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An integrated system to design machine layouts for modular special purpose machines

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An integrated system to design machine layouts for modular special purpose machines

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USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

ABSTRACT

This thesis introduces the development of an integrated system for the design of layouts for special purpose machines (SPMs). SPMs are capable of performing several machining operations (such as drilling, milling, and tapping) at the same time. They consist of elements that can be arranged in different layouts. Whilst this is a unique feature that makes SPMs modular, a high level of knowledge and experience is required to rearrange the SPM elements in different configurations, and also to select appropriate SPM elements when product demand changes and new layouts are required. In this research, an integrated system for SPM layout design was developed by considering the following components: an expert system tool, an assembly modelling approach for SPM layouts, an artificial intelligence tool, and a CAD design environment. SolidWorks was used as the 3D CAD environment. VisiRule was used as the expert system tool to make decisions about the selection of SPM elements. An assembly modelling approach was developed with an SPM database using a linked list structure and assembly relationships graph. A case-based reasoning (CBR) approach was developed and applied to automate the selection of SPM layouts. These components were integrated using application programing interface (API) features and Visual Basic programming language. The outcome of the application of the novel approach that was developed in this thesis is reducing the steps for the assembly process of the SPM elements and reducing the time for designing SPM layouts. As a result, only one step is required to assemble any two SPM elements and the time for the selection process of SPM layouts is reduced by approximately 75% compared to the traditional processes. The integrated system developed in this thesis will help engineers in design and manufacturing fields to design SPM layouts in a more time-effective manner.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

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List of publications

On the basis of the outcome of this research, the following papers have been published:

- Farhan, U., Tolouei-Rad, M. & Osseiran, A. "Indexing and retrieval using case-based reasoning in special purpose machine designs", *The International Journal of Advanced Manufacturing Technology*, 2017. Volume 92, Issue 5–8, pp 2689–2703. Print ISSN 0268-3768. Online ISSN 1433-3015. Publisher: Springer London. DOI: https://doi.org/10.1007/s00170-017-0274-5

- Uday Hameed Farhan, Majid Tolouei-Rad, Adam Osseiran. "Use of AHP in decision-making for machine tool configurations", *Journal of Manufacturing Technology Management*, 2016. Vol. 27 Issue: 6, pp.874-888. Publisher: Emerald Group Publishing Limited. DOI: https://doi.org/10.1108/JMTM-02-2016-0028

- Uday Hameed Farhan, Majid Tolouei-Rad, Adam Osseiran, (2018) "Assembly modelling approach for special purpose machines", Assembly Automation, Vol. 38 Issue: 2, pp.158-172, https://doi.org/10.1108/AA-12-2016-170

- Uday Hameed Farhan, Majid Tolouei-Rad, Adam Osseiran, (2017) "Enhancing the reconfigurability of special purpose machine tools using mechanical module interfaces", *Journal of Achievements in Materials and Manufacturing Engineering.* Vol. 2 Issue: 84, pp.56-66, DOI: 10.5604/01.3001.0010.803

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LIST OF ABBREVIATIONS

Common abbreviations that have been used in this thesis are listed below:

CAD: Computer aided design

CAM: Computer aided manufacturing

SPMs: Special purpose machines

AI: Artificial intelligence

CBR: case-based reasoning

AHP: analytical hierarchy process

API: application programming interface

SIM: similarity between attributes in CBR

MRR: material removal rate

CNC: Computer Numerical Control

In the memory of my mother ....

Chapter One

1. Introduction

1.1 Problem Statement

Demand for new products has increased as a result of global competition, and as a result, manufacturing companies need to apply new strategies and methods to enable them to face unpredictable changes in product design. Traditional manufacturing systems were inflexible and the production of high-quality products required a high level of skills. Therefore, high production costs were associated with the use of traditional systems. In order to reduce production costs, it was important to improve the flexibility and efficiency of the manufacturing systems, and that was achieved by applying automation technologies to many aspects of manufacturing [1]. One of the applications of automation is flexible manufacturing systems (FMSs), which use computer numerical control (CNC) machine tools. These systems were developed to produce a variety of parts with high flexibility. However, when large numbers of products are needed, FMSs are expensive. Reconfigurable manufacturing systems (RMSs) have been also designed and applied to produce a group family of products [2]. Another area of automation is SPMs, which are machine tools that can be used to manufacture parts in a high production rate [3]. The main benefits of SPMs are increasing the accuracy of the product and reducing labour and production times. The use of these machine tools is still limited in industry because knowledge of this type of machine is not yet fully developed and is still developing.

Computer technology has been developed rapidly and this has had a direct impact on the automation of manufacturing systems, and artificial intelligence (AI) technology has been applied to automate the design and assembly process of manufacturing systems [4]. While different approaches and AI methods have been implemented, expert systems have been used most often to build the engineering knowledge required to automate the design process in manufacturing systems. Modelling by computers has also become necessary to improve the

design phase and to define possible errors in manufacturing systems. Modelling is important in designing and simulating different engineering systems [5], and many software packages have been developed to build efficient modelling systems for automation and simulation purposes. However, there appears to be little knowledge and research on building integrated and automated applications for manufacturing systems, particularly for SPMs. This knowledge is needed to rearrange the SPM elements in different configurations when the demand for products is changed. The response to this change must be accomplished quickly by selecting the required SPM elements and defining the most suitable SPM layouts to achieve better productivity. In addition, each part or workpiece has specific features and specifications: identifying the feasible SPM layouts can be time-consuming, costly, and complex. To address this issue, this research developed an integrated system using appropriate AI methods and a CAD software program. The system that emerged from this work provides further support for the use of SPMs in manufacturing and facilitated the automatic selection of SPM elements and layouts.

1.2 Research Questions

1- Engineering knowledge is a crucial factor in developing automated design systems. Expert systems have been used to implement this knowledge due to their unique features. However, there is a lack of knowledge around SPMs. A key question, therefore, is how can SPM knowledge be developed, and how can this knowledge be used and implemented in order to automate the selection of SPM elements?

2- Assembly relationships are an important measure when performing the assembly process for machine components. 3D CAD software programs have tools, assembly features, and 3D modelling capabilities which are able to assemble different machine components. How can the assembly relationships for the SPM elements be defined? How can these defined

assembly relationships be used with 3D CAD software programs to accelerate the assembly process of SPM layouts and reduce assembly time?

3- Automation is an important technique that has been applied to manufacturing systems. This technique can be used to improve the design and assembly processes of manufacturing systems. How can the selection of SPM layouts and elements be automated and what methods can be implemented?

4- The integration of different techniques and software programs can bring many benefits for design activities and make them faster and compact. How can different components of the SPM layouts design system be integrated?

1.3 Aims and Significance

Designing feasible SPM layouts includes the selection of the necessary SPM elements, and it is important that this selection process is automated to reduce the design time. Therefore, the objectives of this research are as below:

(1) To develop a knowledge-base for SPMs and implement it in an expert system tool.

Developing an SPM knowledge-base is important in order to address the domain knowledge for SPMs. This helps engineers and designers to select the appropriate SPM elements for different machining operations. VisiRule expert system is used in this work as a decision-making tool to implement the developed SPMs knowledge-base. This is because VisiRule has unique features enabling it to implement different types of rules and generate a code for the knowledge-base developed in this work. This code can be used with other applications and software programs.

(2) To develop an assembly modelling approach for SPMs and implement it in SolidWorks. This includes creating an SPM database and a design library.

Developing an assembly modelling approach for SPMs helps to identify the assembly relationships for the SPM elements. These relationships are then implemented using application programming interface (API) features in SolidWorks in order to automate the assembly process of the SPM elements. This reduces the assembly time for the SPM layouts.

(3) To develop an indexing and retrieval approach for SPMs using case-based reasoning (CBR).

Developing this approach helps in the selection of suitable SPM layouts by suggesting similar solutions for new target workpieces. This leads to reducing the overall design time for SPM layouts.

(4) To integrate the above components in the SolidWorks environment.

The importance of this integration is that it makes these components accessible in one environment. This enables the design process of the SPM layouts to be completed quickly and effectively.

The aim of the combination of these objectives is to develop an integrated system that will support the selection of feasible SPM layouts. In addition to these objectives, this work considers other techniques that can also be investigated regarding the determination of SPM configurations and the enhancement of the SPM reconfigurability degree.

1.4 Organisation of Thesis

This thesis is divided into seven chapters. Chapter 1 provides the general introduction, and the literature review for this research is presented in Chapter 2. Chapter 3 presents the development of the SPM knowledge-base and explains how it can be coded by VisiRule. The assembly modelling approach of SPMs is explained in Chapter 4, which includes a full description of its application. Chapter 5 presents the development of the indexing and retrieval approach and how it can be applied to SPMs. Chapter 5 also explains the integration of the

main components developed in this work with the SolidWorks environment. Other techniques that can be used in SPMs are investigated and discussed in Chapter 6, which gives a description of an AHP method to be applied to SPMs, in addition to a proposed design of a mechanical adapter that can be used in SPMs. Conclusions and suggestions for future work are given in Chapter 7.

Chapter Two

2. Literature Review and Background

The use of new technologies – including computer assisted technologies – has led to a rapid development in manufacturing systems in order to enhance productivity. Computer technology has brought many benefits, has helped engineers and manufacturers to face the demand of high productivity. Many design and manufacturing activities have been automated or guided by computers, and this has brought great flexibility and saved time and cost. This chapter provides a description of manufacturing systems and discusses their advantages and disadvantages. The chapter discusses simulation and assembly modelling and investigate AI methods for automated design of manufacturing systems. Background information about SPMs is given in Section 2.4, along with their principles and features. Section 2.5 investigates integration methods for automated design and assembly processes. The final section (Section 2.6) integrates the information and methods discussed in this chapter to provide a context of this research, and a descriptive approach is outlined.

Computer aided manufacturing (CAM) can be defined as the use of computer technology in an effective way in manufacturing to improve productivity [6]. Computers are employed in direct and indirect manufacturing processes. The former involve CNC, flexible manufacturing systems (FMS), robotics, and automated manufacturing cells [7]. The latter involve computer-aided process planning (CAPP), computer-aided facility planning and design, and manufacturing process planning. In addition, computer technology is used to support the decision-making process employing AI and expert systems in manufacturing. As a result, CAM has played an important role in increasing the productivity in manufacturing systems. A large number of functions, from FMS to machine control, are included in CAM, which is part of computer integrated manufacturing (CIM). CIM integrates computer technology into all aspects of manufacturing organisation such as product design, process planning, distribution, production, operation, and management [1]. **Figure 2-1** illustrates an example of CIM structure.

Computer aided design (CAD) can be described as the use of computers to facilitate the design process for models and drawings, and it has been employed in many applications for electric and electronic circuits, architectural design, the animation of movies, fashion design, and design of mechanical systems [7-9]. CAD was initially developed in the 1960s and most engineering designs are now created with CAD systems, which involve interactive computer graphics [1, 7]. In addition, CAD is used to model products and derive their specifications and information. Therefore, CAD is important to CAM because CAD creates the link between these two technologies. Examples of CAD systems are AutoCAD and SolidWorks. Other software such as CATIA can be used with CAD systems to conduct engineering analysis of the products designed by CAD systems. However, SolidWorks has the capability to perform engineering analysis and simulation for many applications. In order to communicate between different CAD systems, there are certain formats that facilitate the saving and exchanging of the designed products between CAD systems. Examples of these formats are drawing exchange format (DXF), initial graphics exchange specification (IGES), and the standard for the exchange of product model data (STEP), as listed by Kalpakjian and Schmid [1].

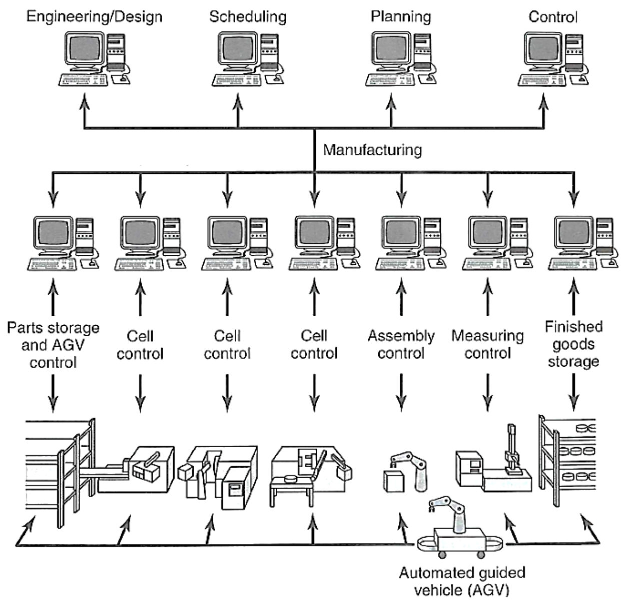


Figure 2-1. A structure of CIM in manufacturing [1].

2.1 Manufacturing Systems

Due to the increasing demand for new products and greater competition as a result of globalisation, manufacturing companies face unpredictable changes in the market. For this reason, manufacturing systems must be designed to meet the factors that enable the companies to remain competitive. These factors are high quality of products, low product cost, and flexible response to changes in the market and consumer needs [10]. These factors are very important for achieving greater productivity in manufacturing systems [11, 12]. Traditional machinery was used to carry out manufacturing operations until the beginning of the 1950s. This included lathes, drill presses, milling machines, and other equipment for operations such as shaping, forming, and joining. However, using traditional machinery and equipment was relatively inflexible and a high level of skilled labour was required to operate and produce parts with the required specifications. These disadvantages led to high production costs. Therefore, production cost needed to be reduced by improving the flexibility and efficiency of manufacturing systems [1]. This led to meeting the requirements of the major factor in manufacturing, which is productivity. In order to improve the productivity of manufacturing systems, some important techniques have been implemented. One of these techniques is automation, which is a process to automate the operation of a machine by following a predetermined sequence of processes. **Figure 2-2** shows a traditional lathe and a pallet-based automation system.

(a) (b)

Figure 2-2. (a) A traditional lathe [13], and (b) an automated machining system [14].

Automation has various levels, starting with simple hand tools and continuing on to computer numerical control machine tools (CNC) and, ultimately, the implementation of expert systems. Automation has been implemented in many areas, such as manufacturing processes, material handling and movement, inspection, assembly, and packaging [15, 16]. The main advantages of automation are improving the productivity and quality of products, reducing human errors and workpiece damage, arranging machines and other equipment efficiently, and integrating various aspects of manufacturing operations [1]. The most popular manufacturing systems are briefly described below.

2.1.1Dedicated manufacturing systems

Dedicated manufacturing systems (DMS) are used to produce high volumes of products. The production in these systems is constant as there is no change in product requirements during the production process [17]. The machines used in DMS are simple and not expensive as they are designed to perform single operations. Therefore, they produce parts with high reliability, repeatability, and productivity [17]. Moreover, the cost per part in DMS is low when the product demand is high [10]. However, DMS are considered as unscaleable and inflexible, and they cannot respond to the changes in product's specifications [18].

2.1.2 Flexible manufacturing systems

Flexible manufacturing systems (FMS) are applied when more than one type of products are machined on the same machine or production line, and they can perform multiple machining operations [17]. CNC machines are the core of these systems, and they are capable of producing a variety of parts. Although FMS are flexible and scalable, they are considered to be expensive solution for mass production of products [18]. **Figure 2-3** shows a flexible manufacturing system with a machining centre.

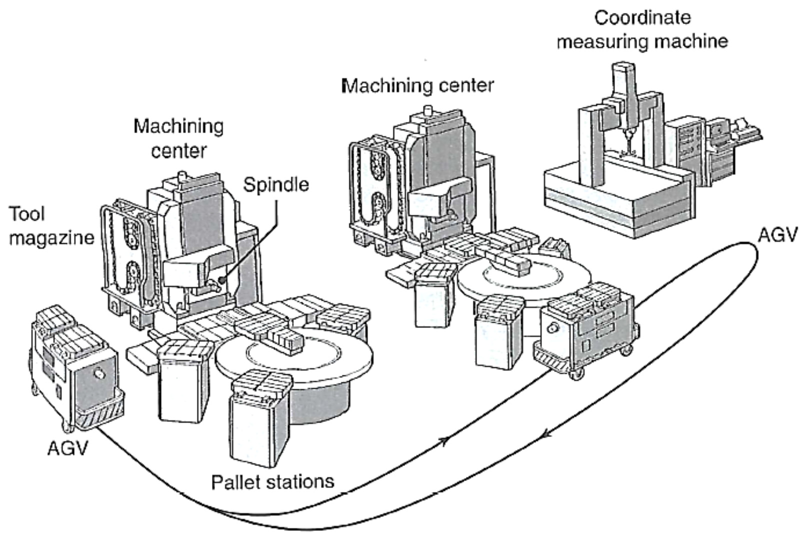


Figure 2-3. A Flexible manufacturing system [1].

2.1.3 Reconfigurable manufacturing systems

Reconfigurable manufacturing systems (RMS) are designed to produce a part family of products [2]. This is because their customised flexibility leads to lower costs than FMS [17]. The main features of RMS are integrability, convertibility, modularity, customisation, scalability, and diagonsibility. The customised flexibility allows RMS to be converted to a new set of production requirements. Therefore, RMS are robust and economical when product requirements are changed [19]. **Figure 2-4** shows an example of RMS, converting a three axes line-boring machine to a three axes milling machine. **Table 2-1** represents the features of each of the three systems explained above.

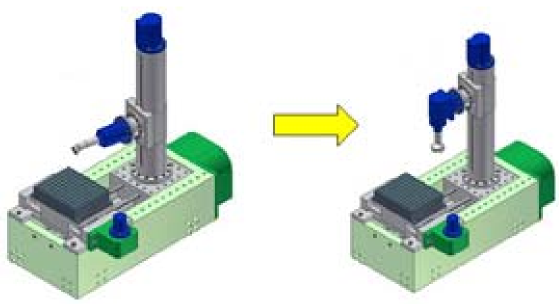


Figure 2-4. An example of RMS [20].

Table 2-1. The features of the three manufacturing systems.

	DMS	FMS	RMS
System structure	Fixed	Changeable	Changeable
Machine structure	Fixed	Fixed	Changeable
System focus	Part	Machine	Part family
Scalability	No	Yes	Yes
Flexibility	No	General	Customised
Productivity	Very high	Low	High
Cost per part	Low	Reasonable	Medium

2.2 Simulation and assembly modelling of manufacturing systems

The rapid development of computer technology had a crucial impact on computer simulation. Simulation models multiple processes in order to help designers to layout the machines and other facilities in a factory. In addition, simulation involves modelling a specific operation to determine the viability of a process [21]. The model is also used to optimise or improve the performance of a specific process. An example of simulation software is finite element analysis (FEA) and there are software packages available to simulate manufacturing systems. Various mathematical schemes have been used in the modelling of individual processes [1]. By using animation in computers, modelling and simulation can help to assess, change, improve, and implement complex production processes. Therefore, simulation and modelling have become necessary for companies needing to improve their performance and to implement new strategies for assessing complex industrial systems [22]. Computer simulation can be done by a computer program in minutes, or can involve a network-based collection of computers that operate for hours or days depending on the complexity of the task [23].

Simulation is very important when dealing with a 3D modelling environment. Its power comes from using 3D models to solve the problems in many systems

[24]. **Figure 2-5** shows a simulation of CNC machining. This technology is considered to be an important tool that helps engineers to plan, operate, and implement complex technical systems. Moreover, simulation has many benefits such as increasing quality and demands regarding flexibility with shorter product life cycles, supporting product complexity and variety, and responding to competitive pressures [25].

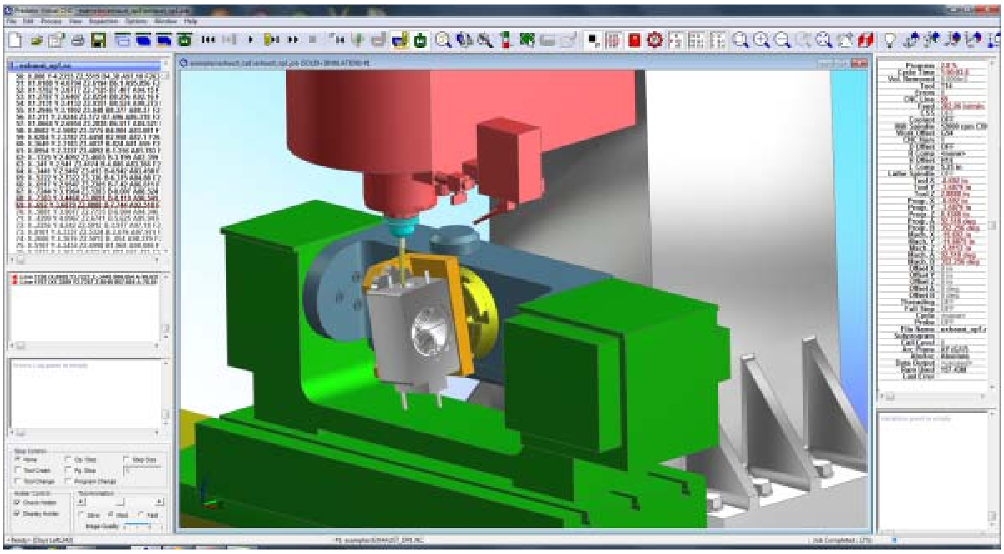


Figure 2-5. Simulation of a produced part in CNC machining tools [26].

Simulation and modelling of manufacturing systems have been carried out to develop an object-oriented simulator for the design, installation, modification, and operation of these systems [27]. The simulation process for FMS includes three steps: the design, the development, and the deployment of the model. These steps enable engineers/manufacturers to decide how the product will be produced [28]. In addition, simulation is applied in designing and optimising the functionality of robots [29]. As the computer simulation is considered to be the link between the theory and the experiment, it is also a tool for computer experiments that may involve dangerous and expensive conditions, and when these experiments need to be done in the laboratory [30].

Several modelling packages which can perform both geometric and assembly modelling have been developed and implanted in CAD/CAM systems such as Pro/Engineer, Mechanical Desktop, and SolidWorks. These systems establish the link between geometric and assembly modellers, and therefore, any modifications to the individual parts in geometric modellers are automatically updated in assembly modellers [31]. SolidWorks is used in the research described in this thesis as a modelling environment because of its 3D modelling capabilities and API features, which can be applied to assembly automation.

Different assembly modelling approaches have been used for several engineering applications. For example, a rapid assembly modelling system was developed for mechanical products to reduce the complexity of the assembly process [32]. This system was based on the concept of standard parts and pre-designed elements with typical assembly features that could reduce design time and manage assembly modelling effectively. A tool for assembly simulation and visualisation was developed to assist with the detection of assembly problems and to overcome any possible modelling errors [33]. Another application of assembly process modelling involved establishing a disassembly sequence, and then reversing it in order to get a suitable assembly sequence [34]. An application of virtual assembly modelling was introduced to model a basic mechanical structure, using an INVENTOR software package in order to make effective decisions in the design and manufacturing stages [35]. Virtual assembly was used to develop an assembly environment for automobiles based on network applications. This system allowed the designers to perform assembly operations interactively [36]. Moreover, a virtual assembly environment was needed to simulate the assembly of automobiles in real time [37]. A virtual reality system was developed to be used for training, design analysis, and path planning. The key features of this system were its attention to assembly planning and evaluation [38]. Another role of virtual assembly was its use in the assembly design of complex products. The role of virtual assembly was investigated in real time along with a dynamic assembly approach [39]. As well as considering virtual assembly, many researchers have looked at automatic assembly approaches. A

group of researchers developed a multi-expert system to enable designers to make changes to designs in order to improve assembly processes [40]. Another application of automatic assembly was assembly planning for robots, which was applied to automate the generation of robot layouts and overcome limitations [41]. In addition, an automatic assembly method was applied in a robotic assembly system for the automatic programming of new assembly tasks [42]. A framework to integrate assembly modelling and simulation was also introduced to eliminate the errors in specifying assembly constraints [43]. Some applications investigated the generation of the assembly sequence, considering issues such as geometrical, mechanical, and stability predicates [44].

2.3 Automated design of manufacturing systems

Following the rapid development of manufacturing processes, the automated design of machine tools has become very important, particularly in regard to achieving time and cost reduction goals. Computer-aided systems have been developed to simplify the design process; however, the need for automated systems has become crucial due to the development of CAD/CAM activities [16, 45]. AI techniques have been implemented for this purpose. The concept of AI is to teach machines how to characterise human intelligence [46]. Behaviours that are associated with intelligence can be summarised as using experience and expertise to solve problems, recognising patterns, recording new experiences, and applying judgment to compensate for incomplete or unavailable data [46]. Some AI systems are presented in Sections 2.3.1, 2.3.2, 2.3.4, and 2.3.5.

2.3.1Genetic algorithm

Genetic algorithm (GA) is a “method for generating solutions and optimising problems using natural evolutionary techniques and it is based on a population of strings to encode candidate solutions in binary form and this develops toward better solutions” [4]. GA begins by generating random individuals in the population, and continues by evolving other generations. The fitness of these individuals is evaluated in each generation to form a new population. When a

satisfactory fitness level is achieved or a maximum number of generations is created, the GA process is stopped.

GA has some advantages: they are easy and simple to operate, they minimise computing requirements, and they can deal with multiple search points [47]. GA has been used in various applications in layout design in different ways [48-51]. However, there is a lack of information and research regarding the application of GA in machine tool design. It has also been noticed that GA cannot complete the whole automated process on its own [4].

2.3.2 Fuzzy logic

Three stages are involved in the use of Fuzzy logic to control a process:

1- Defining the fuzzy inferences (fuzzification);

2- Writing the control laws (fuzzy inference); and

3- Generating an engineering output from the result.

Each value in fuzzification "has a degree of membership, varying from 100% (1) to 0% (0) and this varies from the crisp value (this can only be a true value while the others are false)" [52]. Moreover, membership functions are generated from the values for input and output in fuzzification and the rule base, which is considered to be the controller in the process, is built. Niku noted that a fuzzy inference engine "is used to check the rules and find the corresponding outputs and to define a useful engineering description for each fuzzy descriptor and several graphs can be plotted from the fuzzification and then the membership degree of different values in different fuzzy variables can be described" [52]. The rules for input and output variables are explained in the following example:

IF INPUT1= Degree-of-membership in INPUT1-SET AND
INPUT2= Degree-of-membership in INPUT2-SET
THEN OUTPUT= Degree-of-membership in OUTPUT-SET

General forms of the base rules can be as follows:
If <condition> then <consequence>

If <condition1 and (or) condition2> then <consequence>

If <condition1 and (or) condition2> then <consequence1 and (or) consequence2>

Originally, fuzzy logic was developed by Lotfi Zadeh (1965): more details about fuzzy logic and its underlying theory can be found in Karry and De Silva [53]. Fuzzy logic has been used to represent the knowledge required to reason with expert systems [54]. It has also been applied to fixture design applications, where it has been used to define the fixture layout for different workpieces [55-58]. However, it has also been found that fuzzy logic can be applied to define solutions for specific problems [4] but in these situations, the solutions would not be generalisable. There is also a lack of information and knowledge about applying this method to automate the design process for machine tools.

2.3.3 Case-based reasoning

Case-based reasoning (CBR) is a process based on previous experience that is used to find solutions for different problems [4]. The CBR process involves four steps:

1- Retrieving cases to identify the solution from the memory for a targeted problem;

2- Reusing a solution from the previous cases;

3- Testing and modifying the new solution; and

4- Saving the new solution.

CBR is considered to be a quick method for finding solutions for problems in different applications [59], such as organising a series of steps to achieve suitable results and finding solutions for the designed systems. In general, the designed systems could be complex and may involve inputs from experts. CBR can be used for diagnostic purposes to provide explanations for given symptoms [59]. CBR has been applied in different engineering applications, especially for design

issues. A hybrid CBR/CAD system, which included CBR incorporated with generalised design knowledge, was developed for an injection mould design to make a flexible and comprehensive design model [60]. CBR was also used for a rapid design process with injection moulding [61]. A CBR approach combining parametric and constant satisfaction adaptations was applied in the design of mechanical bearings [62]. Another application used parametric design tasks integrated with heuristic search techniques [63]. CBR was also integrated with model-based diagnosis to develop an approach called Experience Aided Diagnosis (EAD) that overcame errors in real-world devices [64]. A CBR method was applied to select, modify, and design modular fixtures [65]. The purpose of this application was to automate the design process of modular fixture layouts. Another system developed for fixture design used CBR combined with rule-based reasoning to build a virtual reality-based integrated system [66]. Cutting tool selection is another application that used CBR to find the optimum cutting tool in order to manufacture a part. In order to increase productivity, a web-based approach was developed for the selection of tooling configurations in turning operations [67]. This method was implemented in applications to design the fixture design layout [58, 68, 69] (see **Figure 2-6**).

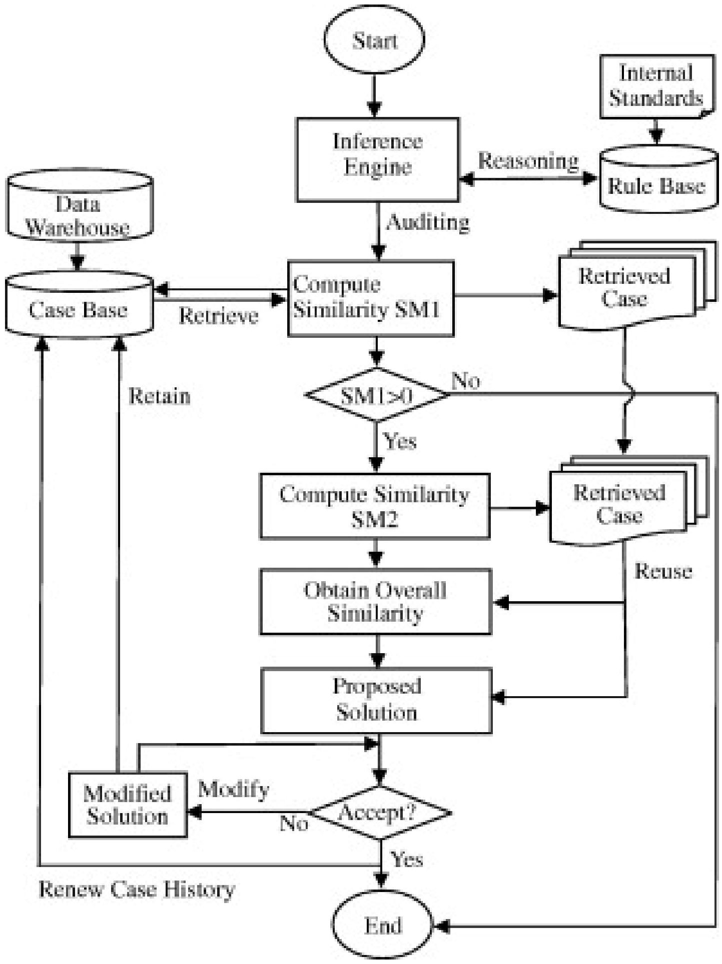


Figure 2-6. A methodology using CBR for fixture design [70].

2.3.4 Artificial neural networks

Artificial neural networks (ANN) is a tool that can be used for different applications [71, 72]. It is a system based on the function and structure of the human brain [47]. This system consists of computational elements called neurons that are paralleled and distributed in a huge network [53]. These elements are connected together by weighted connections that transmit signals [47]. The knowledge needed to solve specific problems is stored in these connections [71]. **Figure 2-7** shows a typical ANN structure.

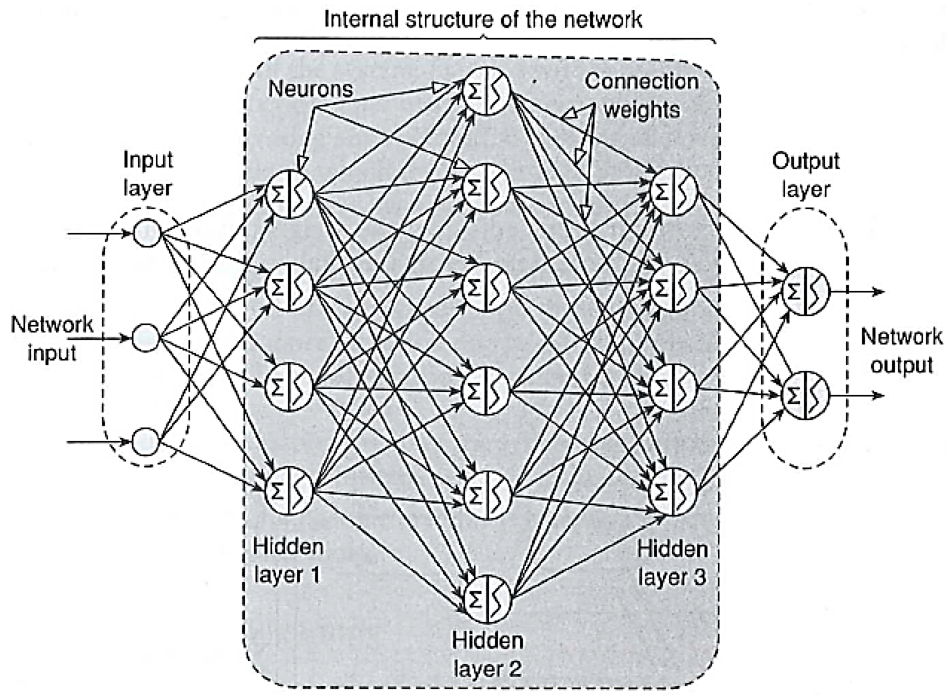


Figure 2-7. An ANN structure [53].

