from the most to the least preferred (11). The purpose is to function as an aid to the thinking and decision-making, and not to take decisions. It gives a way to solve complex problems, by breaking the problem into more manageable pieces to allow data and judgement to be applied and then reassembling the various pieces for an overall picture. MCDA also provides a set of techniques for ways of disaggregating the complex problem, measuring the degree to which options achieve objectives, weighting of objectives, and reassembly of the pieces.

4.1 Steps in MCA

The steps in the MCA process are as follows (11):

1. Establish the decision context. What are the aims of the aims of the MCA, and who are the decision-makers and other key players?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria.
5. Weighting. Assign weights for each of the criteria to reflect their relative importance.
6. Combine the weights and scores for each of the options to derive an overall value.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores and weights.

These steps will later be broken down into further detailed steps (Par 4.5).

4.2 Overview of MCA Techniques

There are many types of MCA procedures. In this section firstly two approaches for aggregating the overall value for an option will be given and then several techniques used for MCA will be described briefly. Most of these techniques require some input from the decision-maker and the input usually consists of ranking, weighting or attainability information of the objectives.

4.2.1 Multi-attribute Utility Theory

This is a theoretical tool for mapping a multidimensional goal vector in a one-dimensional real number.

Keeney and Raiffa [31] developed a set of procedures, consistent with the earlier normative foundations that allow decision-makers to evaluate multi-criteria options in practice.

There are three building blocks to this method (11). The first is the performance matrix, the second are the procedures to determine whether the criteria are independent of each other. Ways of estimating the parameters in a mathematical function provide the third block. The decision-maker's overall valuation of an option in terms of the value of its performance on each separate criterion is expressed by the estimation of a single number index, *U*.

The following steps are used for this method (16):

1. Define the alternatives and relevant attributes.
2. Evaluate each alternative on each attribute. Remove dominated alternatives. Thus, if there is any alternative that is worse than another alternative on all attributes, it should be discarded from the set of options. These alternatives are called "dominated" alternatives, and will never be chosen.

3. Assign relative weights to the attributes. There are many ways to do this.
4. Combine the attribute weights and evaluations to yield an overall evaluation of each alternative.
5. Perform sensitivity analysis and make a decision. This means considering places in the analysis where values may not be exact, and varying them to see what happens to the final recommendation. The recommendation is classified as "robust" when it is insensitive to these changes.

This model takes uncertainty into account by incorporating uncertainty directly into the decision support models. It also allows attributes to interact with each other in an additive manner (Vincke [7]).

This method, however, does not directly help the decision-makers in undertaking complex multi-criteria decisions. The drawback is that neither the proposal to determine the utilities using lotteries, nor the method to reduce the dimensions step by step by means of transformation, is convincing.

4.2.2 Linear Additive methods

If the criteria are preferentially independent and there is no uncertainty built into the MCA model then this approach could be used. With this approach an option's values of the many criteria may be combined into one overall value.

Multiplying the value score of each criterion by the weight of that criterion and adding them all up, achieves this end, as follows:

$$S_i = \sum_{j=1}^{n} w_j s_{ij} = w_1 s_{i1} + w_2 s_{i2} + \ldots + w_n s_{in} \qquad \ldots.1$$

Where

$w_j = weight\ of\ criterion\ j$

$s_{ij} = score\ of\ option\ i\ for\ criterion\ j$

The sum of the weights always has to be one.

There may be uncertainty about the accuracy of either w_j or s_{ij}, or both in terms of the two inputs, being weights and scores. Confidence is usually lower for the weights in most cases. Therefore, typically the scores are assumed to be known and a formal analysis of imprecision is concentrated on the weight w_j.

The decision-maker has to follow the steps given in Par. 4.1 on page 58 very carefully. If one should deviate, it will nevertheless result in an MCDA that appears clear and well-founded, but which is actually misleading and not a true reflection of the decision-making group's understanding of the problem (11).

4.2.3 Outranking Methods

Outranking, as a basis for MCA, originated in France in the work of Bernard Roy and colleagues in the mid-1960s and has continued to be applied and extended since that time.

This approach depends on the concept of outranking. Outranking is used to eliminate those alternatives that are dominated. Weights are used to give more influence to some criteria than others.

Outranking may be defined as follows (Vincke [7]):

> *Option* A *outranks Option* B *if, given what is understood of the decision-maker's preferences, the quality of the evaluation of the options and the context of the problem, there are sufficient arguments to decide that* A *is at least as good as* B*, while there is no overwhelming reason to refute that statement.*

When one option performs better than another, based on enough criteria of sufficient importance and is not outperformed by the other option by having a considerably lower performance on any one criterion, then this option outperforms the other.

The extent to which all options exhibit sufficient outranking with respect to the full set of options considered is then assessed. This is measured against a pair of threshold parameters.

A series of procedures have been developed to operationalise outranking as a way of supporting multi-criteria decision-making. Two phases are typically involved (11). First, a precise way of determining whether one option outranks another must be specified. In the second phase it is necessary to determine how all the pairwise outranking assessments can be combined to suggest an overall preference ranking among the options.

This outranking method is dependant on the way that its definition is formalised and how the threshold parameters are set and manipulated by the decision-maker (Vincke [7]).

The advantage of outranking is that it encourages more interaction between the decision-maker and the model in seeking out sound options.

4.2.4 Goal programming

This common approach involves solving problems containing more than one specific objective. The objectives are thought of as goals with target values that are desired. Goals are assigned some priority or weighting to indicate their importance relative to others. The goal criteria could be: greater than or equal to, less than or equal to, equal to or range. In the goal programming approach, one objective is minimised while the remaining objectives are constrained to be less than given target values.

When some of the goals are more important than the others, one could assign larger weights to them that would remove the possibility of any undesirable deviations from them. This is called *pre-emptive goal programming*.

A summary of the steps in goal programming is as follows, (Ragsdale [8]):

- Identify the decision variables in the problem.
- Identify any hard constraints in the problem and formulate them in the usual way.
- State the goals of the problem along with their target values.
- Create constraints using the decision variables that would achieve the goals exactly.
- Transform the above constraints into goal constraints by including deviational variables.
- Determine which deviational variables represent undesirable deviations from the goals.
- Formulate an objective that penalises the undesirable deviation.
- Identify appropriate weights for the objective.
- Solve the problem.
- Inspect the solution to the problem.

The decision-maker should remember to compare the solutions that are produced, and not the objective function values.

This method is especially useful if the user can afford to solve just one optimisation problem, (14). However, it is not always easy to choose appropriate 'goals' for the constraints. Goal programming cannot be used to generate the Pareto set effectively, particularly if the number of objectives is greater than two.

4.2.5 Fuzzy sets

This is a new field that is used for decision-making. Instead of the membership of a set being crisp – meaning that an element is either definitely a member of a given set or it is not – set membership is graduated, or fuzzy or imprecise (11).

The fuzzy sets attempt to capture the idea that our natural language in discussing issues is not precise (11). Options are described as 'fairly attractive' rather than simply 'attractive'. The approach then tries to qualify these assessments using the idea of membership functions. With this membership function idea an option would belong to the set of for example 'attractive' options with a degree of membership ranging between 0 and 1.

Fuzzy MCA recognises the reality that many of the concepts involved in decision-making are far from clear or precise to those involved (Rommelfanger [15]). Fuzzy sets provide a clear way of representing that vagueness in the decision-maker's mind.

This method tends to be difficult for non-specialist users to understand. It also has no clear theoretical foundations as yet, and no critical advantages have been established that makes this method better than any of the other already available.

4.2.6 Weighting Objectives Method

This is the most commonly used approach for single dimensional problems. This method takes each objective function and multiplies it by a fraction of one. This gives the "weighting coefficient" which is represented by w_i. The modified functions are then added together to obtain a single cost function, which could easily be solved using any single objective optimisation method.

The alternative with the highest value is the best.

$$Score = \sum_{i=1}^{n} w_i f_i(x) \qquad w_i > 0, i = 1,2,\ldots,n \qquad \ldots.2$$

where $f_i(x)$ represents the actual value of the *i*-th alternative.

This method functions according to the additive utility assumption, which states that the total value of each alternative is equal to the sum of the products given in equation 2.

This method becomes difficult when applying it to multi-dimensional problems. The additive assumption is violated and results in '*adding apples to oranges*' when trying to combine different dimensions with different units.

4.3 Advantages of MCA over Informal Judgement

- It is open and explicit and offers a consistent basis for making decisions.
- The choice of objectives and criteria that the decision-making group may make are open to analysis and change if they are felt to be inappropriate.
- It provides a means of communication within the decision-making group and also subsequently between that group and the community.
- Scores and weights are used; they are also explicit and are developed according to established techniques.
- Performance measurements may be sub-contracted to experts.

4.4 Limitations of MCA

- It cannot indicate that an action adds more to welfare than it detracts.
- There is no rule that benefits should exceed costs.
- The results are only as good as the inputs to model.
- There is an unrealistic characterisation of the decision process.
- The decision-making group has to supply the weight to be assigned to goals, which thus makes it subjective.

4.5 Stages in MCDA

The various stages for multi-criteria decision analysis will now be given, (11). The steps given in Par 4.1 on page 58 for MCA are divided into further detailed steps for MCDA.

1. Establish the decision context. i. Establish aims of the MCDA and identify decision makers and other key players. ii. Design the socio-technical system for conducting the MCDA. iii. Consider the context of the appraisal.
2. Identify the options to be appraised.
3. Identify objectives and criteria. i. Identify criteria by clustering the consequences of each option. ii. Organise the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4. Scoring. Assign the expected performance of each option against the criteria. Then assess the value associated with the

consequences of each option for each criterion.

i. Describe the consequences of the option.

ii. Score the options on the criteria.

iii. Check the consistency of the scores on each criterion.

5. Weighting. Assign weights for each of the criteria to reflect their relative importance to the decision.

6. Combine the weights and scores for each option to derive an overall value.

i. Calculate overall weighted scores at each level in the hierarchy.

ii. Calculate overall weighted scores.

7. Examine the results.

8. Sensitivity analysis.

i. Conduct a sensitivity analysis: do other preferences or weights affect the overall ordering of the options?

ii. Look at the advantages and disadvantages of the selected options, and compare the pairs of options.

iii. Create possible new options that might be better than those originally considered.

iv. Repeat the above steps until a 'requisite' model is obtained.

The decision context in step 1 is the group of administrative, political and social structures surrounding the decision being made and includes the objectives, the administrative and historical content, as well as who are responsible for decision-making.

It is very important to determine the purpose of the MCDA, as it may change as the MCDA progresses. A key player is anyone who makes a considerable contribution to the MCDA and must be chosen to represent all the important perspectives on the subject of analysis. To establish the objectives and the criteria for the MCDA, the decision-makers, and also those persons whom the decision would affect, should be established. With the current situation being described and the goals to be achieved being clear, the discrepancy between now and the vision for the future will clarify the role of the MCDA.

The options are important for the value they create by achieving objectives. Step 2 may be revisited if no options are found acceptable during the MCDA process.

With step 3 it is important to measure how well each option performs on the criteria chosen. The number of criteria should be kept as low as possible to make a well-founded decision. The completeness, redundancy, operationality, mutual independence of preferences and size of the chosen criteria is important to consider.

Step 6 is achieved for an alternative by calculating the sum of each of its attribute evaluations, multiplied by that attribute's weight. The alternative with the highest evaluation is the one that one should choose.

The objective of the sensitivity analysis done in step 8 is to ascertain when the input data are changed into new values and how these would change the ranking of the alternatives.

4.6 Software for MCDA

Software packages become very useful during the later stages of the MCDA process. These packages provide a means to easily modify input data and present outputs in an attractive and informative manner. The most basic programs such as spreadsheets usually facilitate the correcting of errors in initial scoring and weighting, the calculations, changes to the underlying model structure through addition or deletion, and graphing of results (11).

More sophisticated programs include benefits such as tailored input screens for information on option performance measures, alternative ways of inputting weight information, direct on-screen representation of the value tree hierarchy and some automation of sensitivity testing. Examples include VISA, MACBETH and HIVIEW.

The software packages HIPRE 3+ and Expert Choice provide support for AHP implementation and automate most of the computations for AHP.

4.7 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) developed by Thomas Saaty in the early 1970s is a multi-criteria analysis technique and provides a powerful tool used to make decisions in situations involving multiple objectives (Winston [10]).

In the previous section an overview was given on MCA and some of its techniques. The AHP method is considered for choosing between a number of machines with various criteria.

This approach develops a linear additive model, but uses procedures for deriving weights and scores achieved by alternatives that are based on a pairwise comparison matrix and between options. The user is asked how important one particular criterion is relative to another. This method allows the designer to rank the objectives in a descending order of importance, from 1 to *k*. Each objective function is then minimised individually, subject to a constraint that does not allow the minimum for the new function to exceed a prescribed fraction of a minimum of the previous function.

There are three principles used in AHP for problem-solving (Smith et al [18]):

1. Decomposition of the decision problem - structuring the elements (objectives and criteria) of the problem into a hierarchy.
2. Comparative judgment of the elements - generating a pairwise comparison matrix for all the alternatives and the criteria. For this relative comparison, the fundamental scale of Table 11 (page 71) can be used. It allows one to express the comparisons in verbal terms, which are then translated to the corresponding numbers.
3. Synthesis of the priorities - getting the priorities of the alternatives with respect to each criterion and the weights of each criterion with respect to the goal. The local priorities are then multiplied by the weights of the respective criterion. The results are summed up to obtain the overall priority of each alternative.

Applications of AHP in industrial engineering are in integrated manufacturing, evaluation of technology decisions, flexible-manufacturing systems, layout design and other engineering problems (Triantaphyllou [13]).

The following section gives the detailed steps followed when using AHP.

4.7.1 Steps in AHP

The following steps are applied when using the AHP method.

Step 1: Create a pairwise comparison matrix.

For a problem with n objectives create an n x n pairwise comparison matrix $\boldsymbol{A}$ as shown in the figure below. Pairwise comparisons are used to determine the relative importance of each alternative in terms of each criterion. The entry in row i and column j of $\boldsymbol{A}$ indicates how much more important objective i is than objective j. This is called the 'importance ratios' (Vincke [7]). This importance is measured verbally and interpreted with Table 11 to a number from 1 to 9. The decision-maker thus has to express his/her opinion about the value of one single pairwise comparison at a time, for example "*A is more important than B*" or "*A is of the same importance as B*", (13).

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots a_{1j} \\ a_{21} & a_{22} & a_{23} & \cdots a_{2j} \\ \vdots & \vdots & \vdots & \vdots \quad \vdots \\ a_{i1} & a_{i2} & a_{i3} & \cdots a_{ij} \end{bmatrix}$$

Figure 1 Pairwise Comparison Matrix

It is important that $a_{ii} = 1$ for all i. Also if $a_{ij} = k$, it is necessary for consistency that $a_{ji} = 1/k$.

Table 11 Interpretations of Entries in a Pairwise Comparison Matrix.

Level of Importance	Definition	Interpretation
1	Equally important, likely or preferred	Two activities contribute equally to the objective
3	Moderately more important, likely or preferred	Experience and judgment slightly favour one activity over another
5	Strongly more important, likely or preferred	Experience and judgment strongly favour one activity over another
7	Very strongly more important, likely or preferred	An activity is strongly favoured over another and its dominance demonstrated in public.
9	Extremely more important, likely or preferred	The evidence favouring one activity over another is of the highest degree possible
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences listed above
Reciprocals	Reciprocals for inverse comparison	

(Source: Triantaphyllou [12])

Step 2: Calculate weights for all the criteria, w_{max}.

This step consists of a two-step procedure:

First the normalised matrix for ***A*** is determined. This is done by dividing each entry in the column *j* of ***A*** by the sum of the entries in column *j*. This gives the matrix $\boldsymbol{A}_{norm.}$, in which the sum of the entries in each column *j* is 1.

Next a weight for each criterion, w_i, is estimated by calculating the average of the entries in row *i* of $\boldsymbol{A}_{norm.}$ Thus adding all the values in the row and then dividing it by the number of entries in that row. This results in the weight matrix ***W***.

Step 3: Check consistency of comparisons.

This part consists of a four-step procedure:

First the matrix $A\mathbf{w}^{T}$ is calculated. This is the pairwise comparison matrix, ***A***, multiplied by the transposed weights matrix, **w** that was calculated in the previous step.

Next the following value is calculated:

$$V = \frac{1}{n}\sum_{i=1}^{i=n}\frac{ith\,entry\,in\,Aw^{T}}{ith\,entry\,in\,w^{T}} \qquad ....3$$

Here *n* is the number of criteria (rows).

The **Consistency Index** (CI) is then calculated as follows:

$$CI = \frac{(V)-n}{n-1} \qquad ....4$$

The consistency index is then compared with the random index for the appropriate value of *n*, as reflected in Table 12. For perfect consistency

CI=0. If CI/RI < 0 the degree of consistency is satisfactory, but if CI/RI > 0, then serious inconsistencies may exist and the AHP may not give meaningful results.

Table 12 Values of Random Index

n	RI
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Step 4: Finding the score for each alternative.

In this step it is determined how well each alternative, for example a machine, scores for each of the *n* objectives. This is done by constructing a pairwise comparison matrix for each objective in which the rows and columns are possible alternatives, for example different machines.

The same procedure followed to calculate the weights is applied. First $\mathbf{A}_{norm}$ is calculated for the specific objective and then the weights are determined by taking the average of each row in $\mathbf{A}_{norm}$. This gives the matrix **w** that holds the weights for the alternatives for the specific objective.

Step 5: Calculate overall score.

As mentioned in the third principle (see page 70), the objective weights are synthesized with the score for each alternative to obtain an overall score for each alternative.

The overall score is calculated for each alternative by multiplying the score that the alternative has for an objective by the objective's weight.

$$S_j = \sum_{i=1}^{n} w_i (alternative\ j's\ score\ on\ objective\ i) \qquad ....5$$

This is done for all the weights for that alternative and added together. The alternative with the highest score is considered the best.

4.7.2 Advantages

Pairwise comparisons are generally readily accepted in practice as a means of establishing information about the relative importance of criteria and the relative performance of options. Users also find the pairwise comparison form of data input straightforward and easy.

AHP may have a major impact on the understanding by the participants of the factors, which influence the value of a project.

Besides a broad agreement on the ranking of projects, the process provides profound insight in the art of complex decision-making and encourages the participants to pool their knowledge and expertise.

AHP fits easily with circumstances where judgements, rather than measurements of performance, are the predominant form of input information.

4.7.3 Limitations

Populating the pairwise comparison matrices may become fairly time-consuming if a large number of alternatives and objectives need to be evaluated.

The user has to fill in a matrix for each alternative and when there are a fairly high number of alternatives this takes up a great deal of time. E.g. for m = 3 alternatives and n = 6 objectives, then we need 7 pairwise comparison matrices and 90 alternatives to be completed.

The rank reversal method causes some concern. Simply by adding another option to the list for evaluation the ranking of two other options could be reversed, which is inconsistent with rational evaluation of options and thus this questions the theoretical basis of AHP.

When using AHP in engineering problems caution is needed. The recommendations made by the AHP should not be taken literally, especially if the scores are close to each other.

According to French [9] some doubts about AHP are that the 1 – 9 scale given in Table 11 on page 71 has the potential to be internally inconsistent. There is also no theoretical foundation for the link between the points on the 1 – 9 scale and the corresponding verbal descriptions.

4.8 Quotient Exponential Method for MCDA

A new method for deciding between *m* alternatives was devised. This method uses the existing real world data of *m* alternatives to choose an ideal value for each of the *k* criterions evaluated. For each criterion the real values are compared to the ideal values and raised to an exponent that represents a scaled importance of the criterion. This is done for all the criteria.

Two methods for calculating the individual and overall scores are proposed. These are outlined below.

4.8.1 Steps in the QE process – Method 1

The following equation is used to determine the score of an alternative:

$$Overall\ Score = \left(\frac{\text{Real Value}_1}{\text{Ideal Value}_1}\right)^{Exp_1} + \left(\frac{\text{Real Value}_2}{\text{Ideal Value}_2}\right)^{Exp_2} + \ldots + \left(\frac{\text{Real Value}_k}{\text{Ideal Value}_k}\right)^{Exp_k} \quad \ldots .6$$

Where $\text{IdealValue}_i = \min \text{ or } \max_j \{\text{RealValue}_j\} > 0$ for all *i*.

The process consists of the following eight steps:

Step 1: Determine Ideal State

The first step in the process is to decide which of the criteria will be maximised and what will be minimised. The ideal state will thus be the minimum or maximum of a criterion. If the criterion is for example a machine price, the decision-maker may choose to minimise it.

In practice some ideal values would be unrealistic for use in equation 6 given above, for example cost = 0 is an ideal and profit = infinity is also an ideal. In this project it was decided to use the realistic ideal for an alternative of the values given for a problem and not the theoretical ideal.