ANN has been used in the design process for several applications such as a fixture design layout with GA [73]. Although this tool has powerful capabilities, there is a lack of information about using this tool in the design of the machine tool layouts and SPMs.

2.3.5 Rule-based expert systems

Another AI method is rule-based expert systems, which are based on using knowledge to solve problems. Knowledge can be defined as a theoretical understanding of a subject or domain [54]. It is considered to be the only production factor that cannot be mitigated [74]. It can be expressed by rules in order to solve problems, and these rules are written as IF-THEN structures. The IF part relates to the facts or the given information: this is usually called the condition or antecedent. The THEN part relates to the required action: it is called the action or consequent [54]. The rules are considered to be a suitable format to represent relations, directions, recommendations, strategies, and heuristics. Expert systems can be defined as intelligent computer programs that have the

ability to apply reasoning techniques or knowledge to solve problems in a specific field in a similar way to human experts [75]. The existence of the knowledge required to solve the problem characterises expert systems [76, 77]. The knowledge in the expert systems consists of human experience and expertise [78]. the use of this kind of knowledge in developing expert systems is quite promising and provides the benefits of optimisation, modelling, and powerful preference acquisition [47].

Typical processes that can deal with via expert systems are diagnosis, selection, prediction, classification, optimisation, and control. Developing an expert system requires the cooperation of five members: the project manager, the knowledge engineer, the domain expert, a programmer, and the end user. The domain expert has the greatest expertise in a given domain. This person should be able to share their knowledge and spend an appropriate amount time in the development process of the expert system. The knowledge engineer should have the ability to design, build, and test the expert system [54]. The responsibilities of the knowledge engineer are to select the expert system task, communicate with the domain expert to find the best solution for the specific problem, choose the software or expert system shells, and make sure that the expert system is working properly in the workplace.

The programmer is responsible for describing the domain knowledge in a way that the computer can understand. This individual should have the required programming skills and must have complete knowledge of programming languages. The project manager is responsible for keeping the development of the expert system focused and following the right procedures. The end user is usually the user of the expert system, and the expert system must meet the needs of this user. Moreover, the end users must be confident and comfortable when they use the expert system. This can be achieved by designing a suitable user interface for the expert system, and this is crucial in designing the expert system [54]. **Figure 2-8** shows the development of an expert system.

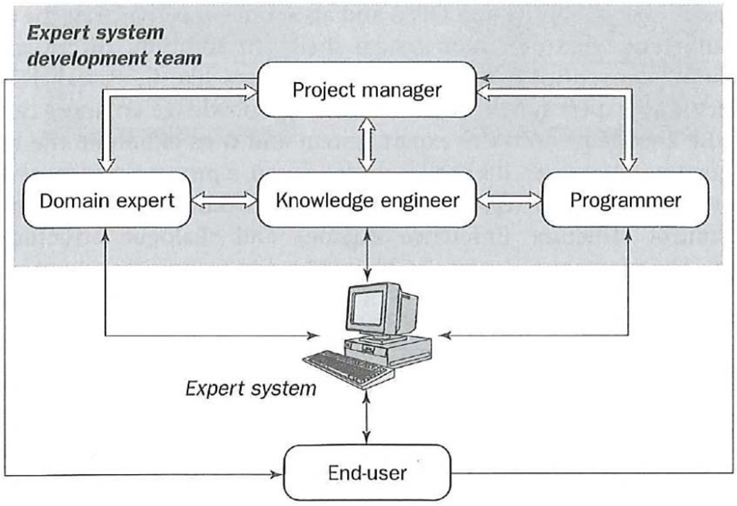


Figure 2-8. The development of an expert system [54].

Rule-based expert systems have been applied in many areas such as engineering, business, geology, medicine, mining, and power systems. The software for these systems is produced by many companies, and expert system shells have been developed to be applied in personal computers. These shells are becoming popular because they concentrate on knowledge rather than learning new programming languages [54]. In an expert system shell, the user only needs to add the knowledge to the system in a rule format with the relevant data in order to solve problems. Expert systems have been employed successfully in different applications involving subjective and uncertain information [54, 75, 79]. However, the real capability of applying the expert systems has been not adequately explored [47]. Therefore, the work reported in this thesis aimed to address expert systems capability in design and assembly tasks by taking SPMs as an application.

2.3.5.1 Expert systems characteristics

A particularly important characteristic of expert systems is their high quality performance. This high performance is achieved because the expert systems are built to be applied in a specified domain, and to be performed at a human expert level. Reaching solutions in a short time is also important, and experts should

therefore find shortcuts to solutions by applying the pre-existing knowledge. In this case, experts use rules-of-thumb or heuristics and these should be applied by the expert systems in the reasoning process to reduce the search area for solutions.

Another characteristic of expert systems is explanation capability. This is a unique feature that gives the ability to review reasoning processes and prove conclusions. In the conventional programs for data processing, algorithms or a series of step by step operations are used. The algorithms perform the same operations in the same order, and they provide exact solutions. However, expert systems do not follow an exact sequence of steps and they can deal with fuzzy and incomplete data [54]. In addition, symbolic reasoning is employed in expert systems to solve problems and to present different types of knowledge such as facts, concepts, and rules.

The difference between expert systems and other conventional systems can be discussed by considering two important factors. First, expert systems can deal with incomplete information and can still get reasonable conclusions, while in conventional programs, the data must be complete and exact to solve problems and then give the correct solution. Second, the knowledge base is separated from the inference engine in expert systems, while the two are mixed in the conventional systems. Because the knowledge is separated in expert systems, this makes them much easier to build and maintain. In addition, they can be easily modified by adding new rules or changing the existing rules. However, this is not the case in the conventional programs as it is difficult to review the program code because this affects both the knowledge and the inference engine [54].

The first development of expert systems uses IF-THEN rules to represent the stored knowledge. A latter development involved integrating these systems with other AI tools to pursue a higher decision performance. Expert systems have been applied to many applications for different purposes. They were applied in manufacturing design, representing some design tasks such as part design, process planning, equipment selection, and facility layout [80]. Knowledge-based

expert systems (KBESs) were used to identify and examine wind engineering applications and to describe how these systems should be applied [81]. Other developments implemented KBESs in web-based applications and online fault diagnosis in technical processes [82, 83]. Moreover, KBESs were investigated in several manufacturing processes such as welding, casting, machining, and metal forming [84].

Expert systems are employed in decision-making processes, which leads to increases in productivity and decreases in costs [85, 86]. Expert systems have been applied to the development of a knowledge-based manufacturing advisor by Vosniakos and Giannakakis [87]. Models to solve machine layout problems were developed by Sunderesh et al, and knowledge-based systems were used for NC (numerical control) programming and modelling by Pan and Rao [88, 89]. Moreover, rule-based systems have been utilised to automate the assembly of a model die and to select the materials for the cutting tool, while other systems were developed for the design of machine layout [90, 91]. Knowledge-based expert systems have been applied to store and then reuse human expertise for solving complicated engineering problems [92]. In addition, they have been used for design and assembly problems and process planning [93, 94]. Expert systems were employed in manufacturing systems to define layout and planning capacity [95]. An expert system was developed by Hedi et al to select the machine layout in manufacturing systems [96]. A knowledge-based expert system was used in an intelligent analysis of the use of SPMs [97]. **Figure 2-9** illustrates an example of implementing an expert system in an industrial robot.

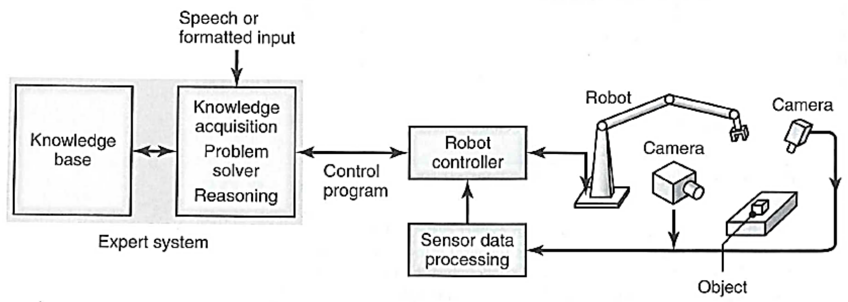


Figure 2-9. An industrial robot guided by an expert system [1].

There are many types of expert systems which are used for different purposes, and a summary of some expert systems in the market is given below.

2.3.5.2 Exsys Corvid expert system

Exsys Corvid is used to automate the decision-making process based on expert knowledge [98]. Through this expert system, knowledge is captured and there is an active interface between the users and the human experts. In addition, an online software system, which can be run from a website, is available to solve problems with various types of platforms. An IF-THEN format is used for creating rules in this expert system and thereby capturing knowledge.

2.3.5.3 Jess Java expert system

Jess Java shell is a rule-based language for specifying expert systems. This shell is a translator for the Jess language [99]. Jess, which is a rule engine for the Java platform, provides the capability for rule-based programming in the expert systems for automation purposes [100]. This shell is considered to be the fastest rule engine available because it is small, light, and available at no cost for academic purposes, and it provides access to all of Java's APIs for the user.

2.3.5.4 Vanguard knowledge automation system

The Vanguard system provides ways to automate processes in a web application form which is easy for any user to use [101]. Many benefits can be received by using Vanguard software such as improving quality, reliability, consistency, speed of result, reducing overall costs, and improving customer satisfaction. Examples of Vanguard software are Vanguard CMS, Vanguard Studio, and Vanguard Server [101].

2.3.5.5 VisiRule expert system

VisiRule is a tool for drawing questions and expressions graphically in chart form in order to create decision support software [102]. The questions and expressions are addressed into a rule format, and this tool is suitable for users with minimal programming skills. Moreover, VisiRule can improve productivity

by considerably reducing the time required to produce decision support systems. A source code is generated by VisiRule and this code can be used and executed with other programs. VisiRule is considered to be an intelligent charting tool because of its ability to build knowledge-based systems. In addition, the construction process of the charts is guided by real time semantic checking, which prevents errors being made by the user [102].

2.3.6 Analytical hierarchy process (AHP)

AHP was introduced by Saaty as a method that can be used to solve complicated and unstructured problems [103]. It provides a way to deal effectively with complex decision-making tasks [104]. This method is completed in four steps:

1- Generate a decision hierarchy for decision problem elements.
2- Make a pairwise comparison of decision elements and construct comparison matrices.
3- Estimate the relative priorities of the elements using the “eigenvalue” method.
4- Synthesise relative priorities from the previous step to achieve the final weights of decision alternatives.

In step one, the hierarchy is divided into different levels as shown in **Figure 2-10**. Level 1 is the main goal of the decision-making process. Level 2 contains criteria that contribute to the quality of decision-making. Sub-criteria follow in Level 3, and the last level of the hierarchy contains decision alternatives or the selection options [105].

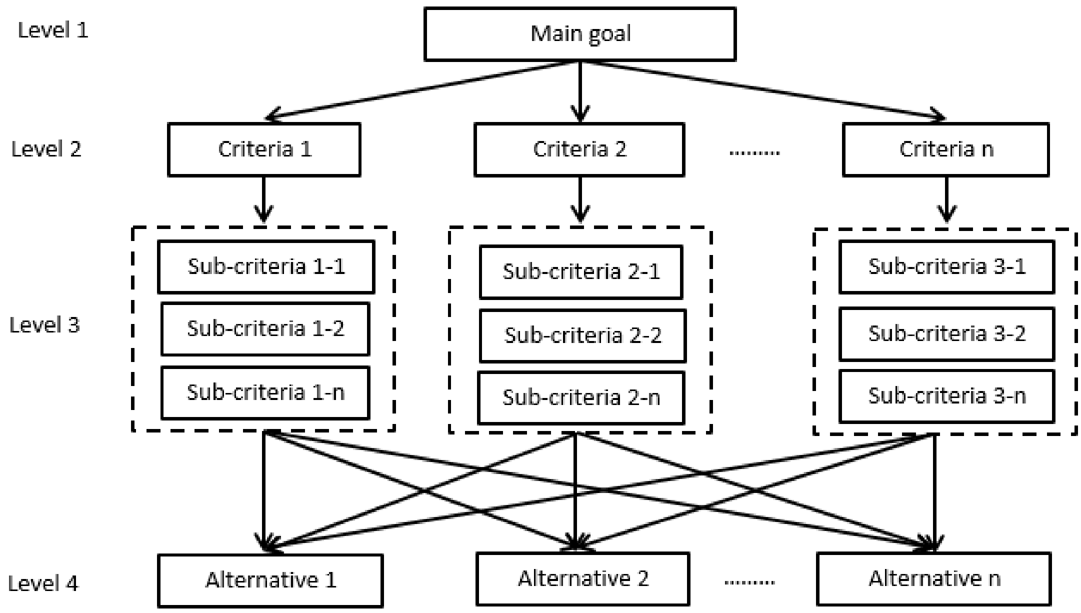


Figure 2-10. A standard hierarchy structure for a decision problem elements.

The decision-making process is facilitated by generating a decision hierarchy and developing a mathematical model to assign priorities for criteria, sub-criteria, and alternatives that contribute to a decision problem. A theoretical foundation developed for AHP by Saaty takes into consideration both tangible and intangible aspects of complex problems. Decisions can be made based on the experience, knowledge, and intuition of the decision-makers [105]. The hierarchy in **Figure 2-10** is defined as a complete hierarchy since the alternatives in Level 4 are affected by all the elements in level 3. If the alternatives are not affected by all the elements in the upper level, then the hierarchy is called incomplete as shown in **Figure 2-11**. After constructing the hierarchy, pairwise comparison matrices are made to compare the elements in each level with respect to the elements in the upper level. For example, the criteria in Level 2 are compared with regard to the main goal, and sub-criteria in Level 3 are compared with respect to immediate criteria in Level 2. The pairwise comparison matrices compute the priority for the elements in the hierarchy. A scale is used to compare the elements as shown in **Table 2-2**. The scale for pairwise comparison in AHP.. This scale is

developed by Saaty to translate qualitative judgments into numerical values, including intangible attributes [105].

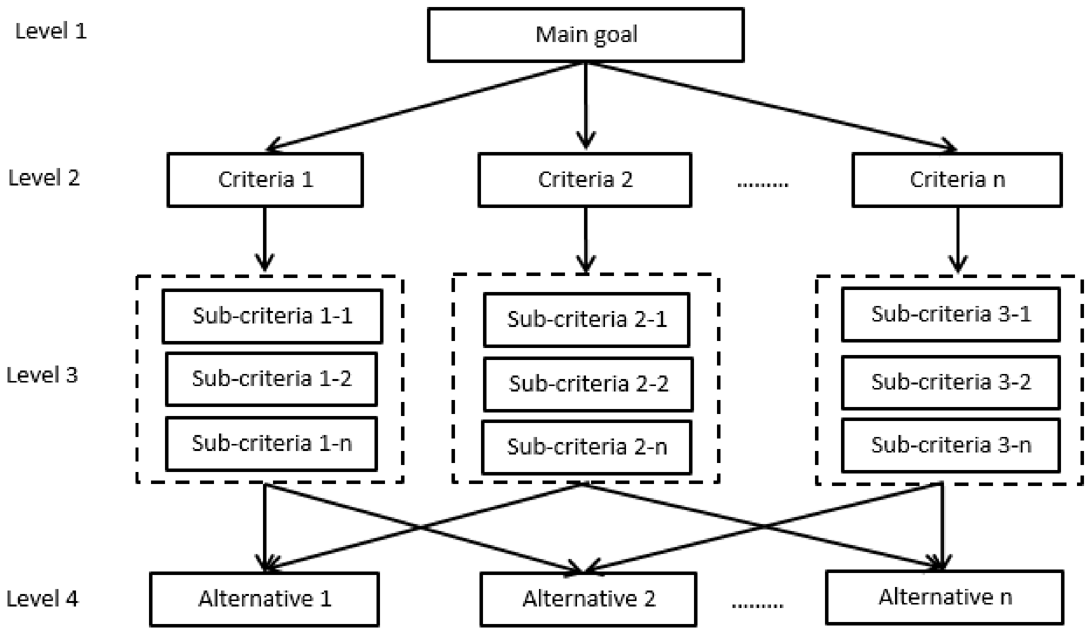


Figure 2-11. Incomplete hierarchy structure for decision problem elements.

Table 2-2. The scale for pairwise comparison in AHP.

Scale value	Interpretation	Meaning
1	Equally preferred	Two elements contribute equally
3	Moderately preferred	An element is favoured over another
5	Strongly preferred	An element is strongly favoured over another
7	Demonstrably preferred	An element is demonstrably favoured over another
9	Extremely preferred	An element is extremely favoured over another
2, 4, 6, 8	Intermediate values	Used halfway between the values on either side

Comparison matrices are used to determine the degree of importance of elements in the hierarchy. Let's consider C1, C2…, Cn as a set of criteria. The

result of pairwise comparison on n criteria can be shown in an (n x n) matrix A as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

The matrix is consistent when it is a positive reciprocal matrix (n x n), in which the elements satisfy the relation $a_{ij} \times a_{jk} = a_{ik}$ for $i,j,k = 1, 2, \ldots, n$. The elements a_{ij} ($i,j = 1, 2, \ldots, n$) are the rating of importance of the criterion i over j. The rules of this rating input are: $a_{ij} = 1$, and $a_{ij} = 1/a_{ji}$.

The priorities of elements in each level are computed by determining the principal eigenvector W of matrix A, as shown in Equation 2 [103]:

$$AW = \lambda\max W \quad (2)$$

Where W is the matrix vector which is normalised to become the priority vector of elements in one level with respect to the upper level, while $\lambda\max$ is the largest eigenvalue of matrix A [103].

The largest eigenvalue $\lambda\max$ is used to assess the consistency of the comparison matrix A. For a consistent reciprocal comparison matrix, the largest eigenvalue should be equal to the size of the matrix, which means $\lambda\max = n$. A consistency index CI was identified for this purpose as follows [103]:

$$CI = \frac{\lambda\max - n}{n-1} \quad (3)$$

The consistency ratio CR of a comparison matrix is calculated as follows [103]:

$$CR = \frac{CI}{RI} \quad (4)$$

Where *RI* is the random index of the matrix and can be identified by using **Table 2-3**. Average *RI* values.. A value of 0.1 or less for *CR* is acceptable for a comparison matrix to be consistent. For values higher than 0.1, the decision process needs to be repeated to achieve more reliable values.

Table 2-3. Average *RI* values.

Matrix size (n)	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

AHP has been used by many researchers and decision-makers for different problems and applications [106]. This method was used simulate automotive manufacturing systems to select the appropriate transmission line [107]. AHP was applied for selection of machine tool systems and to choose the most appropriate manufacturing system [108]. It was also used to develop an expert system for non-traditional machining process selection [109]. AHP was used in several engineering applications such as engineering education [110], selecting the best concept in the lean environment in a manufacturing organisation and lean tools [106, 111], developing a model of maintenance decision-making and maintenance procedure [104, 112], selecting appropriate flexible manufacturing systems [113, 114], developing a model for facility layout selection [115], selecting machining schemes [116], measuring the performance of manufacturing systems [117], selection of conceptual design alternatives [118], selection of the appropriate manufacturing process for e-textile structure [119], analysing pattern techniques for sheet metal geometries [120], and developing a platform to support the design of injection molds [121]. Most of these applications were multiple criteria decision problems and included evaluation of decision alternatives. These applications addressed problems when no prior quantification of alternatives was available, and this explains the acceptance of AHP in these applications [122].

2.3.6.1 The justification of AHP

AHP can be described as a method of deriving a set of weights which are related to n activities to achieve judgments on the relative importance of these activities. It is important that these judgments are quantified in a way that can allow quantitative interpretation of them among the activities [103]. By considering that $C1$, $C2$,….., Cn are a set of activities, the quantified judgements in regard to pairs activities Ci, Cj are expressed by an n-n matrix: $A = (a_{ij})$, $(i,j = 1,2,\ldots, n)$. The entries for aij are: If $a_{ij} = \alpha$, then $a_{ji} = 1/\alpha$, $\alpha \neq 0$

If Ci is judged to have equal relative importance to Cj, then $a_{ij} = a_{ji} = 1$. Therefore, the matrix A can be represented as [103]:

$$A = \begin{vmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{vmatrix}$$

The process is to assign a set of numerical weights w_1, w_2,…, w_n to the activities $C1$, $C2$,…, Cn. In order to do this, the uncertain problem is transformed into a mathematical form. The process describes how the weights w_i are related to the judgments a_{ij}, and this can be achieved by the following steps:

Step 1: Consider first that a set of workpieces ($C1$, $C2$, ..., Cn) with a precision scale are given and the judgments are related to physical measurements. To compare two of these workpieces ($C1$with $C2$), their weights are scaled and they are w_1 = 305 grams and w_2 = 244 grams for $C1$ and $C2$, respectively. Dividing w_1 by w_2 gives 1.25, and this indicates that $C1$ is 1.25 times heavier than $C2$, and this judgement is recorded as $a_{12} = 1.25$. Therefore, the relation between the weights w_i and the judgements aij are given as:

$w_i / w_j = a_{ij}$, $(i,j = 1,2,\ldots,n)$, and the matrix A will be [103]:

$$A = \begin{vmatrix} w1/w1 & w1/w2 & \dots & w1/wn \\ w2/w1 & w2/w2 & \dots & w2/w1 \\ \dots & \dots & \dots & \dots \\ wn/w1 & wn/w2 & \dots & wn/wn \end{vmatrix}$$

Step 2: It is important to consider an allowance for deviations in this mathematical approach. For this purpose, consider the *ith* row in the matrix *A* with entries: $a_{i1}, a_{i2}, \dots, a_{ij}, \dots, a_{in}$. These entries are the same as the ratios (in the ideal case): w_i / w_1, w_i / w_2, …, w_i / w_j,.., w_i / w_n. By multiplying the first entry in *ith* row by w_1, and the second entry by w_2, and so on, the results are: $w_i / w_1 \times wi = wi$, $w_i / w_2 \times wi = wi$, …, $w_i / w_j \times wj = wi$,.., $w_i / w_n \times wn = wi$, which means that the result is a row of the same entries : $wi, wi, \dots, wi$.

In a general case, a row of entries which represent a statistical scattering of values around w_i, would be obtained, and it seems reasonable to have w_i equal to the average of these values. Therefore, the following relation is given instead of the ideal case relation [103]:

$w_i = a_{ij}\, w_j$, $(i,j = 1,2,\dots,n)$,

and for each fixed i, the relation talks the form:

w_i = the average of ($a_{i1}\, w_i$, $a_{i2}\, w_2, \dots, a_{in}\, w_n$)

More explicitly, the relation will be: $wi = \frac{1}{n} \sum_{i=1}^{n} a_{ij}\, w_i$, , $(i = 1, 2, \dots, n)$

Step 3: To explain how the weight vector *w* should be related to the quantified judgments, the value of *n* in the last relation is donated by $\lambda_{\max}$, and therefore:

$wi = \frac{1}{\lambda_{\max}} \sum_{i=1}^{n} a_{ij}\, w_i$, , $(i = 1, 2, \dots, n)$

Deviations in *aij* values can lead to large deviations in both λmax and *wi* values. In contrast, this is not applied for a reciprocal matrix which satisfies the rules of entries explained above.

2.4 The principles of SPMs

SPMs are considered to be a new series of machine tools that produce high rates of produced parts [3]. SPMs have superior efficiency in increasing the quality and quantity of production lines [123]. Engineers' knowledge and experience are important in the SPM design process and in applying this technology [97]. Moreover, the modularity gives SPMs an advantage in the production processes of various types of parts, and SPMs can therefore be applied in different configurations [3].

There are specific advantages achieved by applying SPM technology, such as mass production in a short time, high accuracy of products, reduced labour requirements, and the ability to undertake simultaneous machining [3]. To compare SPMs with other machining tools, production volumes and the variety of products should be considered. **Figure 2-12** shows the comparison of three types of machine tools: CNC, universal machine tools, and SPMs.

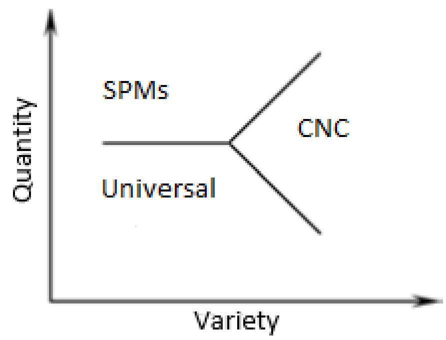


Figure 2-12. The comparison of three types of machine tools [3].

This figure shows that universal machine tools are used for low production mass with low variety. CNC is suitable in the production of various parts, while SPMs are the best solution for high production quantities with low variety [3].

SPMs are used to perform drilling and related operations such as tapping, reaming, counterboring and countersinking [97]. The machining forces in these operations are relatively low; therefore, the machine-tool vibrations can be eliminated. On the other hand, SPMs can be used to perform milling and some other machining operations, and in these cases, high cutting forces are generated [97]. **Figure 2-13** shows an example of an SPM.

Figure 2-13. An example of an SPM [124].

2.4.1 The basic units of SPMs

SPMs consist of two basic units: machining units and sliding units. The former are responsible for performing the machining operations and come in five types: MONO master, MULTI master, POWER master, TAP master, and CNC master units. MONO and MULTI units are used for light drilling operations while POWER units are used for large capacity drilling and milling operations. CNC units can also be used for drilling, milling, and tapping while TAP master units are used for tapping operations [3].

CNC units can be programmed, and they can produce parts with high controlled accuracy during machining operations. Sliding units are used to carry the machining units, and they also supply the required feed motion during machining operations. These units provide a flexible mounting of the machining units whether they are mounted perpendicular or parallel to the sliding direction depending on the requirements of the machining operations [97].

2.4.2The Concept of SPMs

In SPMs, different machining operations such as drilling, tapping, reaming, milling, and cutting can be performed at the same time by using multiple machining units from different directions, while in the machining centre (which uses CNC), only one operation can be performed in the same cycle time. For example, a part whose production involves twenty machining operations including drilling, countersinking, reaming, and tapping can be machined in 1.6 minutes by SPMs. However, it takes about 20 minutes to perform the same operations for the same part in the traditional machining centre [124]. This proves the efficiency of SPMs in reducing production time and costs.

Another example providing a comparison between SPMs and traditional machining tools involved three different types of machining systems - the traditional lathe, CNC, and SPMs - to perform machining operations for the same part [97]. From this example, the total time required to produce the part in SPMs was lower than the times for the other machining systems, as represented in **Table 2-4**. SPMs offer a range of machining units that can perform different machining operations by considering factors such as materials, quantities, geometric specifications of the workpiece, and the type of machining operations.

Table 2-4. The time required for machining a part in three different machining systems [97].

	Machining time in seconds (Lathe)	Machining time in seconds (CNC)	Machining time in seconds (SPMs)
Counterboring	5.0	3.0	3.0
Drilling	8.0	4.0	4.0
Tapping	10.0	5.0	5.0
Cutting	23.0	12.0	5.6
Tool changing per part	6.0	0.12	
Free tool traveling per part	6.0	0.6	
Indexing time per part			1.2
Loading/unloading	15.0	2.40	5.0
Non-cutting time	27.0	3.12	1.2
Total time per part	50.0	15.12	6.8
Number of parts per hour	72	238.10	529.41

2.4.3 Drilling units

There are two types of drilling units: direct drive drilling units and multiple drive units. The first is driven by a direct electric drive and the second is driven by flexible drive shafts. A combination of these two units can be used to achieve efficient solutions.

Flexible drive shafts transmit the power from the motor to the drilling spindle. They provide many advantages to the drilling system such as a very long life span, smooth running, flexible settings for the drilling spindles at any required position, and easy connection and disconnection. Multiple drive drilling units are more economical than direct drive units.

2.4.4Tapping units

SPMs offer a complete program of tapping units suitable for any supplier. There are six types of units for applying tapping technology from very small pitches - up to 5 mm - to an M48 thread size [124]. Tapping units can be used together with drilling units (MONO master or MULTI master), and these units form perfect threads in a fast and reliable way.

2.4.5 CNC units

There are three types of CNC units in SPMs: CNC with one-axis spindle, with two-axes spindles, and with three-axes spindles. These units are controlled numerically, and they are driven by AC- servomotors. In addition, there are three basic slides for CNC units, and these slides come with an integrated preloaded ball screw and a digital AC-servomotor drive.

2.4.6 Multiple spindle heads

SPMs have the most economical multiple spindle heads for drilling and tapping technology with five angle heads. There are two-, three-, and four-spindle heads which are adjustable. These include special heads with fixed hole-spacing and up to 30 spindles.

2.4.7Tool holders

There is a comprehensive program of tool holders in SPMs that provides the ideal combination for the machining units. This is very important in obtaining suitable machining results and helping to extend the tool's life.

2.4.8 Assembly components

Machining and sliding units need to be assembled in order to achieve SPM layouts and perform the machining operations. Therefore, assembly components are used in SPMs with both machining and sliding units. Base plates are one of these components, and they are used to mount the machining units. These plates are available in standard specifications and they can be designed and made on special request [124].

There are other assembly components used in SPMs. For instance, horizontal supports are used to adjust the height of the machining units depending on the workpiece specifications and the type of machining unit. They are available in different dimensions and they can be designed and made for special requirements [124]. In addition, vertical supports are used, and they are designed with multiple tapped locations to achieve different height positions for the machining units.

Slide blocks are used with SPMs units in one axis, two axes, and three axes. Universal supports are designed to adjust the vertical and angular positions of the machining units in the Z- axis. They can adjust the position in three axes and they can be used to install the machining units in four axes.

2.4.9 Machine components

Besides the assembly components, there are other elements called machine components. One of these components is the indexing table, which is important in SPMs because it is used to position and move the workpiece between different machining stations. Technical considerations and production volume are considered to determine the number of stations required to complete all operations [97]. Self-centring chucks are other machine components with two-jaw system functions. These chucks generate and transfer the clamping forces, and they have a compact design for internal and external clamping. They are operated pneumatically with pressure up to 12 bar. Swing clamps are provided in SPMs in four standard sizes, and each size is available with five types of clamping arms. The clamping arms can be mounted at any angle and these clamps are provided with no rotation (fixed) or with clockwise and counter-clockwise rotations [124].

There are also other parts which contribute to the layout of SPMs. Examples of these parts are the angle support, the header, the support for vertical units, the base module (four and six stations), the long and short columns, the coolant system, the hydraulic system, and the safety door.

2.5 Integration methods

A number of methodologies have been considered for the automation of design and assembly, and different approaches have been implemented in these methodologies. In order to build an integrated system for automating design and assembly processes, it is important to include the following components:

- A Computer programming platform.

- A 3D modelling environment.
- A database or a library of features.

2.5.1 The computer programming platform

A computer programming platform is needed to integrate different software, and it facilitates the automation of design and assembly. Computer programming languages can be classified into three types: imperative, functional and logic, and object-oriented programming [94]. For design and assembly automation, an object-oriented programming language is preferred because it has advantages such as simple software design and effective use of real world objects for modelling, because it reduces development risks for complex designs, and because it is easy to maintain and upgrade [125-127]. Moreover, object-oriented languages have many characteristics such as abstraction of data, modularity, and inheritance. These characteristics help engineers to define specific values and organise assembly automation into classes [94]. Some of the common programming languages are reviewed below.

2.5.1.1 Visual Basic programming language

Visual basic (VB) is an object-oriented programming language that was developed by Microsoft and applied by developers as a primary development tool [128]. An Integrated Development Environment (IDE) is one of the features in VB which enables this language to create, run, and debug the operations more efficiently [129]. Many features and functions can be supported by VB, such as accessing Win32 API, building and running graphical user interfaces, and creating macros in most software. Therefore, VB has become a very important programming language across many applications [130, 131].