Step 2: Determine Curve Type.

Next the decision-maker should decide regarding each criterion what type of curve best represents the perceptive importance of the attribute. The curve types are given in the following figure. Each of these curve types represent an exponent that is used in the equation for calculating the score. The exponents are given in Table 13. Choosing for example curve

3 will mean that the value of the attribute is not important to the decision-maker until a certain value is reached and from there on the value is very important.

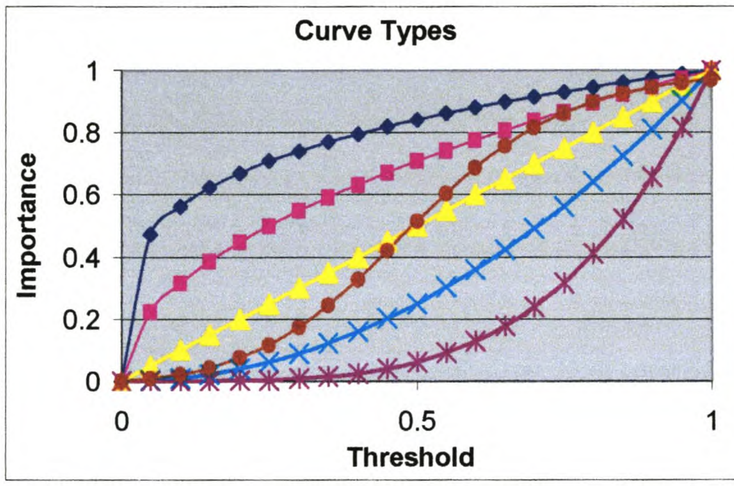

Figure 2 Curve Types

These curves were obtained by using two equations. The first equation is as follows:

$$y = x^t \qquad ....7$$

The *k* exponent is used as the exponent to which the ratio is raised in equation 6.

The second equation is for the s-curve:

$$y = \frac{x}{x + \exp(2 - xt)} \qquad ....8$$

Table 13 QE Method Exponents

Curve	Curve number	Exponent
	1	0.25
	2	0.5
	3	5.5
	4	1
	5	2
	6	4

Step 3: Determine Ideal Value for Criterion.

When a decision has been made on the curve type and ideal state of a criterion, the ideal value has to be obtained from the alternatives that are evaluated. If the ideal state chosen is to minimise the criterion, the minimum value is chosen from the real data of the *m* alternatives. This is then the ideal value. In the same way, if the ideal state is to maximise the criterion, the maximum value is chosen from the real data of the *m* alternatives.

Step 4: Calculate Score for Criterion *i* of Alternative *j*.

Calculate the score, using the term as shown below, for criterion *i* so as to calculate the overall score. This is the ratio of the real data value of alternative *j* over the ideal value (calculated in previous step) raised to the exponent power chosen in step 2.

$$Score_i = \left(\frac{\text{Real value}}{\text{Ideal value}}\right)^{Exp} \qquad \text{....9}$$

Step 5: Repeat for all the criteria.

Step 6: Calculate Overall Score for Alternative *j* and Repeat for each Alternative.

After the individual scores for all the criteria are determined using equation 9, the overall score for the alternative could be calculated. This is the sum of all the separate scores. The weights of the scores are chosen as 1. Steps 4 to 6 are then repeated for each of the *m* alternatives.

Step7: Determine Ideal Score

The ideal value for a criterion is its ideal value (determined in step 3) and the ideal ratio for a criterion is 1. The individual score for each criterion will thus result in a value of 1 and the ideal score, as calculated with equation 4, will then be 1*k.

Step 8: Compare Overall Score to Ideal Score for each Alternative.

The overall score for each alternative is compared with the ideal score. The alternative with the score closest to the ideal score is the best option.

4.8.2 Steps in QE process – Method 2

Another possibility for evaluating alternatives is proposed. This method is very similar to the first QE method except that it calculates the individual and overall scores differently. The steps are as follows:

Step 1 to 3: Same as for the QE Method 1 as given in Par 4.8.1 on page 76 – 78.

Step 4: Calculate Score for Criterion *i* of Alternative *j*.

Calculate the score, using the terms as shown below, for criterion *i* so as to calculate the overall score. When a criterion must be maximised, the ratio of the real data value of alternative *j* over the ideal value (calculated in previous step) raised to the exponent power (chosen in step) 2 is calculated.

When a criterion must be minimised, the ratio of the ideal value over the real data value of alternative *j* raised to the exponent power (chosen in step 2) is calculated.

$$Score_i = \left(\frac{\text{RealValue}_j}{\text{IdealValue}_i}\right)^{Exp} \text{ if highest possible value for criterion}_i \text{ is desired} \qquad ....10$$

$$\text{Score}_i = \left(\frac{\text{IdealValue}_i}{\text{RealValue}_j}\right)^{Exp} \text{ if lowest possible value for criterion}_i \text{ is desired}$$

Then $\text{Score}_i \leq 1$

Step 5: Repeat for all the criteria.

Step 6: Calculate Overall Score for Alternative *j* and Repeat for each Alternative.

After the individual scores for all the criteria are determined using equation 10, the overall score for the alternative could be calculated. This is the sum of all the separate scores over the number of criteria as shown in the equation below. Steps 4 to 6 are then repeated for each of the *m* alternatives.

$$Overall\ Score = \frac{\left(\frac{\text{Real Value}_1}{\text{Ideal Value}_1}\right)^{Exp_1} + \left(\frac{\text{Real Value}_2}{\text{Ideal Value}_2}\right)^{Exp_2} + \ldots + \left(\frac{\text{Real Value}_k}{\text{Ideal Value}_k}\right)^{Exp_k}}{n} \qquad ...11$$

Where n = number of criteria

Step 7: Compare Overall Score to Ideal Score for each Alternative.

The ideal score for an alternative is 1 and each alternative is compared to this ideal score of 1. As shown in equation 11 the overall score of an alternative cannot be larger than 1 thus the alternative with the highest score will be the best option.

4.8.3 Advantages

This method is simple and easy to use. There is not much detail for the user to complete.

4.8.4 Limitations

With method 1 because some criteria are maximised and some are minimised a value bigger and smaller than the ideal score may occur.

This results in ambiguity because it could be difficult to decide what the best score is. For example if the ideal score is 15 and two alternatives have scores 14.5 and 15.5 respectively it is difficult or impossible to determine the best alternative. A possibility would be to determine the frequency of minimisations and maximisations. If the score is below the ideal, and there are more minimisations, then the lower score should be considered. If the score is above the ideal and there are more maximisations, then the higher score should be considered.

4.8.5 Example of QE Method 1

An example of how the first QE method works will now be given.

Three machines and four objectives are considered. These objectives are feed, accuracy, metal removal rate (MRR) and price. The table below indicates the real values, exponent, ideal state and ideal value of each objective for each machine.

Table 14 Data for Example of QE Method

Alternatives	Decision Values			
	Feed m/min	**Accuracy** μm	**MRR** mm^3/min	**Price** R
Machine1	340	6.5	298	23 000
Machine2	550	5.0	323	45 000
Machine3	235	6.0	405	25 000
Exponent	2	0.5	2	1
Ideal state	Max	Min	Max	Min
Ideal value	550	5.0	405	23 000

First the user chooses the ideal states for the four objectives. This is shown in the table above. The curve types for each of the criteria are then chosen according to Figure 2 on page 77. The corresponding exponents found from Table 13 on page 78 are given in the table above.

The ideal values are now determined. From the table one can see that the feed rate of the machines must be maximised, thus the maximum value from the three real values is taken as the ideal value. The ideal value for the feed rate is 550 m/min. In the same way, the price must be minimised, thus the lowest value from the real data is taken as the ideal value, i.e. R23 000. This is done for all the objectives.

The individual scores are now calculated. For machine 1 the individual scores and overall score are as follows:

$$Score_{Feed} = \left(\frac{340}{550}\right)^{2} = 0.382$$

$$Score_{Accuracy} = \left(\frac{6.5}{5.0}\right)^{0.5} = 1.140$$

$$Score_{MRR} = \left(\frac{298}{405}\right)^{2} = 0.541$$

$$Score_{\Pr ice} = \left(\frac{23000}{23000}\right)^{1} = 1$$

$$OverallScore_{Machine1} = 0.382 + 1.140 + 0.541 + 1 = 3.06$$

For machine 2 the scores are calculated as follows:

$$Score_{Feed} = \left(\frac{550}{550}\right)^{2} = 1$$

$$Score_{Accuracy} = \left(\frac{5}{5}\right)^{0.5} = 1$$

$$Score_{MRR} = \left(\frac{323}{405}\right)^{2} = 0.636$$

$$Score_{\Pr ice} = \left(\frac{45000}{23000}\right)^{1} = 1.957$$

$$OverallScore_{Machine2} = 1 + 0.877 + 0.636 + 1.957 = 4.593$$

The scores for machine 3 are given below.

$$Score_{Feed} = \left(\frac{235}{550}\right)^{2} = 0.183$$

$$Score_{Accuracy} = \left(\frac{6}{5}\right)^{0.5} = 1.100$$

$$Score_{MRR} = \left(\frac{405}{405}\right)^{2} = 1$$

$$Score_{\Pr ice} = \left(\frac{25000}{23000}\right)^{1} = 1.087$$

$$OverallScore_{Machine3} = 0.183 + 1.1 + 1 + 1.087 = 3.365$$

The ideal score for the problem is 4, thus the machine with the score closest to 4 will be the best machine. From the results given above one can see that machine 2 is the best alternative for this example.

4.8.6 Example of QE Method 2

An example of how the second proposed QE method works is now given. The same input as in the example for method 1 is used and given in Table 14 (on page 82). Steps 1 to 3 are applied as in the example for method 1.

The individual scores are now calculated. For machine 1 the individual scores and overall score are as follows:

$$Score_{Feed} = \left(\frac{340}{550}\right)^2 = 0.382$$

$$Score_{Accuracy} = \left(\frac{5}{6.5}\right)^{0.5} = 0.877$$

$$Score_{MRR} = \left(\frac{298}{405}\right)^2 = 0.541$$

$$Score_{Price} = \left(\frac{23000}{23000}\right)^1 = 1$$

$$OverallScore_{Machine1} = \frac{0.382 + 0.877 + 0.541 + 1}{4} = 0.700$$

For machine 2 the scores are calculated as follows:

$$Score_{Feed} = \left(\frac{550}{550}\right)^2 = 1$$

$$Score_{Accuracy} = \left(\frac{5}{5}\right)^{0.5} = 1$$

$$Score_{MRR} = \left(\frac{323}{405}\right)^2 = 0.636$$

$$Score_{Price} = \left(\frac{23000}{45000}\right)^1 = 0.511$$

$$OverallScore_{Machine2} = \frac{1 + 1 + 0.636 + 0.511}{4} = 0.787$$

The scores for machine 3 are given below.

$$Score_{Feed} = \left(\frac{235}{550}\right)^{2} = 0.183$$

$$Score_{Accuracy} = \left(\frac{5}{6}\right)^{0.5} = 0.913$$

$$Score_{MRR} = \left(\frac{405}{405}\right)^{2} = 1$$

$$Score_{\Pr ice} = \left(\frac{23000}{25000}\right)^{1} = 0.92$$

$$OverallScore_{Machine3} = \frac{0.183 + 0.913 + 1 + 0.92}{4} = 0.754$$

The ideal score is 1 thus for this example machine 2 is the best option. This is the same result as found in the example for method 1.

This concludes the discussion of multi-criteria decision analysis. In the next section a description will be given on how AHP and the QE method, described in this section, are implemented in MS-Access.

5. Implementation in MS-Access

An MS-Access database was created in which information about machines and their values for each of their attributes, defined in section 3, could be stored. Also, one existing and one new method were implemented in this MS-Access database to compare machines of a specific type with each other so as to choose the best one for a specific machine task. These methods are the Analytic Hierarchy Process (AHP) and the QE method, described in the previous section. This section reports on the implementation of the data entry option, as well as how these two methods were implemented in MS-Access.

5.1 Implementation for Data Input

A database was created in MS-Access to store information about machines. The database could store seven types of machines: the broach, CNC lathe, drill press, EDM, engine lathe, grinder and milling machine.

The first step in implementation was to create all the tables where information about the machines and their attributes would be stored. The following table gives a description of all the tables that were created and used.

Table 15 Machine Data Tables Description

Table Name	Description
tMachines	Consists of all the machines: their IDs, type and description.
tMachinetypes	Holds all the machine types as well as the corresponding subform and report name for the specific machine type.
tFunctionality	Holds the common functionality attributes as defined in Par 3.8 on page 52.
tEconomics	Holds the economical attributes as defined in Par 3.9 on page 55.

Table Name	Description
tReliability	Holds the reliability attributes as defined in Par 0 on page 56.
tBroach	Holds all the broach specific attributes defined in Par 3.1 on page 36.
tCNCLathe	Holds all the CNC lathe specific attributes defined in Par 0 on page 39.
tDrill	Holds all the drill specific attributes defined in Par 3.5 on page 47.
tEDM	Holds all the EDM specific attributes defined in Par 3.4 on page 44.
tEngineLathe	Holds all the engine lathe specific attributes defined in Par 0 on page 39.
tGrinder	Holds all the grinder specific attributes as defined in Par 3.6 on page 49.
tMill	Holds all the mill specific attributes as defined in Par 3.3 on page 41.

The relationships between the tables are shown in the following figure:

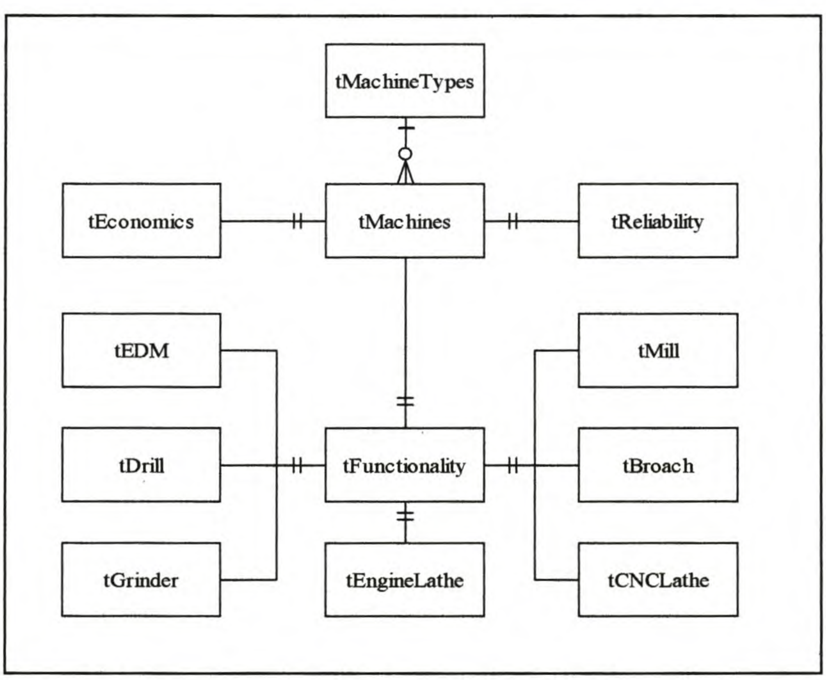

Figure 3 Database Relationships

The data dictionary for the Access tables is given in Appendix A.

Next a form, **frmMachines**, was created so that the user is enabled to input machines and their information. This form's main record source is the table **tMachines**. The form contains three tab pages named *Functionality, Costs and Availability/Reliability.* Three forms were created having record sources, namely **tFunctionality**, **tEconomics** and **tReliability** respectively. These forms were added to each of the three tabs on the main form **frmMachines**.

Subforms were created for the specific attribute tables for all seven machine types and given the names specified in table **tMachinetypes**. On the *Functionality* tab a command button was added. This button opens the subform for the specific attributes of a machine type. For example, if the current machine type is a grinder, the form for grinder specific attributes (with record source tGrinder) will be opened when the command button is clicked. This was achieved using a VBA event procedure. When the button is clicked, the procedure opens the table **tMachinetypes** and reads what subform name corresponds with the current machine type on the form. It then opens the form with this name. A command button to close the form was also added.

The user could thus use this form to enter information about any machine, which falls into one of the machine types covered. For this project only information for 3 machines of each type was entered into the database. This information is given in Appendix F.

To obtain a summary of all the information in the database two reports could be generated.

A form was created to enable the user to generate reports for information about specific machines. A drop-down menu that lists all the machines in the table **tMachines** was used, thus giving a list of all the machines currently in the database. Queries were created for each of the machine types. The query retrieves the machine ID value from the drop-down menu and then obtains the data for that machine. Reports were generated based on these queries and given the names specified in table **tMachinetypes**.

A command button was added to the form. This command button initiates a VBA procedure, which opens the table **tMachinetypes** and reads the report name for the specific machine type. It then opens the report with this name. Another command button was added to use for closing the form.

A machine information report was generated listing all the machines in the database.

A user guide for entering machine information and generating reports is given in Appendix B and the VBA code for the procedures in Appendix E.

5.2 Analytic Hierarchy Process in MS-Access

AHP was implemented in MS Access, using VBA procedures as well as tables and forms. The implementation of the method will be described for the broach machine.

The first step was to create a table **TBroachMatrix** that represents the pairwise comparison matrix as described in Par 4.7.1 on page 70. The criteria are the attributes of the machine.

The table **TBroachCalc** was created to use for calculations done in the VBA procedure. It stores the sum of each column of the pairwise comparison matrix **TBroachMatrix**. The table **TBroachNorm** was created to store the normalised pairwise comparison matrix determined in step 2 of the AHP method.

A table was created to store the weights for each of the attributes. This table was named **TBroachWeights**. It is also used to store values of calculations done in the VBA procedure.

To store the scores for each of the machines a table **TAHPBroach** was created. It holds the machine ID as well as the machine's score.

A user form was created with the table **TBroachMatrix** as the record source. It enables the user to fill in the pairwise comparison matrix. A command button is added on the form and calls a VBA procedure when clicked. This procedure will be described later on. A command button to close the form was also added.

In the procedure new tables are created and added to the tables of the database. For each attribute a pairwise comparison matrix for the alternatives is created. One example of these tables is **TPriceBroach**.

To help with adding new tables to the database the table **TTemp0** is also created.

Tables are created to store the normalised matrix used in determining the scores of alternatives for each attribute. One example of these tables is **TPriceBroachNorm**.

These three tables are created in the procedure for all the attributes.

The following table gives a summary of all the MS-Access tables created to implement AHP.

Table 16 Summary of Tables used in AHP

Table Name	Description
T*Machinetype*Matrix, for example TBroachMatrix	This table represents the pairwise comparison matrix of each machine type.
T*Machinetype*Norm, for example TBroachNorm	The normalised matrix of each machine type.
T*Machinetype*Calc, for example TBroachCalc	Table used for calculations to determine normalised matrix and weights.
T*Machinetype*Weights, for example TBroachWeights	Stores the weights for each of the attributes.
TTemp*x*, *x* = 0,1,...	Used when adding new tables to the database with VBA.

Table Name	Description
T*AttributenameMachinetypename,* for example TPriceBroach	For each attribute it represents the pairwise comparison matrix of the machines.
T*AttributenameMachinetypename*Norm, for example TPriceBroachNorm	Stores the normalised values as well as scores for each machine evaluated for a specific attribute.
TAHP*Machinetype,* for example TAHPBroach	Holds the machine ID and the machine's score.

The VBA procedure that is called when one clicks on the command button with the caption *Calculate Score*, will now be described.

5.2.1 The VBA Procedure Calculate Score

Steps 2-5 as set out in Par 4.7.1 on pages 71-75 are applied with a VBA procedure.

First from the pairwise comparison matrix table **TBroachMatrix** the normalised values are calculated. When moving through the matrix, one would want to address the importance between for example the machine price and feed. This is achieved by using two variables that could move to a desired position in the matrix. The variable *Attrname* points to a column in the matrix and the attribute *RecordName* points to a row in the matrix. The procedure can then loop until a certain *RecordName* (row) is reached and then moves in this row to the *Attrname* (column) desired.

There is stepped record by record through the table. The attribute name currently being worked with is stored in the variable *Attrname*. For each attribute record the sum of that column is determined. This sum is then stored in the table **TBroachCalc** in the first and only record at the field with the name *Attrname*.

For this attribute (column) the normalised value is calculated for each row in the column by dividing the real value for the attribute in **TBroachMatrix** by the sum for the attribute found in **TBroachCalc**. This value is then stored in the table **TBroachNorm** at the row *RecordNumber* and column *Attrname*.