Different types of projects are supported by VB. A standard EXE project is suitable for simple programming purposes, while ActiveX projects are used for more advanced programming functions. ActiveX DLL (ActiveX dynamic link libraries) project provides the ability to integrate VB with different Windows applications, and to control the operations and features for the other applications

by establishing menus and toolbars in their environments. VB is also used for database management purposes, and it is considered as the engine for Microsoft Access, which is the application for building the database, and this allows programmers to control the database efficiently [4].

2.5.1.2 C++ programming language

C++ is the developed version of the C language containing all the features of the original as well as object-oriented programming support [132]. This improvement makes C++ an attractive language which has been used in many applications [133]. However, it was not used for integration purposes because it is considered more difficult to use than others languages [134].

2.5.1.3 Delphi programming language

Delphi is a powerful and strong programming language which supports object-oriented design [135]. It is based on Delphi Pascal language and has many features such as supportive database facilities, rapid application development facilities, and a visual user interface [136]. The development of Delphi brought many advantages to this language, such as the ability to solve complex problems and efficient performance. Delphi supports many applications, such as mobile and distributed applications for the internet and data base applications, which can be run in Windows, Linux, and .NET.

2.5.1.4 Flex programming language

Flex is a software designed to assist the development and delivering of expert systems. It is considered to be a knowledge specification language (KSL) and it is easy to read [137]. Flex is a very effective language which can deal with most of the procedures that are needed to build knowledge-based systems. It is implemented in Prolog software and its development environment is an extension of the Prolog environment. It can be employed to build knowledge-based systems by using rules, relations, frames, actions, questions, answers, and functions [137].

2.5.1.5 Matlab software

Matlab is a popular language intended for numerical computing and it is used by students and engineers at universities to solve engineering problems [138]. Matlab can be used in signal and image processing, communications, computational finance, and control systems [139]. It has been applied to mathematical modelling for machining an aerodynamic profile [140]. It has been used for the simulation and visualisation of dynamic systems [141]. These capabilities of Matlab were applied to control high speed machine tool axes [142]. However, Matlab was not used for the design of machine layouts. In addition, it lacks integration capabilities with SolidWorks that other programming languages such as VB have, and this limits the use of Matlab for automation and integration purposes. Moreover, Matlab is not a rule-based language, and therefore, it cannot be used to build knowledge-based systems that are based on knowledge and expertise.

2.5.1.6 Application programming interface

Application programming interface (API) is a tool for writing a code in a programming language in different applications [4]. API can also be considered as a language that can be used by an application program to communicate with another program [143]. As a result, a direct integration can be developed between different applications [144, 145]. API is supported in SolidWorks and integrates with different programming languages such as VB, Visual Studio, and C++. SolidWorks API enables engineers and designers to automate the processes of design and assembly. By using SolidWorks API, codes can be created for particular programming languages to be applied in different design tasks [145].

API tools have been applied to the development of different systems in applications such as a web service material database [146]. SolidWorks API was also employed in the development of a standard parts library by sing VB [134]. Visual Basic.Net was applied to the simulation of a 3D module of an architectural process by generating an add-in VB project to automate the

assembly process [147]. SolidWorks API was implemented to create a centrifugal fan impeller model by considering the geometric features [148].

Moreover, CAD systems can be customised for specific tasks by employing API with a user interface and using a knowledge base [149]. A technology of software reuse was developed by applying the secondary development of VB and SolidWorks for a standard part [150]. SolidWorks was implemented to automate an assembly method by developing an assembly procedure in C++ [151]. Furthermore, intelligent systems were produced by the secondary development of SolidWorks for an assembly process based on a parametric design [152]. The tools SolidWorks API, Delphi programming language, and Access database were implemented to develop these systems.

2.5.2 The 3D modelling environment

The 3D modelling of products has become an important factor in many engineering activities. This model provides the essential features and specifications of designed products and helps to avoid many errors by applying engineering analysis such as finite element analysis (FEA) [153]. In addition, 3D modelling provides a reliable environment for product assembly processes, and can help to avoid problems during manufacturing. A 3D modelling environment is provided by CAD software such as AutoCAD and SolidWorks. SolidWorks has a powerful 3D modelling environment for the assembly process which is very important for mechanical mechanisms. SolidWorks is a particularly effective tool for 3D modelling activities due to its specific functions, 3D features, 3D views, assembly features, and mates.

2.5.3 The Database

The database can be defined as an integrated computer structure used to store the necessary information that can be shared and used by a system [154]. The database is an important factor in any integrated system when selection and assembly processes are performed for certain parts. The database can be constructed in SolidWorks by using the design library features. The design

library is flexible in storing, managing, and selecting the elements, and it can simplify the design and assembly process [4]. Moreover, the database can be created in Microsoft Access, which is implemented in VB and SolidWorks.

2.6 Discussion of literature review

2.6.1 Identified problems for SPMs

SPMs have a range of modular components (machining units and other support elements). Together, these enable SPM design to be standardised. This feature helps to combine these components to regenerate new machine designs depending on the design and machining requirements. However, there are some problems that need to be addressed. Although the concept of modularity brings many benefits to SPMs and enables them to be adapted to different situations, a high level of expertise is needed. This extensive domain knowledge may not be available and may require many years of experience. Moreover, the selection of the appropriate SPM components may not be an easy process, because the design and machining requirements change from one situation to another. Most importantly, the change of type, number, and connection type of SPM components has to be achieved rapidly to accommodate new and unpredictable changes in the design of a product. The design of SPMs is different from the design of other machine tools because each SPM machining unit is considered as a machining spindle, while in a machining centre, as an example, only one spindle is used to perform the operations. In addition, SPM components can be disassembled from one design to be used in another under certain conditions, while this is not the case for other machine tools.

As a result, and depending on the application, the design of an SPM can be a complex process that requires knowledge and experience, and for a given workpiece, multiple SPM layouts may exist [155]. SPM layout is the process of placing machining units in appropriate positions and selecting the type and number of SPM elements. This is time-consuming and increases the costs

associated with overall SPM design. Therefore, new computer-supported methods need to be applied to reduce design time and costs for SPMs.

The traditional design process using CAD software has significant limitations in the design process of SPMs, as follows:

- Manual selection of the SPM elements and the type of SPM layouts. This takes a considerable amount of time, which is a critical factor in design and manufacturing processes.
- Traditional assembly process of the SPM elements in 3D design environments in order to generate SPM layouts. This increases the overall design time and requires a high level of knowledge and experience.
- Lack of automated approaches using AI methods in SPM design.
- Lack of integration between different components of the design process such as CAD software, database, and knowledge-base of SPMs.

2.6.2 Literature support to solve SPM problems

In order to automate the design process of SPMs, it is important to apply engineering knowledge from domain experts. In previous research, rule-based expert systems have been employed to implement the knowledge effectively. Other AI methods have been used for automation purposes; however, they are not as efficient as the expert systems. They are either used to solve specific problems or they are applied in specific fields, and they have not been implemented efficiently in the design of manufacturing systems. Expert systems have an advantage over other AI tools because of their features and characteristics. They can be applied when incomplete information or data is provided and a reasonable result can be obtained, While in the other AI methods, exact and complete data is needed to get the correct solution for specific problems [54]. Moreover, expert systems do not need to follow an exact sequence of steps, in contrast to other AI methods which use algorithms to perform operations in the same order. Another difference is that expert systems can apply symbolic reasoning to solve problems,

and this enables different kinds of knowledge (facts, concepts, rules) to be built. The most important advantage of expert systems is that the knowledge base is separated from the inference engine, whereas they are mixed in the other methods. This means that the expert systems have great flexibility so they can be easily built and maintained. Therefore, it is easy to make modifications, adding new rules, or changing the existing rules. They have the ability to build knowledge in a specific field if they were a human expert. This is considered to be the main character of these systems, and it provides many benefits to facilitate problem-solving processes [54]. Expert systems are useful in preserving expert knowledge, and they are excellent tools for documenting knowledge. However, their domain knowledge is narrow, and their creativity and adaptability are low compared to human experts [156]. In addition, less attention has been paid to the utilisation of expert systems in machine tool design specifically for SPMs.

CBR seems to be an appropriate method for automating the design process of SPMs. This is because CBR brings important advantages to the problem-solving process. First, it can significantly reduce the time needed for a process. Second, CBR is very useful when the domain knowledge is not completely available or not easy to obtain [157]. Most importantly, potential errors can be eliminated, and past mistakes can be avoided [158]. However, although CBR has significant advantages, knowledge and expertise are needed to adapt past solutions for use in new cases. CBR has been applied to several applications such as planning, engineering design, and diagnosis. In terms of engineering design, the process of problem solving is to find a solution that satisfies a group of constraints which represent the design requirements [157]. Engineering design requires specific domain knowledge and considerable skills and experience. These may not be available as they need to be acquired over a long period. Therefore, it would be difficult to apply other AI methods such as expert systems.

Based on the discussion in this section and applications for both expert systems and CBR, expert systems use domain knowledge, which is stored as generalised rules, to solve new problems. In contrast, CBR uses past experience, stored in the form of cases of past problem-solving exercises, to solve new cases.

Because of its problem-solving strategy and applications, applying a CBR method is highly advantageous in the SPM design process. CBR relies on similar cases to define new design solutions, and this can limit the application of CBR to specific workpieces and SPM layouts. To overcome this limitation, CBR can be integrated with rule-based expert systems and other elements such as CAD software and databases to develop an automated approach for the SPM design process.

Simulation and assembly modelling help engineers and designers to define problems and to improve the designed systems. Software packages for simulation and assembly modelling have been developed and they are available for optimising or improving the performance of specific processes. The power of simulation comes from modelling the processes and systems. It is very important to define the viability of the processes and systems, especially when 3D modelling is implemented. Simulation in 3D modelling environments has been used in manufacturing systems for design, installation, modification, and operation purposes. SolidWorks has 3D modelling capabilities that can be used for simulation purposes in the design and assembly of manufacturing systems. SolidWorks is used by an enormous community of 3D design and analysis engineers all over the world [159]. It is a feature-based, associative, history-based, and parametric 3D CAD program [160]. In addition, it can simulate other dynamic systems and define the errors and problems associated with these systems. SolidWorks has new features that increase the design power of this software and help engineers to carry out new challenges in the design process of products and production systems. These features can be summarised as new drawing detailing functions, and the ability to perform static, nonlinear, pressure vessel, and thermal studies [161]. The results of the simulation in SolidWorks are calculated and displayed instantly on the full 3D model. SolidWorks has an excellent design and assembly environment as a result of its features and characteristics. The property manager in the software provides a flexible interface which enables the user to carry out the design and assembly process by easily modifying and changing the parameters. It is easy to conduct motion studies and

simulate mechanical systems in SolidWorks, and the user can use the design library features to create a parts library for the designed systems. Moreover, it is possible to automate the design process by applying DriveWorks Xpress wizard in SolidWorks, and the sustainability of the designed process of the products can also be defined [4, 162]. All these features make this software a powerful, flexible, and a reliable 3D modelling tool compared to other CAD software.

It is noteworthy that few applications have used software packages together with innovative assembly modelling approaches for mechanical systems. Most applications have focused on the key tasks for product design and mechanical systems for reducing design and assembly process times. An assembly modelling approach is needed to reduce the time required for the process of assembling SPMs. This assembly modelling approach will help to reduce the overall time needed for the SPM design process. This is a major concern for engineers and designers in the design and manufacturing fields, particularly when different configurations are required to respond to changing customer demands.

2.6.3 The novel approach

It is important to mention that none of the methods discussed above in the literature have been applied effectively in the SPM design process. Taking into account the advantages and disadvantages of existing methods, and in order to deal with the limitations associated with the use of traditional CAD systems in SPM design, this research took the following approach:

- VisiRule expert system toolkit was applied to automate the selection process for SPM elements and layouts by creating an SPM knowledge-base. VisiRule was used because it is effective for building a decision-making process based on a flowchart concept, and because it provides several formats which are useful in creating the knowledge-base.

- SolidWorks CAD software was implemented for the design and assembly modelling of SPM elements and layouts. This software was used due to its powerful capabilities in 3D modelling and assembly. SolidWorks also has

mating features that can be effectively employed to build the assembly relationships between the workpiece and the SPM elements.

- An assembly modelling approach was developed for SPMs. This approach was applied with SolidWorks software to assist in the design and assembly of SPMs. The approach identified the assembly relationships and mating conditions between SPM elements, and this has the potential to decrease the assembly time significantly.

- An automated approach was developed for SPMs, including the integration of CBR, SPM knowledge-base, SPM database, and SolidWorks. This integration was applied using SolidWorks API features, and has the potential to considerably reduce the design time for SPM layouts.

- Other techniques, which are analytic hierarchy process (AHP) and quick-change mechanical adapters, were investigated as further methods to be applied to the selection of SPM configurations and to the enhancement of SPM reconfigurability.

Chapter Three

3. The development of SPM knowledge-base

This chapter presents the development of the SPM knowledge-base. This development is related to knowledge-based expert systems and engineering knowledge and has been brought to the attention of engineers and manufacturers because it can be used in building computer programs to simulate human expertise and experience. Applying this development includes four stages: capturing, presenting, encoding, and evaluating the knowledge [163].

The process of the development of engineering knowledge includes sharing knowledge with different engineering disciplines, applying knowledge to other applications, and creating new knowledge for new cases. Regarding the capturing stage, it is important to consider the flow and the steps in the process of problem-solving. In addition, the factors that affect this process should be defined and their effects should be addressed. Knowledge can be represented by rules, and it can be encoded using software. Human experience and expertise are captured and used to encode a knowledge-base in order to achieve outcomes and solutions [97, 164]. The knowledge-base is a way of storing expertise and experience compared to other non-interactive forms of storage such as manuals and text books. It contains different information such as facts, relationships, definitions, and other types of information, which can be collected from the experts, textbooks, and manuals for a given field as shown in **Figure 3-1** [165].

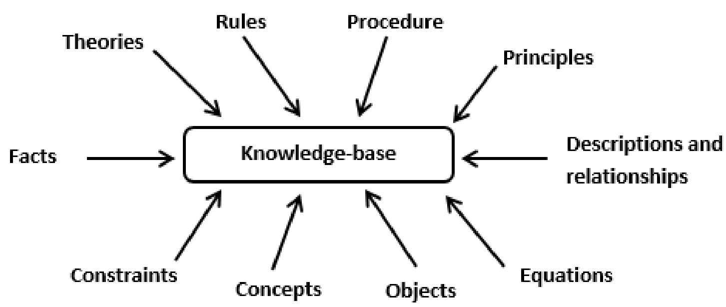


Figure 3-1. The contribution of the collected information in building a knowledge – base.

The collected information is represented by rules with IF-THEN structures. Engineering knowledge is the type of information that should be considered in building a knowledge-base, and this knowledge includes the tools, techniques, and processes that are related to a given domain. Engineering knowledge is used with other information to build a knowledge-base which contributes to the knowledge-based computer stage using software as shown in **Figure 3-2**.

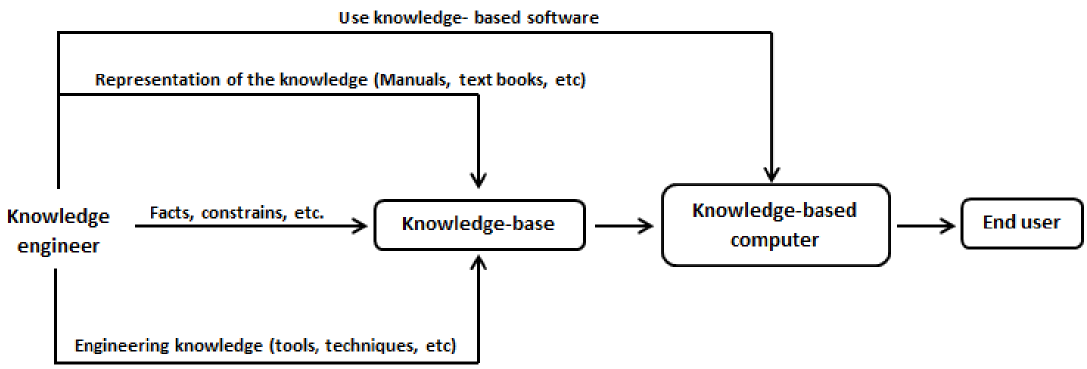


Figure 3-2. The process of implementing the developed knowledge-base with software.

Expert systems are computer software and they have the ability to apply human expertise in order to solve engineering problems. These systems can be used as an approach to encode a developed knowledge-base for a specific engineering domain. This approach was applied in the work presented in this thesis in order to develop a knowledge-base for SPMs. For this purpose, the specifications of workpieces were considered: following this, machining surfaces and machining features were identified. In this work, three machining operations - drilling, tapping, and reaming - were taken into consideration. Defining the required machining operation underpins the development of the knowledge-base for this work. There is also a need for high accuracy and high spindle speed to produce high-quality products: this affects the selection of the machining units required to perform the specific machining operations. Other information was involved in the development of the SPM knowledge-base in this work including to technical information, the power required for the machining units, and the

weight and flexibility of the machining units. The process starts by formulating the available information about SPMs in a structure that helps to capture and represent the knowledge. **Figure 3-3** shows the implementation of the previous information in the development of SPM knowledge-base. The specifications of the machining units are taken from company data and resources. The number and the size of the machining features (drilling, tapping, and reaming) are also taken into consideration to achieve the time-effective selection of SPM layouts.

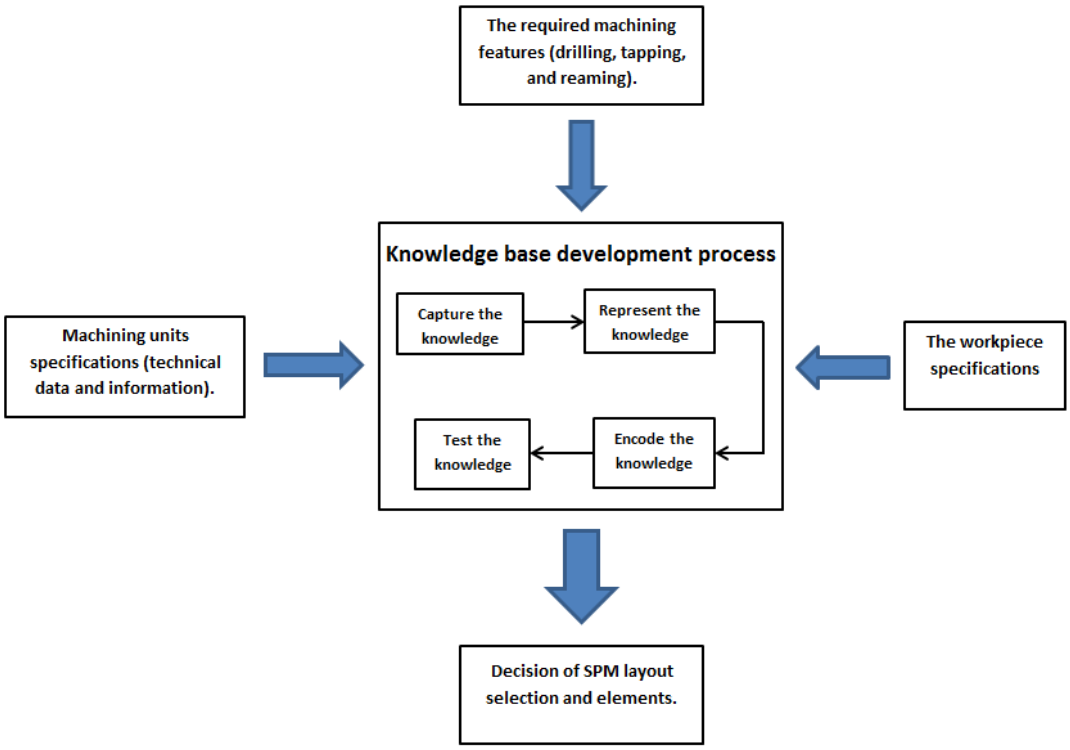


Figure 3-3. The development of the SPM knowledge-base.

3.1 Selecting the number of SPM workstations

In order to achieve the feasible layouts for SPMs, it is important to identify the following information:

- The number of surfaces to be machined on the specific workpiece.
- The number and type of machining features to be created on these surfaces.

- The number of SPM workstations, and the number/type of SPM machining units.

To clarify how these points affect the determination of SPM layouts, the workpiece shown in **Figure 3-4** is taken as an example.

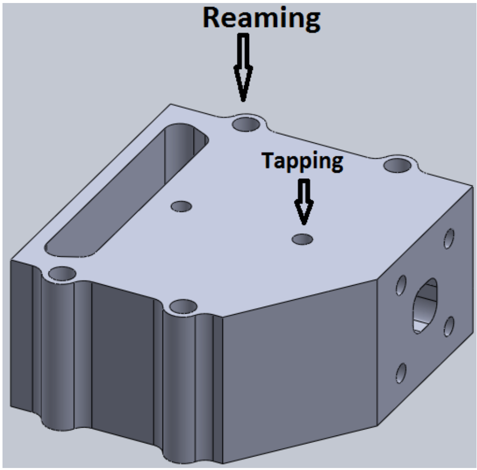


Figure 3-4. A designed cylinder head for motorcycles.

The top surface of this workpiece contains two M6 tapping features and four 12 mm reaming features. In this case, a drilling operation is needed as a first step, and then tapping is performed. Therefore, two workstations are needed: the first station is for drilling the two holes, and the second station is for making the taps. The same procedure is followed for the reaming operation and two workstations are needed: the first station is for making the four holes, and the second station is for performing the reaming operation for each hole. In total, and for the top surface of this workpiece, an SPM layout of four workstations is needed to perform the tapping and reaming operations: the first station is for drilling the two 6 mm holes, the second station is for making the two M6 taps, the third station is for drilling the four 12 mm holes, and the fourth station is for reaming each of the four holes as shown in **Figure 3-5**. Another layout for these operations can also consist of four workstations but in a different order: the first and the second stations are for drilling, the third station is for tapping, and the fourth station is for reaming (see **Figure 3-6**).

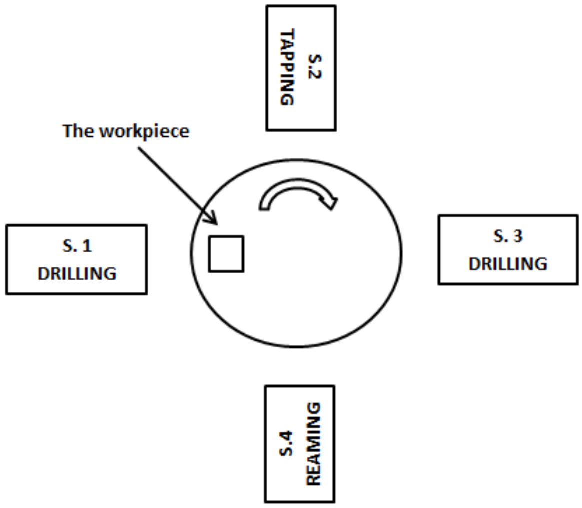


Figure 3-5. The workstations that are needed to perform tapping and reaming for the selected workpiece.

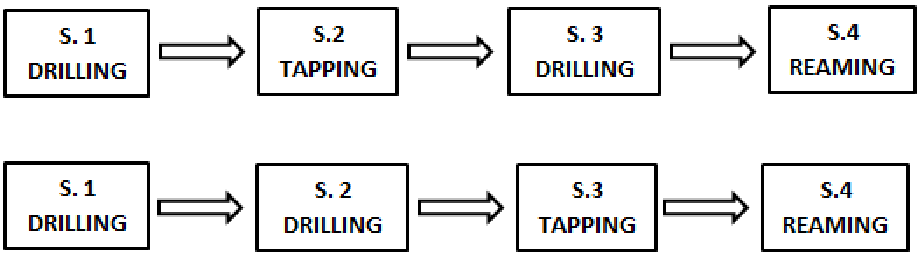


Figure 3-6. Two sequences for the same machining operations for the selected workpiece.

The main feature of SPMs in performing several machining operations at one time is considered in defining the number of workstations. Therefore, the rules for selecting the number of workstation are as follows:

- *If* a drilling operation only is required to be performed on a specific surface of a workpiece, *then* only one workstation is needed. In this case, the number and type of the machining units that are used depend on the number and size of the holes required on this surface. The position of the machining units depends on the surface set up of the workpiece.

- *If* a tapping operation is required to be performed on a specific surface of a workpiece, *then* two workstations are needed. The number and type of the machining units in both stations depend on the number and size of the taps required on the surface.
- *If* a reaming operation is required to be performed on a specific surface of a workpiece, *then* two workstations are needed. The number and type of the machining units depend on the number and size of the holes required on the surface.
- *If* there is more than one machining operation to be performed on the same surface of the workpiece (e.g. drilling *and* tapping), *then* the number of the workstations is equal to the sum of the number of stations required for both machining operations.

For each of the rules mentioned above, more specified rules were created in this work to cover the maximum number of possible cases for each operation. For example, and for the drilling operation, the rules are extended as follows:

If drilling is required and only one hole is created on the surface, *then* one workstation is needed. The type of the machining unit required for this case is determined based on the rules that are created for the drilling operation for one hole in SPMs.

Else, If there is more than one hole on the surface with a similar size, *then* one workstation is needed. In this case, the rules for selecting the multiple spindle heads are followed to determine the pattern and the size of the holes, and to select suitable machining units.

Else, If there is more than one hole on the surface and those holes have different sizes, *then* a workstation is needed for each size. In this case, the sizes of the holes need to be determined in order to select suitable machining units.

End If

Figure 3-7 shows the process of defining the workstations for the drilling operation. In order to perform the drilling operation effectively, it is important to achieve a suitable number of and sequence for the workstations by selecting the most suitable machining units and other SPM elements. The same procedure is followed for tapping and reaming operations.

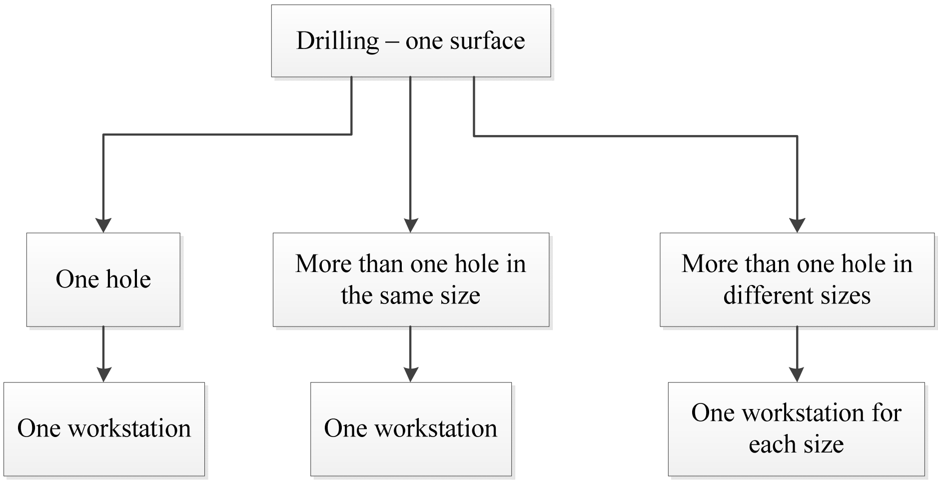


Figure 3-7. The process of selecting the number of workstations for the drilling operation in SPMs.

The selection of the number of workstations starts by defining the number of the machined surfaces on the workpiece. After that, the types of machining operations on each surface are determined, and then the number of the workstations is determined for each machining operation as shown in **Figure 3-8**.

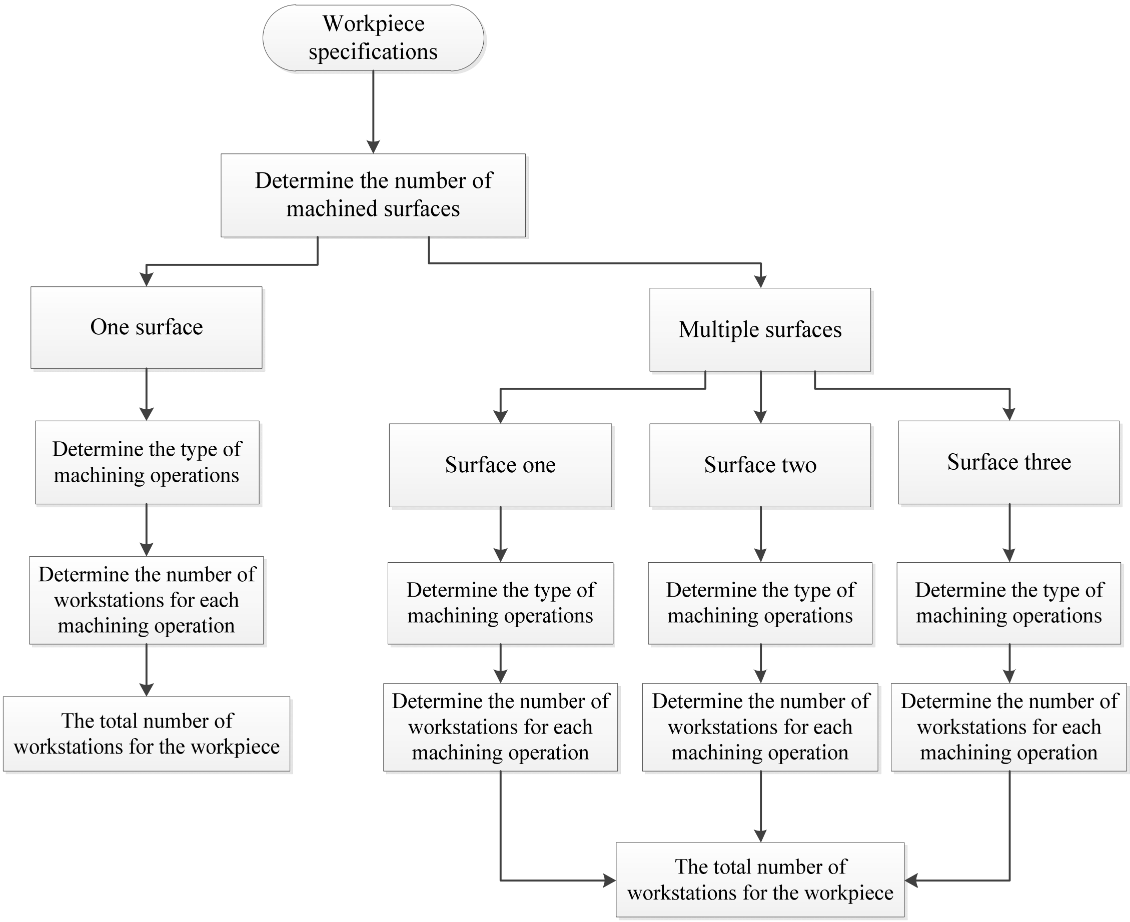


Figure 3-8. The selection process of the number of workstations required in SPMs.

3.2 Creating the knowledge-base

The SPM knowledge-base was developed in the work by implementing the available information and resources in a format that helps to capture engineering knowledge. Rules were developed to represent this information and to achieve the possible solutions for selecting the appropriate machining units in order to perform the specific machining operations. The process of developing the SPM knowledge-base begins by identifying the specifications of the workpiece and the machining operations that should be performed. Rules were developed in this work to select the machining units for drilling, tapping, and reaming operations. Other rules were developed to select machine and assembly components that

need to be used with the machining units to complete the SPM layouts. In addition, the rules for determining the number of workstations for each operation were also considered. Implementing all these rules in the SPM knowledge-base leads to the selection of the most suitable SPM layouts. The process of creating the SPM knowledge-base starts with the following general rules:

Rule 001

If the specifications of the selected workpiece are identified, *then* the number of surfaces that are required to be machined on the workpiece should be determined.

Rule 002

If the number of the machined surfaces is identified, *then* the type of machining operations on each surface should be determined.

Rule 003

If the required machining operation is drilling, tapping, or reaming, *then* the geometric and topological information of the machining features (holes and taps) should be determined on each surface.

3.3 Drilling machining operations

Drilling operations are performed in SPMs by MONO machining units for single-purpose applications [166]. To produce multiple holes, multiple spindle heads are used together with the MONO machining units. The diameter of the drill and the workpiece material are also important in selecting the type of machining units. In addition, if a high cutting speed is required for drilling, then a high spindle speed is needed to perform the drilling operations, and each material has a different cutting speed and machining requirement. The feed rate of the drill has an effect on the spindle speed for the drilling operation, and this rate changes based on the diameter of the drill and the workpiece material.

In general terms, the drill feed increases if the drill size is increased, and soft materials have a faster feed rate than hard materials [167]. By defining the required spindle speed for a specific workpiece and a drilling operation, the drive power is determined by calculating the material removal rate (MRR). It is important to use the correct spindle speed for the material and cutting tools to enhance the finished quality of the surface during the drilling operation. Industry information and recommendations for the above considerations were followed in this work for the drilling operation in order to achieve the best solutions for SPM machining units (see Appendix 9.1). MONO units are used to machine holes up to 28 mm diameter, while CNC units are capable of machining holes up to 60 mm diameter. The multiple spindle heads can be used for holes up to 16 mm, and special multiple spindle heads are used for larger sizes.

Cost and power usage are considered when selecting the suitable machining units to be used with multiple spindle heads. This is because there are several options for each type of multiple spindle head, and it is important to identify the best solution – i.e. one that results in better productivity with lower costs and production times. Rules were created in this work for machining one-, two-, three-, and four-hole patterns in SPMs based on industry recommendations for the machining conditions for each case and by considering the material of the workpiece, the required cutting speed, and the required feed rate. Four types of materials were considered in these rules: cast iron, steel, aluminium and Al alloys, and brass. Plastics and thermoplastics were considered in creating rules for two-, three-, and four-hole patterns and also for tapping operations for the same patterns.

The spindle speed and the power required for the drilling operation were calculated in this work to achieve the best solutions when selecting the machining unit for each case. The number and the diameter of the holes on each of the machined surfaces on the workpiece were used to identify the number of the workstations and the machining units. This work considered the machining of two surfaces on the workpiece with possible one-, two-, three-, and four-hole patterns on each surface. Apart from the case of one hole on the surface, there are

several configurations for the two-, three-, and four-hole patterns that can be taken into consideration to define the number of workstations and machining units. **Figure 3-9** shows some of these configurations for different hole patterns on one and/or two surfaces of a workpiece.

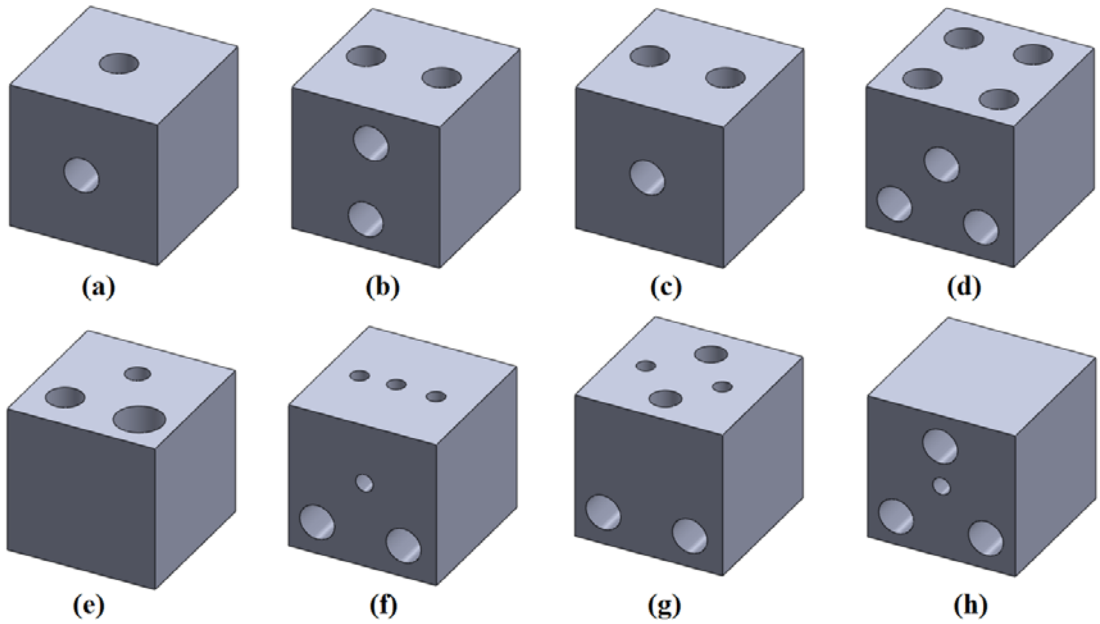


Figure 3-9. Different hole configurations on one and/or two surfaces on a workpiece; (a), (b), (c), and (d) illustrate different numbers of holes in the same diameters, while (e), (f), (g), and (h) show several numbers of holes of different diameters on one and/or two surfaces.

The process of defining the number of workstations for a drilling operation for potential hole configurations on one and/or two surfaces is shown in **Figure 3-10** and **Figure 3-11**. This process can be extended for other configurations depending on design requirements.

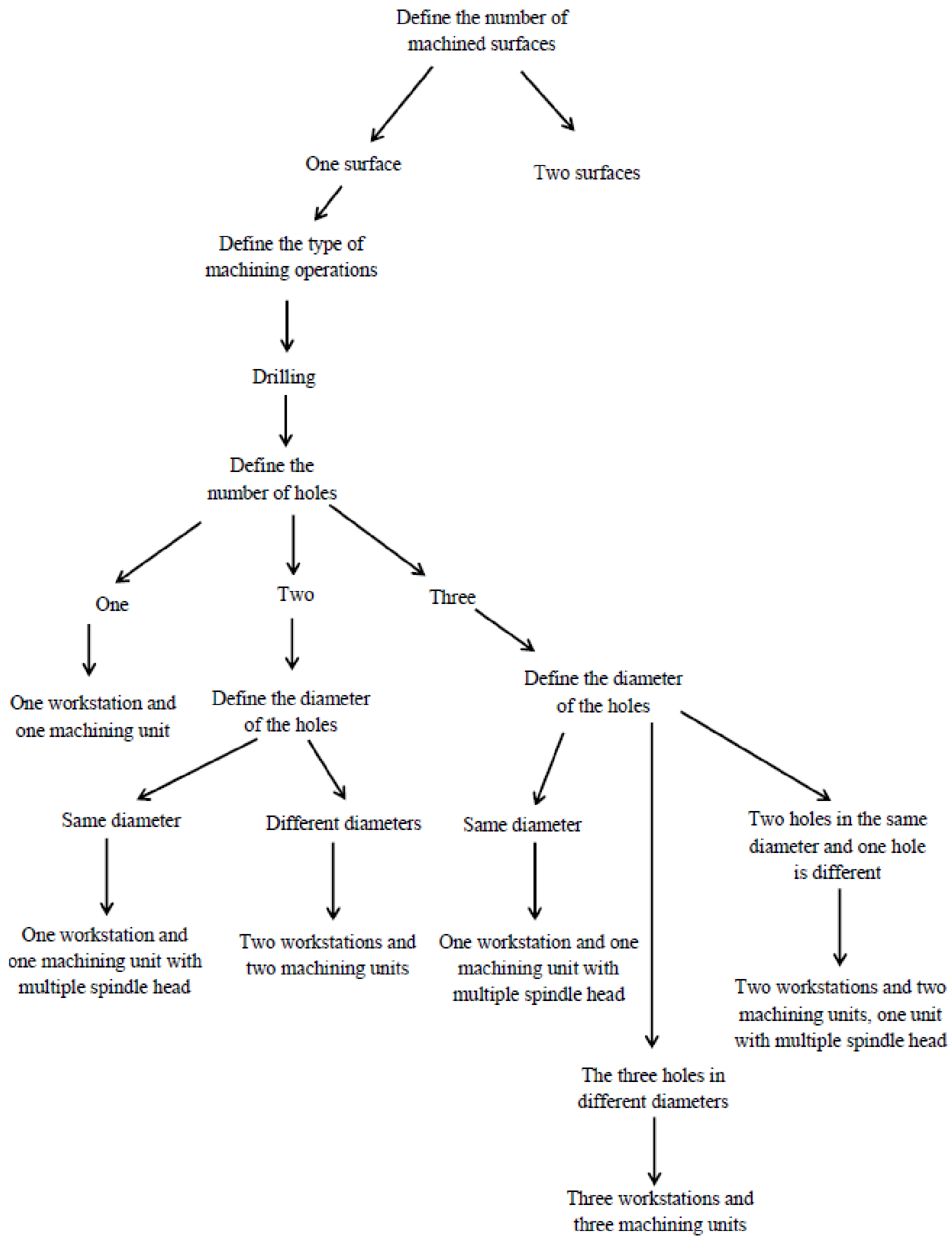
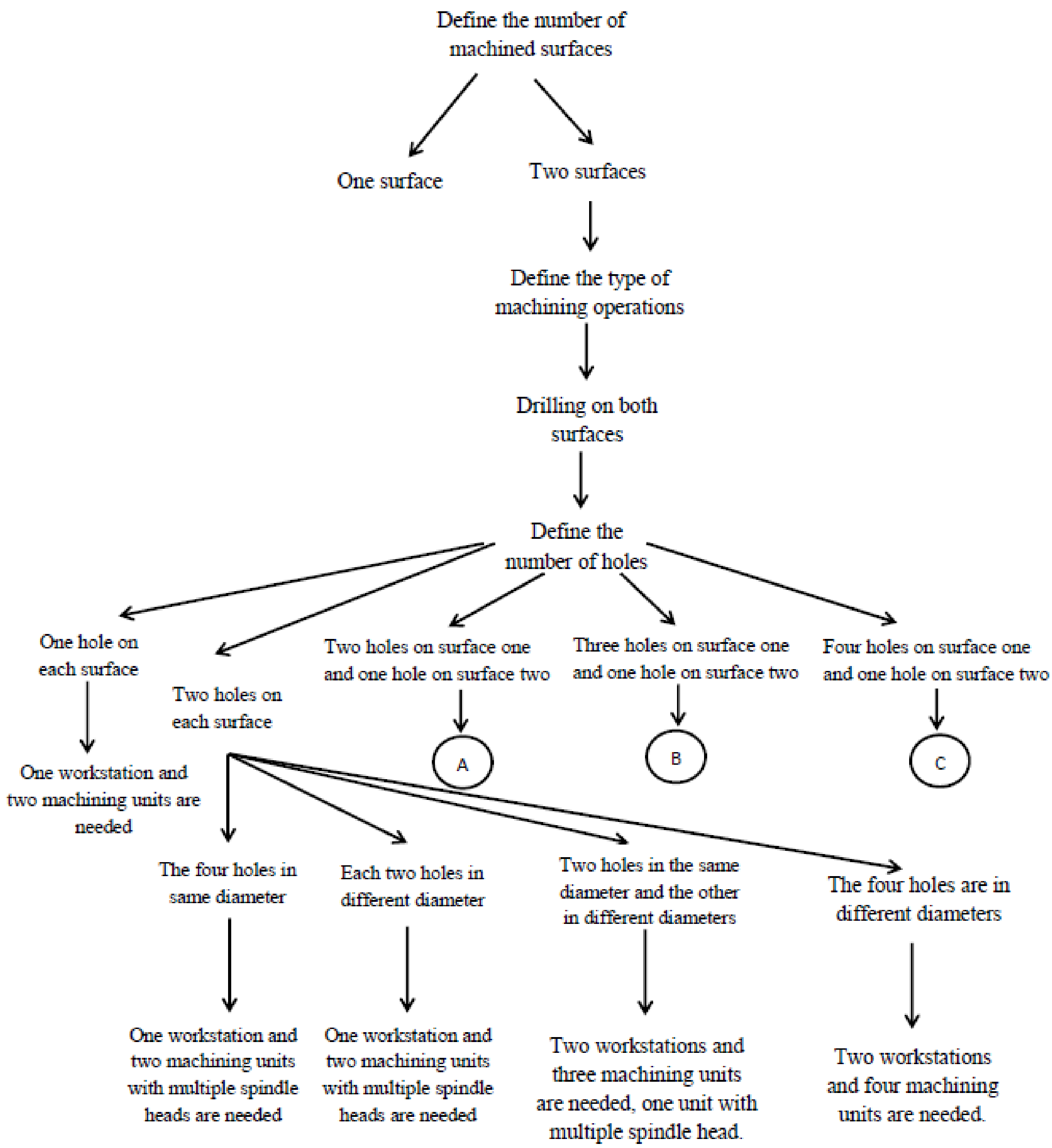


Figure 3-10. The process of determining the number of workstations for drilling on one surface.


Define the number of machined surfaces
One surface
Two surfaces
Define the type of machining operations
Drilling on both surfaces
Define the number of holes
One hole on each surface
Two holes on each surface
Two holes on surface one and one hole on surface two
Three holes on surface one and one hole on surface two
Four holes on surface one and one hole on surface two
A
B
C
One workstation and two machining units are needed
The four holes in same diameter
Each two holes in different diameter
Two holes in the same diameter and the other in different diameters
The four holes are in different diameters
One workstation and two machining units with multiple spindle heads are needed
One workstation and two machining units with multiple spindle heads are needed
Two workstations and three machining units are needed, one unit with multiple spindle head.
Two workstations and four machining units are needed.

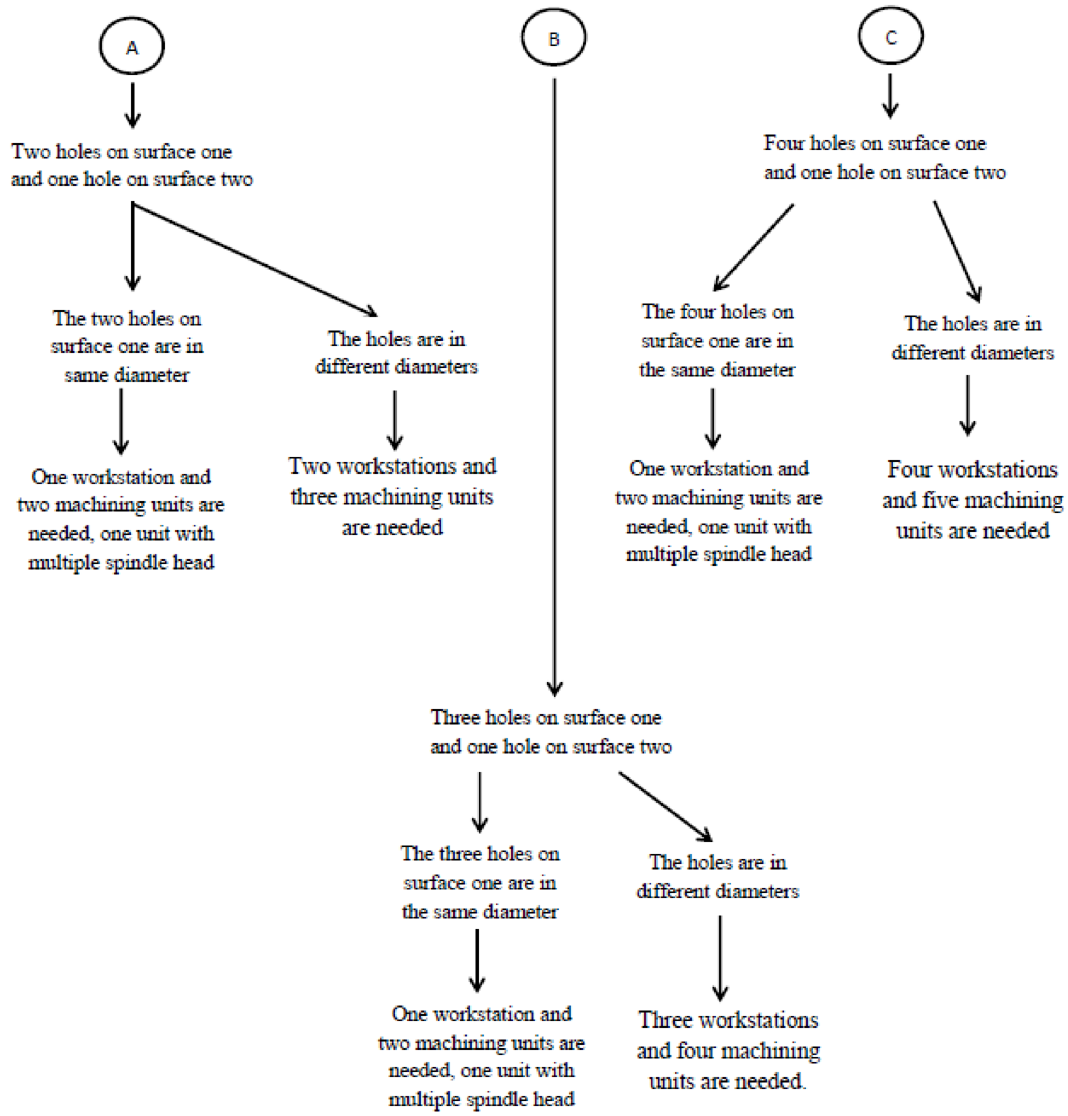


Figure 3-11. The process for defining the number of workstations for drilling on two surfaces.

The four materials which were considered in creating the rules for drilling operations and tapping operations in this work were chosen based on their applications in industry and in several aspects of life. Cast iron is used in the automotive industry to produce many parts such as cylinder heads and cylinder blocks. It is also used in gearbox cases and bearing housings, and **Figure 3-12** shows some of these applications.

(a) (b) (c) (d)

Figure 3-12. Examples of cast iron applications: (a) a cylinder block [168], (b) a cylinder head [169], (c) a gearbox case [170], (d) a bearing housing [171].

Steel is frequently used in a wide range of applications in automobiles, machines, tools, appliances, flanges, and construction applications. **Figure 3-13** shows some of these applications.

(a) (b) (c) (d)

Figure 3-13. Examples of steel applications: (a) a wheel hub [172], (b) a CV joint [173], (c) a door hinge [174], (d) a flange [175].

Aluminium and brass have been used for many applications due to characteristics such as light weight and corrosion resistance. Aluminium is popular in the aerospace industry, transportation and electrical applications. Brass is mostly used in electrical components, fittings, and plumbing applications. **Figure 3-14** and **Figure 3-15** show some of these applications for aluminium and brass.

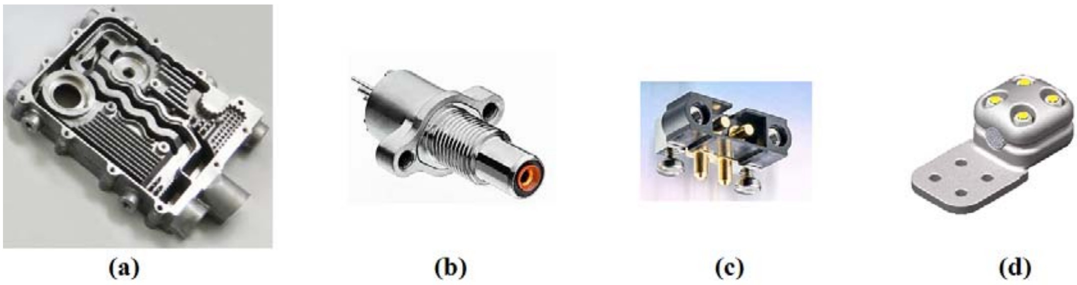


Figure 3-14. Examples of aluminium products: (a) and (b) aerospace applications [176, 177], (c) and (d) electrical applications [177, 178].

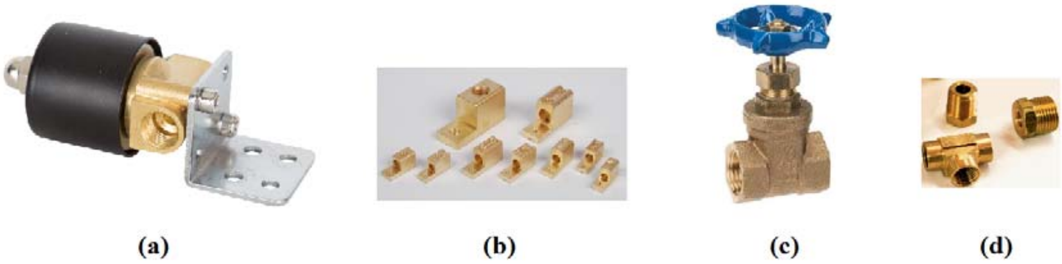


Figure 3-15. Examples of brass products: (a) an electrical air valve [179], (b) electrical brass terminals [180], (c) a brass gate valve [181], (d) plumbing brass fittings [182].

Recently, some materials have been used for specific applications that have special specifications. Plastics and thermoplastics are used now for many applications because they are inexpensive, light, and resistant to corrosion and rust. **Figure 3-16** shows some of applications of these materials.

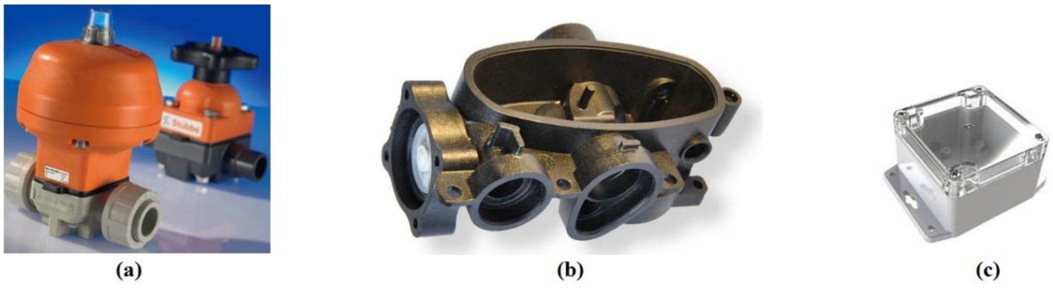


Figure 3-16. Examples of plastics products: (a) PVC valves [183], (b) a plastic housing for automobiles applications [184], (c) a plastic box for electrical applications [185].

The rules for the drilling operation were given numbers (from 004D to 033D) to cover most of the possible hole configurations for two cases: one and two machined surfaces. For each case and configuration, the number of workstations and the machining units were determined. Defining the type of the machining units for a drilling operation for one hole starts from Rule 034D. In total, 164 rules were created in this work for drilling one and multiple holes in SPMs. Examples of these rules are given below (Additional rules can be found in Appendix 9.2):

Rule 004D

If one surface needs to be machined on the workpiece and a drilling operation is required with one hole, *then* one workstation is needed with one machining unit.

Rule 005D

If one surface needs to be machined on the workpiece and a two-hole drilling operation is required, and the holes have the same diameter (16 mm maximum), *then* one workstation is needed with one machining unit and a multiple spindle head.

Rule 017D

If two surfaces need to be machined on the workpiece and a two-hole drilling operation is required with on each surface and the holes have different diameters, *then* two workstations are needed with four machining units.

Rule 018D

If two surfaces need to be machined on the workpiece and a two-hole drilling operation is required on each surface, and the holes have the same diameter (16 mm maximum) on one surface but have different diameters in the other surface, *then* two workstations are needed with three machining units, one with a multiple spindle head.

Rule 035D

If the material is cast iron and the hole size is ≤ 6 mm, and the cutting speed is ≥ 100 m/min, *then* a BEX 35 CNC unit is used with a HM-K20 Carbide drill bit. A sliding unit AU 30 is needed with BEX 35 CNC unit.

Rule 056D

If the material is aluminium and Al alloys and the hole size is > 20 mm and ≤ 40 mm, *then* a BEX 60 CNC unit with a AU 60 slide unit are used for any ranges of cutting speeds and for both Carbide and HSS drill bits.

3.3.1 Selecting the machining units for multiple holes

For SPM machining of multiple holes, multiple spindle heads are used. For this purpose, it is important to select the most suitable machining units depending on the following criteria:

1- The material of the workpiece.
2- The number of the holes required to be machined.
3- The size of the holes.

By considering these criteria, the driving power is calculated for the required operation and the machining units are selected. The information and recommendations from the manufacturer are followed for the calculation and selection of suitable machining units for different sizes of holes. For example, for a case with the conditions below:

Material: carbon steel – 700 N/mm^2
Number of holes = 4
Size of the holes = 12 mm

The drive power needed for this operation is P = 4 KW based on the manufacturer recommendations and MRR method. The most suitable machining units for this operation (using the multiple spindle heads) are BEM 28 MONO for

low cutting speeds or BEX 35 CNC for high cutting speeds [166]. The driving power value changes when the workpiece material varies but the number and size of the holes are constant. Therefore, the rules for the case above are as follows:

If there are four holes to be machined on the workpiece with 12 mm diameter and spacing range between 22 mm and 195 mm, and the material is carbon steel with a high cutting speed, *then* multiple spindle heads MH 40 are used with a BEX 35 CNC unit. A sliding unit AU 30 is needed with the BEX 35 unit.

If there are four holes to be machined on the workpiece with 12 mm diameter and spacing range between 22 mm and 195 mm, and the material is carbon steel with a low cutting speed, *then* multiple spindle heads MH 40 are used with a BEM 28 MONO unit.

For each case, more than one machining unit can be used. Therefore, more than one layout can be generated for the specific machining operation.

3.3.2 Machining two holes in SPMs

For machining two holes on a surface in SPMs, multiple spindle heads are used with two types: adjustable MH20 and fixed MHF spindle heads. The choice of these spindle heads depends on the spacing range between the holes as shown in **Figure 3-17**. The spacing range is the distance between the centres of the holes, referred as (S) in the figure. **Figure 3-18** shows the adjustable multiple spindle heads MH20 and the fixed multiple spindle heads MHF. Rules were created in this work for machining two-hole patterns from 3 mm to 16 mm diameter, and by considering six materials: carbon steel, cast iron, Al-Si alloy, brass, plastics, and thermoplastics. The industry recommendations were followed for calculating the required machining conditions for these machining operations, and for defining the best solution for each case.

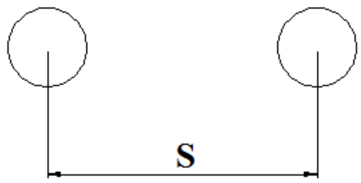


Figure 3-17. Two holes with spacing range (s).

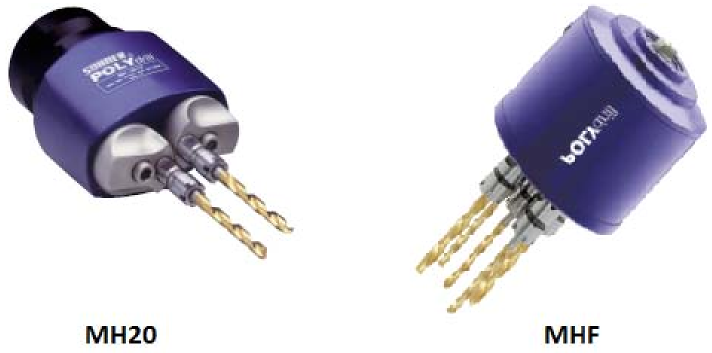


Figure 3-18. The adjustable multiple spindle heads MH20 and the fixed multiple spindle heads MHF [124].

Examples of the rules for machining two-hole patters are given below (Additional rules can be found in Appendix 9.2):

Rule 065D

If there are two holes on the surface to be machined at a low cutting speed at ≤ 3 mm diameter size and S is between 9 mm minimum and 157.5 mm maximum, *then* a BEM 6 MONO unit is used with MH20 multiple spindle heads for any material.

3.3.3 Machining three-hole patterns in SPMs

For machining three holes on a surface in SPMs, two types of spindle heads are used: adjustable MH and fixed MHF multiple spindle heads. For the first type, two spindle heads are available: MH33 and MH30, and the choice depends

on the hole pattern. Two types of three-hole pattern are considered in this work: a straight line pattern, and a staggered pattern as shown in **Figure 3-19** and **Figure 3-20**.

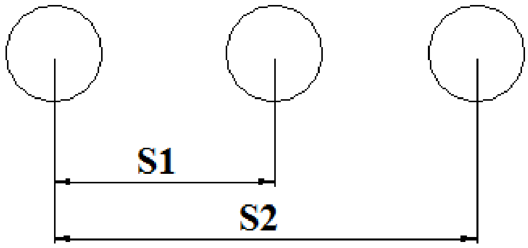


Figure 3-19. Straight line three-hole pattern.

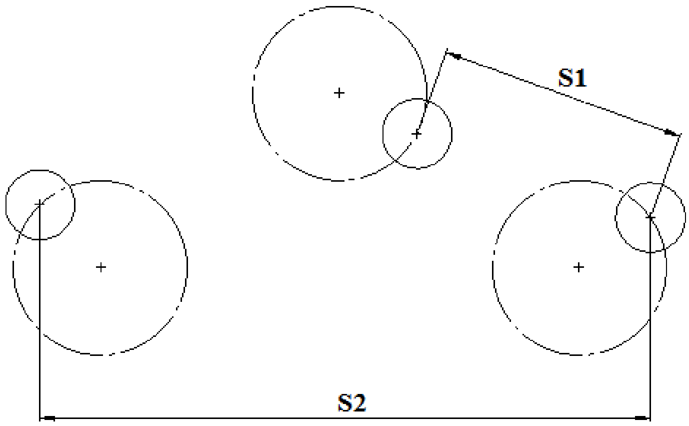


Figure 3-20. Staggered three-hole pattern.

From these figures, there are two values for the spacing range between the holes: S1 and S2. S1 is the minimum space between the holes in the pattern, and S2 is the maximum space between the holes. These two values are considered when selecting the suitable multiple spindle heads for the specific pattern. For the straight line pattern, multiple spindle heads MH33 are used, while multiple spindle heads MH30 are used for the staggered pattern within the specific limits for S1 and S2 based on the manufacturer information. For S1 and S2 values that are not within the limits, MHF spindle heads are used to produce the three-hole patterns. **Figure 3-21** shows both MH33 and MH30 multiple spindle heads.

Figure 3-21. Adjustable multiple spindle heads MH 33 and MH 30 [124].

Rules were created in this work for each of the two patterns by considering six materials: cast iron, carbon steel, Al-Si alloy, brass, plastics, and thermoplastics. Industry recommendations for defining the best solution for each case were followed taking into account of the pattern type and spacing range. Examples of the rules for three holes with straight line pattern are given below (Additional rules can be found in Appendix 9.2):

Rule 093D

If there are three holes to be machined with low cutting speeds on the surface at a diameter ≥ 3 mm and < 6 mm and a straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, *then* a BEM 12 MONO unit is used with a MH33 multiple spindle head.

3.3.4Drilling four-hole patterns in SPMs

For machining four holes on a surface in SPMs, two types of spindle heads are used: adjustable MH40 and fixed MHF multiple spindle heads. The adjustable multiple spindle heads MH40 is shown in **Figure 3-22**.

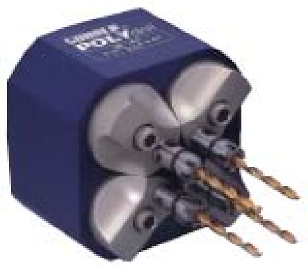


Figure 3-22. Adjustable multiple spindle head MH40 [124].

The most common pattern of four holes is considered as shown in **Figure 3-23**. The minimum and maximum distance between the holes, S1 and S2, in the pattern define the suitable multiple spindle heads for each case. The manufacturer recommendations were followed to calculate and defining the machining conditions for this type of operations. Six materials were included in creating the rules for this drilling operation: carbon steel, cast iron, Al-Si alloy, brass, plastics, and thermoplastics.

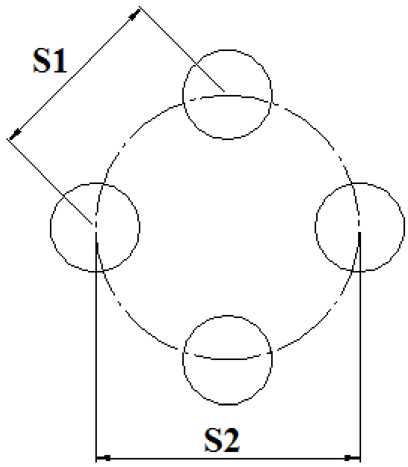


Figure 3-23. Four-hole pattern and the spacing range S1 and S2.

Examples of the rules for four holes are given below (Additional rules can be found in Appendix 9.2):

Rule 141D

If there are four holes to be machined with low cutting speeds on the surface at a diameter ≤ 3 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, *then* a BEM 12 MONO unit is used with a MH40 multiple spindle head.

3.4 Tapping machining operations

Tapping machining operations were included in the development of the SPM knowledge-base by considering the following factors:

1- The material of the workpiece.
2- The number of surfaces to be machined on the workpiece.
3- The number and the size of taps required on each surface.

Tapping machining operations are performed in SPMs by tap machining units for single purpose applications. For machining multiple taps on a specific surface, multiple spindle heads are used as when multiple holes are drilled. Another solution is using a tapping attachment GSX with a MONO machining units for single taps. This solution consumes less power compared to the use of GEM units. For example, using GSX with a BEM 6 unit can save about 0.13 KW compared to using a GEM 6 unit. In addition, the BEM 6 unit weighs 4 kg less [166]. Furthermore, the BEM 6 unit provides higher spindle speeds and greater depth than the GEM 6 unit. **Figure 3-24** shows a GEM unit and a GSX tapping attachment.