The following step in the procedure is to determine the weights as the average of each row in the normalised matrix **TBroachNorm**. This is done for each of the attributes. Again there is stepped record by record through this table. First the number of fields in the table is determined, and then the sum of a row in **TBroachNorm** is calculated. The sum is then divided by the number of fields in the table determined earlier. This gives the weight for the attribute and is then stored in the table **TBroachWeights** in the first record at column *Attrname*.

Next the consistency index is calculated. This is done as given in step 3 for AHP. The pairwise comparison matrix is multiplied with the transposed weights matrix. Again the procedure moves through the process record by record. The value needed to determine the consistency index is calculated with equation 3 (page 73) and with this value the index is determined using equation 4 (page 73). The n value in the equation is determined by calculating the number of fields in the matrix table. The consistency index value stored in variable *CI* is then compared with the corresponding RI index found in table **TRIIndex**. Table 12 only gives RI indexes for n values up to 10, while RI indexes for $n > 10$ are needed in this implementation. Therefore these values for $n > 10$ were plotted in Excel and a regression line drawn. From the regression equation, illustrated in the figure below, RI index values for up to 40 were calculated and stored in the table **TRIIndex**.

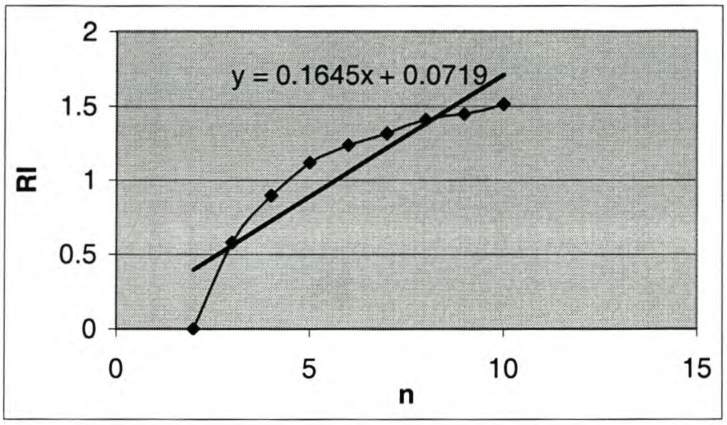

Figure 4 Regression Line for RI

The ratio of CI to RI is calculated. If this ratio is smaller than 0.10, the consistency is satisfactory and the procedure continues. However, if the ratio is higher than 0.10, the procedure is stopped and the pairwise comparison matrix has to be changed.

The number of machines that need to be compared is found by using an input box asking the user to insert the number.

The procedure then creates tables representing a pairwise comparison matrix of machines for each of the attributes. This is done by creating a table with the VBA method *CreateTableDef* and then adding it to the current database's table definitions.

Each table has the name T*AttrnameMachineType* for example **TPriceBroach**. The table has a number of records and fields equal to the number of machines that need to be compared. It also creates tables for the normalised values, named T*AttrnameMachinetype*Norm for example **TPriceBroachNorm**. This table also has a number of records and fields equal to the number of machines that have to be compared. It also stores the score and calculations to obtain the scores for each of the machines compared.

To enable the user to compare any number of machines, but not to lose the information of a table, a temporary table is used. For example when the current table **TPriceBroach** has 3 machines that are compared and the user subsequently would wish to compare 5 machines, a temporary table is created that stores the current table values. A new table is then created with records and fields for 5 machines. The values for the 3 machines are then taken from the temporary table and returned to the new table.

For each attribute table an autoform is created so that the user may complete the importance values of the machines. When the user closes this table, the procedure continues. The scores are then calculated in the same fashion as for the large pairwise comparison matrix. The sum of each column is stored in the table **TPriceBroachNorm** at field *Calc*. The normalised values for each machine are then determined and also stored in this table. The average of each row in this table is then calculated This then reflects the scores for the machines, which are also stored in the **TPriceBroachNorm** table at field *Score*.

The overall score is now calculated. This is done by first deleting any existing records in table **TAHPBroach** and then adding new records for each of the machines that are compared. The overall score for each machine is determined as set out in step 5 (page 74) of the AHP method.

Thus multiplying the score that a machine has for an attribute, stored in for example table **TPriceBroach**, by the attribute's weight, stored in table **TbroachWeights,** provides a machine's individual score for that attribute.

This overall score is then stored in **TAHPBroach** for the corresponding machine.

A user guide for applying the AHP process is given in Appendix C and the complete detailed VBA code is provided in Appendix E.

5.3 MS-Access Implementation of the QE Method

VBA procedures, tables and forms were also used for the implementation of the QE Method. The implementation of the method will be described for the broach machine. The method is applied in a similar fashion for all the machine types.

First a dummy table is created to store the information about a specific machine type. The first field, *Label*, holds all the machine's attributes. This includes the machine specific attributes from for example **tBroach**, as well as the common attributes from the tables **tFunctionality**, **tEconomics** and **tReliability**. The next field is the ideal status, which is a drop-down menu with the options: minimise or maximise. The exponent is stored in the third field. Because the attributes are grouped from four different tables, a field, *TableName*, which stores the name of the table that holds a specific attribute's information, is also included. The last field in the table, *IdealTblName*, is used to store the name of the ideal table for a specific attribute. This field is later used when the ideal values and ratios are calculated. Seven such tables were created, one for each machine type.

Next a user form was created with record source table **TBroachDummy**. This form enables the user to choose the ideal state and exponent and then calculates the scores for the machines currently in the database. When the perceptive importance has to be chosen the user could choose from six curves as described in step 2 of Par 4.8.1 on page 76.

The exponent *n* for each of the curves is stored in the table **TExponent**.

A table **TRecordno** is used to store the record number of the attribute that is current on the form. In other words, if the user is currently setting the exponent for record number 2, that number is stored in the field *Recno* of the table.

A form was created that shows the various curve types of Figure 2 on page 77. On to the form small rectangle boxes were positioned on each of the curves and coloured the same as its curve. When the user clicks on a box to choose a curve, the box calls a VBA procedure. This procedure reads what number is chosen and finds the corresponding exponent in table **TExponent**. This exponent is then stored in the *Exponent* field of table **TBroachDummy** for the current record number obtained from **TRecordno.** When a choice is made, the procedure shows a message box stating what curve was chosen. When the OK button is clicked the procedure automatically closes the form.

A command button to close the form was also added to the form.

A command button was added on the form to execute the VBA procedure that calculates the score of each machine. An option group was used to enable the user to choose what QE method he/she wants to apply. A command button to close the form was also added.

A table **TBroachIdeal** was created to store the ideal values for the broach specific attributes. An ideal record with *Machine_ID* = 10000 was created where the ideal values could then be stored for a broach. This table also stores the ratios of real value to ideal value raised to the exponent chosen for each of the broach machines in the database. These values are stored in records created by the main VBA procedure with machine IDs equal tot the original machine IDs. Thus, when there are three machines in the database, the value for *Machine_ID* for three records in the **TBroachIdeal** table will be 10, 11 and 12.

This table was created for each of the seven machine types. Each machine type, however, starts at a different machine ID number. The following table gives the numbers used for storing ideal values.

Table 17 Machine IDs for Ideal and Ratio Values

Machine type	Ideal Value ID
Broach	10000
CNC Lathe	10001
Drill	10002
EDM	10003
Engine Lathe	10004
Grinder	10005
Mill	10006

The table **TFunIdeal** was created to store the ideal values and individual score terms for the functionality attributes of a machine. The table **TEconIdeal** was also created. It stores the ideal values and individual score terms for the economical attributes of the machine. The table **TRelIdeal** stores the ideal values and individual score terms for the reliability attributes of the machine.

Each of these tables has records 10000 to 10006 for the ideal values of each machine type.

The last table created was **TScore**. This table stores the calculations to determine the overall scores, as well as the overall scores for each of the machines.

The following table gives a summary of all the tables created to implement the QE method in MS-Access.

Table 18 Summary of Tables used in QE Method

Table Name	Fields	Description
T*Machinetype*Dummy, for example TBroachDummy	Label (machine attributes), Minmax (ideal state), Exponent, TableName, IdealTblName	Seven tables each for a specific machine type used to create the userform and calculate scores.

Table Name	Fields	Description
T*Machinetype*Ideal, for example TBroachIdeal	Machine_ID and all the names of the machine types specific attributes.	Seven tables each for a specific machine type used for storing the machine's specific ideal values calculated in the VBA procedure.
TFunIdeal	Machine_ID and all the names of the machine functionality attributes.	Holds the ideal values for a machine's functionality attributes as well as the individual score terms for each of the machine's attributes.
TEconIdeal	Machine_ID and all the names of the machine economical attributes.	Holds the ideal values for a machine's economical attributes as well as the individual score terms for each of the machine's attributes.
TRelIdeal	Machine_ID and all the names of the machine reliability attributes.	Holds the ideal values for a machine type's reliability attributes as well as the individual score terms for each of the machine's attributes.
TScore	Machine_ID, Machine type, Score, IdealScore, Sum1, Sum2, Sum3, Sum4.	Holds the scores for each the machines as well as the separate sums used for calculating the overall sum.
TExponent	ID, Exponent	Holds the exponents for the six curves as shown in Figure 2 on page 77.

The main VBA procedure called by the command button with caption *Calculate Score* will now be described.

5.3.1 Main VBA Procedure (Calculate Score)

Steps 3 to 8 as set out in Par 4.8.1 on pages 76 - 79 is applied in the VBA procedure.

The procedure first deletes all the broach entries in tables **TScore**, **TBroachIdeal**, **TFunIdeal**, **TEconIdeal** and **TRelIdeal**. The number of broach machines in the database are determined and stored in the variable *k*. That number of new records are then added to these tables. To do this, the first broach machine's ID is determined and stored in variable *Machnum*. In each table IDs with values *Machnum + k* are added for the number of machines (*k*) in the database. Thus in each table records with machine IDs 10, 11, 12 are added to store the individual scores for the attributes that is calculated later in the procedure.

Next the first machine ID for a broach is found from the table **tMachines**. This is done to know at what records the real values have to be read from.

Now the ideal value for each attribute in table **TBroachDummy** is determined and stored in the corresponding ideal table.

The procedure moves record by record through the table determining the ideal score for the current attribute and storing it in its ideal table.

This is achieved by first obtaining the values for the attribute name, exponent value, ideal state (min or max), data table name and ideal table name from **TBroachDummy**. These values are stored in variables: *Attrname, MinMax, Expo, TName* and *ITName*. When the ideal state is minimum, the procedure searches in the table called *TName* and reads the attribute values for all the broach machines. The minimum of those values (per attribute) becomes the ideal value and is stored in the ideal table with the name *ITName*. In the same way, if the ideal state is maximum, the procedure searches in the table with the name *TName* and reads the attribute values for all the broach machines. The maximum of those values (per attribute) becomes the ideal value and is then stored in the ideal table called *ITName*.

With the ideal value found, the ratio of the real value to the ideal value is calculated and raised to the exponent in *Expo*. When QE method 1 is chosen the ratio is calculated using equation 9 (on page 78) and if the QE method 2 is chosen it is determined with equation 10 (on page 80). This value is stored in the record added in the beginning of the procedure. Thus for the first broach machine the individual score is stored at the record with *Machine_ID* = 50000 in table *ITName*.

This is repeated for all the attributes in **TBroachDummy**.

Next the overall score is determined. For each attribute this is done by first adding together all the individual score terms of each ideal table, and storing it in the table **TScore**. Thus the sum for the attribute scores in tables **TBroachIdeal**, **TFunIdeal**, **TEconIdeal** and **TRelIdeal** is calculated. These four sums are then added together to reflect the overall score, which is stored in **TScore**. The overall score depends on which method is used. For method 1 it is calculated using equation 6 (on page 76) and if method 2 is chosen the overalls core is determined by equation 11 (on page 80).

The ideal score is determined by counting the number of attributes in **TBroachDummy**.

The procedure then opens a report that provides a summary of all the machine scores.

A user guide for applying the process is given in Appendix D and the complete code is given in Appendix E.

This concludes the discussion on the implementation of methods in MS-Access. In the next section an analysis of the two methods will be done and results given.

6. Analysis

In the previous section the MS-Access database and implementation of two MCDA methods were described. To illustrate how these methods function the two methods will be applied in this section. The AHP method will be applied for the drilling machine and the QE method for the drilling and broach machines. Finally the results will also be given.

The AHP method is applied for only one machine because it merely repeats the methods for the other machines. The two methods are used with the knowledge that they generate the correct calculations. The calculations were verified throughout the design process.

6.1 AHP Input

The pairwise comparison matrix for the drill attributes is shown below. The user decided on these importance values for the attributes.

Table 19 Input for AHP of Drill

Label	Xtrav	Ytrav	TWS	SpinS	ChS	NoA	Mpow	Feed	PosAcc	RepAcc	MRR	Price	ToolC	ElecC	LabC	MainC	DeprC	FlrSpR	FlrSpC	DownC	FluidC	MTBF	MTTR	WW	WL	WH	Wwid
Xtrav	1	1	0.5	0.33	2	4	1	0.33	0.25	0.25	0.33	0.25	1	1	1	1	2	2	0.5	1	2	0.33	0.33	0.5	1	1	1
Ytrav	1	1	0.5	0.33	2	3	1	0.33	0.25	0.25	0.33	0.33	1	1	2	2	2	1	0.5	1	1	0.33	0.33	0.5	1	1	1
TWS	2	2	1	0.33	1	4	0.5	0.33	0.25	0.25	0.5	0.33	2	2	2	2	1	1	1	2	1	0.5	0.33	1	1	1	1
SpinS	3	3	3	1	0.25	4	1	1	0.5	0.5	1	1	2	2	2	2	4	4	2	4	2	2	2	4	2	4	4
ChS	0.5	0.5	1	0.25	1	1	0.5	0.5	0.25	0.25	0.33	0.25	1	1	1	1	0.5	1	1	0.5	1	0.33	0.33	0.5	0.5	0.5	0.5
NoA	0.25	0.33	0.25	0.25	1	1	0.33	0.33	0.2	0.25	0.33	0.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.33	0.33	0.5	0.5	0.5	0.5
Mpow	1	1	2	1	2	3	1	0.5	0.33	0.25	0.33	0.25	4	1	2	1	1	1	4	1	2	0.33	0.33	2	0.5	1	0.5
Feed	3	3	3	1	2	3	2	1	0.33	0.33	0.5	1	2	2	2	2	2	2	1	2	2	1	1	2	3	1	0.5
PosAcc	4	4	4	2	4	5	3	3	1	1	1	1	4	4	2	4	4	4	4	4	2	2	2	4	2	2	4
RepAcc	4	4	4	2	4	4	4	3	1	1	1	1	4	2	2	2	4	4	4	4	2	2	2	4	2	2	4
MRR	3	3	2	1	3	3	3	2	1	1	1	0.5	2	2	3	2	2	2	2	2	3	1	1	2	1	1	4
Price	4	3	3	1	4	5	4	1	1	1	2	1	4	2	2	2	2	2	2	1	2	0.5	1	1	2	1	1
ToolC	1	1	0.5	0.5	1	2	0.25	0.5	0.25	0.25	0.5	0.25	1	1	1	1	1	1	1	1	1	0.33	0.33	0.5	0.5	0.5	0.5
ElecC	1	1	0.5	0.5	1	2	1	0.5	0.25	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1	0.33	0.33	0.5	0.5	0.5	0.5
LabC	1	0.5	0.5	0.5	1	2	0.5	0.5	0.5	0.5	0.33	0.5	1	1	1	1	1	1	1	1	1	0.33	0.33	0.5	0.5	0.5	0.5
MainC	2	3	3	0.5	3	3	3	1	0.5	0.5	1	1	3	3	3	1	4	3	3	2	3	1	1	2	2	2	2
DeprC	0.5	0.5	1	0.25	2	2	1	0.5	0.25	0.25	0.5	0.5	1	1	1	2	1	2	1	1	1	0.25	0.25	1	2	2	1
FlrSpR	0.5	1	1	0.25	1	2	1	0.5	0.25	0.25	0.5	0.5	1	1	1	2	1	1	0.5	1	0.5	0.25	0.33	1	1	2	0.5
FlrSpC	2	2	1	0.5	1	2	0.25	1	0.25	0.25	0.5	0.5	1	1	1	2	1	2	1	1	0.5	0.33	0.33	1	2	2	1
DownC	1	1	0.5	0.25	2	2	1	0.5	0.25	0.25	0.5	1	1	1	1	1	1	1	1	1	1	0.33	0.5	1	2	4	2
FLuidC	0.5	1	1	0.5	1	2	0.5	0.5	0.5	0.5	0.33	0.5	1	1	1	2	1	2	2	1	1	0.25	0.33	1	1	1	1
MTBF	2	3	2	0.5	3	3	3	1	0.5	0.5	1	2	3	3	3	3	4	4	3	1	4	1	1	1	2	2	2
MTTR	2	3	3	0.5	3	3	3	1	0.5	0.5	1	1	3	3	3	3	4	3	3	2	3	1	1	2	2	2	2
WW	1	1	1	0.25	2	2	2	0.5	0.25	0.25	0.25	1	2	2	2	1	1	2	1	0.5	1	0.5	0.5	1	1	1	1
WL	1	1	1	0.5	2	2	2	0.33	0.5	0.5	1	0.5	2	2	2	2	0.5	1	0.5	0.5	1	0.5	0.5	1	1	1	1
WH	1	1	1	0.25	2	2	1	1	0.5	0.5	1	1	2	2	2	1	0.5	0.5	0.5	0.25	1	0.5	0.5	1	1	1	1
Wwid	1	1	1	0.25	2	2	2	0.5	0.25	0.25	0.25	1	2	2	2	1	1	2	1	0.5	1	0.5	0.5	1	1	1	1

The description of each attribute term used in the pairwise comparison matrix for all the machine types is given in Appendix G.

The importance values of the 27 attribute pairwise comparison tables for comparing 3 machines are given in Appendix H.

6.2 AHP Results

For the pairwise comparison matrix chosen by the student, the CI/RI value is 0.03089, which is satisfactory.

The results obtained from the AHP method are shown in Table 20. The machine with the highest overall score is the best. Thus machine 1 is the machine with the best score, and the best alternative for the input specified by the user.

Table 20 Results of AHP Method for Drill

Machine	Score
1	**0.555**
2	0.173
3	0.272

When observing the importance values chosen for each of the attributes, one could see that these results are correct. The tables indicate that machine 1 was chosen to be more important than the other machines for each attribute. The student chose the scores of each of the attribute pairwise comparisons in such a way that machine 1 should be the best, for validation purposes.

The evaluation was repeated, but this time the real data for the three machines were used. The following table provides the results found.

Table 21 AHP Results for Drill

Machine	Score
1	0.238
2	0.325
3	**0.436**

The results indicate that machine 3 is the best machine. This corresponds with the input data used. The real data for the drilling machines were used and form this data one can see that machine 15 is the best machine. Thus the correct answer is achieved. Machine 3 is the machine with ID = 15.

6.3 QE Method Input

The two proposed QE methods will now be applied for the drill and broach machines. The same input is used for both methods.

6.3.1 QE Method Applied to Drill Data

First the user form **frmDrillDummy** was used to fill in the ideal states and exponents. The following table shows the values chosen for the drill attributes.

Table 22 QE Method Drill Input

Label	MinMax	Exponent
X travel	Max	0.25
Y travel	Max	1
Table work size	Max	0.5
Max spindle speed	Max	2
Chuck size	Min	0.25
Machine price	Min	1
Tool cost	Min	1
Electricity cost	Min	1

Label	MinMax	Exponent
Labour cost	Min	1
Maintenance cost	Min	1
Depreciation cost	Min	1
Floor space required	Min	1
Floor space cost	Min	1
Downtime cost	Min	1
Cutting fluid cost	Min	1
Number of axes	Max	2
Max workpiece height	Max	4
Max workpiece length	Max	5.5
Max workpiece width	Max	2
Max workpiece weight	Max	2
Main motor power	Min	0.5
Feed rate	Max	4
Positioning accuracy	Min	0.25
Repeatability accuracy	Min	1
Metal removal rate	Max	4
MTBF	Max	2
MTTR	Min	0.5

The information for the three drilling machines entered into the database is reflected in the table below:

Table 23 Drill Machine Information

	Machine_ID		
Attributes	**13**	**14**	**15**
X travel	300	320	550
Y travel	450	515	550
Table work size	139690	192500	269997
Max spindle speed	1800	2000	2000
Chuck size	8	13	8
Number of axes	2	2	2
Max workpiece height	250	280	350

	Machine_ID		
Attributes	**13**	**14**	**15**
Max workpiece length	458	500	500
Max workpiece width	300	300	550
Max workpiece weight	200	350	250
Main motor power	2	10	5
Feed rate	840	1050	560
Positioning accuracy	10.00	6.00	6.60
Repeatability accuracy	6.00	6.50	2.50
Metal removal rate	255.00	360.00	255.00
Machine price	8500	12550	9788
Tool cost	808	1288	788
Electricity cost	267	1127	508
Labour cost	4508	4966	3600
Maintenance cost	1022	1111	998
Depreciation cost	800	1200	800
Floor space required	139690	192500	269997
Floor space cost	3102	3999	4500
Downtime cost	866	1000	988
Cutting fluid cost	655	802	420
MTBF	129600	216000	216000
MTTR	2880	8640	2880

6.3.2 QE Method Applied to Broach Data

For the broach the user form **frmBroachDummy** was used to fill in the ideal states and exponent. The following table shows the values chosen for the broach attributes.