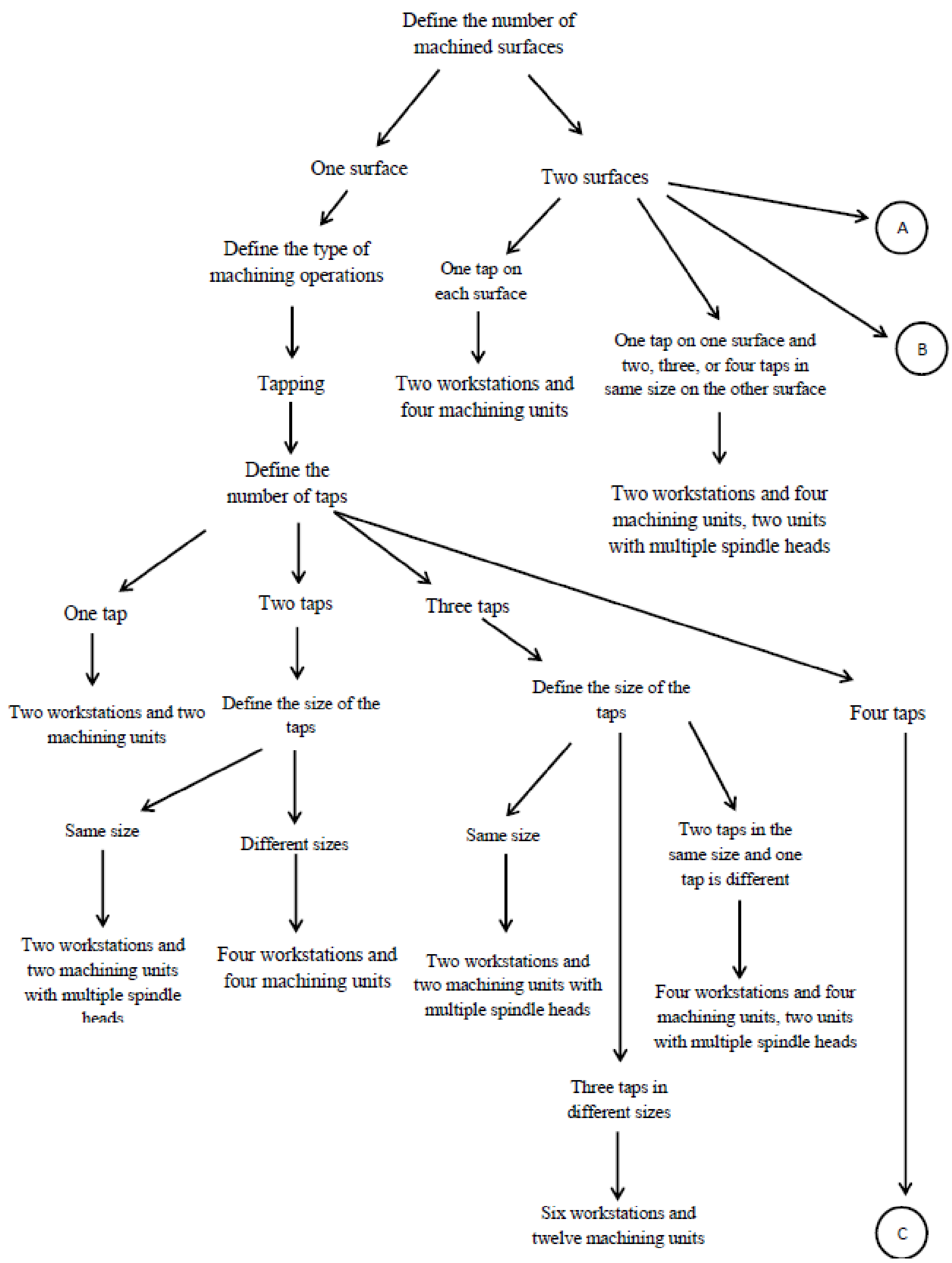
Figure 3-24. (a) a GEM tapping unit, (b) GSX tapping attachment [124].

The above factors are considered when selecting the most suitable types of machining units and the number of workstations to perform tapping operations. In addition, industry recommendations are also followed to calculate the required drive power and spindle speed by considering the cutting speed and the feed rate for each material. In general, tapping machining operations require prior drilling operations and the cutting speed for tapping a specific material is the same as for drilling that material [186].

GEM units are used for taps sizes up to M48, while GSX tapping attachments can machine taps up to M30. Multiple spindle heads are used for machining taps up to M22.

3.4.1 Machining one tap in SPMs

For machining one tap on a surface, rules were developed in this work by considering nine common sizes of taps: M3, M4, M5, M6, M8, M10, M12, M16, and M20. The machining conditions for each size were followed based on industry recommendations. From this, the drive power and the spindle speed can be calculated. Four materials were included: cast iron, steel, aluminium alloys, and brass. The first general rules for developing the SPM knowledge-base are the same (Section 3.2), and tapping rules start with determining the number of the workstations and the machining units for each machined surface on the workpiece. **Figure 3-25** shows the process of determining the number of workstations for tapping on one and/or two surfaces.



Define the number of machined surfaces
One surface
Two surfaces
A
B
Define the type of machining operations
One tap on each surface
Tapping
Two workstations and four machining units
One tap on one surface and two, three, or four taps in same size on the other surface
Define the number of taps
Two workstations and four machining units, two units with multiple spindle heads
One tap
Two taps
Three taps
Two workstations and two machining units
Define the size of the taps
Define the size of the taps
Four taps
Same size
Different sizes
Same size
Two taps in the same size and one tap is different
Two workstations and two machining units with multiple spindle heads
Four workstations and four machining units
Two workstations and two machining units with multiple spindle heads
Four workstations and four machining units, two units with multiple spindle heads
Three taps in different sizes
Six workstations and twelve machining units
C

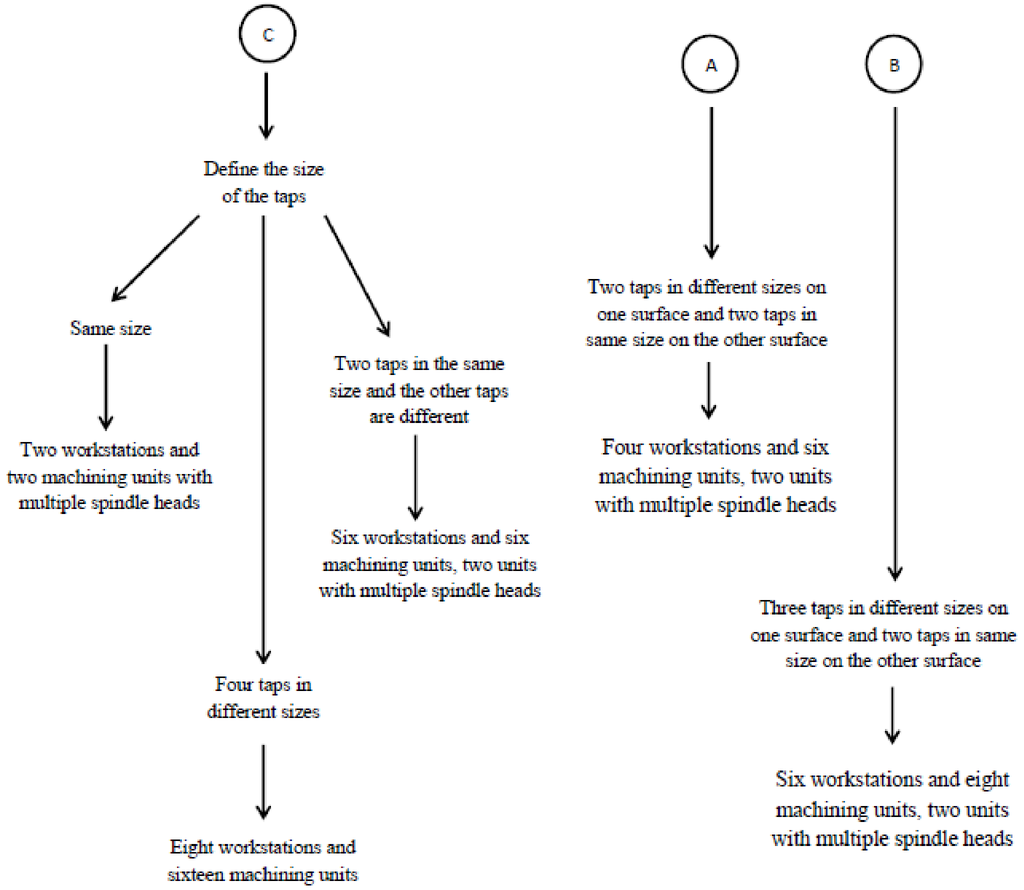
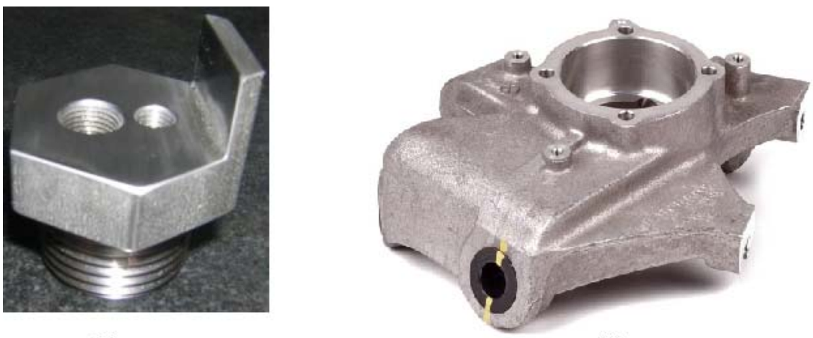


Figure 3-25. The process of defining the number of workstations for tapping on one and two surfaces.

In this work, common cases are considered for tap patterns for machining one surface or/and two surfaces on the workpiece. **Figure 3-26** and **Figure 3-27** show examples of these cases.

(a) (b)

Figure 3-26. (a) A workpiece with one machine surface and one tap [187], (b) a workpiece with one machined surface and two taps in the same size [188].



(a) (b)

Figure 3-27. (a) A workpiece with one machined surface and two taps in different sizes [189], (b) a workpiece with four taps on the top surface and two taps on the side surface [190].

The rules for tapping start at number 004T and continue to 033T for defining the number of workstations and machining units for machining one and/or two surfaces with one, two, three, and four tap patterns on each surface. The rules for selecting the type of machining units for each material and tap size start from rule 034T. In total, 182 rules were created in this work for tapping one and multiple taps in SPMs. Examples of these rules are given below (Additional rules can be found in Appendix 9.3):

Rule 004T

If one surface needs to be machined on the workpiece and a tapping operation is required with one tap, *then* two workstations are needed with two machining units: one for drilling and one for tapping.

3.4.2 Machining two taps in SPMs

For machining two taps on a surface in SPMs, adjustable MH20 and fixed MHF multiple spindle heads are used. The use of these spindles depends on the spacing range between the taps. The spacing range is the distance between the centres of the taps and is referred to as (S) as shown in **Figure 3-28**. Rules were created in this work for machining two tap patterns of the same size from M3 to M14, by considering six materials: steel, cast iron, Al-Si alloy, brass, plastics, and thermoplastics. The industry recommendations were followed for calculating the required machining conditions for these machining operations and for defining the best solution for each case.

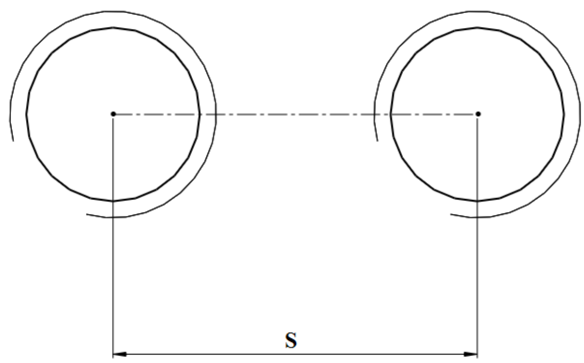


Figure 3-28. Two taps with spacing range (S).

Examples of these rules are given below (Additional rules can be found in Appendix 9.3):

Rule 049T

If there are two taps at M3, M4, or M5 sizes on the surface to be machined at low cutting speeds with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, brass or plastics, *then* a BEM 6 MONO unit is used with MH20 multiple spindle heads.

3.4.3 Machining three taps in SPMs

For machining three taps on a surface in SPMs, three types of spindle heads are used: MH33, MH30, and MHF, and this depends on the pattern of the taps and the spacing ranges S1 and S2 between the taps. Two types of three-tap patterns are considered in this work: a straight line pattern, and a staggered pattern as shown in **Figure 3-29** and **Figure 3-30**. Rules for tapping three taps in SPMs were created in this work for each of the two patterns, and by considering six materials: cast iron, steel, Al-Si alloy, brass, plastics, and thermoplastics. Industry recommendations for defining the best solution for each case were followed taking into account the considerations of the pattern type and spacing range.

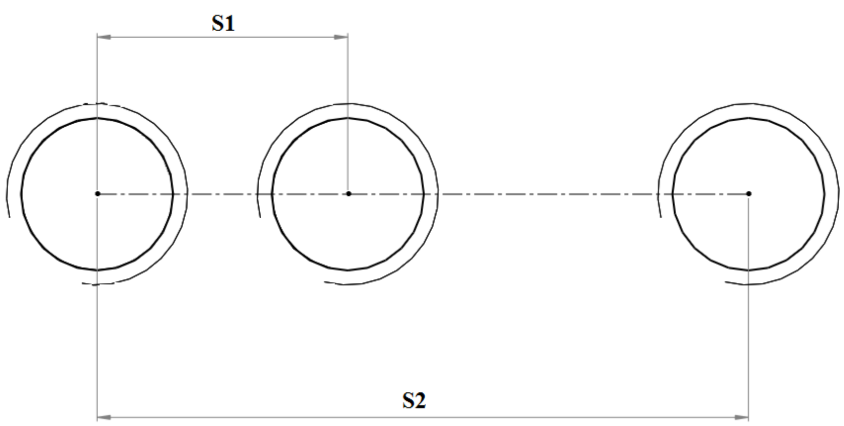


Figure 3-29. Straight line pattern of three M6 taps with maximum spacing range S2 and minimum spacing range S1.

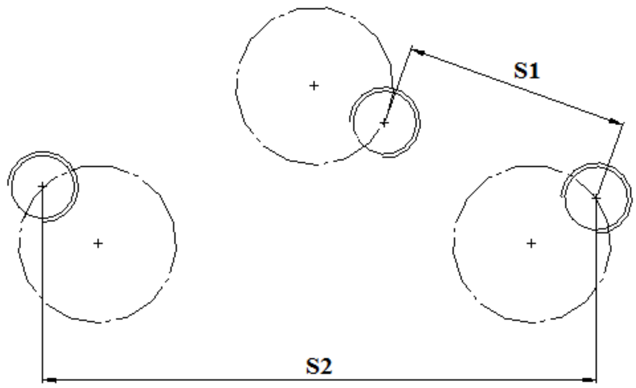


Figure 3-30. Staggered pattern for three M6 taps with maximum spacing range S2 and minimum spacing range S1.

Examples of these rules are given below (Additional rules can be found in Appendix 9.3):

Rule 085T

If there are three taps at M3 or M4 sizes with a straight line pattern to be machined with low cutting speeds on the surface, and with S1 = 9.5 mm and S2 = 97.5 mm, and the material is steel, aluminium or brass, *then* a BEM6 MONO unit is used with a MH33 multiple spindle head.

3.4.4Machining four taps in SPMs

For machining four taps on a surface in SPMs, two types of spindle heads can be used: adjustable MH40 and fixed MHF multiple spindle heads. The most common pattern for four taps is shown in **Figure 3-31**. The minimum and maximum distances between the taps, S1 and S2 in the pattern, define the appropriate multiple spindle heads for each case. The manufacturer recommendations were followed to calculate and define the machining conditions for this type of operations. Six materials were included in the rules for this tapping operation: steel, cast iron, Al-Si alloy, brass, plastics, and thermoplastics.

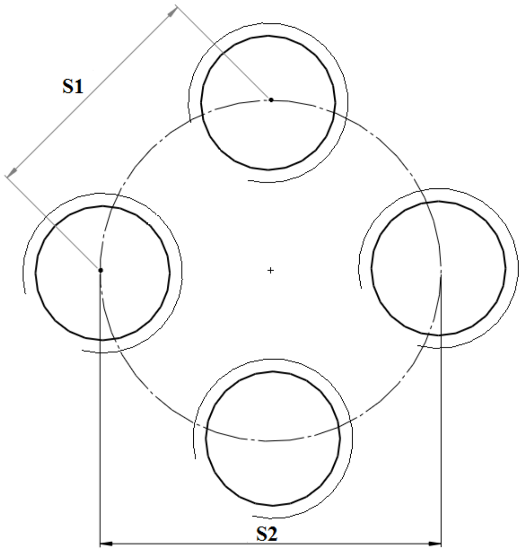


Figure 3-31. Four-tap pattern with maximum and minimum distances S2 and S1 between the taps.

Examples for these rules are given below (Additional rules can be found in Appendix 9.3):

Rule 151T

If there are four taps at M3 or M4 sizes to be machined with low cutting speeds on the surface with S1 = 22 mm and S2 = 195 mm, and the material is steel, Al-Si alloy or brass, *then* a BEM 6 MONO unit is used with MH40 multiple spindle heads.

3.5 Selecting the assembly and machine components

There are other components that should also be identified to complete the SPM layouts. These components are divided into assembly and machine components. The assembly components are used for mounting the machining units in both horizontal and vertical positions in the layout to perform the

required machining operations. **Figure 3-32** shows two types of these components: horizontal supports and vertical supports.

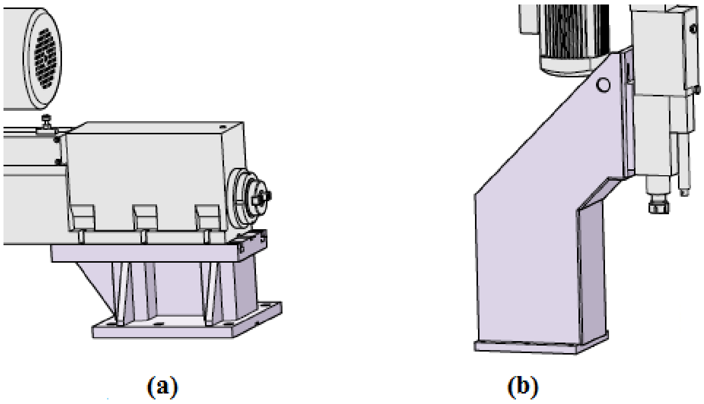


Figure 3-32. (a) A machining unit with a horizontal support, (b) a machining unit with a vertical support [124].

Other components such as base plate positioning slides, slide blocks, and universal supports are also used in SPM layouts. **Figure 3-33** shows some of these components.

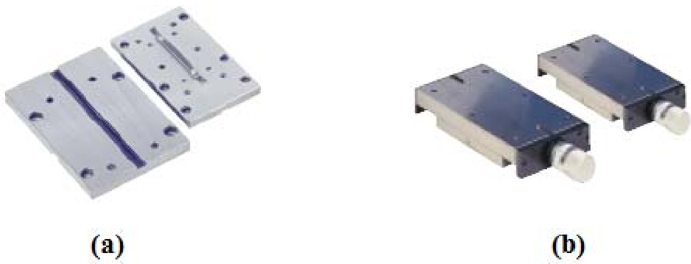


Figure 3-33. (a) Base plates, (b) slide blocks [124].

3.5.1 Horizontal and vertical supports

The selection of the horizontal and vertical supports is required in drilling and tapping operations. Horizontal supports are used when operations are required for the side surfaces of the workpiece. The criterion that should be taken into consideration for selecting these components is the height of the machining unit

spindle from the zero level of the machine. To obtain this height, it is important to define the height of the machining feature (the hole or the tap) on the side surface of the workpiece. **Figure 3-34** illustrates how this height is obtained.

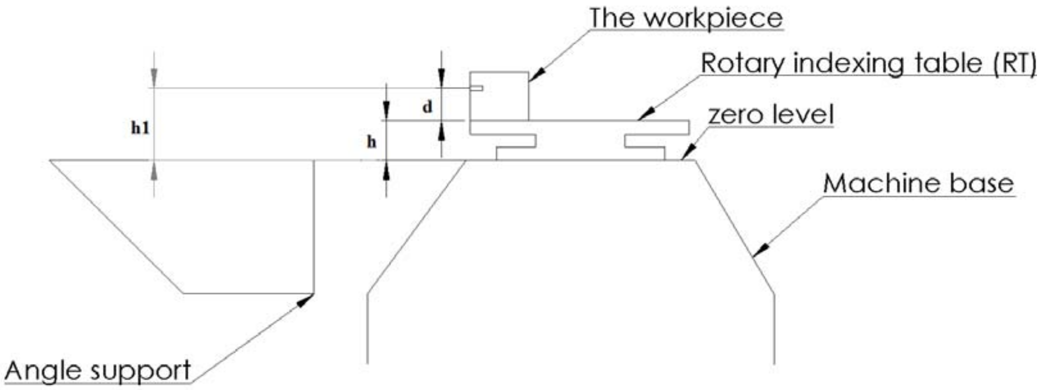


Figure 3-34. Calculating the spindle height for a specific machining operation.

From this figure, **d** is the distance from the machining feature to the bottom of the workpiece, while **h** is the height of the rotary indexing table (RT) which is mounted on the base of the machine. The top surface of the base is considered as the zero level. The spindle height is referred as **h1** and is calculated as: **h1 = d + h**

By defining the value of **h1**, the height of the horizontal support is determined. This is achieved by subtracting the distance from the spindle to the bottom face of the machining unit (**h2**), as shown in **Figure 3-35**, from the spindle height **h1**. Therefore, the height (H) of the horizontal support is determined as: **H = h1 – h2**

This height (**H**) is also considered as the height of the machining unit from the zero level of the machine. The values of **h** for the indexing table (RT) are based on the manufacturer's specifications, and they are in two types: 160 mm RT and 205 mm RT [166]. When using a dia-plate with an RT, then the height of this plate should be added to the height of the indexing table.

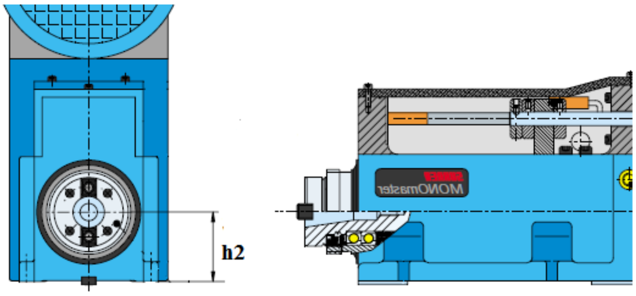


Figure 3-35. The distance from the spindle to the bottom surface of the machining unit [124].

In terms of rules, the process of identifying the **H** value is as follows:

Rule 001A

If a drilling or a tapping operation is required on the side surface of the workpiece, *then* the distance from the drill or the tap to the bottom of the workpiece (**d**) should be identified.

Rule 002A

If the value of **d** is identified, and the rotating indexing table (RT) is used and mounted on the machine base, *then* the height of RT should be added to (**d)** in order obtain the required value of the spindle height (**h1**).

Rule 003A

If the RT used is 320 mm diameter, *then* **h1** value is equal to (**d** + 160 mm).

Rule 004A

If the RT used is 500 mm diameter, *then* **h1** value is equal to (**d** + 205 mm).

Rule 005A

If the value of spindle height (**h1**) is calculated, *then* the required height for the horizontal support (H) is calculated by subtracting the distance from the spindle to the bottom of the machining unit (**h2**), as in the formula: H = **h1- h2**.

The letter (A) associated with the rule number indicates that these rules are for selecting the assembly components, and it was used in this work to distinguish the rules of the assembly components from the other rules. An example is taken to illustrate this process by considering the workpiece shown in **Figure 3-36** with a machining feature (6 mm hole and cast iron material) in one side. The height of the hole from the bottom face of the workpiece is 50 mm.

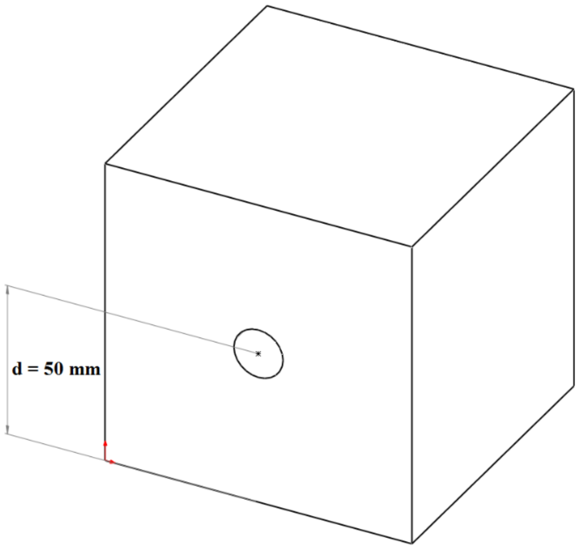


Figure 3-36. A workpiece with a hole feature on the side surface 50 mm from the bottom surface.

From the previous rules, the distance from the bottom (50 mm) is added to the height of the indexing table RT. The RT height is identified by considering some factors such as the number of the workstations that are needed to perform the machining operation, the workpiece size (the dimensions of the workpiece), the number of the workpieces that should be produced, and the number of the machining operations that are required to complete the process. In general, two types of RT can be used, with two different diameters: 320 mm RT and 500 mm

RT. The height for the 320 mm RT is 160 mm, while the height for the 500 mm RT is 205 mm [166]. Therefore, the value of the spindle height in this case is calculated as follows:

For 320 mm RT, **h1** = 50 + 160 = 210 mm.
For 500 mm RT, **h1** = 50 + 205 = 255 mm.

For machining the 6 mm hole and by referring to the rules of the machining unit for the drilling operation, a BEM 12 MONO machining unit is used at a cutting speed of 50 m/min. The value of **h2** is taken from the specifications of this unit based on the manufacturer's information, and is equal to 40 mm. Therefore, the H value is calculated as:

H = **h1** – **h2**, so H = 210 – 40 = 170 mm, this value is for 320 mm RT, or
H = 255 – 40 = 215 mm, this value is for 500 mm RT.

This is the required height for the horizontal support, or in other words, it is the height of the machining unit above the zero level of the machine base that is required to perform this drilling operation. The same procedure is followed for any individual drilling or tapping machining operation.

For performing drilling or tapping machining operations on the top surface of the workpiece, vertical supports are used. In this case, the height of the workpiece should be identified and added to the height of the RT to determine the total height from the zero level. The value of the total height identifies the type of the vertical support that is required for the specific drilling or tapping operation on the top surface. The height of the workpiece is referred to as **h3** and the total height from the zero level is given as **ht**. **Figure 3-37** shows how the value of **ht** is calculated for a workpiece with a machining feature on the top surface. The value of the total height defines the height of the machining unit (from the zero level) that is required to perform a vertical machining operation.

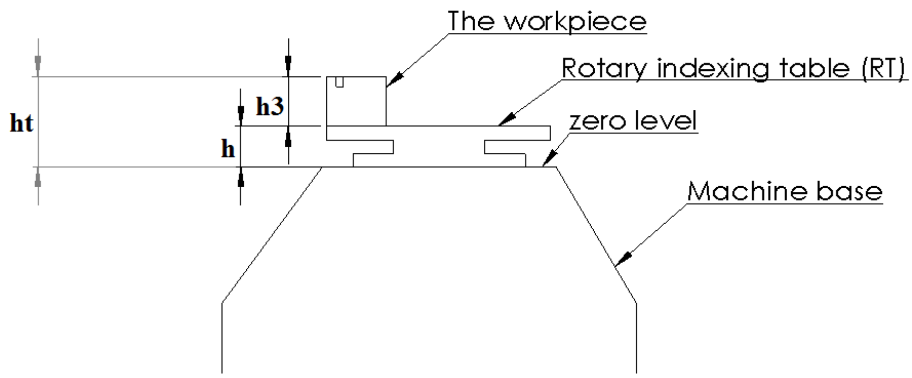


Figure 3-37. Calculating **ht** value which is equal to the sum of the height of the workpiece (**h3**) and the height of the RT (**h**).

In general, two types of vertical supports are available: VST 12 vertical support and SV 20 vertical support [166]. Each type is used for specific machining units (for drilling or tapping operations), and for each machining unit, the height from the zero level has a fixed upper limit. The values of this height and the machining unit specifications are based on the manufacturer's information and manuals. These specifications and information were formed in rules in this work as follows:

Rule 006A

If a drilling or a tapping machining operation is required on the top surface of the workpiece, *then* the height of the workpiece (**h3**) should be identified.

Rule 007A

If the value of **h3** is identified and the indexing table RT is used, *then* h3 is added to the height of RT to determine the total height (**ht**) from the top surface to the zero level of the machine base.

Rule 008A

If the RT used is 320 mm diameter, *then* **ht** value is equal to (**h3** + 160 mm).

Rule 009A

If the RT used is 500 mm diameter, *then* **ht** value is equal to (**h3** + 205 mm).

Rule 010A

If **ht** value is between 305 mm and 365 mm and the machining unit is a BEM 6 MONO, *then* a VST 12 vertical support is used.

Rule 011A

If **ht** value is more than 365 mm and a BEM 6 unit is used, *then* a horizontal support is used with the vertical support VST 12 to achieve the desire height.

Rule 012A

If **ht** value is less than 305 mm and a BEM 6 unit is used, *then* VST 12 cannot be used and the manufacturer should be consulted about the type of the vertical support.

Rule 013A

If **ht** value is between 285 mm and 350 mm and the machining unit is a BEM 12 MONO, *then* a VST 12 vertical support is used.

Rule 014A

If **ht** value is more than 350 mm and a BEM 12 unit is used, *then* a horizontal support is used with the vertical support VST 12 to achieve the desire height.

Rule 015A

If **ht** value is less than 285 mm and a BEM 12 unit is used, *then* VST 12 cannot be used and the manufacturer should be consulted about the type of the vertical support.

Rule 016A

If **ht** value is between 320 mm and 380 mm and the machining unit is a GEM 6 TAPMASTER, *then* VST 12 vertical support is used.

Rule 017A

If **ht** value is more than 380 mm and a GEM 6 unit is used, *then* a horizontal support is used with the vertical support VST 12 to achieve the desired height.

Rule 018A

If **ht** value is less than 320 mm and a GEM 6 unit is used, *then* VST 12 cannot be used and the manufacturer should be consulted about the type of the vertical support.

Rule 019A

If **ht** value is between 300 mm and 360 mm and the machining unit is a GEM 12 TAPMASTER, *then* a VST 12 vertical support is used.

Rule 020A

If **ht** value is more than 360 mm and a GEM 12 unit is used, *then* a horizontal support is used with the vertical support VST 12 to achieve the desire height.

Rule 021A

If **ht** value is less than 300 mm and a GEM 12 unit is used, *then* VST 12 cannot be used and the manufacturer should be consulted about the type of the vertical support.

Rule 022A

If **ht** value is between 400 mm and 600 mm and the machining unit is BEM 20, BEM 25, BEM 28, BEX 35, or GEM 20, *then* a SV 20 vertical support is used.

Rule 023A

If **ht** value is more than 600 mm and BEM 20, BEM 25, BEM 28, BEX 35, or GEM 20 units are used, *then* a horizontal support is used with the vertical support SV 20 to achieve the desired height.

Rule 024A

If **ht** value is less than 400 mm and BEM 20, BEM 25, BEM 28, BEX 35, or GEM 20 units are used, *then* SV 20 cannot be used and the manufacturer should be consulted about the type of the vertical support.

Rule 0025A

If multiple spindle heads MH 20, MH 33, MH 30, MH 40, or MHF are used with any of the machining units to perform vertical drilling or tapping machining operations, *then* the machine component VBG is used instead of the vertical supports VST 12 and SV 20.

Rules 006A to 024A are for performing individual drilling or tapping operations. For using multiple spindle heads for machining multiple holes or taps at the same time, the dimensions of these spindle heads should be considered when determining the height position of the machining unit (Rule 025). VBG machine components are used for vertical machining operations when multiple spindles heads are used with the machining units. This is because the extra dimension of the spindle heads is added to the original dimension of the machining units as shown in **Figure 3-38**. These components are available in two types: VBG 4 and VBG 6. VBG components are also used for performing two machining operations at the same time and at the same workstation on both the side and top surfaces of the workpiece. The angle support is used for horizontal machining operations and also for the vertical machining operations in the specified limits for the vertical supports. **Figure 3-39** shows an SPM frame with these components.