Table 24 QE Method Broach Input

Lable	MinMax	Exponent
Max stroke	Max	1
Broaching/Cutting speed	Max	2
Return stroke speed	Max	4
Broaching force	Max	0.25
Max broach diameter	Max	0.5
Max broach length	Max	2
Surface finish	Min	0.5
Machine price	Min	1
Tool cost	Min	1
Electricity cost	Min	1
Labour cost	Min	1
Maintenance cost	Min	1
Depreciation cost	Min	1
Floor space required	Min	1
Floor space cost	Min	1
Downtime cost	Min	1
Cutting fluid cost	Min	1
Number of axes	Max	1
Max workpiece height	Max	0.5
Max workpiece length	Max	4
Max workpiece width	Max	1
Max workpiece weight	Max	1
Main motor power	Min	1
Feed rate	Max	5.5
Positioning accuracy	Min	1
Repeatability accuracy	Min	4
Metal removal rate	Max	1
MTBF	Max	1
MTTR	Min	0.25

The real values entered into the database are given in the following table.

Table 25 Broach Machine Information

	Machine_ID		
Attribute	**10**	**11**	**12**
Max stroke	1250	1600	1850
Broaching/Cutting speed	6.25	8	6.25
Return stroke speed	25.4	24	25.4
Broaching force	16000	25000	18000
Max broach diameter	92	117	90
Max broach length	45	65	50
Surface finish	23	55	23
Number of axes	1	1	1
Max workpiece height	350	330	315
Max workpiece length	455	215	255
Max workpiece width	415	525	500
Max workpiece weight	550	720	890
Main motor power	30	37	25
Feed rate	400	400	400
Positioning accuracy	6.60	6.00	6.90
Repeatability accuracy	8.00	5.90	5.90
Metal removal rate	355.00	446.00	562.00
Machine price	102000	152000	115000
Tool cost	7902	4701	6672
Electricity cost	2545	4422	2055
Labour cost	8000	9122	7898
Maintenance cost	1680	754	698
Depreciation cost	1255	2602	1806
Floor space required	259021	540260	426000
Floor space cost	7112	10802	8598
Downtime cost	1800	1658	2380
Cutting fluid cost	458	445	967
MTBF	259200	308800	216000
MTTR	10080	17280	5760

6.4 QE Method Results - Method 1

The results obtained from applying the QE method for the drill are provided below:

Table 26 Result of QE Method 1 for Drill

Machine_ID	Ideal Score	Score
13	27	23.460
14	27	34.749
15	27	**27.038**

The best score is the score closest to the ideal value, and thus the drilling machine with machine ID 15 is the best choice for what the user specified in the input. Since there are 27 attributes, the ideal score is 27.

Inspecting Table 23 shows that machine 15 is the best option. Thus the QE method provides the correct answer. In the table one could observe that this has the best values for many of the attributes. For example the MTBF should be maximised and machine 15 has the highest value. The MTTR must be minimised and machine 15 has the lowest value. It has the largest *x* travel, table work size, workpiece width all of which should be maximised. It also has the lowest repeatability accuracy, maintenance cost, labour costs and cutting fluid cost all of which should be minimised. So, for the combination of requirements in the input form, this machine proves to be the best.

The scores for the broach machines are now given.

Table 27 Results of QE Method 1 for Broach

Machine_ID	Ideal Score	Score
10	29	31.711
11	29	33.183
12	29	**30.297**

The best score according to the results is machine 12. From Table 25 one could see that machine 12 has the largest values for max. stroke, cutting speed, number of axes, feed and workpiece weight, all of which should be maximised. It also has the lowest values for surface finish, main power, repeatability, accuracy, electricity cost, labour cost, maintenance cost and MTTR all of which must be minimised. Thus, for the combination of requirements in the input form, machine 12 proves to be the best option.

6.5 QE Method Results – Method 2

The results obtained from applying the second QE method for the drill are provided below:

Table 28 Results of QE Method 2 for Drill

Machine_ID	Ideal Score	Score
13	1	0.732
14	1	0.779
15	1	**0.848**

The ideal score is 1, thus from the table it can be seen that the drilling machine with machine ID 15 is the best option to be considered. This is the same result as found in the analysis of the drilling machines with QE method 1.

The scores for the broach machines are now given.

Table 29 Results of QE Method 2 for Broach

Machine_ID	Ideal Score	Score
10	29	0.829
11	29	0.825
12	29	**0.843**

Since the ideal value is 1, the best option to consider is the machine with machine ID 12. This is also the same result as found in the analysis of broaching machines with QE method 1.

6.6 Comparison of Results

It is difficult to compare the AHP and QE method. With the AHP the decision-maker decides on which machine is better and what attributes are more important. For the QE Method the decision maker decides on an ideal state and a scaled importance of the attribute.

However, when the two methods were both applied for the drill, it provided the same result. In both methods machine 15 was reflected as the best option. The two methods thus provide the same answer when the real data is used as input in both methods.

This concludes the analysis of the two decision methods. In the next section a conclusion will be made.

7. Conclusions

In the previous section an analysis of the two methods was provided. In this section conclusions are made.

The objectives of the project were achieved to such an extent that an MS-Access database was designed and developed, which contains machine information as well as two methods to compare various machines with each other in order to identify the best one.

Two methods for comparing various machines were implemented: the Analytic Hierarchy Process and a new method, named the Quotient Exponential Method. Successful implementation of these methods in MS-Access was achieved. These methods could only be used as decision support tools and are not a means to find a final answer. Both methods rely on input from a decision-maker, which thus causes them to be subjective. The results that these methods yield should consequently only be used as indications of what may be the best alternative. Within MCDA it will be difficult to find the truly best answer.

The student also established that it was very important to carefully decide beforehand on the criteria that had to be evaluated. Only the most important criteria should be included, because when the number of criteria becomes too large, AHP becomes a tiring process. The amount of input by the decision-maker becomes excessive and will take a great deal of time to complete.

The analysis done for the drilling machines, gave the same result for both methods. Thus for this specific application the methods resulted in what was expected of it. However, further testing will be needed to fully verify the method's results. Of the two QE methods developed, method 2 proved to be easier to use. Method 2 provides a clearer result to see what machine is the best option because all the scores are less or equal to 1.

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Appendix A Data Dictionary

Table: **tMachines**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘			Number	Long
Machine type				Number	Long
Machine Description			✘	Text	150

Table: **tMachinetypes**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
MachineType_ID	✘			Number	Long
Type				Text	50
SubformName				Text	50
ReportName				Text	50

Table: **tFunctionality**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
Number of axes				Number	Long
Max workpiece height				Number	Single
Max workpiece length				Number	Single
Max workpiece width				Number	Single
Max workpiece weight				Number	Single
Mainmotor power				Number	Single
Feed rate				Number	Single
Positioning accuracy				Number	Single
Repeatability accuracy				Number	Single
Metal removal rate				Number	Single

Table: **tEconomics**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
Machine price				Number	Single
Tool cost				Number	Single
Electricity cost				Number	Single
Labour cost				Number	Single
Maintenance cost				Number	Single
Depreciation cost				Number	Single
Floor space required				Number	Single
Floor space cost				Number	Single
Downtime cost				Number	Single
Cutting fluid cost				Number	Single

Table: **tReliability**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
MTBF				Number	Single
MTTR				Number	Single

Table: **tBroach**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
Max stroke				Number	Single
Broaching/Cutting speed				Number	Single
Return stroke speed				Number	Single
Broaching force				Number	Single
Max broach diameter				Number	Single
Max broach length				Number	Single
Surface finish				Number	Single

Table: **tCNCLathe**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✖	✖		Number	Long
Z-axis travel				Number	Single
X-axis travel				Number	Single
Distance between centers				Number	Single
Number of tools				Number	Single
Max spindle speed				Number	Single
Rapid traverse rate - x				Number	Single
Rapid traverse rate - z				Number	Single
Surface finish				Number	Single
Number of controlled axes				Number	Single
Number of simultaneous controlled axes				Number	Single
Self-diagnosis				Number	Single

Table: **tDrill**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✖	✖		Number	Long
X travel				Number	Single
Y travel				Number	Single
Table work size				Number	Single
Max spindle speed				Number	Single
Chuck size				Number	Single

Table: **tEDM**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
X travel				Number	Single
Y travel				Number	Single
Z travel				Number	Single
U travel				Number	Single
V travel				Number	Single
Best surface roughness				Number	Single
Electrode wear ratio				Number	Single
Dielectric tank capacity				Number	Single
Work table size				Number	Single
Max electrode weight				Number	Single
Max cutting speed				Number	Single
Feed rate- rapid traverse				Number	Single
Max machining current				Number	Single
Controlled Axes				Number	Single
Simultaneous controlled axes				Number	Single
Self-diagnosis				Number	Single

Table: **tEngineLathe**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
Z-axis travel				Number	Single
X-axis travel				Number	Single
Distance between centers				Number	Single
Number of tools				Number	Single
Max spindle speed				Number	Single
Rapid traverse rate - x				Number	Single
Rapid traverse rate - z				Number	Single
Surface finish				Number	Single

Table: **tGrinder**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
Max grinding length				Number	Single
Max grinding width				Number	Single
Table work size				Number	Single
Magnetic Chuck size				Number	Single
Cutting speed				Number	Single
Surface finish				Number	Single

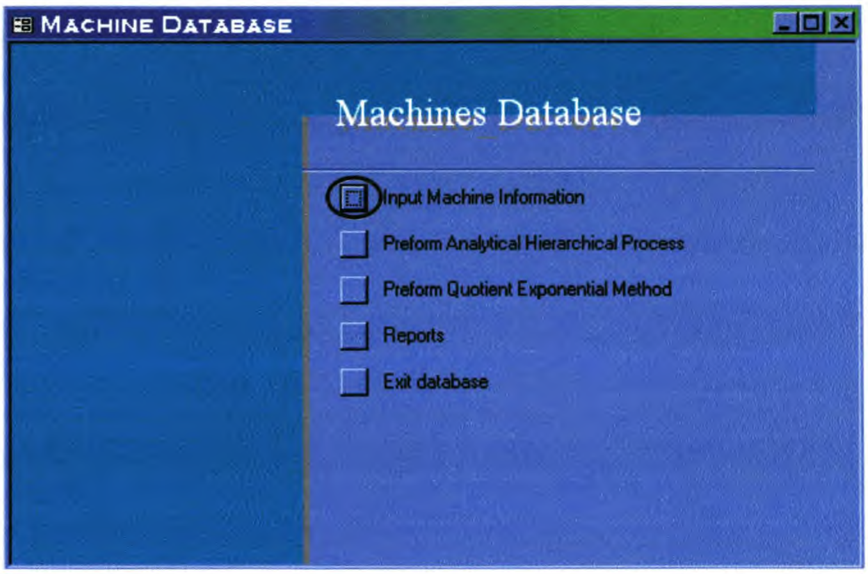
Table: **tMill**

Attribute	Primary Key	Foreign Key	Null OK	Type	Width
Machine_ID	✘	✘		Number	Long
X travel				Number	Single
Y travel				Number	Single
Z travel				Number	Single
A travel				Number	Single
B travel				Number	Single
Max spindle speed				Number	Single
Rapid traverse feed				Number	Single
Tool mag capacity				Number	Single
Tool change time, average				Number	Single
Work table size				Number	Single
Surface finish				Number	Single
Number of controlled axes				Number	Single
Simultaneous controlled axes				Number	Single
Self-diagnosis				Number	Single

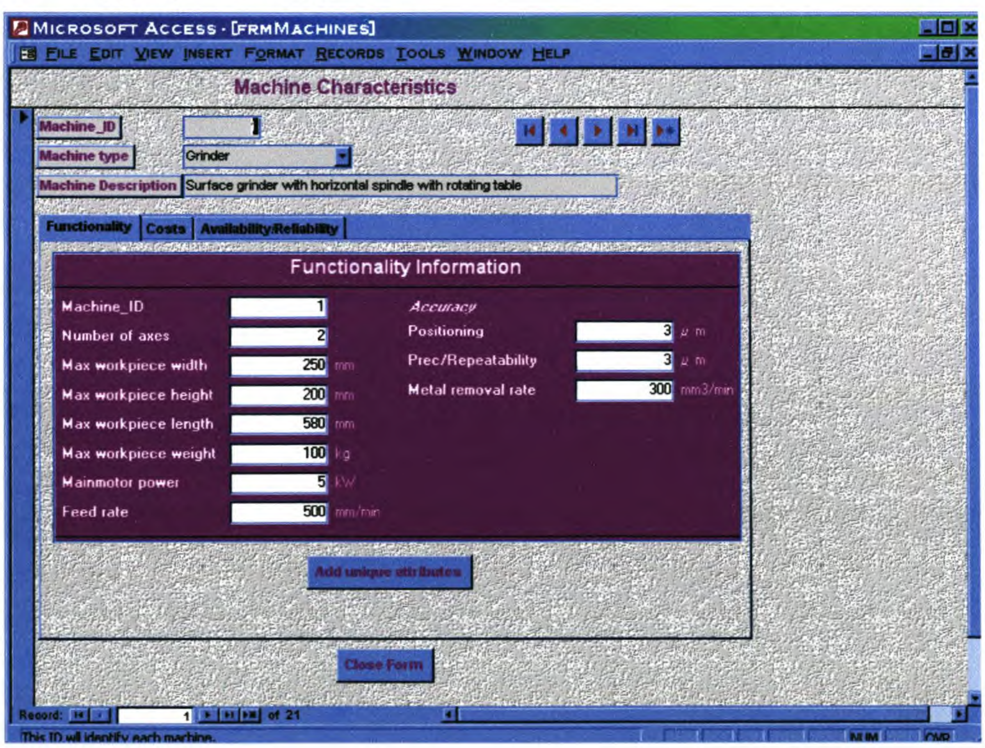
Appendix B Data Input User Guide

The following steps provide the procedure to input data into the database.

1. When the database is opened a switchboard will automatically open. Click on the *Input Machine Information* option to input information for a machine.

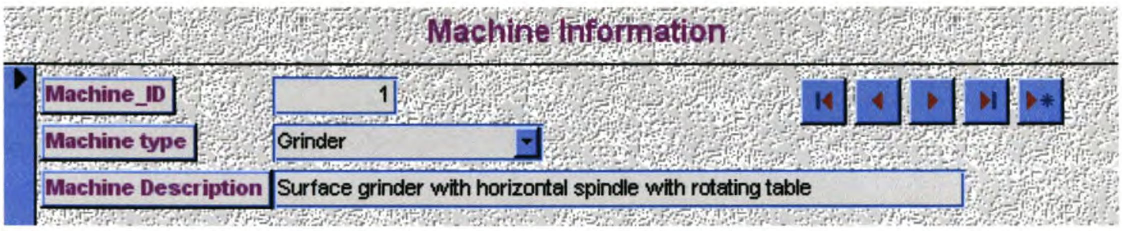


2. The following input form appears:

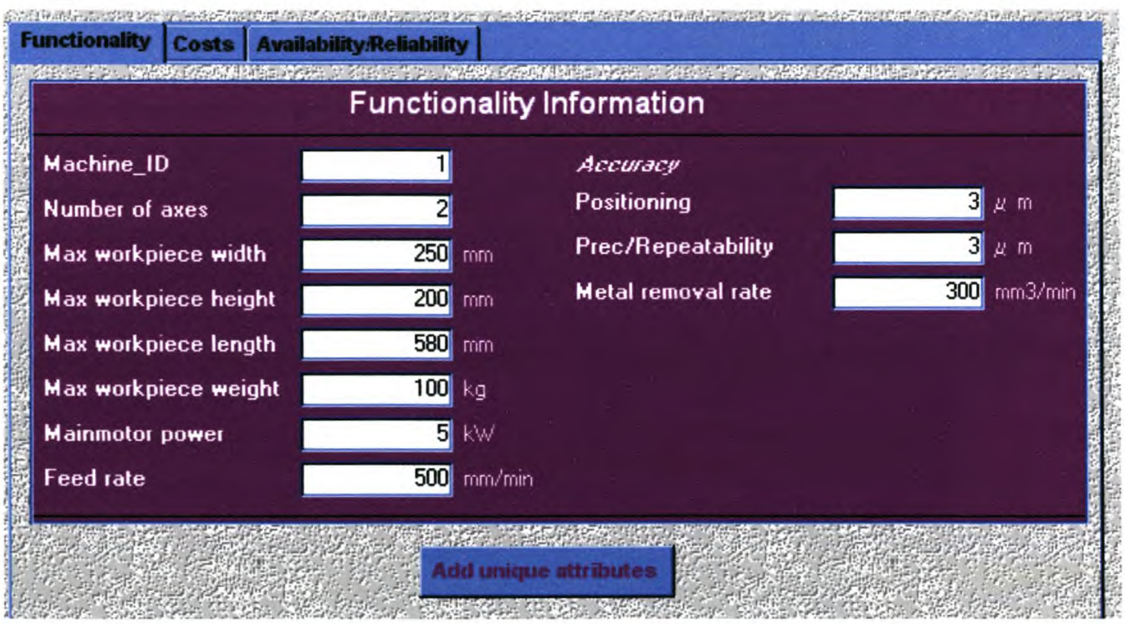


The main form consists of the machine id, type and description as well as three tabs that point to functionality, costs and reliability attributes information.

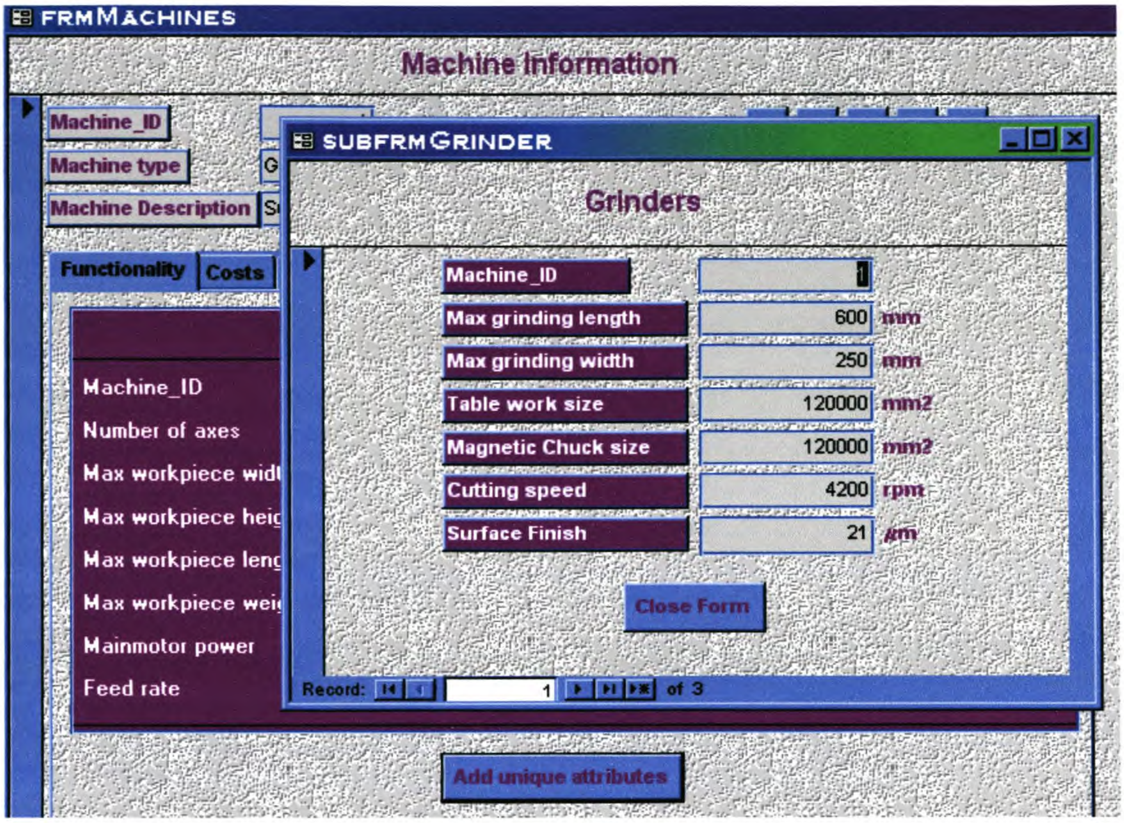
3. First fill in the machine information on this main form as shown below for a grinder. A machine id is automatically given. Choose a machine type from the dropdown list. Also fill in a description for the machine.