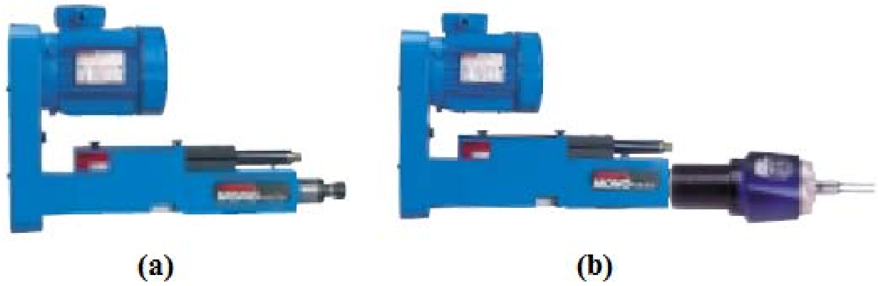


Figure 3-38. A MONO machining unit - BEM 6 -, (a) without a spindle head and, (b) with a multiple spindle head [124].

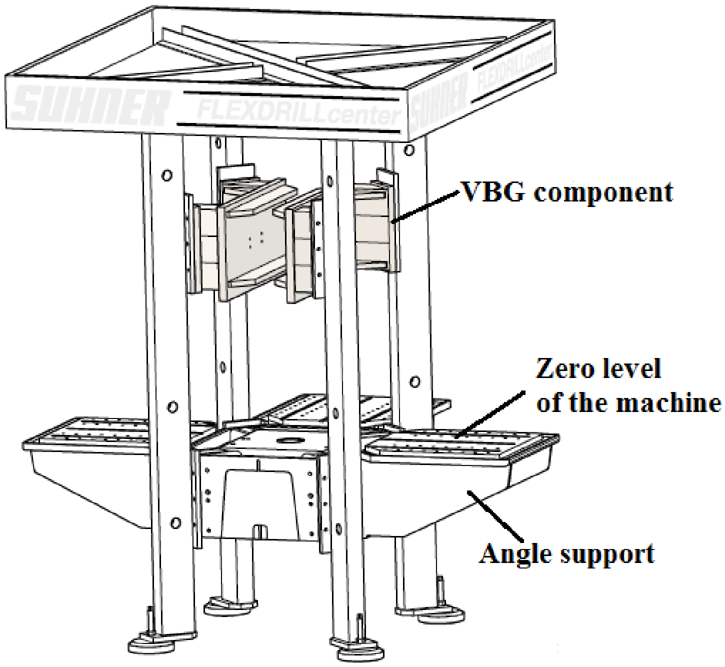


Figure 3-39. An SPM frame consisting of with angle supports and VBG components. The zero level is the top surface of the angle support [124].

3.6 Implementation of the expert system tool (VisiRule)

The rules that were developed for drilling and tapping operations in the previous sections were implemented in the VisiRule tool to build the SPM knowledge-base in this work. VisiRule was used to enact the rules in flowchart

form: this automates the defining of the number of workstations and the number/type of machining units. An example of this implementation is shown in **Figure 3-40** and **Figure 3-41**.

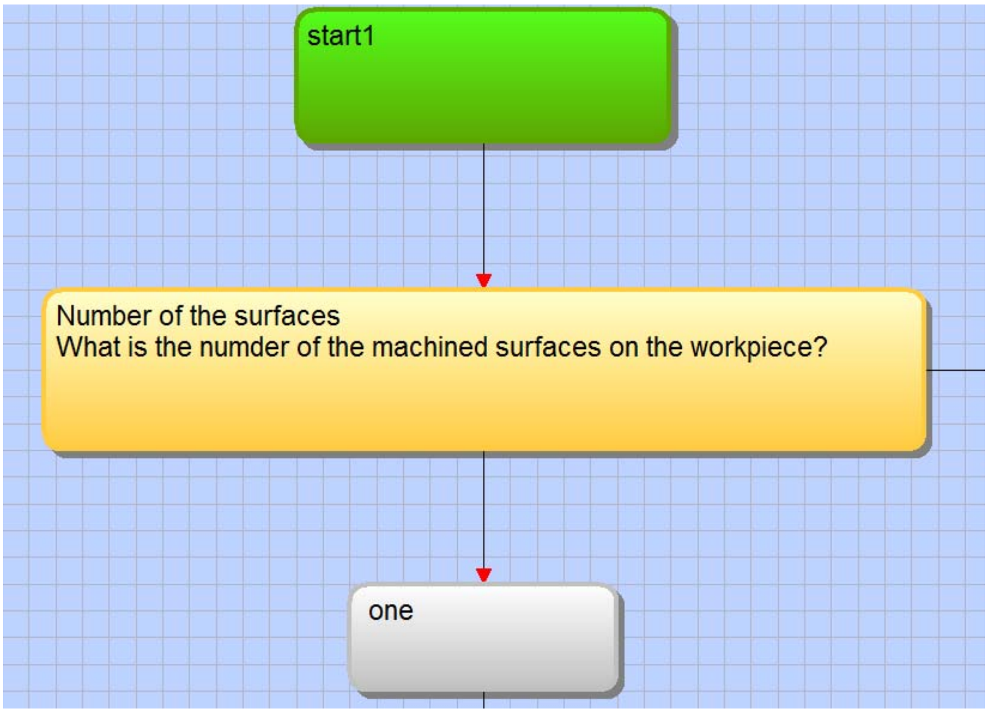


Figure 3-40. Initial stages of a flowchart in VisiRule.

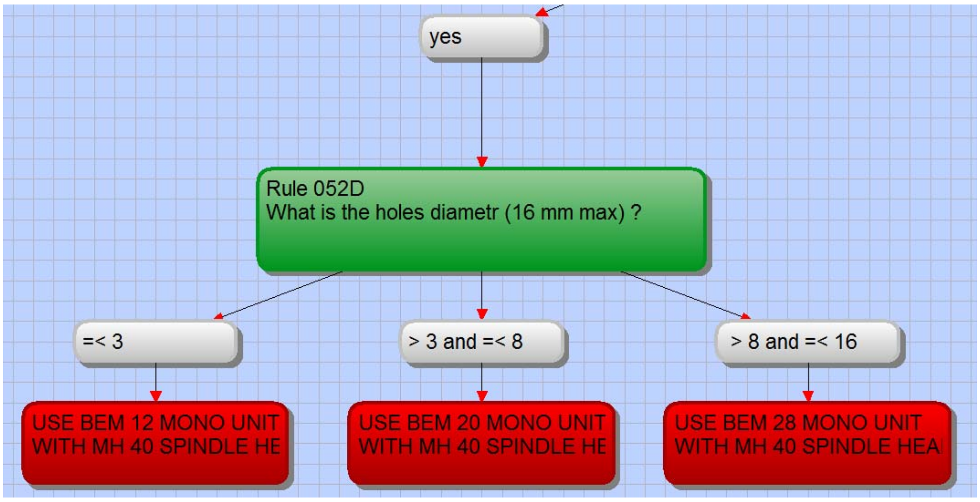


Figure 3-41. Mapping the rules as question and expression boxes in VisiRule.

Different types of boxes were used to map the rules based on the information that was provided by the rules. Question and expression boxes were used to ask the user questions and identify the answer in order to achieve outcomes. End boxes were used to show results for each case. A code was generated automatically by VisiRule. **Figure 3-42** shows the VisiRule starting window with the generated code. Part of the generated code is given in Appendix 9.4. Additional VisiRule charts developed in this work can be found in Appendix 9.5.

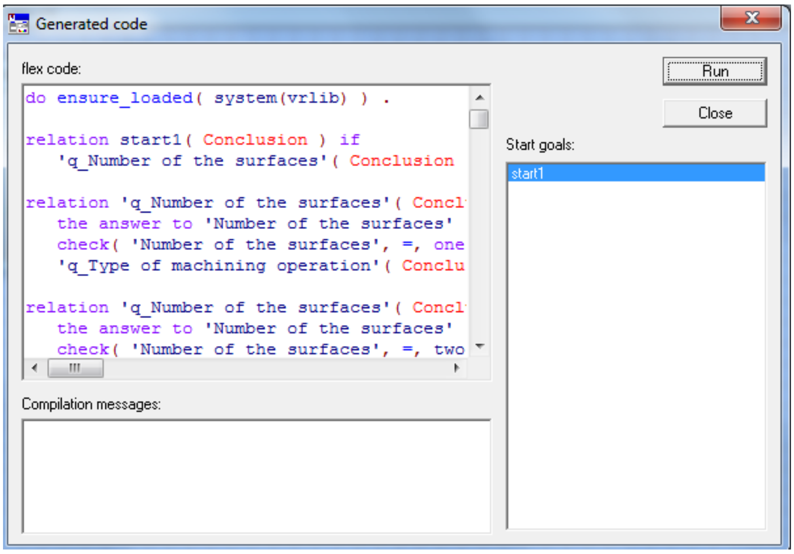


Figure 3-42. The start window with the generated code.

A half-collar workpiece for shaft mounting was used as an example (as shown in **Figure 3-43**) to apply the developed SPM knowledge-base. The design information for this example is given in Appendix 9.6.

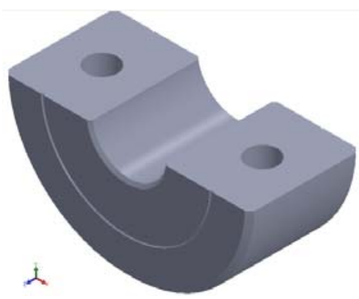


Figure 3-43. A designed workpiece (half-collar).

The implementation of the SPM knowledge-base for this workpiece and the results are shown in **Figure 3-44** and **Figure 3-45**. These figures show the process of using VisiRule to implement the SPM knowledge-base and achieving the desired result.

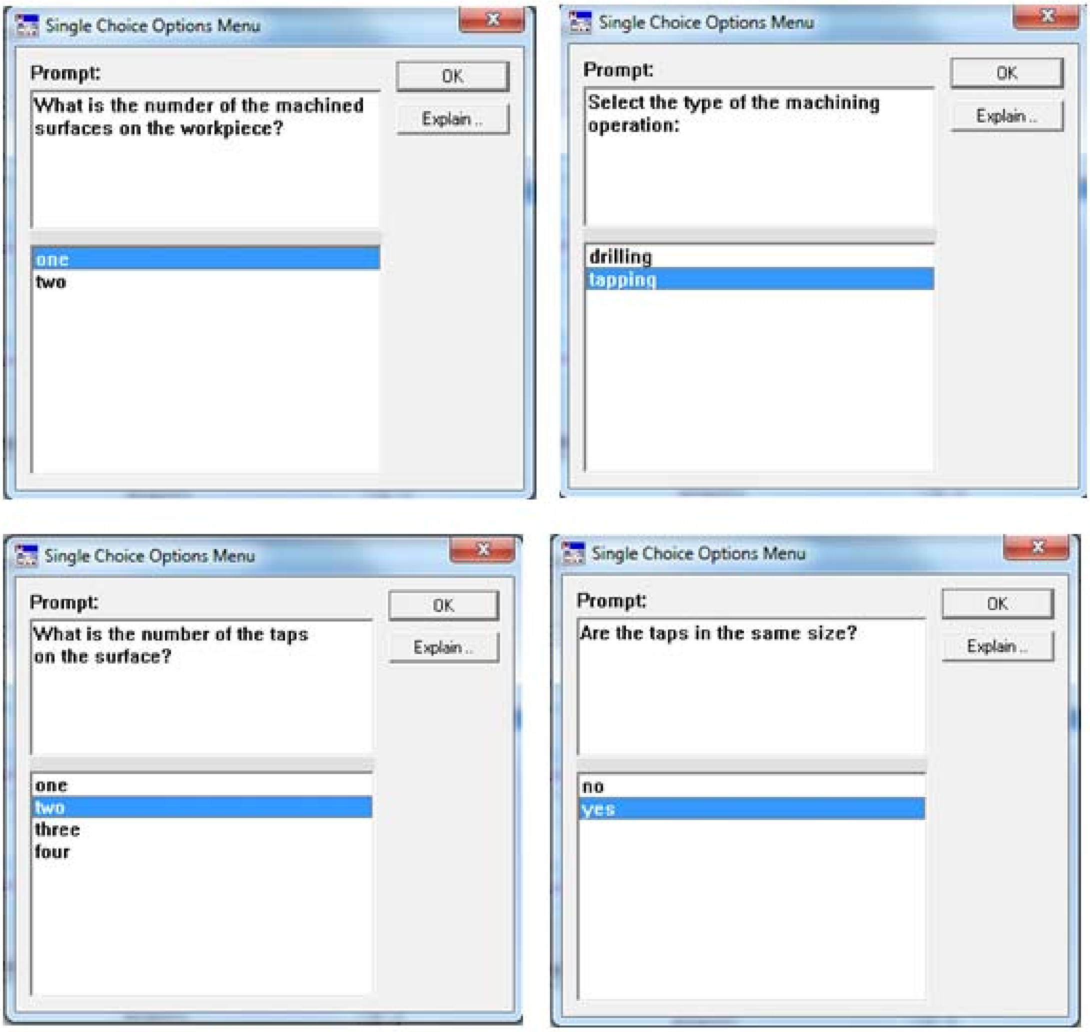


Figure 3-44. Examples of the screen captures in VisiRule.

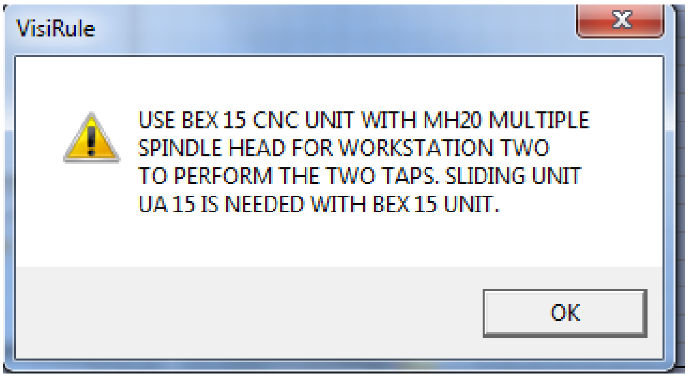


Figure 3-45. The result of the implementation of the SPM knowledge-base in VisiRule.

In this example, a BEX 15 CNC machining unit and a multiple spindle head type MH20 were recommended to complete the required machining operations. The developed SPM knowledge-base in this work can be applied to similar parts, and it can be extended to include additional information about other parts and other machining operations such as milling, reaming, and cutting.

3.7 Summary

This chapter has explained the development of the SPM knowledge-base. The chapter has shown how both engineering knowledge and expertise can be captured and combined with relevant manufacturing information for SPMs. This development included creating rules in IF-THEN format for different machining features in order to select the appropriate components for SPMs. The SPM knowledge-base was implemented using the VisiRule expert system tool in relation to a practical application. A typical workpiece was taken as an example to apply the developed SPM knowledge-base in order to achieve appropriate combinations of SPM elements and workstations for SPM layouts.

Chapter Four

4. Assembly modelling and automation for SPMs

This chapter introduces the development of an assembly modelling approach for SPMs. This approach was applied with a software package (SolidWorks) and the necessary components for this application, including an SPM elements database, a design library for SPM elements in SolidWorks, and an assembly relationships graph, were created. The approach developed in this work was implemented using SolidWorks API features in order to automate the assembly modelling of SPM layouts.

Assembly modelling is a very important step in many engineering applications and activities. An assembly can be defined as a collection of individual parts that have independent specifications. In order to model the assembly in an appropriate way, the nature and the structure of dependencies between the parts in the assembly should be understood, and assembly modelling facilitates this. There are two types of modellers that are be used for the design process in CAD/CAM systems: geometric modellers and assembly modellers [31].

A geometric modeller is used to generate solid models for the individual parts. These models can provide multi-views and complete information for designers in order to support design and manufacturing activities such as part analysis and process planning. An assembly modeller is used to synthesise models for individual parts which are modelled by the geometric modeller. These parts are combined together using mate commands to form an assembly model. The mate commands define the assembly constraints or mating conditions between the individual parts. The independent movements for individual parts in an assembly model are related to their degrees of freedom (DOF). In general, there are six DOF: three rotational DOF and three translational DOF. Combining the parts using mate commands constrains their associated DOF. Both geometric and assembly modellers are represented in **Figure 4-1**.

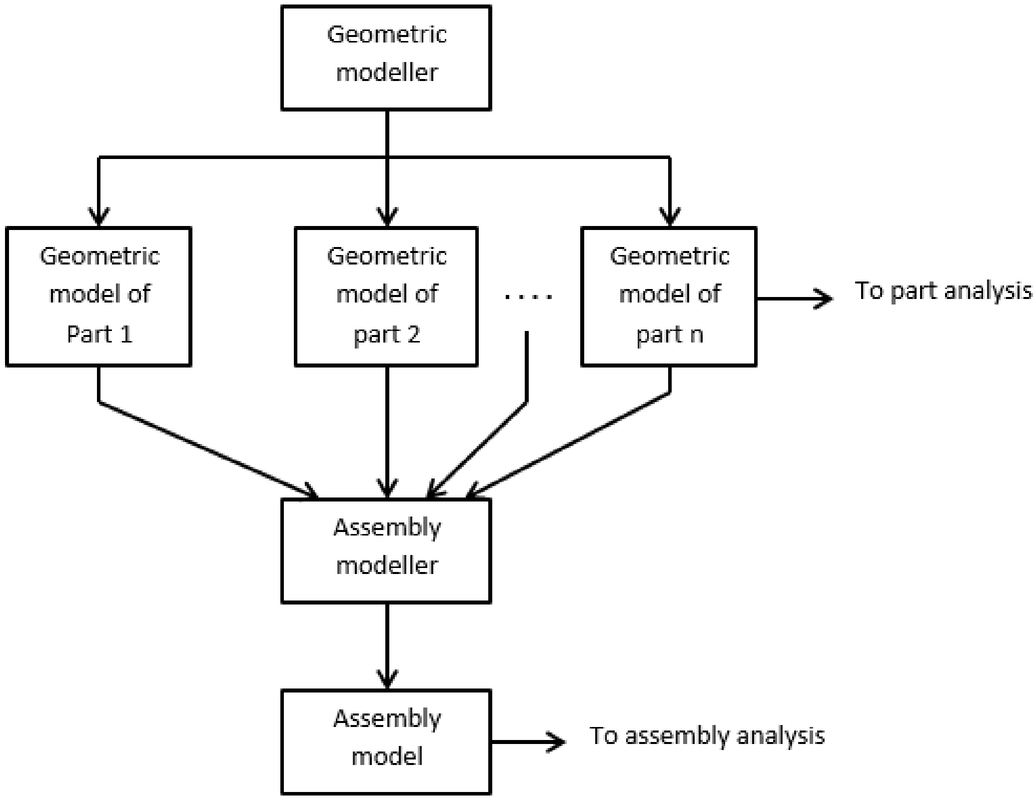


Figure 4-1. Geometric and Assembly Modellers [191].

A hierarchical structure can be used to explain the idea of assemblies using an assembly tree. The overall assembly is divided into subassemblies and parts, and an assembly tree helps to illustrate how the parts and subassemblies are connected or attached, as shown in **Figure 4-2**.

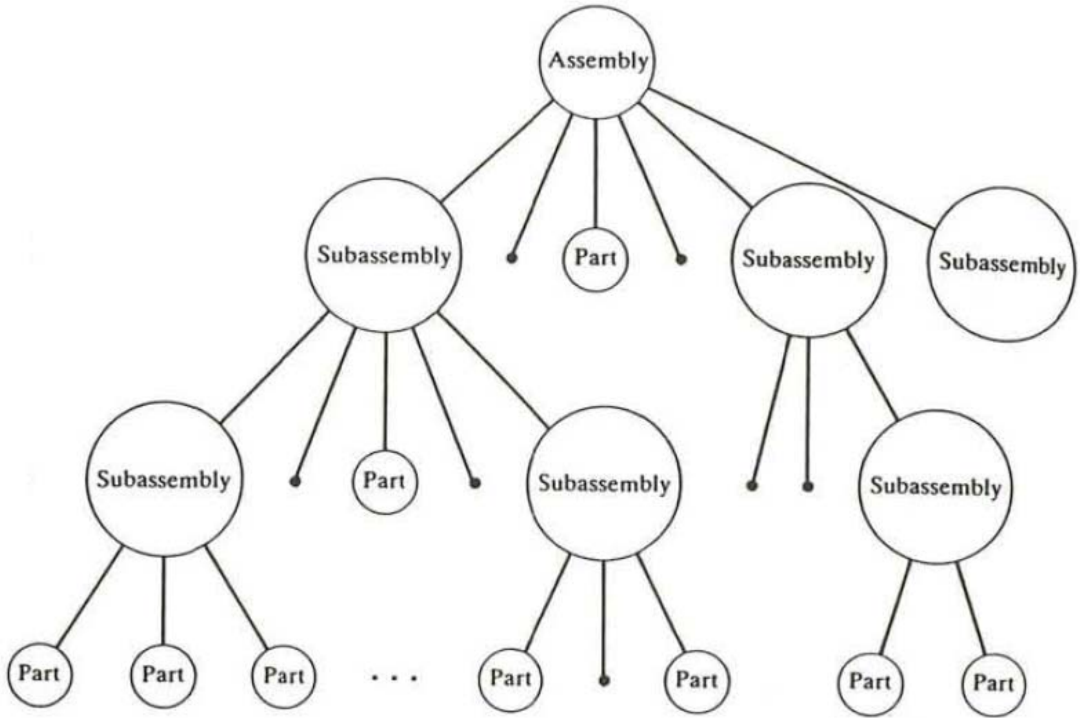


Figure 4-2. An assembly tree illustrating the connection between parts and subassemblies [191].

The importance of assembly modelling comes from its ability to generate a bill of materials, to show how the parts fit together, and to create multi-views of the assembly. In addition, assembly models are very important in performing engineering analyses such as kinematic, dynamic, finite element analyses, and interference checking. More importantly, assembly modelling is significant for simulating and evaluating the product design and assembly.

Several modelling packages have been developed and implemented with CAD/CAM systems to facilitate the assembly modelling including Pro/Engineer, Mechanical Desktop, and SolidWorks. These packages can perform both geometric and assembly modelling. The parts are first designed in the geometric modeller, and then they are combined by the assembly modeller to form the assembly. The main advantage of using these systems is that the link between both geometric and assembly modeller is established, and any modifications of the individual parts in the geometric modeller are therefore automatically updated

in the assembly modeller [31]. SolidWorks was used in this work as the modelling environment to model the SPM assembly process. In SolidWorks, the geometric modeller is called **Part** as a 3D representation of a single design component, while the assembly modeller is called **Assembly** as a 3D arrangement of parts and/or assemblies. The first step of developing an assembly modelling approach for SPMs is building a database of SPM elements that provides all the necessary information needed for the assembly. After that, an assembly relationship graph is created to define the assembly relationships and mating conditions between the SPM elements. The type of mates between SPM elements is then defined and used with SolidWorks API to automate the SPM assembly process.

4.1 Building the SPM elements database

In order to build a database for SPM elements, it is important to consider the following factors:

- The category of each element.
- The supporting and supported faces of each element.
- The assembly features on the supporting and supported faces of each element.
- The geometric parameters of each element.
- The classification of each element with regard to its role in the SPM design.

With regards to the first factor, SPM elements are divided into four main categories: function, motion, supporting, and accessory elements. Function elements are used to perform machining processes such as drilling, milling, tapping, and reaming. Motion elements provide rotational and linear movements. A linear movement is needed when function elements are required to move during machining processes, and it can be in one to four directions. A rotational movement is required to transfer the workpiece from one station to another in order to perform multiple machining processes. Supporting elements are needed to provide the positioning support for the function elements. Accessory elements

such as clamps, chucks, and multi-spindle heads are used to complete the design of SPM layouts. Regarding factors 2, 3, and 4, the assembly features and geometric information need to be defined and used to represent SPM elements in order to define the assembly relationships between these elements. In this work, eight assembly features were identified: supporting faces, supported faces, locating holes, counterbore holes, screw holes, fixing slots, pins, and screw bolts, as shown in **Figure 4-3**. A supporting face is the surface on an element that supports other SPM elements or the workpiece, while a supported face is the surface on an element that is supported by other SPM elements. A locating hole can be used as a locating point with a locating pin, while a counterbore hole and a fixing slot are used to join two SPM elements with screw bolts. In SPM elements, the assembly features are designed with standard dimensions and are perpendicular to the supporting or supported faces. These features are identified as associated assembly features with supporting and supported faces of the elements, and because the features have standard designs and dimensions, their positions and orientations are known.

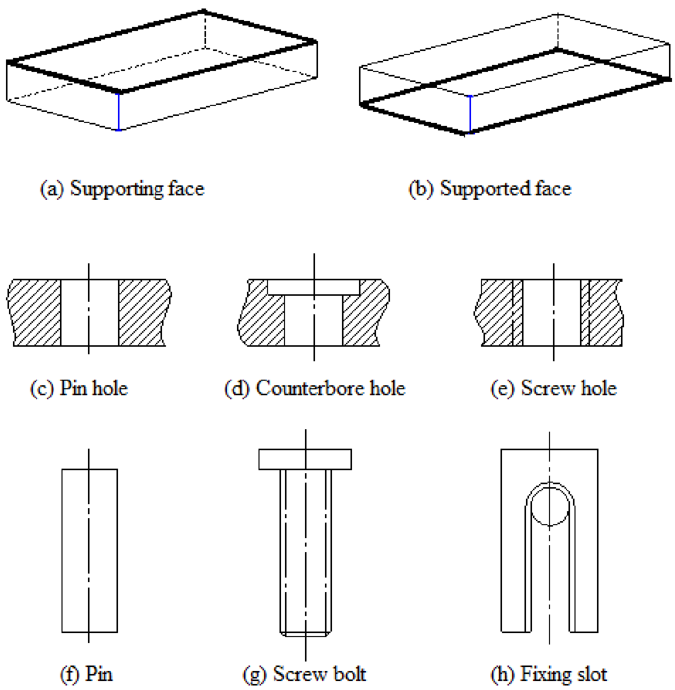


Figure 4-3. The eight assembly features.

Some SPM elements have supporting and supported faces and they can be used to support an element, while they are already supported by other elements, as shown in **Figure 4-4**.

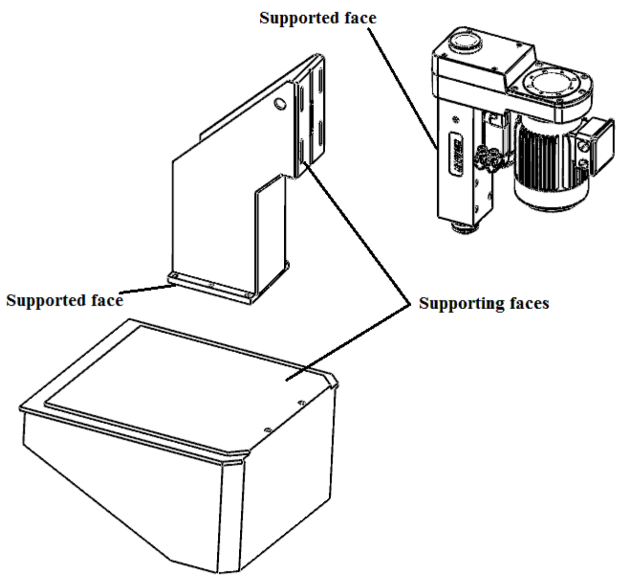


Figure 4-4. Supporting and supported faces for SPM elements.

The classification of SPM elements is based on their roles. Function elements are classified into MONO master, CNC master, TAP master, POWER master, and MULTI master. Motion elements are classified into sliding units and rotary indexing tables. Supporting elements are classified into horizontal, vertical supports, base plates, universal supports, and slide blocks. Accessory elements are classified into POLYdrill, TOOL holders, and machine components [124]. **Figure 4-5** shows the main categories and classifications of SPM elements.

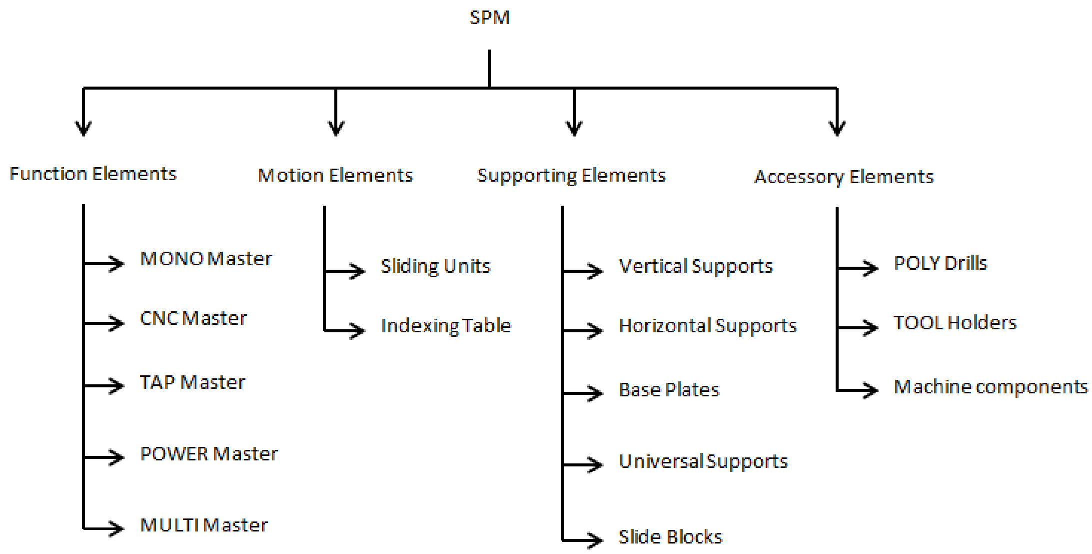


Figure 4-5. The categories and classifications of SPM elements.

By considering the above factors for building an SPM database, a linked list structure was developed in this work to represent SPM elements. This structure shows how the information is organised for each element with regards to its category, classification, number of supported and supporting faces, number and type of the associated assembly features, and geometric information. A general example of this structure is shown in **Figure 4-6**. This structure was used as a basis for developing the SPM database. Each element has a *Record* which contains information about this element at different levels and how these levels are linked. **Figure 4-7** shows an example of the linked list structure for a function element (BEM 6). The SPM database was developed using Microsoft Access in this thesis and contains the necessary information for SPM elements. In addition, 3D models for these elements were designed and stored in a design library in SolidWorks to be used in performing the SPM assembly.

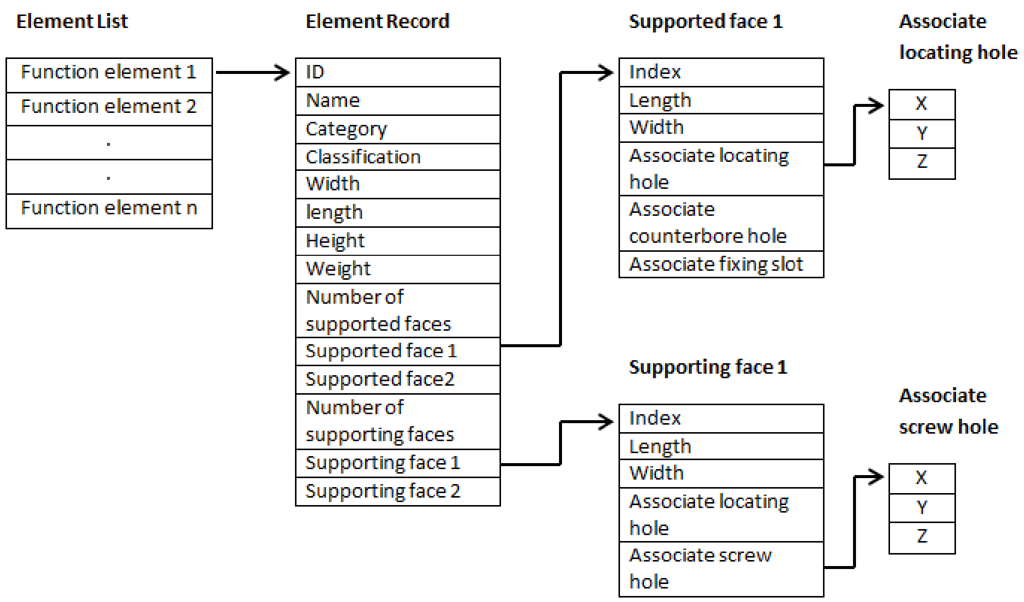


Figure 4-6. A general list data structure.