4. Also fill in the functionality information of the machine.

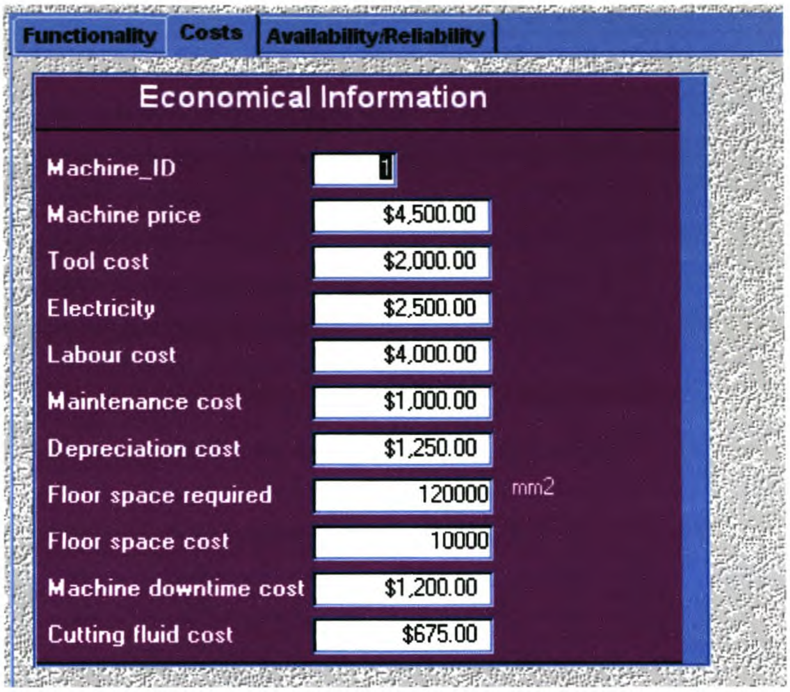


5. Click on the *Add Unique Attributes* button located on the functionality form shown above. A new form will open. Fill in the attributes specific to the type of machine as shown below for the grinder.

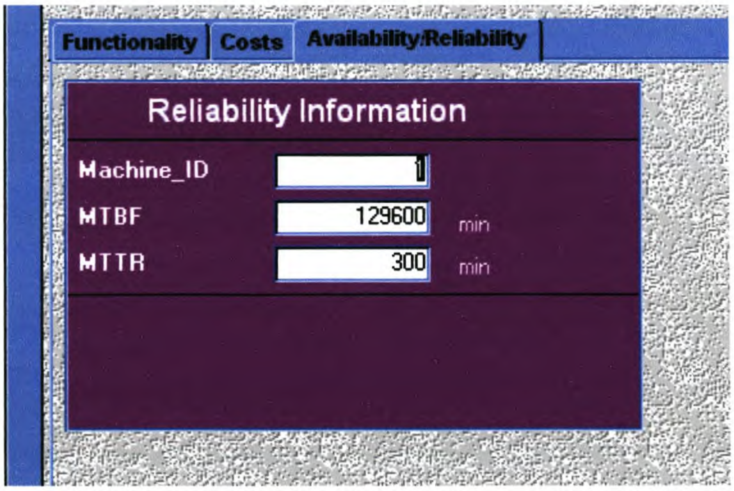


To close the form and return to the main input form click on the *Close Form* button.

6. Now click on the *Costs* tab on the main input form and fill in the costs for the machine, as on the form below:

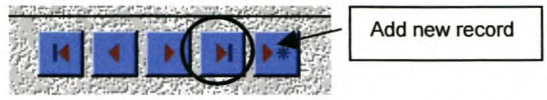


7. After the costs are filled in click on the *Availability/Reliability* tab to fill in the attributes for the machine.



All the information is now entered. To close the form click on the *Close Form* button.

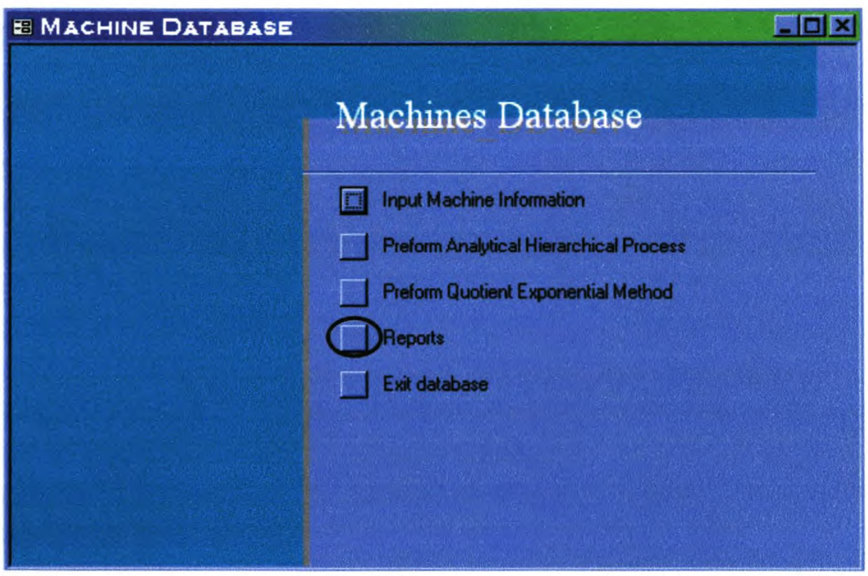
8. To add a new record, use the navigation buttons given at the top of the main input form.



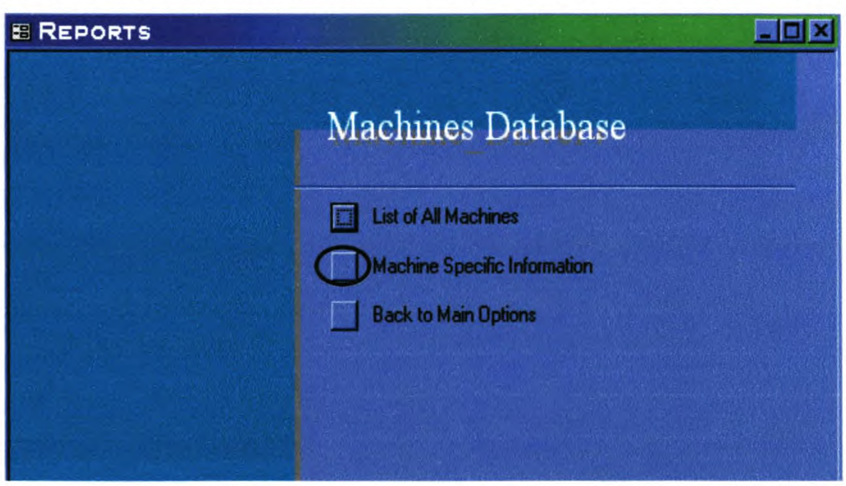
Also use this navigation buttons to move forward and backwards through the machines.

Machine information on specific machines:

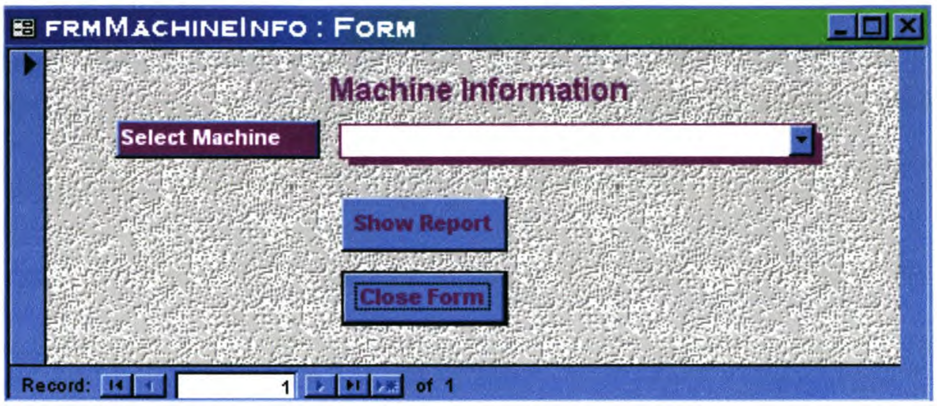
1. On the switchboard choose the *Reports* option.



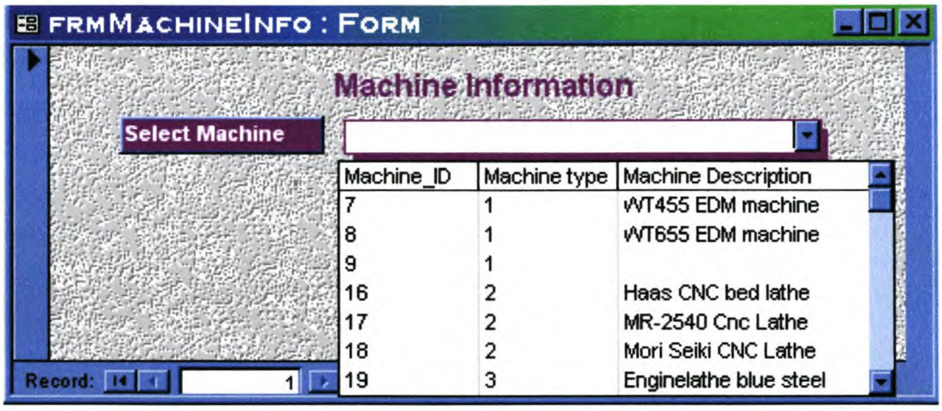
2. Choose the *Machine Specific Information* option on the second switchboard.



This option opens the form as shown below.



3. Now click on the drop-down menu and select a machine. Click on *Show Report* button to view the report of the specific machine information.



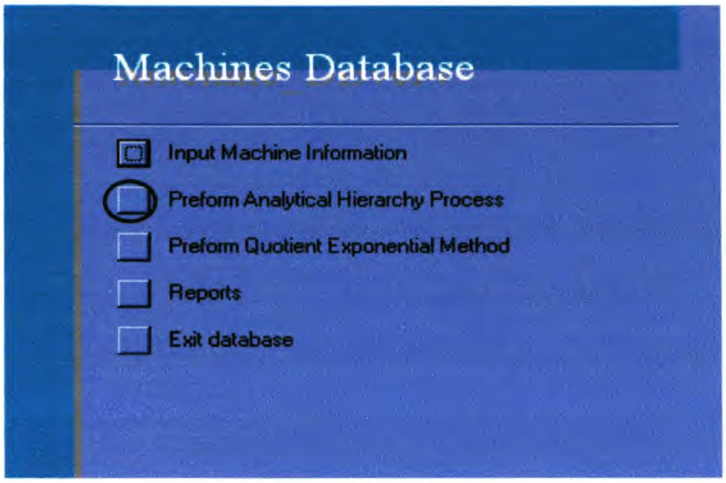
4. Read, print and/or close the report.
5. To close the form click on the *Close Form* button.
6. To continue with other options on the main switchboard choose *Back to Main Options*.

To list all the machines in the database:

1. On the switchboard choose the *Reports* option. On the next switchboard choose the *List of All Machines* option.
2. This will open a report giving a list of all the machines. Their IDs, type and description are given.
3. Read, print and/or save report.
4. To continue with other options on the main switchboard choose *Back to Main Options*.

Appendix C AHP Implementation User Guide

1. To execute the AHP for a machine choose the *Perform Analytic Hierarchy Process* option on the switchboard.

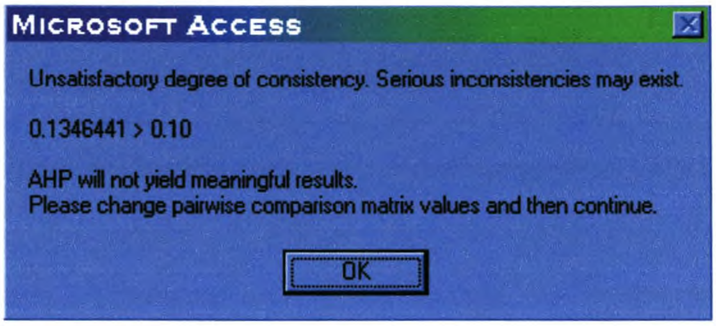


2. A form will open that shows a pairwise comparison matrix as shown below for the drill. Now complete this matrix for all the attributes.

Attribute	WW	WL	WH	WWid	Xtrav	Ytrav	TWS	SpinS	NoA	MPow	Feed	PosAcc	RepAcc	MRR	Price	ToolC	ElecC	LabC
DeprC	1	4	1	0.25	0.33	1	0.25	3	4	1	0.2	0.33	0.5	2	0.25	0.5	4	3
FlrSpR	0.25	1	2	0.25	3	2	0.25	0.25	2	3	4	0.2	1	0.5	0.2	3	0.25	0.5
WL	3	1	4	0.25	1	2	1	5	1	1	0.5	0.25	1	1	3	1	2	1
Xtrav	4	2	2	0.5	1	2	0.2	0.5	2	1	5	3	3	2	0.5	0.25	0.5	0.2
SpinS	2	2	1	0.5	3	2	1	1	0.25	0.33	2	3	1	5	3	0.33	0.33	0.25
Mpow	2	2	3	0.5	0.25	0.33	0.25	5	4	1	1	1	2	0.5	0.5	0.33	0.33	0.5
PosAcc	4	4	0.3	0.5	0.25	2	2	1	5	0.25	0.25	1	0.5	0.33	3	0.33	3	0.25
Price	0.25	4	0.3	0.5	1	0.25	3	2	0.25	2	1	2	4	5	1	0.25	0.33	0.33
DownC	0.33	1	0.3	0.5	5	4	0.33	0.33	3	3	0.25	3	3	0.2	3	2	4	2
MTBF	1	1	1	0.5	1	0.25	0.33	2	4	4	4	4	2	3	1	3	3	3
TWS	1	2	1	1	5	0.5	1	2	0.25	0.25	3	0.33	0.33	1	4	3	1	1
NoA	0.25	0.3	0.5	1	3	0.5	2	3	1	0.25	0.25	0.33	2	3	0.33	0.33	3	3
Feed	0.33	0.3	1	1	0.5	2	0.5	2	3	4	1	0.25	0.25	1	1	1	3	2
ElecC	0.33	0.3	4	1	3	0.33	1	0.5	3	0.5	2	4	3	1	5	5	1	0.2
MainC	4	3	0.3	1	0.25	0.33	1	1	0.33	1	0.33	3	0.25	3	0.25	0.5	2	4
MTTR	0.25	0.2	1	1	1	0.25	3	0.25	1	4	3	2	2	0.25	3	4	1	4
WW	1	1	2	1	1	3	2	4	1	2	2	0.25	2	3	1	2	4	1
Wwid	2	1	1	1	3	2	0.25	0.5	3	2	1	4	0.33	3	3	3	2	2
MRR	2	0.5	0.5	2	2	3	3	0.25	0.5	1	2	1	4	2	4	0.2	0.33	0.2

To execute the AHP click on the *Calculate Score* button at the bottom of the form. Calculations will then be done by VBA code and may take a few seconds.

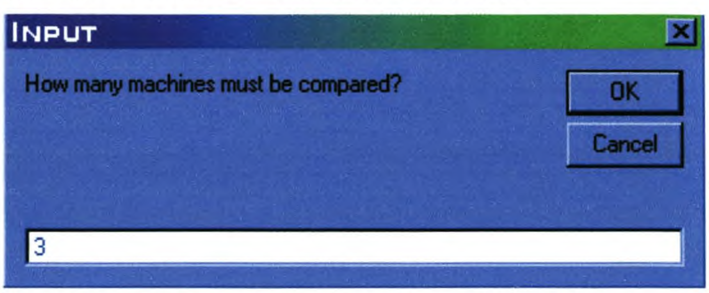
3. If the following message box appears there are inconsistencies in the pairwise comparison matrix. Click on the *OK* button.



Now change the pairwise comparison matrix on the form and again click on the *Calculate Score* button. Repeat the process until the consistency is satisfactory (see next step).

4. If the following message appears the consistency is satisfactory. To continue click on the *OK* button.

5. Now fill in the number of machines that must be compared in the input box that will appear and click on the *OK* button to continue.



6. Complete the tables that will appear for each of the attributes.

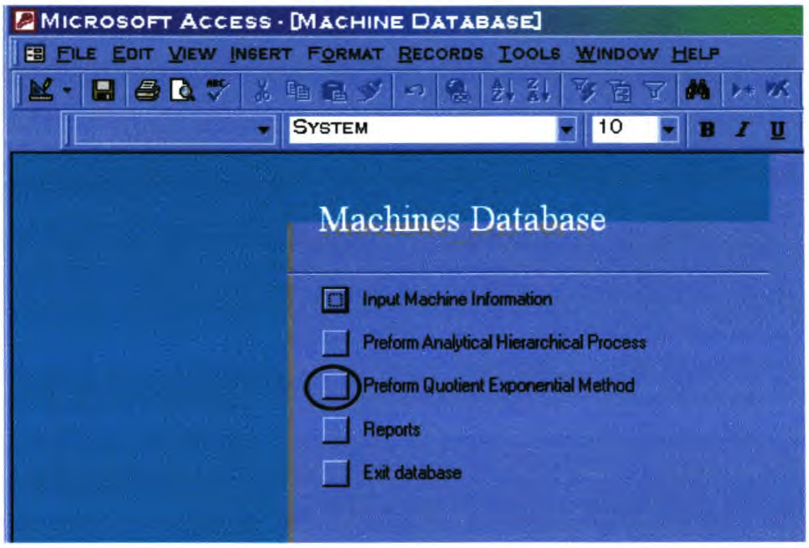
6. Complete the tables that will appear for each of the attributes.
7. When an *Invalid use of Null* error occurs, it means that the user has missed filling in a value somewhere in an attribute matrix table or in the pairwise comparison matrix.

8. When the report opens, read, print and/or close the report.
9. To close the form click on the *Close Form* button.

Appendix D QE Methods Implementation User Guide

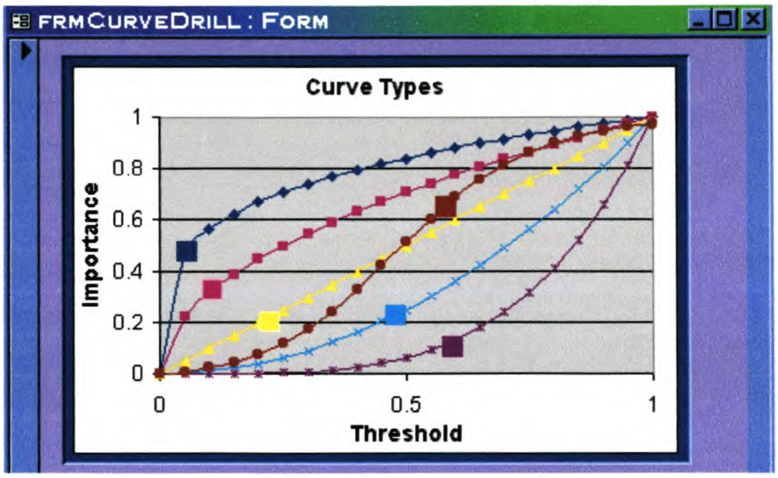
The steps for the QE Method now follows:

1. On the switchboard menu choose the option *Perform Quotient Exponential Method* to use this method.

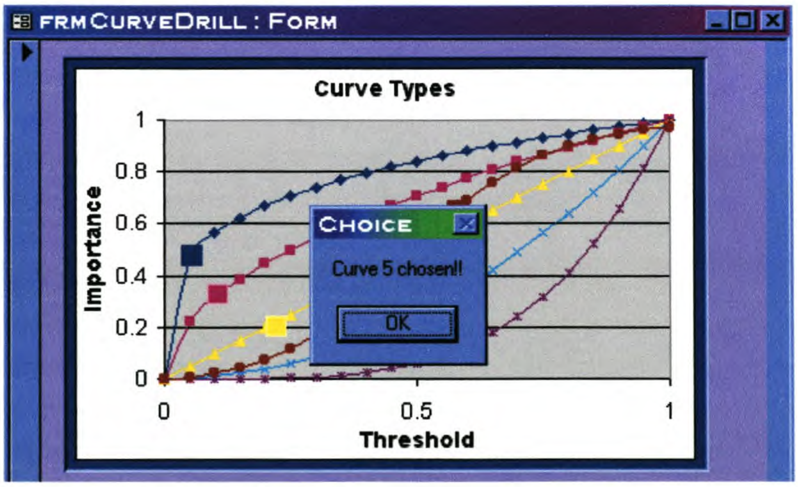


2. A form then opens, as shown below for the drill. This form will execute the QE method.

4. Now click on the exponent box of the attribute. A new form with a figure of six curves will appear as shown in the figure below.

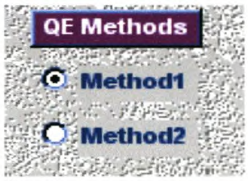


Choose a curve type that represents the attributes perceptive importance by clicking on a square box with the same colour as curve type chosen. A message box stating the curve number chosen will appear. To continue click the *OK* button and the form will automatically close.



5. Repeat steps 3 and 4 for all the attributes on the form.

6. To execute QE Method 1 click on the *Method1* option as shown in the figure below. For QE Method 2 click on the *Method2* option.



7. Now click on the *Calculate Score* button to determine the overall score for each of the machines.

8. A report will open giving the machines and their individual scores. Read, print and/or close the report.

Drill Machine Scores: QE Method 1

Machinetype: Drill

Machine_ID	IdealScore	Score
13	27	22.953
14	27	34.749
15	27	26.531

Best Score 26.531

Drill Score: QE Method 2

Machine type: Drill

Machine_ID	Score
13	0.713
14	0.779
15	0.829

Best Score 0.829

9. To close the form click on the *Close Form* button.

Appendix E VBA Code

Code for opening sub form to enter machine type specific information:

```
Private Sub cmdUniqueAttributes_Click()

    Dim stDocName As String
    Dim stLinkCriteria As String
    Dim ThisDb As Database
    Dim rs As Recordset
    Dim TheForm As String

    Set ThisDb = CurrentDb
    'Open the table tMachineTypes
    Set rs = ThisDb.OpenRecordset("tMachinetypes")

    TheForm = ""
    rs.MoveFirst

    'Find for what machine type information is currently entered and
    'open the form that corresponds with that machine type.
    Do While Not rs.EOF
        If rs.Fields("MachineType_ID").Value = Me.Machine_type.Value Then
            TheForm = rs.Fields("subformname").Value
            Exit Do
        End If
        rs.MoveNext
    Loop

    'Open this form so that the user could enter machine specific information.
    DoCmd.OpenForm TheForm, , , stLinkCriteria

End Sub
```

Code for showing the machine information report for a specific machine type:

```
Private Sub cmdMachineInfo_Click()
 'Define variables and database
 Dim ThisDb As Database
 Dim rs As Recordset
 Dim TheReport As String

 Set ThisDb = CurrentDb

 'Open the table tMachinetypes
 Set rs = ThisDb.OpenRecordset("tMachinetypes")

 TheReport = ""
 rs.MoveFirst

 'Find what the machine type number of the machine chosen in the combo box is.
 'Open the corresponding report for that machine type.
 Do While Not rs.EOF
   If rs.Fields("MachineType_ID").Value = Val(Me.cmbMachineInfo.Column(1)) Then
     'Assign the name of the report to a variable.
     TheReport = rs.Fields("reportname").Value
     Exit Do
   End If
   rs.MoveNext
 Loop

 'Open the report with name TheReport
 DoCmd.OpenReport TheReport, acPreview


End Sub
```

Code for AHP application for Broach Machine:

```
Private Sub AHPBroach_Click()
    'Declare all variables.
    Dim ThisDb As Database
    Dim rs As Recordset
    Dim rss As Recordset
    Dim rs1 As Recordset
    Dim rs2 As Recordset
    Dim rs3 As Recordset
    Dim rs4 As Recordset
    Dim rs5 As Recordset
    Dim rs6 As Recordset
    Dim rs7 As Recordset
    Dim rstemp As Recordset
    Dim NewTable As TableDef
    Dim NormTable As TableDef

    Dim Sum As Single
    Dim WSum As Single
    Dim Attrname As String
    Dim RecordName As String
    Dim wName As String
    Dim TableName As String
    Dim TableName2 As String
    Dim MachName As String
    Dim FieldName As String
    Dim i As Single
    Dim k As Single
    Dim NormVal As Single
    Dim RealVal As Single
    Dim NumFields As Single
    Dim NumRecords As Single
    Dim wValue As Single
    Dim MultVal As Single
    Dim CIVal1 As Single
    Dim CIVal2 As Single
    Dim CIVal3 As Single
    Dim CIVal4 As Single
    Dim CI As Single
    Dim RI As Single
    Dim NumMachines As Single
    Dim Recordfound As Boolean
    Dim FieldsCreated As Boolean
    Dim OverallScore As Single
    Dim MachScore As Single
    Dim TempName As String
    Dim x As Single
    Dim TempValue As Single
    Dim j As Integer
    Dim CompValue As Single

    Dim NewForm As Form
    Dim MyTable As String
```

```
    'When an error occur the program jumps to the error
    'routine line at the end of the sub procedure.
    On Error GoTo ErrRoutine

    Set ThisDb = CurrentDb ' Open current database for calculations
    ' Open the matrix table with the pairwise comparison matrix.
    Set rs = ThisDb.OpenRecordset("TBroachMatrix")
    Set rss = ThisDb.OpenRecordset("TBroachCalc")
     'Open the table to store normalised values.
    Set rs1 = ThisDb.OpenRecordset("TBroachNorm")

'Calculate the normalised table from the pairwise comparison matrix.
i = 0
rs.MoveFirst
Do While (rs.EOF = False)

    Attrname = rs.Fields("Label").Value    'Get the current field name.
    Sum = 0
    rs.MoveFirst

    'Loop through the table and determine the sum of the column
    'of the corresponding attribute field.
    Do While rs.EOF = False
        Sum = Sum + rs.Fields(Attrname).Value
        rs.MoveNext
    Loop

    rs.MoveFirst        'Move back to first record.

    'Store the sum of the corresponding column in the calculations table.
    rss.MoveFirst
    rss.Edit            'Put the table in edit mode
    rss.Fields(Attrname).Value = Sum
    rss.Update          'Update database/table to show changes.


    'Calculate the normalised value
    'store this in the normalised table for later use.
    Do While rs.EOF = False
        RealVal = rs.Fields(Attrname).Value     'Get the real value in the matrix table.
        NormVal = RealVal / Sum
        RecordName = rs.Fields("Label").Value
        rs1.MoveFirst
        Do While rs1.EOF = False
            'Move to the particular attribute and store the normalised value for that attribute.
            If rs1.Fields("Label") = RecordName Then
                rs1.Edit
                rs1.Fields(Attrname).Value = NormVal    'Store value in normalise table.
                rs1.Update
                Exit Do
            End If
            rs1.MoveNext

        Loop
        rs.MoveNext
    Loop
```

```
    rs.MoveFirst
    i = i + 1
    rs.Move (i)

Loop

'Calculate the weights by determining the average of each row.
Set rs2 = ThisDb.OpenRecordset("TBroachWeights")
rs2.MoveFirst

'Determine the number of records in the table to be used later when calculating the average.
NumFields = rs.Fields.Count - 1

i = 0
k = 0
Attrname = " "
RecordName = " "
'Loop through the normalised table to access the values.
rs1.MoveFirst
Do While rs1.EOF = False And k <> 29
    WSum = 0
    RecordName = rs1.Fields("Label").Value        'Points to the row in the table.
    rs1.MoveFirst

    Do While rs1.EOF = False
        Attrname = rs1.Fields("Label").Value    'Points to the column(field) in the table.
        Recordfound = False
        rs1.MoveFirst
        Do While Recordfound = False
          'Determine the sum of the row with attribute name RecordName.
            If rs1.Fields("Label") = RecordName Then
                WSum = WSum + rs1.Fields(Attrname).Value    'Calculate the sum of the row.
                Recordfound = True
                Exit Do             'Exit the loop when the value for the attribute is found.
            End If

            rs1.MoveNext
        Loop

        'Move to next record.
        rs1.MoveFirst
        i = i + 1
        rs1.Move (i)


    Loop

    i = 0
    'Calculate weight as the average of a record's
    'normalised values for the attributes.
    wName = "w" & RecordName
    wValue = WSum / NumFields

    'Store the value in the weights table.
    rs2.Edit
    rs2.Fields(wName).Value = wValue
```

```
    rs2.Update

    'Move to next record.
    rs1.MoveFirst
    k = k + 1
    rs1.Move (k)

Loop

'Determine consistency index
'First calculate [A][w]^T.
Sum = 0
k = 0
rs.MoveFirst

Do While rs.EOF = False
    rs2.MoveFirst
    RecordName = rs.Fields("Label").Value       'Specifies the row to move to.
    rs.MoveFirst
    Sum = 0
    Do While rs.EOF = False
        Attrname = rs.Fields("Label").Value     'Specifies the column to read value from.
        rs.MoveFirst
        Do While rs.EOF = False
            'Move to specified row.
            If rs.Fields("Label") = RecordName Then
            wName = "w" & Attrname

             'Calculate A (normalised value)* w(weight for specific attribute)
            MultVal = rs.Fields(Attrname).Value * rs2.Fields(wName)
            Sum = Sum + MultVal
            Exit Do

            End If
            rs.MoveNext

        Loop

        rs.MoveFirst
        i = i + 1
        rs.Move (i)

    Loop
    i = 0
    rs2.Move (1)
    'Store this multiplication sum in the weights table's second row.
    wName = "w" & RecordName
    rs2.Edit
    rs2.Fields(wName) = Sum
    rs2.Update

    'Loop to next record.
    rs.MoveFirst
    k = k + 1
    rs.Move (k)
```

```
Loop

rs.MoveFirst
Sum = 0
'Calculate the values used for the CI as given in the AHP process.
Do While rs.EOF = False
   rs2.MoveFirst
   Attrname = rs.Fields("Label").Value
   wName = "w" & Attrname
   CIVal1 = rs2.Fields(wName).Value    'Get the weight value.
   rs2.MoveLast
   CIVal2 = rs2.Fields(wName).Value    'Get the multiplication value.

   CIVal3 = CIVal2 / CIVal1
   'Calculate the sum of these values for each attribute.
   Sum = Sum + CIVal3

   rs.MoveNext
Loop

'Determine CI index as given in AHP process.
CIVal4 = (1 / NumFields) * Sum
CI = (CIVal4 - NumFields) / (NumFields - 1)

'Store this index in table TCIIndex for the type of machine.
Set rs3 = ThisDb.OpenRecordset("TCIIndex")

rs3.MoveFirst
Do While rs3.EOF = False
   If rs3.Fields("Machine").Value = "Broach" Then   'Move to the specified machine record.
      rs3.Edit
      rs3.Fields("CI").Value = CI  'Store the CI index in the table for the corresponding machine.
      rs3.Update
      Exit Do
   End If
   rs3.MoveNext
Loop

'Compare the CI index with RI index.
Set rs4 = ThisDb.OpenRecordset("TRIIndex")  'Open the table containing the RI indexes.
rs4.MoveFirst

'Find the RI index that corresponds with the number of attributes in the matrix.
Do While rs4.EOF = False
   If rs4.Fields("n") = NumFields Then
      RI = rs4.Fields("RI").Value
      Exit Do
   End If
   rs4.MoveNext
Loop

'Compare the CI and RI values determined and show the user the result.
CompValue = CI / RI
If (CI / RI) <= 0.1 Then
   MsgBox "Satisfactory degree of consistency." & Chr(13) & CompValue & " < 0.10", vbOKOnly
Else
```

```
    MsgBox "Unsatisfactory degree of consistency. Serious inconsistencies may exist." & Chr(13) &
Chr(13) & CompValue & " > 0.10" & Chr(13) & Chr(13) & "AHP will not yield meaningful results." & Chr(13)
& "Please change pairwise comparison matrix values and then continue.", vbOKOnly
    'If consistency is unsatisfactory exit the procedure so that the user could change the matrix.
    Exit Sub
End If


'xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
'Find the score for each attribute of the drill.
'Determine how well each job satisfy or score for each attribute.

Set rs = ThisDb.OpenRecordset("TBroachMatrix")

'Get the number of machines that are compared with each other.
NumMachines = InputBox("How many machines must be compared?", "Input", i)
rs.MoveFirst
x = 40

'Create new matrix and normalised tables for each attribute.
Do While rs.EOF = False

   k = 1
   Attrname = rs.Fields("Label").Value        'Get the name of the current attribute.
   TableName = "T" & Attrname & "Broach"       'Specify the name of the new matrix table.
   TableName2 = "T" & Attrname & "BroachNorm"  'Specify name of the new normalised table.


   'Create new table with the name Tablename.
   Set NewTable = ThisDb.CreateTableDef(TableName)
   With NewTable
   'Create new fields and append them to new TableDef
   'object.
      .Fields.Append .CreateField("Label", dbText)
      'Create fields according to the number of machines to be compared.
      Do While k <> NumMachines + 1
         FieldName = "Machine" & k
         .Fields.Append .CreateField(FieldName, dbSingle)
         k = k + 1
      Loop

   End With

   k = 1
   'Delete the normalised table if it already exists.
   ThisDb.TableDefs.Delete TableName2

   'Create new normalised table with the name Attrname and Norm and
   'machine type giving for example XtravNormDrill.
   Set NormTable = ThisDb.CreateTableDef(TableName2)
   With NormTable
   'Create fields and append them to new TableDef
   'object.
      .Fields.Append .CreateField("Label", dbText)
      .Fields.Append .CreateField("Calc", dbSingle)
      .Fields.Append .CreateField("Score", dbSingle)
```

```
    'Create new fields according to the number of machines to be compared.
    Do While k <> NumMachines + 1
        FieldName = "Machine" & k
        .Fields.Append .CreateField(FieldName, dbSingle)
        k = k + 1
    Loop

  End With

  'Add the tables to the group of current tables:
  ThisDb.TableDefs.Append NewTable
  ThisDb.TableDefs.Append NormTable


'If more machines must be compared than what the current matrix table could hold,
'fields are added.
  k = 1
  TempName = "TTemp" & x
  'Delete the temp table if it already exists
  ThisDb.TableDefs.Delete TempName

  'Store the current table values in the temp table by renaming the table.
  DoCmd.Rename TempName, acTable, TableName

  'Create new table.
  Set NewTable = ThisDb.CreateTableDef(TableName)
  With NewTable
  'Create new fields and append them to new TableDef
  'object.
    .Fields.Append .CreateField("Label", dbText)

    Do While k <> NumMachines + 1
        FieldName = "Machine" & k
        .Fields.Append .CreateField(FieldName, dbSingle)
        k = k + 1
    Loop

  End With
    'Add this table to the group of current tables.
    ThisDb.TableDefs.Append NewTable


  'Add new records to new table according to the number of machines that must be compared.
  Set rss = ThisDb.OpenRecordset(TableName)
  k = 1
  NumRecords = rss.RecordCount
  Do While k <> NumMachines + 1
    FieldName = "Machine" & k
    rss.AddNew
    rss!Label = FieldName
    rss.Update
    k = k + 1
  Loop

  'Replace the temp values back into the new table.
```

```
'Open the temp table to read the values.
Set rstemp = ThisDb.OpenRecordset(TempName)
'Only replace values if there are something in the table.
If rstemp.RecordCount > 0 Then

rstemp.MoveFirst
rss.MoveFirst
k = 0
j = 0

Do While rstemp.EOF = False
   RecordName = rstemp.Fields("Label").Value   'Get the row it must read.
   rstemp.MoveFirst
   k = 0
   Do While rstemp.EOF = False
      FieldName = rstemp.Fields("Label").Value    'Get the column it must read.
      rstemp.MoveFirst
      'Get the temp value for the specified machine number.
      Do While rstemp.EOF = False
         If rstemp.Fields("Label") = RecordName Then
            TempValue = rstemp.Fields(FieldName).Value
            Exit Do
         End If
         rstemp.MoveNext
      Loop

      rss.MoveFirst
      Do While rss.EOF = False
      'Store this temp value in the new table at the same machine
      'number as in the temp table.
         If rss.Fields("Label") = RecordName Then
            rss.Edit
            rss.Fields(FieldName).Value = TempValue
            rss.Update
            Exit Do         'When value is found exit the loop.
         End If
         rss.MoveNext
      Loop

      'Move to next record/machine.
      rstemp.MoveFirst
      k = k + 1
      rstemp.Move (k)
   Loop

   'Move to the next record.
   rstemp.MoveFirst
   j = j + 1
   rstemp.Move (j)
Loop

End If

'Add records to normalised table according to the number of machines that must be compared.
k = 1
Set rs6 = ThisDb.OpenRecordset(TableName2)
```

```
NumRecords = rs6.RecordCount
Do While k <> NumMachines + 1
   FieldName = "Machine" & k
   rs6.AddNew
   rs6!Label = FieldName   'Specify the name of the field.
   rs6.Update
   k = k + 1
Loop

NumFields = rs6.Fields.Count - 3

'Show the table to the user so that he/she could fill in the values
'for the pairwise comparison matrix.

Attrname = rs.Fields("Label").Value
TableName = "T" & Attrname & "Broach"

DoCmd.SelectObject acTable, TableName, True
DoCmd.RunCommand acCmdNewObjectAutoForm
'The new form is the current active object and assigned to variable MyTable
MyTable = Application.CurrentObjectName

'Open the form in design mode to add a close button.
DoCmd.OpenForm MyTable, acDesign
Set ctlButton = CreateControl(MyTable, acCommandButton, acDetail, , , 3800, 750, 600, 400)

For i = 1 To Forms.Count
      If forms(i).Name = MyTable Then Exit For
Next I
Forms(i).OnClose = "JB"
'Open the form so the user could complete the pairwise comparison matrix for this attribute.
DoCmd.OpenForm MyTable, acNormal, , , acFormEdit, acDialog
DoCmd.Restore

a = 1
While a <> 0
      DoEvents
Wend

'When table has been closed the program continues.
'Calculate the score for each attribute using the same method as before.

'Open the matrix and normalised tables for the attribute.
Set rss = ThisDb.OpenRecordset(TableName)
Set rs6 = ThisDb.OpenRecordset(TableName2)

i = 0
rss.MoveFirst
'Determine the sum of each column in the matrix table.
Do While (rss.EOF = False)

   MachName = rss.Fields("Label").Value        'Get field name.
   Sum = 0
   rss.MoveFirst

   Do While rss.EOF = False
```

```
        'Determine the sum of the column of corresponding field.
        Sum = Sum + rss.Fields(MachName).Value
        rss.MoveNext

    Loop

    rss.MoveFirst       'Move back to first record.
    rs6.MoveFirst
    Do While rs6.EOF = False
    'Store the sum of the corresponding column in the calculations table.
        If rs6.Fields("Label").Value = MachName Then
            rs6.Edit                    'Put the table in edit mode.
            rs6.Fields("Calc").Value = Sum
            rs6.Update
        End If
        rs6.MoveNext
    Loop

    Do While rss.EOF = False
        RealVal = rss.Fields(MachName).Value
        NormVal = RealVal / Sum           'Calculate the normalised value.
        RecordName = rss.Fields("Label").Value
        rs6.MoveFirst
        Do While rs6.EOF = False
            If rs6.Fields("Label") = RecordName Then
                rs6.Edit
                rs6.Fields(MachName).Value = NormVal    'Store value in normalise table.
                rs6.Update
            Exit Do
            End If
            rs6.MoveNext

        Loop
        rss.MoveNext
    Loop

    rss.MoveFirst
    i = i + 1
    rss.Move (i)

Loop

'Calculate the score by determining the average of each row.
rs6.MoveFirst
'Determine the number of records in the table to be use later in calculating average.
NumRecords = rs6.RecordCount
i = 0
k = 0
RecordName = " "

rss.MoveFirst
Do While rs6.EOF = False
    WSum = 0
    RecordName = rs6.Fields("Label").Value    'Points to the row in the table.
    rs6.MoveFirst
```

```
        Do While rs6.EOF = False
          MachName = rs6.Fields("Label").Value    'Points to the column(field) in the table.
          Recordfound = False
          rs6.MoveFirst
          Do While Recordfound = False
          'Determine the sum of the row with name RecordName.
            If rs6.Fields("Label") = RecordName Then
              WSum = WSum + rs6.Fields(MachName).Value    'Calculate the sum of the row.
              Recordfound = True
              Exit Do
            End If

            rs6.MoveNext
          Loop

          'Move to next record.
          rs6.MoveFirst
          i = i + 1
          rs6.Move (i)

        Loop

        i = 0
        'Calculate the score as the average of a record/machine.
        rs6.MoveFirst
        wValue = WSum / NumFields
        Do While rs6.EOF = False
        'Store this score in the norm table.
          If rs6.Fields("Label") = RecordName Then
            rs6.Edit
            rs6.Fields("Score").Value = wValue
            rs6.Update
            Exit Do
          End If
          rs6.MoveNext
        Loop

        rs6.MoveFirst
        k = k + 1
        rs6.Move (k)

    Loop

'Move to the next attribute.
x = x + 1
rs.MoveNext

Loop

'Calculate the overall score for each of the machines.
'First delete and add record spaces to the score table.

Set rs7 = ThisDb.OpenRecordset("TAHPBroach")
rs7.MoveFirst

'Delete records if table already has records in it.
```

```
If rs7.RecordCount <> 0 Then
    Do While rs7.EOF = Fals
        rs7.Delete
        rs7.MoveNext
    Loop
End If

rs7.MoveFirst
'Add new records to the table to store each machine's score.
k = 1
Do While k <> NumMachines + 1
    FieldName = "Machine" & k
    rs7.AddNew
    rs7!Machine = FieldName
    rs7.Update
    k = k + 1
Loop

'Calculate the overall score for each machine.

rs.MoveFirst    'Move to first record in matrix table.
rs2.MoveFirst   'Move to first record in weights table.
rs7.MoveFirst   'Move to first record in AHP score table.


Do While rs7.EOF = False
    'Get the machine for which score will be calculated.
    MachName = rs7.Fields("Machine").Value
    OverallScore = 0
    rs.MoveFirst

    Do While rs.EOF = False

        Attrname = rs.Fields("Label").Value        'Get the first field to read.
        TableName2 = "T" & Attrname & "BroachNorm"
        wName = "w" & Attrname
        wValue = rs2.Fields(wName).Value           'Find the weights value for this attribute.

        Set rs6 = ThisDb.OpenRecordset(TableName2)
        rs6.MoveFirst                              'Move to first record in attribute norm table.
        Do While rs6.EOF = False
            'Read the score of the machine for the specific attribute.
            If rs6.Fields("Label") = MachName Then
                MachScore = rs6.Fields("Score").Value
                Exit Do
            End If
            rs6.MoveNext
        Loop

        'Sum all the scores for the attributes for the specific machine.
        OverallScore = OverallScore + (MachScore * wValue)
        rs.MoveNext

    Loop

    'Store the overall score for the machine in the table.
```

```
    rs7.Edit
    rs7.Fields("Score").Value = OverallScore
    rs7.Update

    'Move to the next machine.
    rs7.MoveNext
Loop

'Show the user the results of the AHP process.
DoCmd.OpenReport "repAHPBroach", acViewPreview


Exit Sub
'The error routine called when error occurs.
ErrRoutine:
    If Err.Number = 3010 Then    'Error routine that keeps a table if it already exists.
        Err.Clear
        Resume Next     'Move to the next line of code after the one where error occurred.
    ElseIf Err.Number = 3265 Then    'Error routine that Clear error if no table exists.
        Err.Clear
        Resume Next

    Else
        MsgBox Err.Number & " " & Err.Description, vbOKOnly
        MsgBox Err.Source, vbOKOnly
    End If

End Sub
```