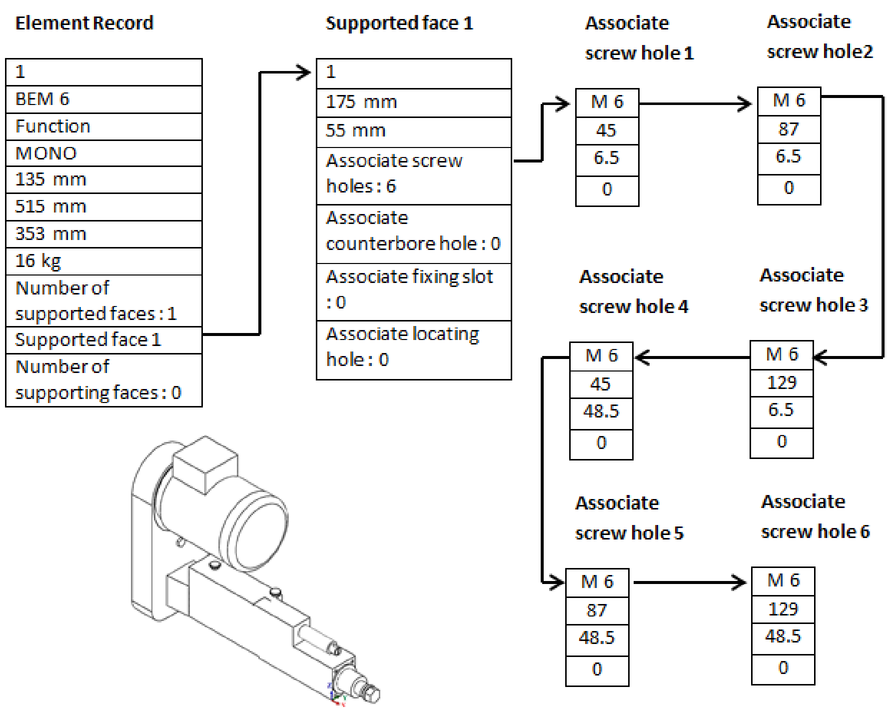


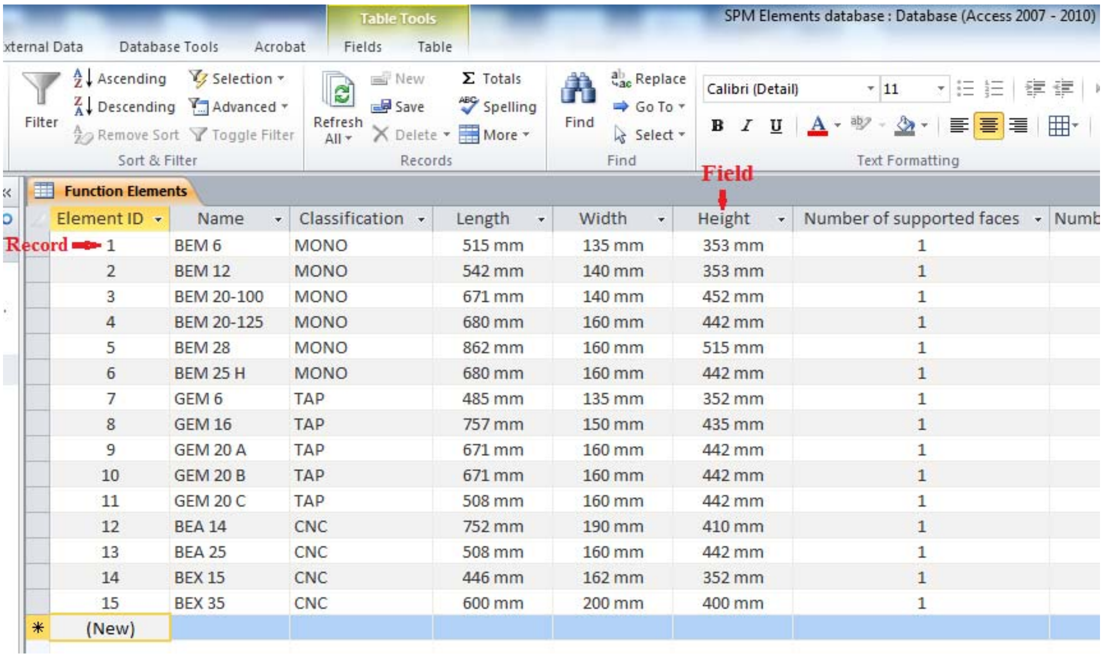
Figure 4-7. A data structure representing an BEM 6 element.

4.1.1 Microsoft Access database for SPMs

The information about SPM elements was used in this work to build an Access database. Microsoft Access is used to design and create databases for many applications. This is because it can deal with lists and tables of information. Although there are other software programs that have features to create and manage lists and tables, Access is the only software program that can handle large quantities of complex information. Access has the ability to create multiple tables in a way that allows the information in these tables to be linked. This is a very effective feature when analysing and extracting data from multiple tables is required. Access also has very useful features such as the ability to create customised routines, print a variety of reports, and design fine-tuned forms for data entry. These features were used to build a database for SPM elements and each element is given a *record*, which includes the following information:

- Element ID.
- Element name.
- Element classification.
- Element geometric information.
- Number of supported faces.
- Number of supporting faces.
- Number of associated assembly features (screw holes, locating holes, counterbore holes, and fixing slots).

The process of establishing the database starts by creating a table for each category of SPM elements. This facilitates the use of the database by entering new information or by modifying the existing information, and four tables are created: Function Elements, Motion Elements, Supporting Elements, and Machine Components - Accessory Elements. Each of these tables contains the information listed above for each element in the related category. **Figure 4-8** shows an example of a table for function elements.



Element ID	Name	Classification	Length	Width	Height	Number of supported faces
1	BEM 6	MONO	515 mm	135 mm	353 mm	1
2	BEM 12	MONO	542 mm	140 mm	353 mm	1
3	BEM 20-100	MONO	671 mm	140 mm	452 mm	1
4	BEM 20-125	MONO	680 mm	160 mm	442 mm	1
5	BEM 28	MONO	862 mm	160 mm	515 mm	1
6	BEM 25 H	MONO	680 mm	160 mm	442 mm	1
7	GEM 6	TAP	485 mm	135 mm	352 mm	1
8	GEM 16	TAP	757 mm	150 mm	435 mm	1
9	GEM 20 A	TAP	671 mm	160 mm	442 mm	1
10	GEM 20 B	TAP	671 mm	160 mm	442 mm	1
11	GEM 20 C	TAP	508 mm	160 mm	442 mm	1
12	BEA 14	CNC	752 mm	190 mm	410 mm	1
13	BEA 25	CNC	508 mm	160 mm	442 mm	1
14	BEX 15	CNC	446 mm	162 mm	352 mm	1
15	BEX 35	CNC	600 mm	200 mm	400 mm	1
(New)						

Figure 4-8. A table for function elements in the SPM database.

Each type of information has a specific *field* (column) as shown in **Figure 4-8**. The information for each SPM element is identified and entered in the right table for a specific category. Multiple tables can be opened at the same time so the user can browse and access the information in these tables. Additional figures about SPM Access database can be found in Appendix 9.7.

4.1.2 The design library of SPM elements

The information provided in the tables is not sufficient for the SPM assembly process, and 3D models for SPM elements should also be designed and stored to be used in performing the assembly process. These models are also important to provide a complete picture of how SPM elements are assembled using the information of the assembly features information in the database. SolidWorks was used in this work as the modelling software to design 3D models for SPM elements and to perform the assembly process for these elements. The 3D models were created in the *Part* modeller (Part document) and stored in the design library in SolidWorks. The design library has the ability to organise SPM

elements in categories by creating new folders for each category. **Figure 4-9** shows the design library in SolidWorks and the created SPM folders.

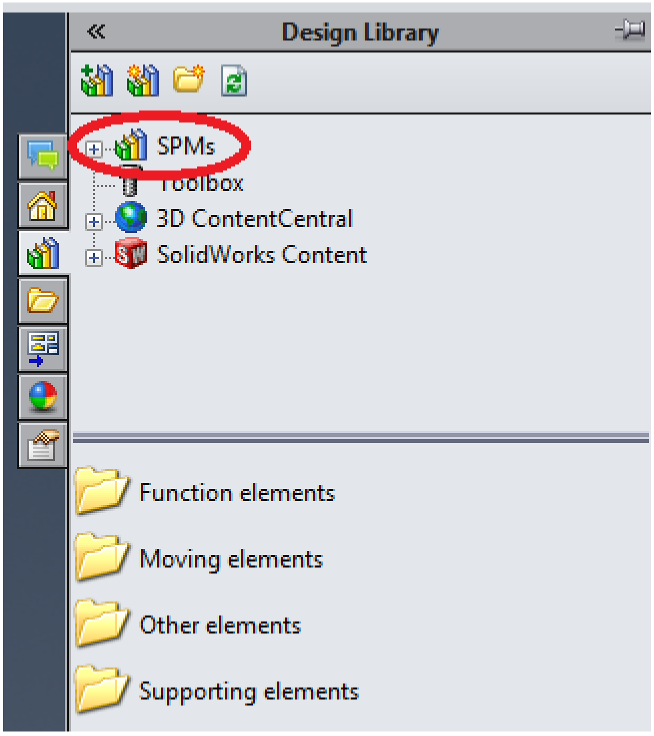
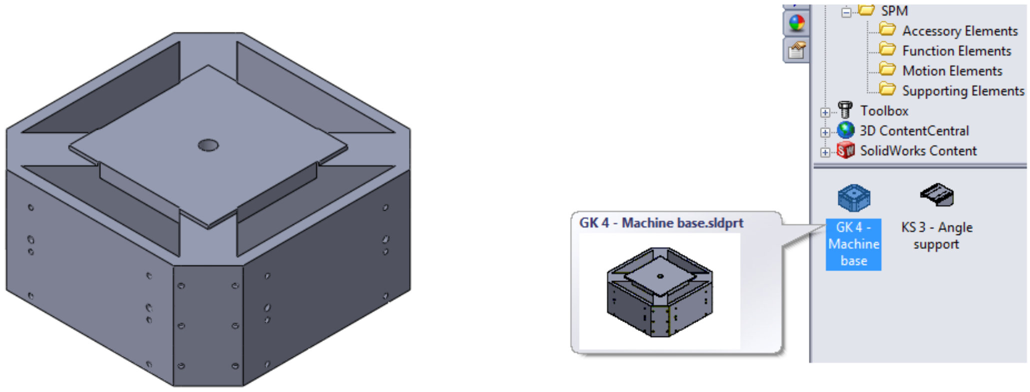


Figure 4-9. Creating the SPM folders in the design library in SolidWorks.

For each element, a 3D model was designed and added to the relevant folder. **Figure 4-10** shows an example of an SPM element designed in SolidWorks and added to the design library. A significant amount of effort has been put into making the large number of 3D models of the SPM elements required in this work, and some models that are downloaded from corporate websites have also been used. The availability of 3D models for SPM elements is important to determine the assembly relationships between these elements and this helps to create the assembly graph and the assembly relationships database for SPM elements.



(a) (b)

Figure 4-10. (a) A machine base designed in SolidWorks and (b) adding this element to the design library.

4.2 Assembly relationship graph

The assembly relationships between SPM elements were determined in this work and represented using an assembly relationship graph (ARG), as shown in **Figure 4-11**, which can address assembly problems [192, 193]. This graph is used to illustrate the combined relationships between SPM elements. Because the graph shows how these elements can be assembled, it helps to establish an assembly relationship database (ARDB) for SPM elements.

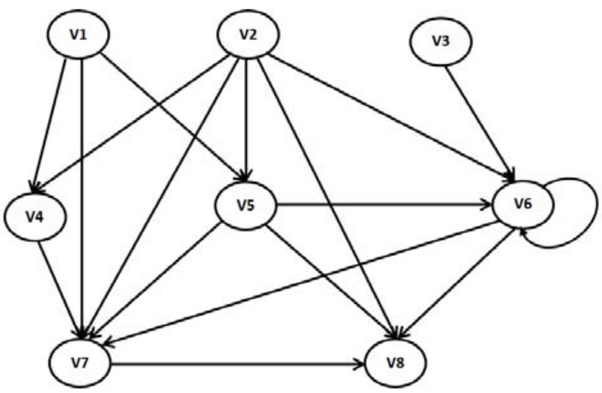


Figure 4-11. The assembly relationships graph (ARG).

Figure 4-11 shows a direct path (G) representing the assembly relationships between elements. From this graph:

$$G = (V, E)$$

$$V = \{v \mid v \equiv \text{ SPM elements}\}$$

$$E = \{e \mid e\,(vi\,,\, vj) \wedge (vi\,,\, vj \equiv V)\}$$

where V is a set of vertices, and each vertex represents an element. E indicates a set of direct pairs of members of V and the edge represents the assembly relationship between elements (*i* and *j*). The edge *e* ($vi \rightarrow vj$) indicates that element vi, which is the starting vertex of the edge *e*, can be assembled to element vj, which is the ending vertex of the edge *e*.

The number of edges going from a vertex denotes the outdegree of this vertex, and the number of coming edges to a vertex indicates the indegree of that vertex. If an element can be assembled to another of its own type, then the edge is called a self-loop [192]. A sequence of edges indicates a direct path that represents the possible assembly relationships between elements. If the indegree of a vertex in the ARG is zero (V1, V2, and V3 in **Figure 4-11**), then no other elements can be mounted to these elements. If the outdegree of a vertex is zero (V8 in **Figure 4-11**) then this element cannot be mounted to other elements. The ARG was used in this work to develop a model to represent the assembly relationships for SPM elements by referring to the information from the SPM database developed in Section 4.1. **Figure 4-12** illustrates selected SPM elements that were designed and stored in the design library, and **Figure 4-13** shows the developed ARG model of these elements.

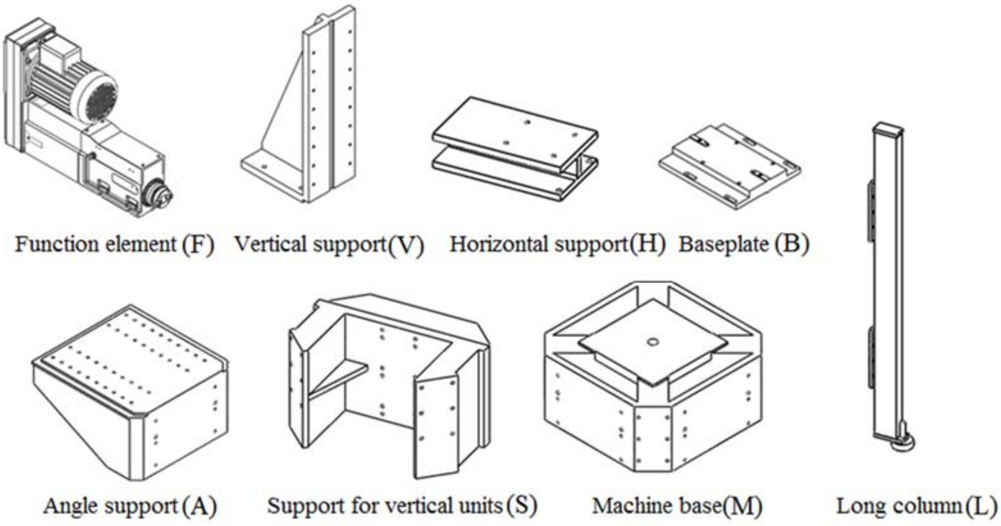


Figure 4-12. Different SPM elements designed and stored in the design library.

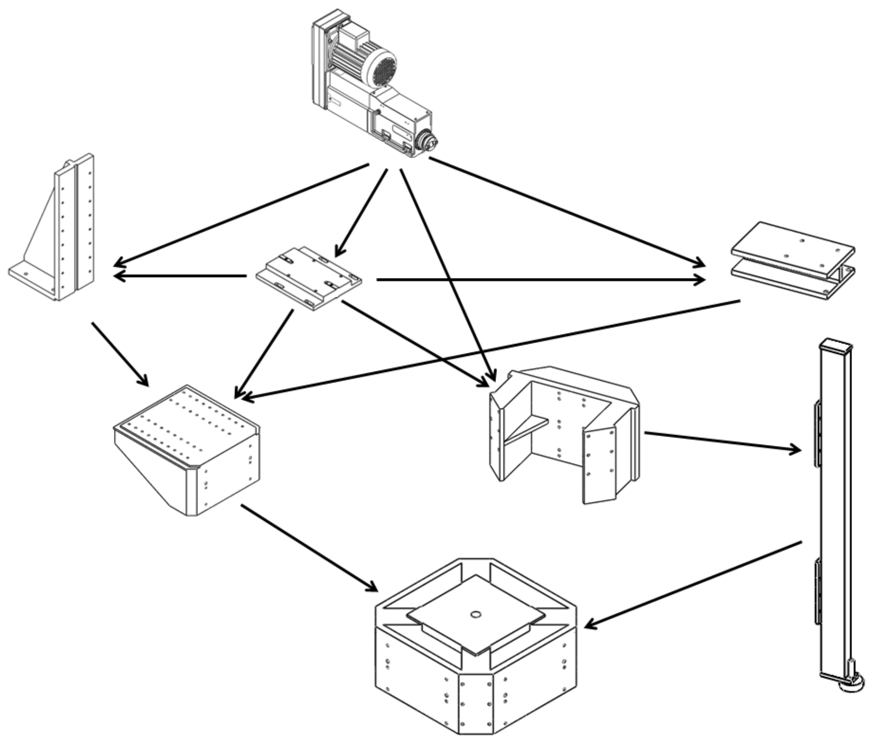


Figure 4-13. The developed ARG of SPM elements.

The assembly process of these elements should be accomplished by restricting the DOF between each pair of elements. The DOF between these elements were determined, and they are illustrated in matrix form in **Table 4-1**. In this table, F refers to a function element and A refers to an angle support and so on. Zero indicates that all DOF are eliminated between the two elements, and they cannot therefore be assembled, while number 3 indicates that there are three DOF between the two elements. These DOF were identified in this work as two linear (as the elements can slide on each other), and one rotational (as the elements can rotate around one axis relative to each other). **Figure 4-14** shows an example of these DOF between two elements (F and V) taken out from **Figure 4-10**.

Table 4-1. The DOF of SPM elements as determined from the ARG model. The elements are referred as the first letter of their names as shown in **Figure 4-12**.

	F	V	H	B	A	S	L	M
F	0	3	3	3	0	3	0	0
V	3	0	0	3	3	0	0	0
H	3	0	0	3	3	0	0	0
B	3	3	3	0	3	3	0	0
A	0	3	3	3	0	0	0	3
S	3	0	0	3	0	0	3	0
L	0	0	0	0	0	3	0	3
M	0	0	0	0	3	0	3	0

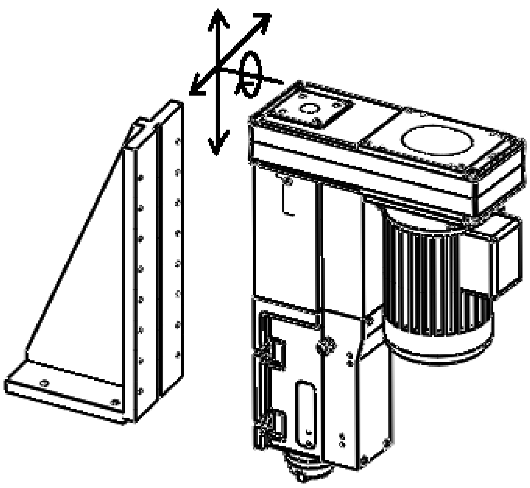


Figure 4-14. Three DOF, two linear and one rotational, between two SPM elements F and V.

4.2.1 Mating conditions identification and representation

SPM elements are standard designed components, and the position and orientation of their associated assembly features are therefore fixed [194]. In this case, a mark is used to represent the position of an assembly feature. The mark is defined by a point and a vector in the local coordinates of an element as follows [195]:

- Mark: *M*ar → (*P*nt, *V*ec).
- Point: *P*nt → (x, y, z).
- Vector: *V*ec → (ʋx, ʋy, ʋz).

Figure 4-15 shows the definition of the mark for plane and cylindrical faces. The mark of each assembly feature in an element can be identified and stored in the database as a property of that element. Mating conditions have been used to determine the assembly relationships between elements, and there are five mating conditions: against, fits, tight fits, contact, and coplanar [196].

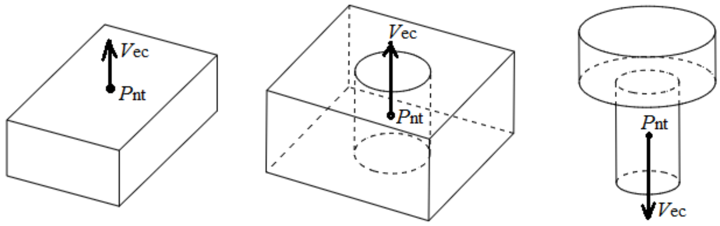


Figure 4-15. Three definitions of the mark for three different faces, one plane and two cylindrical.

The against condition is used when two faces (planar-planar or planar-cylindrical) are brought together as illustrated in **Figure 4-16 (a)**. The grey faces of the two elements are the faces to be mated. A point and a vector are used to specify each face: P1 and V1 for element 1, and P2 and V2 for element 2. To satisfy the against condition, the two vectors, V1 and V2, must oppose each other, and the two faces should touch each other [31]. The fits mating condition is used to hold two cylindrical faces as shown in **Figure 4-16 (b)**. To satisfy this condition, the axes for the cylindrical faces must be forced to be collinear.

The same principles for point and vector are used for the against condition. The against and fits mating conditions restrict some DOF for the combined elements: two rotational and one linear for the against condition (as Element 1 and Element 2 can slide in two directions and rotate in one direction (**Figure 4-16 (a)**), and two rotational and three linear for the fits condition (as Element 1 and Element 2 cannot slide in any direction and can only rotate in one direction (**Figure 4-16 (b)**). Therefore, additional mating conditions such as contact, tight fits, and coplanar, are required to achieve the fully defined assembly. The contact condition is used together with the against condition, while tight fits is used together with the fits condition to fully constrain the DOF. The coplanar condition is used to mate two faces when they lie in the same plane. It is similar to the against condition; however, the vectors of the mated faces should be in the same direction and not opposite to each other [31]. This representation was used in this work for SPM elements to determine the mating conditions as shown in **Table 4-2**.

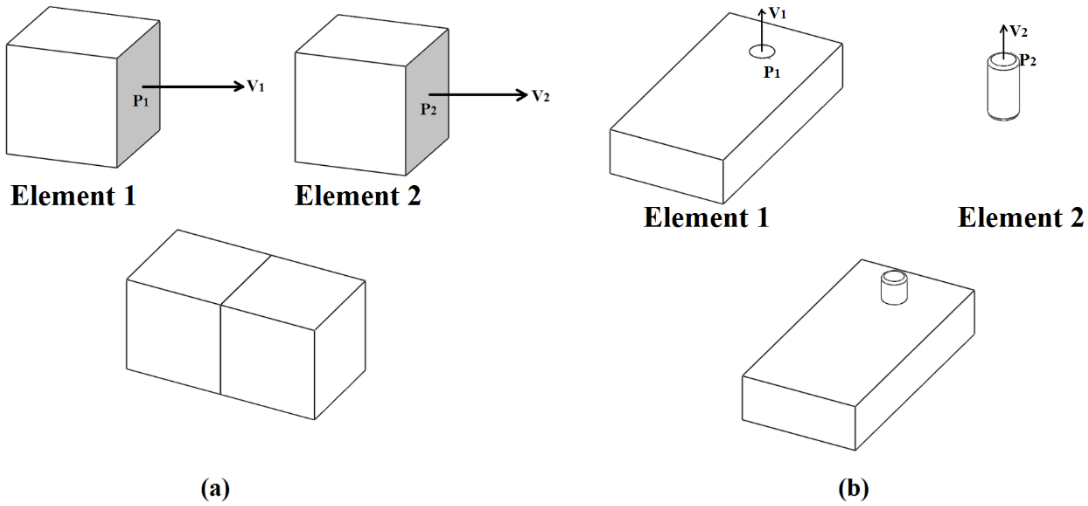


Figure 4-16. (a) The against condition between two faces, and (b) the fits mating condition between two elements. Element 2 is a pin with the cylindrical face and is assembled to element 1 by the fits condition with the hole.

Table 4-2. Examples of mating conditions between some of the SPM elements.

Element 1	Element 2	Mating condition
Function element	Vertical support	against and contact
Horizontal support	Angular support	against and contact
Long column	Machine base	against
Long column	Support for vertical units	against
Bolt	Function element	fits
Bolt	Vertical support	fits

The contact condition is used to coincide two parts by specifying two points, one on each part. It is usually used with the against condition to eliminate the undesired DOF that the against condition may allow. **Figure 4-17** shows the application of the contact condition. The faces $F_{1,1}$, $F_{2,1}$, and $F_{3,1}$ are related to Part 1, and faces $F_{1,2}$, $F_{2,2}$, and $F_{3,2}$ are related to Part 2. The against condition is used for these two parts between $F_{1,1}$ and $F_{1,2}$, between $F_{2,1}$ and $F_{2,2}$, and between $F_{3,1}$ and $F_{3,2}$. However, after applying these mating conditions, Part 1 can still slide against $F_{2,2}$. Therefore, the contact condition is used between points $P_{1,1}$ and

$P_{1,2}$ to coincide them, and this eliminates the relative movement of Part 1 to Part 2.

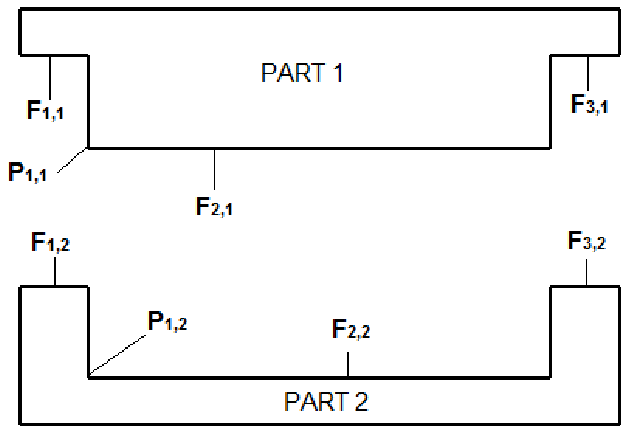


Figure 4-17. An example to illustrate the application of the contact condition with the against condition between two parts.

In order to identify the mating conditions between SPM elements, an algorithm was developed in this work. This algorithm is a part of the framework of the assembly approach that is explained in Section 4.3. First, the supporting and supported faces (F1 and F2 respectively) of the two elements are selected. Then, the mating conditions between these two elements are identified. Four cases are defined for mating conditions. Case 1 (against and contact) is applied if there is more than one locating hole on both faces. Case 2 (against, contact, and fits) is applied if there are one or more counterbore holes on the supported face aligned with screw holes on the supporting face. Case 3 (against, fits, and tight fits) is applied if there is a fixed slot on the supported face. Case 4 (fits and tight fits) is applied if the supported face is a screw. **Figure 4-18** shows these four cases, and the algorithm is presented in **Figure 4-19**.

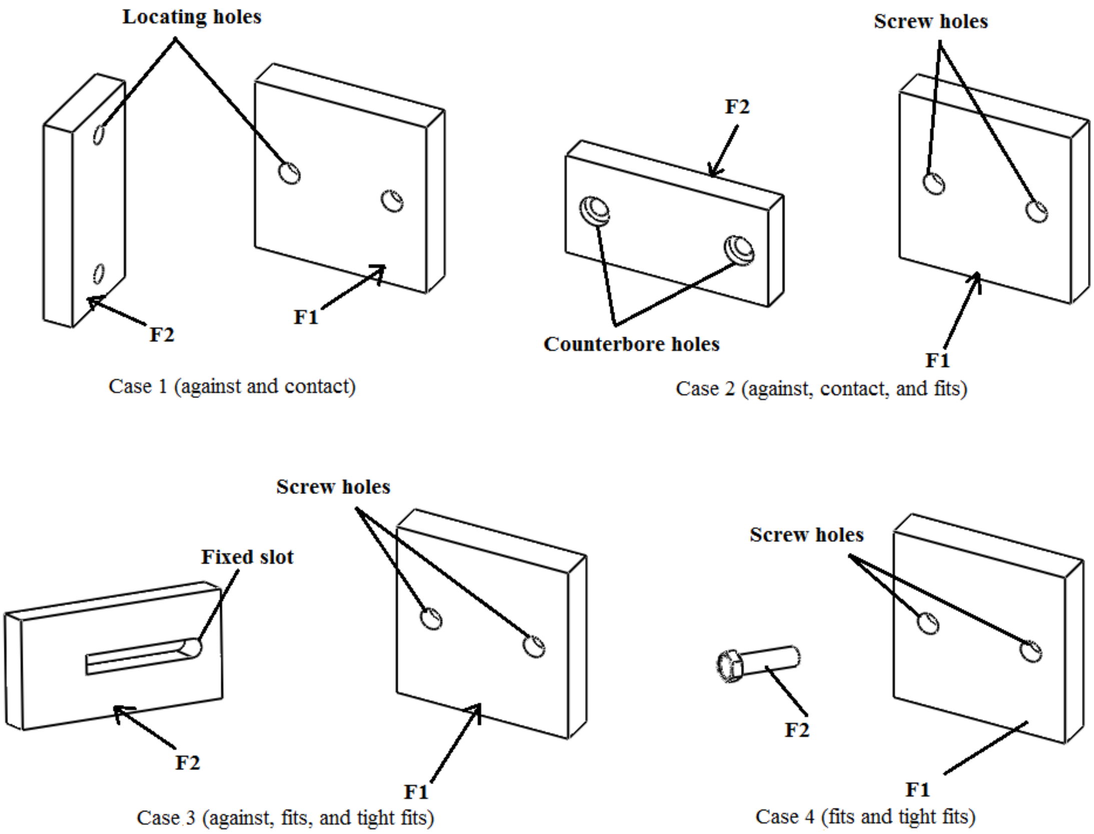


Figure 4-18. The four cases for mating conditions.

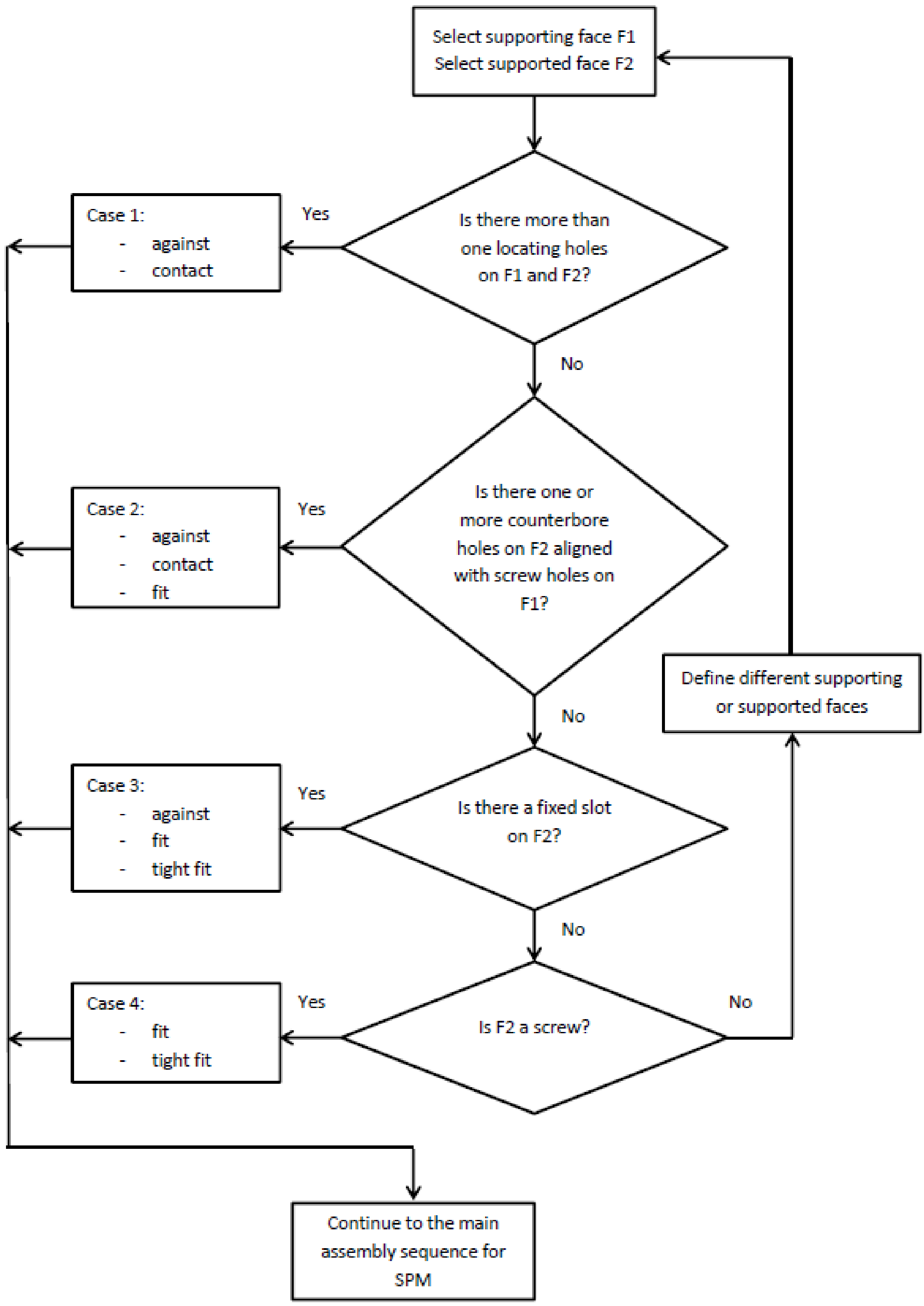


Figure 4-19. The algorithm for identifying mating conditions for SPM elements.