Code for QE Method Application:

```
Private Sub cmdBroachScore_Click()
    'Declare all variables and recordsets.
    Dim ThisDb As Database
    Dim rs As Recordset
    Dim rss As Recordset
    Dim rs1 As Recordset
    Dim rs2 As Recordset
    Dim rs3 As Recordset
    Dim rs4 As Recordset
    Dim rsIdeal1 As Recordset
    Dim rsIdeal2 As Recordset
    Dim rsIdeal3 As Recordset
    Dim rsIdeal4 As Recordset

    Dim Recno As Single
    Dim Attrname As String
    Dim MinMax As String
    Dim Expo As Single
    Dim TName As String
    Dim TestVal As Single
    Dim MaxVal As Single
    Dim MinVal As Single
    Dim Machnum As Single
    Dim ITName As String
    Dim MachineIDfound As Boolean
    Dim Recordfound As Boolean
    Dim i As Integer
    Dim k As Integer
    Dim IdealIDFound As Boolean
    Dim NumMachFound As Boolean
    Dim RealVal As Single
    Dim IdealVal As Single
    Dim SomeVal As Single
    Dim CalcVal As Single
    Dim Val As Single
    Dim Sum1 As Single
    Dim Sum2 As Single
    Dim Sum3 As Single
    Dim Sum4 As Single
    Dim OverallScore As Single
    Dim IdealScore As Single
    Dim SumFound As Boolean
    Dim n As Single
    Dim ScoreValue As Single


    Set ThisDb = CurrentDb
    'Open the tables: TFunIdeal, TEconIdeal, TRelIdeal , TScore and TBroachIdeal.
    Set rsIdeal1 = ThisDb.OpenRecordset("TFunIdeal")
    Set rsIdeal2 = ThisDb.OpenRecordset("TEconIdeal")
    Set rsIdeal3 = ThisDb.OpenRecordset("TRelIdeal")
    Set rsIdeal4 = ThisDb.OpenRecordset("TBroachIdeal")
    Set rs4 = ThisDb.OpenRecordset("TScore")
```

```
'Search for machine id of the first broach machine.
Set rss = ThisDb.OpenRecordset("tMachines")
Do While MachineIDfound = False
   rss.MoveFirst
   Do While rss.EOF = False
   ' We step through the machines table to see what is the first broach machine's ID.
      If rss.Fields("Machine type") = 6 Then
         Machnum = rss.Fields("Machine_ID").Value   'Store the ID in the variable Machnum.
         MachineIDfound = True
         Exit Do
      End If
      rss.MoveNext
   Loop
Loop

'First all the current calculated records stored in
'TScore, TFunIdeal, TEconIdeal, TRelIdeal and TBroachIdeal are deleted.
'This is done to ensure no errors occur by records being duplicated.

If rs4.RecordCount <> 0 Then 'Check if there are any records in the table.
   'If true all records for the broaching machines calculations are deleted.
   k = 0
   rs4.MoveFirst
   Do While rs4.EOF = False 'Step through TScore.
      If rs4.Fields("Machine_ID") = Machnum + k Then         'Move to first broach record.
         rs4.Delete               'Delete record.
         k = k + 1                'Increase counter by one to move to next machine.
      End If
      rs4.MoveNext

   Loop

End If

k = 0          'Reset count.
rsIdeal1.MoveFirst
'Delete all broach calculation records in TFunIdeal using the same method as above.
Do While rsIdeal1.EOF = False
   If rsIdeal1.Fields("Machine_ID") = Machnum + k Then
      rsIdeal1.Delete
      k = k + 1
   End If

   rsIdeal1.MoveNext
Loop

k = 0  'Reset count.
rsIdeal2.MoveFirst

Do While rsIdeal2.EOF = False
   'Delete all broach calculation records in TEconIdeal.
   If rsIdeal2.Fields("Machine_ID") = Machnum + k Then
      rsIdeal2.Delete

      k = k + 1
   End If
```

```
    rsIdeal2.MoveNext
Loop

k = 0  'Reset count.
rsIdeal3.MoveFirst

Do While rsIdeal3.EOF = False
    'Delete all broach calculation records in TRelIdeal.
    If rsIdeal3.Fields("Machine_ID") = Machnum + k Then
        rsIdeal3.Delete
        k = k + 1
    End If

    rsIdeal3.MoveNext
Loop

k = 0 'Reset count.
rsIdeal4.MoveFirst

Do While rsIdeal4.EOF = False
    'Delete all broach calculation records in TRelIdeal.
    If rsIdeal4.Fields("Machine_ID") = Machnum + k Then
        rsIdeal4.Delete
        k = k + 1
    End If

    rsIdeal4.MoveNext
Loop

i = 0
'Determine the number of broaching machines by counting
'the number of records in the tBroach table.
Set rs3 = ThisDb.OpenRecordset("tBroach")    'Open the TBroach table for use.
rs3.MoveFirst

Do While rs3.EOF = False
    i = i + 1
    rs3.MoveNext
Loop

k = 0   Reset the count
rs3.MoveFirst 'Move to the first record of TBroach and
                            'loop through the table to ensure that only the number
                            'of records needed are created.

rsIdeal1.MoveLast   'Add records after the last record in the table.

'Add new records to the TFunIdeal for the calculated values to be stored in.
Do While rs3.EOF = False
    rsIdeal1.AddNew                             'Use addnew method to add records.
    rsIdeal1!Machine_ID = Machnum + k      'Assign the new record a machine ID.
    rsIdeal1.Update                         'Update database/table to show changes.
    k = k + 1
    rs3.MoveNext
Loop
```

```
'Repeat above method to add new records to the TEconIdeal.
k = 0
rs3.MoveFirst
rsIdeal2.MoveLast
Do While rs3.EOF = False
   rsIdeal2.AddNew
   rsIdeal2!Machine_ID = Machnum + k
   rsIdeal2.Update
   k = k + 1
   rs3.MoveNext
Loop


'Repeat method to add new records to the TRelIdeal.
k = 0
rs3.MoveFirst
rsIdeal3.MoveLast
Do While rs3.EOF = False
   rsIdeal3.AddNew
   rsIdeal3!Machine_ID = Machnum + k
   rsIdeal3.Update
   k = k + 1
   rs3.MoveNext
Loop

'Repeat method to add new records to the TBroachIdeal.
k = 0
rs3.MoveFirst
rsIdeal4.MoveLast
Do While rs3.EOF = False
   rsIdeal4.AddNew
   rsIdeal4!Machine_ID = Machnum + k
   rsIdeal4.Update
   k = k + 1
   rs3.MoveNext
Loop

k = 0
rs3.MoveFirst          'Move to the first record of TBroach to use the this as the
                          'counter of how many records to add.

'Check if there are any records in the table so to move to the last record.
If rs4.RecordCount <> 0 Then
   rs4.MoveLast
End If

'Add new records to TScore for the calculated values to be stored in.
Do While rs3.EOF = False
   rs4.AddNew
   rs4!Machine_ID = Machnum + k
   rs4.Update
   k = k + 1
   rs3.MoveNext
Loop
```

```
    'Set variables to null values.
    Attrname = " "
    MinMax = " "
    Expo = 0
    TName = " "
    ITName = " "

Set rs = ThisDb.OpenRecordset("TBroachDummy")     'Open the dummy table
                                                  'from where settings are read.
rs.MoveFirst

'Calculate the ideal score for a machine.
Do While rs.EOF = False
   IdealScore = IdealScore + 1
   rs.MoveNext
Loop

'Calculate ideal value of attribute and store the value in corresponding ideal table.
rs.MoveFirst
Do While rs.EOF = False

   Attrname = rs.Fields("Lable").Value     'Find the attribute name.
   MinMax = rs.Fields("MinMax").Value              'Find the min/max status.
   Expo = rs.Fields("Exponent").Value              'Find the exponent for the attribute.
   TName = rs.Fields("TableName").Value            'Find the table from which real values are found.
   ITName = rs.Fields("IdealTblName").Value 'Find the table where the ideal values must be stored.

   'Get the ideal value for the attribute.
   MaxVal = 0
   MinVal = 1000000
   k = 0
   Set rs1 = ThisDb.OpenRecordset(TName, dbOpenDynaset, dbConsistent)
   'Loop for the number of machines times.
   Do While k <> i         'i equals the number of broaching machines in the database.
      rs1.MoveFirst
      Do While (rs1.EOF = False) And (k <> i)
         If rs1.Fields("Machine_ID") = Machnum + k Then      'Step to the first broaching machine.
         'Calculate the maximum value of the machines if this attribute is chosen to be maximised.
            If MinMax = "Max" Then
               TestVal = rs1.Fields(Attrname).Value
               If MaxVal < TestVal Then
                  MaxVal = TestVal
               End If

            'Otherwise calculate the minimum value of all the broaching machines if this
            'attribute is chosen to be minimised.
            ElseIf MinMax = "Min" Then
               TestVal = rs1.Fields(Attrname).Value
               If MinVal > TestVal Then
                  MinVal = TestVal
               End If

            End If
            k = k + 1
```

```
            End If
           rs1.MoveNext
        Loop
    Loop

    'Write max/min (ideal) value to a new record forming the ideal record.
    Set rs2 = ThisDb.OpenRecordset(ITName)  'Open the corresponding table for this attribute to
                                              'store the ideal values.

    Do While IdealIDFound = False
       rs2.MoveFirst
       Do While rs2.EOF = False
          If rs2.Fields("Machine_ID") = 10000 Then          'Look for the first broach machine's ID in the
ideal table.
             rs2.Edit            'Put the record set in edit mode.
             If MinMax = "Max" Then
                'Write the maximum value to the corresponding attribute field in the ideal table.
                rs2.Fields(Attrname).Value = MaxVal
             ElseIf MinMax = "Min" Then
                'Write the maximum value to the corresponding attribute field in the ideal table.
                rs2.Fields(Attrname).Value = MinVal

             End If
             rs2.Update      'Update database/table to show changes.
             IdealIDFound = True
             IdealVal = rs2.Fields(Attrname).Value   'Store the ideal value in a variable for later use.
             Exit Do
          End If
          rs2.MoveNext
       Loop
    Loop


    'Calculate the value = (real/ideal)^expo.

    k = 0                    'Reset count.
    Do While k <> i          'Loop for the number of machines times.
       rs1.MoveFirst

       Do While (rs1.EOF = False) And (k <> i)
          'Move to the broaching machines in corresponding table with real values.
          If rs1.Fields("Machine_ID") = Machnum + k Then
             RealVal = rs1.Fields(Attrname).Value       'Find the real value for a machine.

             If MinMax = "Max" Then
                SomeVal = RealVal / IdealVal

             ElseIf MinMax = "Min" Then
                If OptMethod.Value = 0 Then
                   SomeVal = RealVal / IdealVal
                ElseIf OptMethod.Value = 1 Then
                   SomeVal = IdealVal / RealVal
                End If

             End If
```

```
            CalcVal = SomeVal ^ Expo
            rs2.MoveFirst

            'Write this calculated value to the corresponding ideal table.
            Do While rs2.EOF = False
               If rs2.Fields("Machine_ID") = Machnum + k Then
                  rs2.Edit
                  rs2.Fields(Attrname) = CalcVal
                  rs2.Update
                  Exit Do
               Else

               End If
            rs2.MoveNext
            Loop
            'Increase the counter.
            k = k + 1
          End If

          rs1.MoveNext
      Loop
   Loop

   IdealIDFound = False
   rs.MoveNext
   Loop    'Do this for all the attributes.

'Calculate overall score and write to table TScore.
'Open all the ideal tables as well as the score table.
Set rs4 = ThisDb.OpenRecordset("TScore")
Set rsIdeal1 = ThisDb.OpenRecordset("TFunIdeal")
Set rsIdeal2 = ThisDb.OpenRecordset("TEconIdeal")
Set rsIdeal3 = ThisDb.OpenRecordset("TRelIdeal")
Set rsIdeal4 = ThisDb.OpenRecordset("TBroachIdeal")

rs4.MoveFirst
rsIdeal1.MoveFirst
rsIdeal2.MoveFirst
rsIdeal3.MoveFirst
rsIdeal4.MoveFirst
k = 0   'Reset count.

Do While (rs4.EOF = False) And (k <> i)
   'Move to the same broach machine in table TScore and table TFunIDeal.
   If (rs4.Fields("Machine_Id") = Machnum + k) And (rsIdeal1.Fields("Machine_Id") = Machnum + k) Then
      'Determine the sum of the calculated values for this machine.
      Sum1 = rsIdeal1.Fields("Number of axes").Value + rsIdeal1.Fields("Max workpiece height").Value +
rsIdeal1.Fields("Max workpiece length").Value + rsIdeal1.Fields("Max workpiece width").Value +
rsIdeal1.Fields("Max workpiece weight").Value + rsIdeal1.Fields("Mainmotor power").Value +
rsIdeal1.Fields("Feed rate").Value + rsIdeal1.Fields("Positioning accuracy").Value +
rsIdeal1.Fields("Repeatability accuracy").Value + rsIdeal1.Fields("Metal removal rate").Value
      rs4.Edit
      rs4.Fields("Sum1").Value = Sum1    'Write the score for functionality to table TScore.
      rs4.Update
      k = k + 1
   End If
```

```
    'Do not move to the next record if machine is already found in one table and not the other.
    If rs4.Fields("Machine_Id") <> Machnum + k Then
      rs4.MoveNext
    End If

    If rsIdeal1.Fields("Machine_Id") <> Machnum + k Then
      rsIdeal1.MoveNext
    End If

Loop

'Repeat this for the economic calculated values in table TEconIdeal.
rs4.MoveFirst
k = 0
Do While (rs4.EOF = False) And (k <> i)

    If (rs4.Fields("Machine_Id") = Machnum + k) And (rsIdeal2.Fields("Machine_Id") = Machnum + k) Then
      Sum2 = rsIdeal2.Fields("Machine price").Value + rsIdeal2.Fields("Tool cost").Value +
rsIdeal2.Fields("Electricity cost").Value + rsIdeal2.Fields("Labour cost").Value +
rsIdeal2.Fields("Maintenance cost").Value + rsIdeal2.Fields("Depreciation cost").Value +
rsIdeal2.Fields("Floor space required").Value + rsIdeal2.Fields("Floor space cost").Value +
rsIdeal2.Fields("Downtime cost").Value + rsIdeal2.Fields("Cutting fluid cost").Value
      rs4.Edit
      rs4.Fields("Sum2").Value = Sum2
      rs4.Update
      k = k + 1
    End If
    If rs4.Fields("Machine_Id") <> Machnum + k Then
      rs4.MoveNext
    End If

    If rsIdeal2.Fields("Machine_Id") <> Machnum + k Then
      rsIdeal2.MoveNext
    End If

Loop

'Repeat this for the reliability calculated values in table TRelIdeal.
rs4.MoveFirst
k = 0
Do While (rs4.EOF = False) And (k <> i)

    If (rs4.Fields("Machine_Id") = Machnum + k) And (rsIdeal3.Fields("Machine_Id") = Machnum + k) Then
      Sum3 = rsIdeal3.Fields("MTBF").Value + rsIdeal3.Fields("MTTR").Value
      rs4.Edit
      rs4.Fields("Sum3").Value = Sum3
      rs4.Update
      k = k + 1
    End If

    If rs4.Fields("Machine_Id") <> Machnum + k Then
      rs4.MoveNext
    End If

    If rsIdeal3.Fields("Machine_Id") <> Machnum + k Then
      rsIdeal3.MoveNext
```

```
   End If

Loop

'Repeat this for the broach specific calculated values in table TBroachIdeal.
rs4.MoveFirst
k = 0
Do While (rsIdeal4.EOF = False) And (k <> i)

   If (rs4.Fields("Machine_Id") = Machnum + k) And (rsIdeal4.Fields("Machine_Id") = Machnum + k) Then
      Sum4 = rsIdeal4.Fields("Max stroke").Value + rsIdeal4.Fields("Broaching/Cutting speed").Value +
rsIdeal4.Fields("Return stroke speed").Value + rsIdeal4.Fields("Broaching force").Value +
rsIdeal4.Fields("Max broach diameter").Value + rsIdeal4.Fields("Max broach length").Value +
rsIdeal4.Fields("Surface finish").Value
      rs4.Edit
      rs4.Fields("Sum4").Value = Sum4
      rs4.Update
      k = k + 1
   End If

   If rs4.Fields("Machine_Id") <> Machnum + k Then
      rs4.MoveNext
   End If

   If rsIdeal4.Fields("Machine_Id") <> Machnum + k Then
      rsIdeal4.MoveNext
   End If


Loop

'Write the overall score in the table TScore.
n = rs.RecordCount
k = 0
rs4.MoveFirst
Do While (rs4.EOF = False) And (k <> i)
   If rs4.Fields("Machine_ID") = Machnum + k Then
      'Calculate the overall score as the sum of four sums read from the table itself.
      If OptMethod.Value = 0 Then
         OverallScore = rs4.Fields("Sum1").Value + rs4.Fields("Sum2").Value + rs4.Fields("Sum3").Value +
rs4.Fields("Sum4").Value
      ElseIf OptMethod.Value = 1 Then
         ScoreValue = rs4.Fields("Sum1").Value + rs4.Fields("Sum2").Value + rs4.Fields("Sum3").Value +
rs4.Fields("Sum4").Value
         OverallScore = ScoreValue / n
      End If


      rs4.Edit
      'Write this score to the Score field in table TScore.
      rs4.Fields("Score") = OverallScore
      'Write the ideal score to the IdealScore field in table TScore.
      rs4.Fields("IdealScore") = IdealScore
      'Write the machine type to the Machinetype field in table TScore.
      rs4.Fields("Machinetype") = "Broach"
      rs4.Update
```

```
        k = k + 1

    End If
        rs4.MoveNext

Loop

'Show the results of the QE method to the user.
If OptMethod.Value = 0 Then
    DoCmd.OpenReport "repBroachScore", acPreview
ElseIf OptMethod.Value = 1 Then
    DoCmd.OpenReport "repBroachScore1", acPreview
End If

End Sub
```

Code for exponent box:

```
Private Sub Exponent_Click()
    Set ThisDb = CurrentDb
     Dim rs As Recordset

    ' Store the record number of current record in variable Recno.
    Recno = Me.CurrentRecord

    'Store the record number in table TRecordno for later use.
    Set rs = ThisDb.OpenRecordset("TRecordno")
    rs.Edit
    rs.Fields("Recno") = Recno
    rs.Update

    'Open the form that shows the exponent curves.
    DoCmd.OpenForm "frmCurveBroach", acNormal

End Sub
```

Code for assigning exponent:

```
Private Sub BoxExp1_Click()
    'Define all the variables.
    Dim ThisDb As Database
    Dim rs As Recordset
    Dim rs1 As Recordset
    Dim rs2 As Recordset
    Dim Exp As Single
    Dim k As Single

    'Shows the user the number of curve chosen.
    MsgBox "Curve 1 chosen!!", vbOKOnly, "Keuse"

    Set ThisDb = CurrentDb
    Set rs = ThisDb.OpenRecordset("TExponent")
    rs.MoveFirst
    'Read the exponent value from the table.
    Exp = rs.Fields("Exponent").Value

    Set rs1 = ThisDb.OpenRecordset("TRecordno")
    rs1.MoveFirst
    'Read the current record number from the table.
    Recno = rs1.Fields("Recno").Value

    Set rs2 = ThisDb.OpenRecordset("TBroachDummy")
    k = 1
    rs2.MoveFirst
    'Assign the exponent value to the current record.
    Do While (rs2.EOF = False)
        If k = Recno Then
            rs2.Edit
            rs2.Fields("Exponent") = Exp
            rs2.Update
            Exit Do

        End If
        k = k + 1
        rs2.MoveNext

    Loop

    'Close the form after the value was stored.
    DoCmd.Close acForm, "frmCurveBroach", acSaveYes

End Sub
```

Appendix F Database Machine Information

Broach Machines Information

Attribute	Unit	Machine_ID		
		10	11	12
Max stroke	mm	1250	1600	1850
Broaching/Cutting speed	m/min	6.25	8	6.25
Return stroke speed	m/min	25.4	24	25.4
Broaching force	kg	16000	25000	18000
Max broach diameter	mm	92	117	90
Max broach length	mm	45	65	50
Surface finish	µm	23	55	23
Number of axes	#	1	1	1
Max workpiece height	mm	350	330	315
Max workpiece length	mm	455	215	255
Max workpiece width	mm	415	525	500
Max workpiece weight	mm	550	720	890
Main motor power	kw	30	37	25
Feed rate	mm/min	400	400	400
Positioning accuracy	µm	6.60	6.00	6.90
Repeatability accuracy	µm	8.00	5.90	5.90
Metal removal rate	mm^3/min	355.00	446.00	562.00
Machine price	R	102000	152000	115000
Tool cost	R	7902	4701	6672
Electricity cost	R	2545	4422	2055
Labour cost	R	8000	9122	7898
Maintenance cost	R	1680	754	698
Depreciation cost	R	1255	2602	1806
Floor space required	mm^2	259021	540260	426000
Floor space cost	R	7112	10802	8598
Downtime cost	R	1800	1658	2380
Cutting fluid cost	R	458	445	967
MTBF	min	259200	308800	216000
MTTR	min	10080	17280	5760

CNC Lathe Machines Information

Attributes	Unit	Machine_ID		
		16	17	18
Z-axis travel	mm	1016	590	1170
X-axis travel	mm	356	160	305
Distance between centers	mm	1016	610	1270
Number of tools	#	8	12	18
Max spindle speed	rpm	1500	4200	3100
Rapid traverse rate - x	m/min	790	400	500
Rapid traverse rate - z	m/min	1000	780	711
Surface finish	µm	0.3	0.2	0.35
Number of controlled axes	#	2	2	2
Number of simultaneous controlled axes	#	2	2	2
Self-diagnosis	1 = Yes 2 = No	1	2	1
Number of axes	#	2	2	2
Max workpiece height	mm	250	200	225
Max workpiece length	mm	1000	590	999
Max workpiece width	mm	356	160	305
Max workpiece weight	mm	350	680	1000
Mainmotor power	kw	7.5	15	7.5
Feed rate	mm/min	600	450	400
Positioning accuracy	µm	5.90	6.00	5.00
Repeatability accuracy	µm	6.00	5.20	3.00
Metal removal rate	mm^3/min	315.00	275.00	450.00
Machine price	R	115100	190000	250000
Tool cost	R	7800	5550	8000
Electricity cost	R	3800	5565	3800
Labour cost	R	8080	10110	12150
Maintenance cost	R	4333	3000	3400
Depreciation cost	R	1500	1900	2500
Floor space required	mm^2	94400	444500	361696
Floor space cost	R	6000	10000	8000
Downtime cost	R	800	111	1440
Cutting fluid cost	R	1665	921	1120
MTBF	min	216000	367200	388800
MTTR	min	7200	14400	10080

Drill Machines Information

Attributes	Unit	Machine_ID		
		13	14	15
X travel	mm	300	320	550
Y travel	mm	450	515	480
Table work size	mm^2	139690	192500	269997
Max spindle speed	rpm	1800	2000	1200
Chuck size	Inch	8	13	8
Number of axes	#	2	2	2
Max workpiece height	mm	250	280	250
Max workpiece length	mm	458	500	480
Max workpiece width	mm	300	300	550
Max workpiece weight	mm	200	350	250
Main motor power	kw	2	10	5
Feed rate	mm/min	840	1050	560
Positioning accuracy	μm	10.00	6.00	6.60
Repeatability accuracy	μm	6.00	6.50	2.50
Metal removal rate	mm^3/min	255.00	360.00	255.00
Machine price	R	8500	12550	9788
Tool cost	R	808	1288	1567
Electricity cost	R	267	1127	508
Labour cost	R	4508	4966	3600
Maintenance cost	R	1022	1111	998
Depreciation cost	R	800	1200	900
Floor space required	mm^2	139690	192500	269997
Floor space cost	R	3102	3999	4500
Downtime cost	R	866	1000	1111
Cutting fluid cost	R	655	802	420
MTBF	min	129600	216000	216000
MTTR	min	2880	8640	2880

Engine Lathe Machines Information

Attributes	Unit	Machine_ID		
		19	20	21
Z-axis travel	mm	1016	1500	2045
X-axis travel	mm	508	418	645
Distance between centers	mm	2032	1524	3048
Number of tools	#	10	12	20
Max spindle speed	rpm	387	610	400
Rapid traverse rate - X	m/min	234	203	115
Rapid traverse rate - Z	m /min	467	406	396
Surface finish	µm	0.25	0.3	0.2
Number of axes	#	2	2	2
Max workpiece height	mm	233	335	355
Max workpiece length	mm	1016	1455	2522
Max workpiece width	mm	500	400	600
Max workpiece weight	mm	650	880	530
Main motor power	kw	23	15	10
Feed rate	mm/min	108	85	170
Positioning accuracy	µm	5.60	6.00	5.60
Repeatability accuracy	µm	4.00	6.00	4.40
Metal removal rate	mm^3/min	350.00	256.00	425.00
Machine price	R	12566	19250	18650
Tool cost	R	6000	5450	6999
Electricity cost	R	3060	2555	2155
Labour cost	R	8113	7566	5733
Maintenance cost	R	4870	3000	4500
Depreciation cost	R	2000	2100	1910
Floor space required	mm^2	516128	627000	129000
Floor space cost	R	2128	3988	5666
Downtime cost	R	1880	2111	1980
Cutting fluid cost	R	1111	3476	669
MTBF	min	302400	259200	129600
MTTR	min	8640	7200	14400

EDM Machines Information

Attributes	Unit	Machine_ID		
		7	8	9
X travel	mm	450	650	500
Y travel	mm	300	400	400
Z travel	mm	250	350	200
U travel	mm	100	100	100
V travel	mm	100	100	100
Best surface roughness	μm Ra	0.25	0.25	0.25
Electrode wear ratio	%	0.2	0.3	0.25
Dielectric tank capacity	L	350	600	850
Work table size	mm^2	292500	400000	390000
Max electrode weight	kg	75	80	150
Max cutting speed	mm^2/min	200	200	250
Feed rate- rapid traverse	m/min	800	800	1000
Max machining current	A	20	22	50
Controlled Axes	#	4	4	5
Simultaneous controlled axes	#	5	5	5
Self-diagnosis	1 Yes 2 No	1	2	1
Number of axes	#	5	5	4
Max workpiece height	mm	255	355	420
Max workpiece length	mm	650	800	690
Max workpiece width	mm	900	1100	1290
Max workpiece weight	mm	560	850	1200
Main motor power	kw	10	30	15
Feed rate	mm/min	600	800	1000
Positioning accuracy	μm	7.60	6.50	6.60
Repeatability accuracy	μm	6.00	5.00	7.00
Metal removal rate	mm^3/min	250.00	900.00	770.00
Machine price	R	55455	75000	95000
Tool cost	R	10400	9655	8020
Electricity cost	R	5565	9572	7768
Labour cost	R	9050	7555	10500
Maintenance cost	R	4206	5212	3600
Depreciation cost	R	1060	2000	2958
Floor space required	mm^2	292500	400000	390000
Floor space cost	R	11123	15905	12600
Downtime cost	R	6548	3512	7999
Cutting fluid cost	R	880	1263	800
MTBF	min	345600	259200	172800
MTTR	min	5760	10080	4320

Grinder Machines Information

Attributes	Unit	Machine_ID		
		1	2	3
Max grinding length	mm	600	400	880
Max grinding width	mm	250	200	510
Table work size	mm^2	120000	60000	320000
Magnetic Chuck size	inch	120000	60000	320000
Cutting speed	mm^2/min	4200	4500	4300
Surface finish	μm	21	15	55
Number of axes	#	2	2	2
Max workpiece height	mm	200	200	500
Max workpiece length	mm	580	390	850
Max workpiece width	mm	250	200	500
Max workpiece weight	mm	100	80	200
Main motor power	kw	5	2	15
Feed rate	mm/min	500	200	1000
Positioning accuracy	μm	3.00	3.00	5.00
Repeatability accuracy	μm	3.00	3.00	10.00
Metal removal rate	mm^3/min	300.00	250.00	680.00
Machine price	R	4500	3000	7000
Tool cost	R	2000	2500	2000
Electricity cost	R	2500	2000	4002
Labour cost	R	4000	3000	3535
Maintenance cost	R	1000	2000	1500
Depreciation cost	R	1250	1050	1750
Floor space required	mm^2	120000	60000	320000
Floor space cost	R	10000	5000	17220
Downtime cost	R	1200	1000	1955
Cutting fluid cost	R	675	855	1020
MTBF	min	129600	259200	215000
MTTR	min	300	1440	1880

Milling Machines Information

Attribute	Unit	Machine_ID		
		4	5	6
X travel	mm	762	915	560
Y travel	mm	406	658	409
Z travel	mm	508	406	460
A travel	mm	0	0	1
B travel	mm	0	0	1
Max spindle speed	rpm	7500	2000	8000
Rapid traverse feed	m/min	1016	457	1200
Tool mag capacity	#	20	15	18
Tool change time, average	sec	5	7.5	10
Work table size	mm^2	325740	592200	405000
Surface finish	µm	56	32	56
Number of controlled axes	#	3	3	3
Simultaneous controlled axes	#	4	4	3
Self-diagnosis	1 Yes 2 No	1	1	2
Number of axes	#	3	3	3
Max workpiece height	mm	250	256	355
Max workpiece length	mm	915	880	889
Max workpiece width	mm	356	320	432
Max workpiece weight	mm	680	500	300
Main motor power	kw	7.5	15	8
Feed rate	mm/min	7620	2515	4980
Positioning accuracy	µm	9.50	6.60	6.60
Repeatability accuracy	µm	6.50	5.60	8.50
Metal removal rate	mm^3/min	550.00	245.00	685.00
Machine price	R	15000	21600	29000
Tool cost	R	7000	9550	8950
Electricity cost	R	5050	7230	5050
Labour cost	R	4550	5506	3020
Maintenance cost	R	1020	5440	2500
Depreciation cost	R	800	1002	1200
Floor space required	mm^2	325740	592200	405000
Floor space cost	R	6220	8863	7540
Downtime cost	R	805	352	1252
Cutting fluid cost	R	710	633	900
MTBF	min	129600	216000	10800
MTTR	min	4320	5760	2880

Appendix G Pairwise Comparison Terms

Broach Machine Terms

Label	Description
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
WWid	Workpiece width
Stroke	Max stroke
BrS	Broach cutting Speed
RStrS	Return stroke Speed
BrFrce	Broach force
BrDiam	Broach diameter
MBrL	Max broach length
SF	Surface finish
NoA	Number of axes
MPow	Main motor power
Feed	Feed rate
PosAcc	Positioning accuracy
RepAcc	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair

CNC Lathe Terms

Label	Description
Ztrav	Z axis travel
Xtrav	X axis travel
DBCen	Distance between centers
NoTool	Number of tools
MSpinS	Max spindle speed
RTrRx	Rapid traverse rate –x
RTrRz	Rapid traverse rate –z
SF	Surface finish
NConA	Number of controlled axes
NSConA	Number of simultaneously controlled axes
SelfD	Self diagnosis
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
WWid	Workpiece width
NoA	Number of axes
MPow	Main motor power
Feed	Feed rate
PosAcc	Positioning accuracy
RepAcc	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair

Drilling Machine Terms

Label	Description
Xtrav	X axis travel
Ytrav	Y axis travel
TWS	Table work size
SpinS	Spindle speed
ChS	Chuck size
NoA	Number of axes
Mpow	Main motor power
Feed	Feed rate
PosAcc	Positioning accuracy
RepAcc	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
Wwid	Workpiece width

EDM Terms

Label	Description
Xtrav	X axis travel
Ytrav	Y axis travel
Ztrav	Z axis travel
Utrav	U axis travel
Vtrav	V axis travel
BSR	Best surface roughness
EWRat	Electrode wear ratio
DTkCap	Dielectric tank capacity
WTS	Work table size
MEW	Maximum electrode weight
CutS	Maximum cutting speed
RTrR	Rapid traverse rate
MMC	Maximum machining current
ConA	Number of controlled axes
SConA	Number of simultaneously controlled axes
SelfD	Self diagnosis
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
WWid	Workpiece width
NoA	Number of axes
MPow	Main motor power
Feed	Feed rate
PosAcc	Positioning accuracy
RepAcc	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair

Engine Lathe Terms

Label	Description
Ztrav	Z axis travel
Xtrav	X axis travel
DBCen	Distance between centers
NoTool	Number of tools
MSpinS	Max spindle speed
RTrRx	Rapid traverse rate –x
RTrRz	Rapid traverse rate –z
SF	Surface finish
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
WWid	Workpiece width
NoA	Number of axes
MPow	Main motor power
Feed	Feed rate
PosAcc	Positioning accuracy
RepAcc	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair

Grinder Machine Terms

Label	Description
MGL	Max grinding length
MGW	Max grinding width
TWS	Table work size
ChckS	Chuck size
CS	Cutting speed
SF	Surface finish
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
WWid	Workpiece width
NoA	Number of axes
MPow	Main motor power
Feed	Feed rate
PosACC	Positioning accuracy
RepACC	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair

Milling Machine Terms

Label	Description
Xtrav	X axis travel
Ytrav	Y axis travel
Ztrav	Z axis travel
Atrav	A axis travel
Btrav	B axis travel
SpinS	Spindle speed
RTrF	Rapid traverse feed
TMagC	Tool magazine capacity
TChT	Tool change time, average
WTS	Work table size
SF	Surface finish
NConA	Number of controlled axes
SConA	Number of simultaneously controlled axes
SelfD	Self diagnosis
WW	Workpiece mass
WL	Workpiece length
WH	Workpiece height
WWid	Workpiece width
NoA	Number of axes
MPow	Main motor power
Feed	Feed rate
PosAcc	Positioning accuracy
RepAcc	Repeatability accuracy
MRR	Metal removal rate
Price	Machine price
ToolC	Tool cost
ElecC	Electricity cost
LabC	Labour cost
MainC	Maintenance cost
DeprC	Depreciation cost
FlrSpR	Floor space requirements
FlrSpC	Floor space cost
DownC	Downtime cost
FluidC	Cutting fluid cost
MTBF	Mean time between failures
MTTR	Mean time to repair

Appendix H Machine Scores for Attributes of Drill

The following tables are the pairwise comparison matrices that the student completed for the AHP analysis for the drilling machines. Fictitious data was used for this analysis.

DeprC

Label	Machine1	Machine2	Machine3
Machine1	1	3	2
Machine2	0.5	1	0.25
Machine3	0.5	2	1

DownC

Label	Machine1	Machine2	Machine3
Machine1	1	2	3
Machine2	0.5	1	4
Machine3	0.33	0.33	1

ElecC

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.33	1	0.33
Machine3	0.25	3	1

Feed

Label	Machine1	Machine2	Machine3
Machine1	1	0.33	4
Machine2	3	1	2
Machine3	0.33	0.25	1

FlrSpC

Label	Machine1	Machine2	Machine3
Machine1	1	4	5
Machine2	0.25	1	0.5
Machine3	0.2	2	1

ChS

Label	Machine1	Machine2	Machine3
Machine1	1	3	3
Machine2	0.33	1	1
Machine3	0.33	1	1

FlrSpR

Label	Machine1	Machine2	Machine3
Machine1	1	2	3
Machine2	0.25	1	0.5
Machine3	0.33	4	1

FluidC

Label	Machine1	Machine2	Machine3
Machine1	1	4	0.33
Machine2	0.5	1	0.25
Machine3	2	2	1

LabC

Label	Machine1	Machine2	Machine3
Machine1	1	3	0.33
Machine2	0.25	1	0.5
Machine3	3	2	1

MainC

Label	Machine1	Machine2	Machine3
Machine1	1	4	0.33
Machine2	0.5	1	0.5
Machine3	3	2	1

MPow

Label	Machine1	Machine2	Machine3
Machine1	1	5	3
Machine2	0.2	1	0.33
Machine3	0.33	2	1

MRR

Label	Machine1	Machine2	Machine3
Machine1	1	5	1
Machine2	0.25	1	0.25
Machine3	1	3	1

MTBF

Label	Machine1	Machine2	Machine3
Machine1	1	2	3
Machine2	0.5	1	0.5
Machine3	0.5	1	1

MTTR

Label	Machine1	Machine2	Machine3
Machine1	1	3	2
Machine2	0.33	1	0.33
Machine3	0.25	3	1

NoA

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.25	1	0.5
Machine3	0.33	2	1

PosAcc

Label	Machine1	Machine2	Machine3
Machine1	1	4	2
Machine2	0.25	1	0.5
Machine3	0.33	2	1

RepAcc

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.25	1	0.25
Machine3	0.33	2	1

Price

Label	Machine1	Machine2	Machine3
Machine1	1	3	3
Machine2	0.25	1	0.5
Machine3	0.33	2	1

SpinS

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.25	1	0.33
Machine3	0.5	2	1

ToolC

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.25	1	0.25
Machine3	0.33	2	1

TWS

Label	Machine1	Machine2	Machine3
Machine1	1	4	4
Machine2	0.33	1	0.25
Machine3	0.25	2	1

WH

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.33	1	0.25
Machine3	0.25	2	1

WL

Label	Machine1	Machine2	Machine3
Machine1	1	4	4
Machine2	0.25	1	0.33
Machine3	0.33	2	1

WW

Label	Machine1	Machine2	Machine3
Machine1	1	3	3
Machine2	0.25	1	3
Machine3	0.33	0.25	1

WWid

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.25	1	0.5
Machine3	0.25	3	1

Xtrav

Label	Machine1	Machine2	Machine3
Machine1	1	4	3
Machine2	0.2	1	2
Machine3	0.33	0.33	1

Ytrav

Label	Machine1	Machine2	Machine3
Machine1	1	4	2
Machine2	0.25	1	0.5
Machine3	0.33	3	1

Appendix I Project Plan

	Task Name	Duration	Start	Finish
1	Define thesis subject	5 days	Mon 3/3/03	Fri 3/7/03
2	Visit to the Tool Room	1 day	Mon 3/10/03	Mon 3/10/03
3	Define machine types	4 days	Tue 3/11/03	Fri 3/14/03
4	Identify machine attributes	20 days	Mon 3/17/03	Fri 4/11/03
5	Study MCDA methods	5 days	Mon 4/21/03	Fri 4/25/03
6	Indentify suitable MCDA method	5 days	Mon 4/21/03	Fri 4/25/03
7	Develop new method	5 days	Mon 4/28/03	Fri 5/2/03
8	Implement AHP in MS Access	20 days	Mon 5/5/03	Fri 5/30/03
9	Implement new method in MS Access	20 days	Mon 5/5/03	Fri 5/30/03
10	Document the research done	20 days	Mon 6/2/03	Fri 6/27/03