4.3 The framework of the assembly approach for SPMs

The assembly process of SPM elements is performed by using assembly mates, which are defined as parametric relations, and these mates are used to restrict the DOF of the elements. In the SPM design, it is important to constrain the movement of the elements in the layout to achieve a rigid design to meet the requirements of the SPM functions. This minimises errors that could occur during the SPM design process and creates a visual prototype for the design. Mates are derived from the relationships between geometric entities including planes, lines, points, circular edges, cylinder axes, surfaces, and spheres. Furthermore, mates create geometric relationships between these entities. These geometric relationships include coincident, concentric, distance, parallel, perpendicular, angle, and tangent relationships. Each mate is valid for combinations of entities. **Figure 4-13** defines the connection possibility for SPM elements and indicates the element that should be inserted first. The first element will be the assembly's base element, which provides a reference for numerous relationships among the elements, to support the assembly and act as a platform for the remaining elements [197]. In SPM assembly, the machine base (the M element in **Figure 4-12**) is selected as the base element because it has the largest number of supporting faces and can accommodate nine elements. An assembly sequence reasoning mechanism was developed in this work to determine the assembly degree between the elements as shown in **Figure 4-20**.

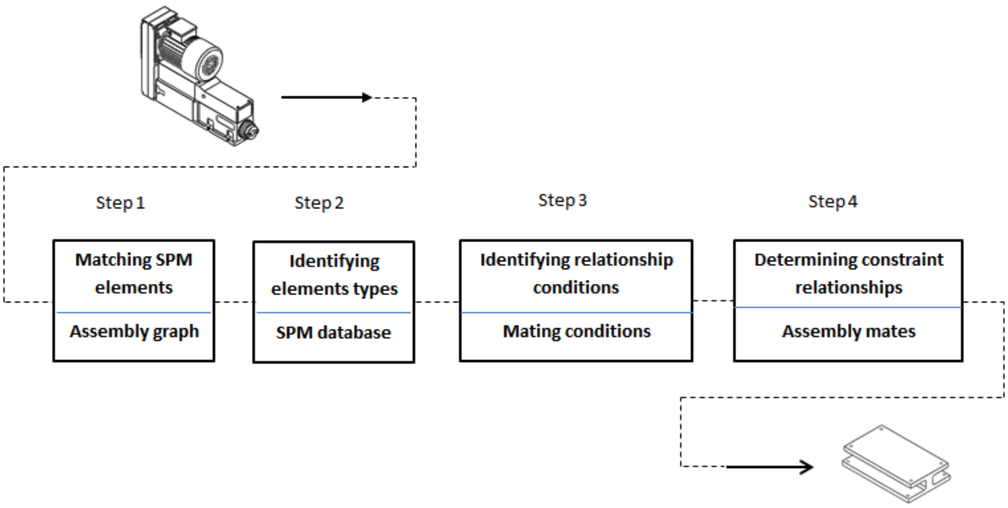
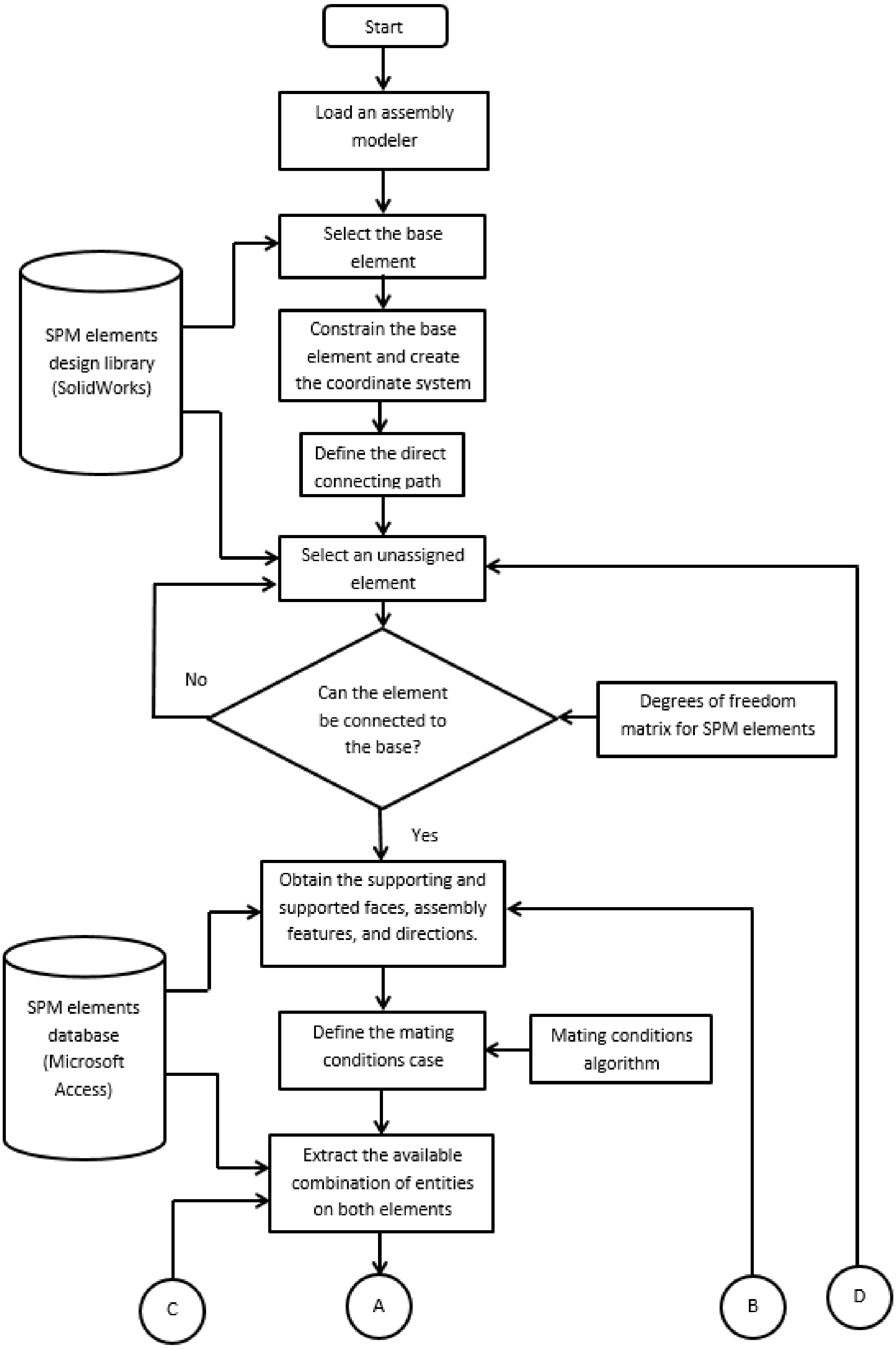


Figure 4-20. The assembly sequence reasoning mechanism for SPMs.

This reasoning mechanism consists of four steps. In step one, the assembly graph is generated to match the SPM elements. In step two, the database is used to identify the assembly features for each of the elements, and the mating conditions can therefore be identified (steps 2 and 3 in **Figure 4-20**). Finally, the type of mates needed to constrain these elements is determined. Based on the steps of the reasoning mechanism, the framework of the assembly modelling approach for SPM elements was developed in this work as shown in **Figure 4-21**.


Start
Load an assembly modeler
Select the base element
SPM elements design library (SolidWorks)
Constrain the base element and create the coordinate system
Define the direct connecting path
Select an unassigned element
No
Can the element be connected to the base?
Degrees of freedom matrix for SPM elements
Yes
Obtain the supporting and supported faces, assembly features, and directions.
SPM elements database (Microsoft Access)
Define the mating conditions case
Mating conditions algorithm
Extract the available combination of entities on both elements
C
A
B
D

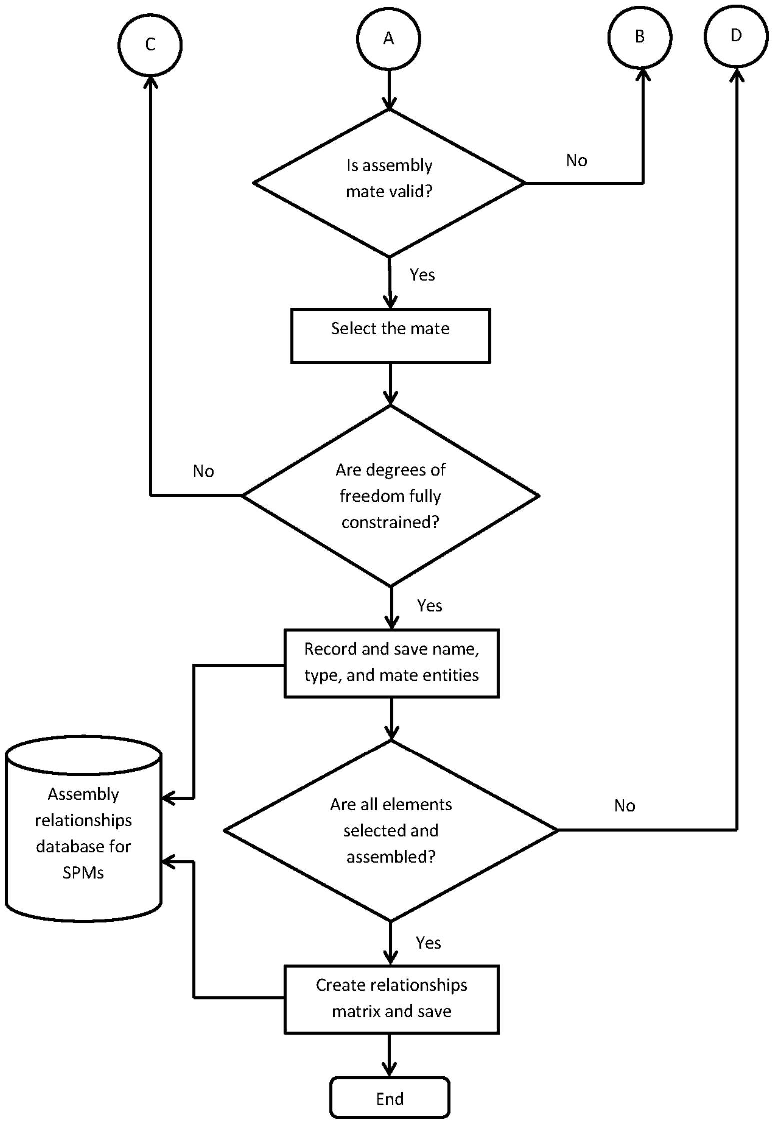


Figure 4-21. The framework of the developed assembly modelling approach for SPMs.

4.4 Implementation and Results

To implement the developed framework in **Figure 4-21** , the SPM elements shown in **Figure 4-12** were selected and their assembly graph is shown in **Figure 4-22**.

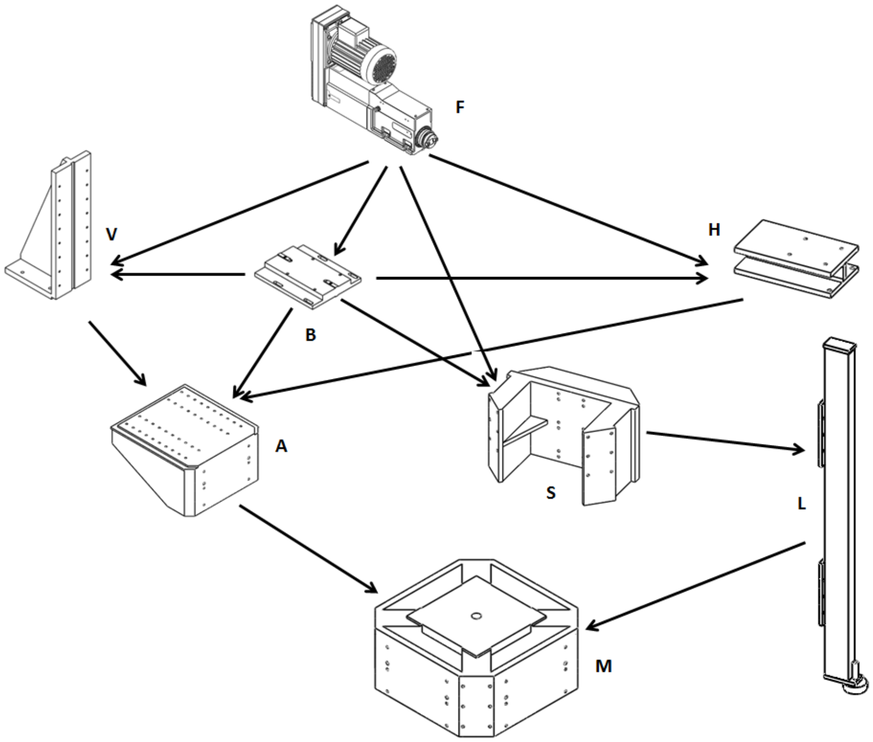


Figure 4-22. The assembly graph for the selected SPM elements.

From **Figure 4-22**, seven direct paths were identified to connect these SPM elements, as shown below:

F → V → A → M   F → S → L → M   F → B → V → A → M

F → B → A → M   F → H → A → M   F → B → H → A → M

F → B → S → L → M

These paths show the possibility of connecting these SPM elements. The selection of the proper path depends on the result from the SPM knowledge-base that was developed in Chapter 3. The direct connection path (F → H → A → M) was taken as an example to demonstrate the developed assembly approach for SPMs. From this path, the element that should be placed first is the machine base (M) and the next selected element is the angle support (A) as shown in **Figure 4-23**.

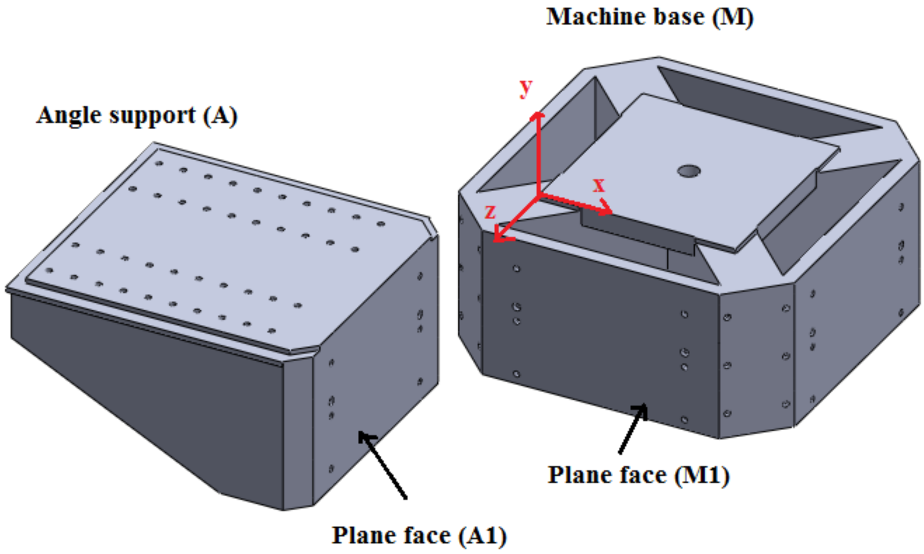


Figure 4-23. The angle support (A) is selected and inserted in the assembly.

The supporting and supported faces were obtained from the SPM database with their associated assembly features (Section 4.1), and the mating conditions were defined as against and contact from the developed algorithm in **Figure 4-19**. The types of entities, constraints, and assembly orientation were extracted as follows:

Assembly constraint 1

- Name : coincident 1
- Type: coincident
- Entity type1: plane face (M1)
- Assembly orientation: 0, 0, 1
- Entity type2: plane face (A1)
- Assembly orientation: 0, 0, -1
- Associated elements: machine base (M) and angle support (A).

The assembly constraint 1 positions the faces M1 and A1 opposite each other; however, it does not restrict all the DOF of element A. Element A is still able to slide on element M in two directions along the x and y axes and can rotate about

the z axis as shown in **Figure 4-24**. Therefore, another constraint is required, and it was extracted as follows:

Assembly constraint 2

- Name : concentric 1
- Type: concentric
- Entity type1: circular edge (M11)
- Assembly orientation: 0, 0, 1
- Entity type2: circular edge (A11)
- Assembly orientation: 0, 0, -1
- Associated elements: machine base (M) and angle support (A).

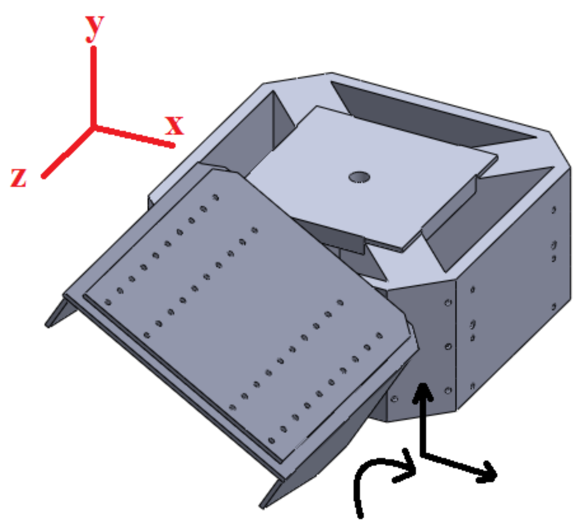


Figure 4-24. Element A still able to move along x and y directions and rotate about z after applying the constraint 1.

The second constraint restricts five DOF of the element A, yet this element is still able to rotate about one direction (z). Therefore, a third constraint was extracted as follows:

Assembly constraint 3

- Name : concentric 2

- Type: concentric
- Entity type1: circular edge (M12)
- Assembly orientation: 0, 0, 1
- Entity type2: circular edge (A12)
- Assembly orientation: 0, 0, -1
- Associated elements: machine base (M) and angle support (A).

Now element A is fully constrained. After assembling element A, the next element, which is the horizontal support (H), was selected to be assembled to element A. The same sequence was applied and the constraints were extracted as follows:

Assembly constraint 4

- Name : coincident 2
- Type: coincident
- Entity type1: plane face (A2)
- Assembly orientation: 0, 1, 0
- Entity type2: plane face (H1)
- Assembly orientation: 0, -1, 0
- Associated elements: angle support (A) and horizontal support (H).

Assembly constraint 5

- Name : concentric 3
- Type: concentric
- Entity type1: circular edge (A21)
- Assembly orientation: 0, 1, 0
- Entity type2: circular edge (H11)
- Assembly orientation: 0, -1, 0
- Associated elements: angle support (A) and horizontal support (H).

Assembly constraint 6

- Name : concentric 4
- Type: concentric

- Entity type1: circular edge (A22)
- Assembly orientation: 0, 1, 0
- Entity type2: circular edge (H12)
- Assembly orientation: 0, -1, 0
- Associated elements: angle support (A) and horizontal support (H).

After assembling element H, the next element, which is the function element (F), was selected to be assembled to element H. The extracted constraints were as follows:

Assembly constraint 7

- Name : coincident 3
- Type: coincident
- Entity type1: plane face (H2)
- Assembly orientation: 0, 1, 0
- Entity type2: plane face (F1)
- Assembly orientation: 0, -1, 0
- Associated elements: horizontal support (H) and function element (F)

Assembly constraint 8

- Name : concentric 5
- Type: concentric
- Entity type1: circular edge (H21)
- Assembly orientation: 0, 1, 0
- Entity type2: circular edge (F11)
- Assembly orientation: 0, -1, 0
- Associated elements: horizontal support (H) and function element (F).

Assembly constraint 9

- Name : concentric 6
- Type: concentric
- Entity type1: circular edge (H22)
- Assembly orientation: 0, 1, 0

- Entity type2: circular edge (F12)
- Assembly orientation: 0, -1, 0
- Associated elements: horizontal support (H) and function element (F).

Overall, nine constraints were needed to fully restrict the DOF for the assembled elements as shown in **Figure 4-25**, and the relationships matrix was created (**Table 4-3**).

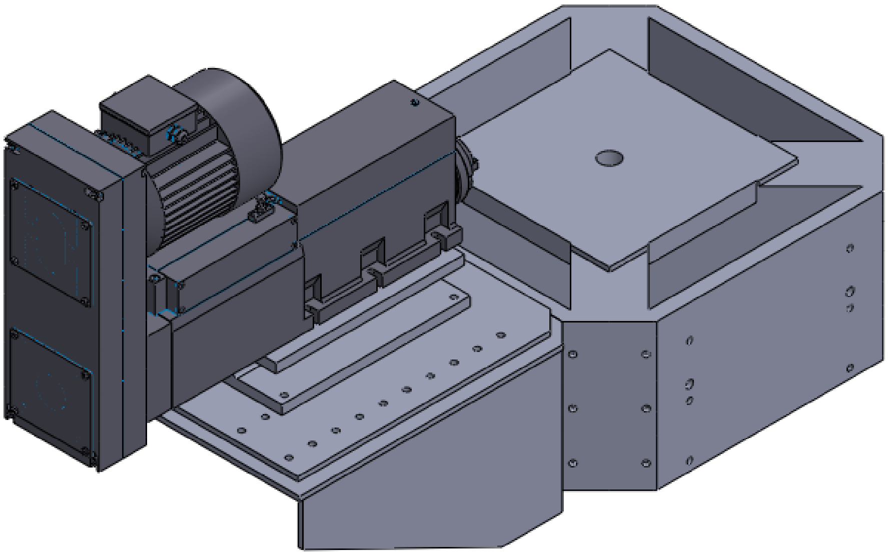


Figure 4-25. The elements M, A, H, and F are assembled in by applying the developed assembly sequence.

Table 4-3. The relationships matrix for the SPM elements shown in **Figure 4-25**.

	M	A	H	F
M	0	3	0	0
A	3	0	3	0
H	0	3	0	3
F	0	0	3	0

This procedure was applied for all elements until the SPM layout was completed. Before applying the developed assembly approach, it is important to define the number of SPM elements and workstations. This step can be completed by using the SPM knowledge-base that was developed in Chapter 3. The design of the workpiece should also be taken into consideration to define the

number of SPM elements and stations. To examine the application of the developed assembly modelling approach, the workpiece that was used in Chapter 3 was selected as an example (**Figure 4-26**).

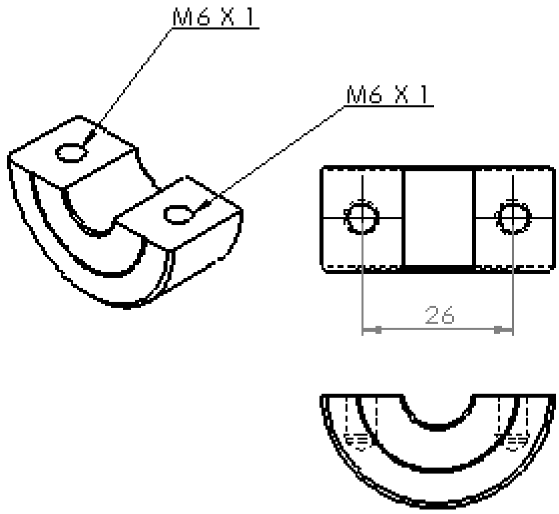


Figure 4-26. The design of the selected workpiece.

This workpiece requires two taps of size M6 to be machined. The results from applying the SPM knowledge-base were:

- Two stations are required to complete the machining process.
- Two machining units (function elements) are needed, one for drilling and one for tapping.
- Two horizontal supports are needed.

In order to complete the SPM layout for machining this workpiece, other elements are needed, and they were identified and presented in this work in the assembly graph in **Figure 4-27**.

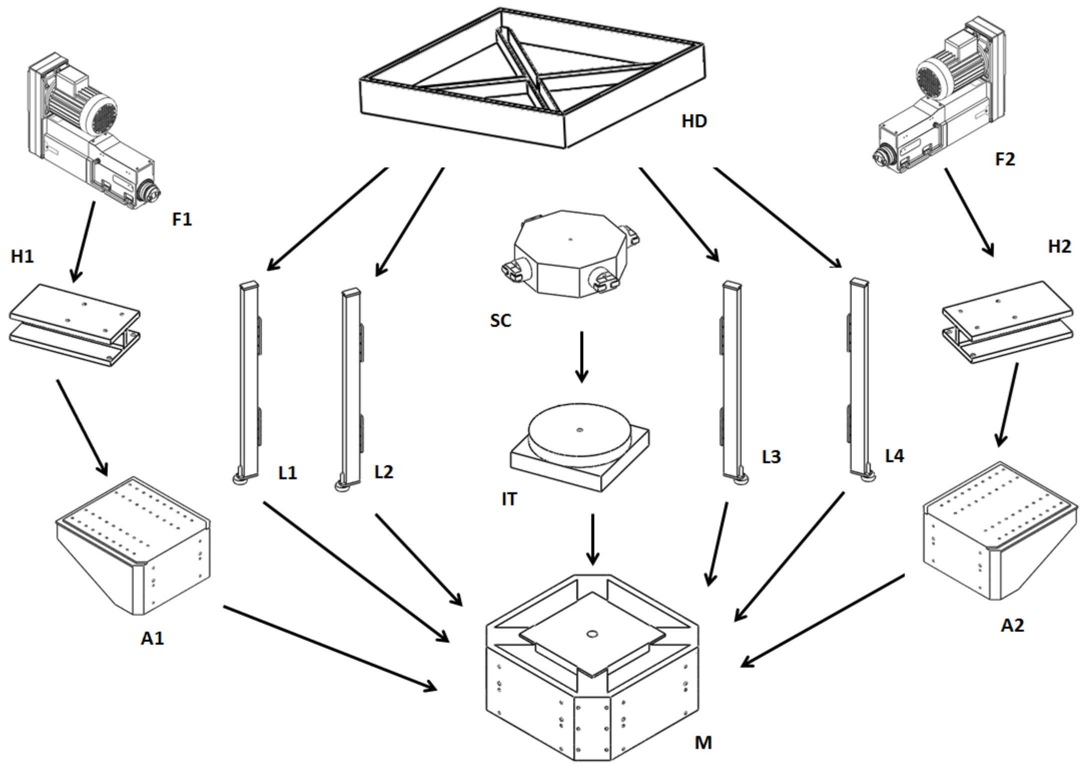


Figure 4-27. The assembly graph of the SPM elements that are required to complete the layout for machining the workpiece shown in **Figure 4-26**.

The elements that are connected to the machine base (M) were selected and assembled first. These elements are A1, A2, L1, L2, L3 L4, and IT. The assembly constraints for these elements were extracted. Examples of these constraints are as follows:

Assembly constraint 1:

- Name : coincident 1
- Type: coincident
- Entity type1: plane face (M1)
- Assembly orientation: 0, 0, 1
- Entity type2: plane face (A11)
- Assembly orientation: 0, 0, -1
- Associated elements: machine base (M) and angle support (A1).

Assembly constraint 2:

- Name : concentric 1
- Type: concentric
- Entity type1: circular edge (M11)
- Assembly orientation: 0, 0, 1
- Entity type2: circular edge (A111)
- Assembly orientation: 0, 0, -1
- Associated elements: machine base (M) and angle support (A1).

Assembly constraint 3:

- Name : concentric 2
- Type: concentric
- Entity type1: circular edge (M12)
- Assembly orientation: 0, 0, 1
- Entity type2: circular edge (A112)
- Assembly orientation: 0, 0, -1
- Associated elements: machine base (M) and angle support (A1).

Assembly constraint 4:

- Name : coincident 2
- Type: coincident
- Entity type1: plane face (M2)
- Assembly orientation: -1, 0, 0
- Entity type2: plane face (A21)
- Assembly orientation: 1, 0, 0
- Associated elements: machine base (M) and angle support (A2).

Assembly constraint 5:

- Name : concentric 3
- Type: concentric
- Entity type1: circular edge (M21)
- Assembly orientation: -1, 0, 0

- Entity type2: circular edge (A211)
- Assembly orientation: 1, 0, 0
- Associated elements: machine base (M) and angle support (A1).

Assembly constraint 6:

- Name : concentric 4
- Type: concentric
- Entity type1: circular edge (M22)
- Assembly orientation: -1, 0, 0
- Entity type2: circular edge (A212)
- Assembly orientation: 1, 0, 0
- Associated elements: machine base (M) and angle support (A1).

The above constraints are for assembling elements A1 and A2 with the machine base M. The same procedure was followed for the rest of the elements until the whole machine layout was completed as shown in **Figure 4-28**. In total, 39 assembly constraints were extracted for all the elements in this layout. The relationship matrix is shown in **Table 4-4**, and the extracted assembly constrains for each of these elements were stored in the SPM database.

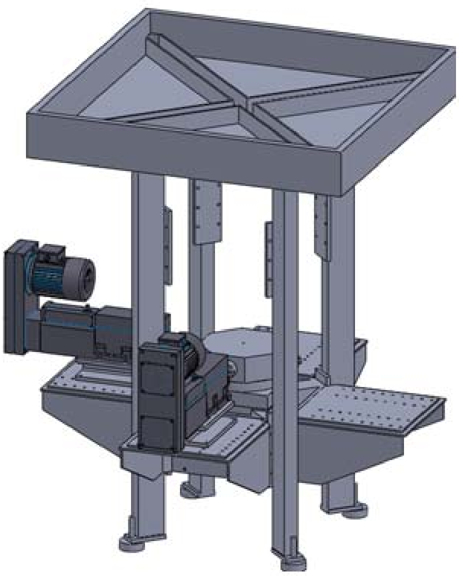


Figure 4-28. The complete SPM layout for the selected workpiece.

Table 4-4. The relationship matrix of the SPM elements.

	F1	F2	H1	H2	A1	A2	L1	L2	L3	L4	SC	IT	M	HD
F1	0	0	3	0	0	0	0	0	0	0	0	0	0	0
F2	0	0	0	3	0	0	0	0	0	0	0	0	0	0
H1	3	0	0	0	3	0	0	0	0	0	0	0	0	0
H2	0	3	0	0	0	3	0	0	0	0	0	0	0	0
A1	0	0	3	0	0	0	0	0	0	0	0	0	3	0
A2	0	0	0	3	0	0	0	0	0	0	0	0	3	0
L1	0	0	0	0	0	0	0	0	0	0	0	0	3	2
L2	0	0	0	0	0	0	0	0	0	0	0	0	3	0
L3	0	0	0	0	0	0	0	0	0	0	0	0	3	0
L4	0	0	0	0	0	0	0	0	0	0	0	0	3	0
SC	0	0	0	0	0	0	0	0	0	0	0	3	0	0
IT	0	0	0	0	0	0	0	0	0	0	3	0	3	0
M	0	0	0	0	3	3	3	3	3	3	0	3	0	1
HD	0	0	0	0	0	0	2	0	0	0	0	0	1	0

The pre-defined constraints for the SPM elements were used in this work to generate a code in Visual Basic programming language. This code was then implemented in SolidWorks API to automatically orientate and assemble the elements into the required positions during the assembly process. This can be explained by taking the elements (M and A) in **Figure 4-23** as an example. The traditional assembly process of these two elements in SolidWorks involves three steps as follows:

Step 1: Element A should be placed in the design environment.

Step 2: Element A is repositioned to be in the opposite direction of the plane face (M1).

Step 3: Element A is assembled to element M.

These steps are applied and repeated to assemble each element A to element M in the SPM layout. In SPMs, up to six A elements can be needed in the assembly, and the above three steps should be applied for each of these A elements. These three steps were reduced to only one step in this work by implementing the pre-defined constraints in SolidWorks API. In addition, the assembly process of all A elements to element M in the layout was completed in one step only without the need to repeat the three steps for each A element.

Therefore, the assembly time for these elements was reduced significantly. The results achieved in this chapter show how the limitations of the traditional assembly process of SPM layouts are eliminated by the developed assembly approach in this chapter. This was stated in the literature review Section 2.6.1 as one of the major limitation in the design process of SPMs. The trial and error methods as well as the unnecessary steps in the traditional process are all avoided in the developed approach, and as a result, the assembly time is reduced significantly. To evaluate the incorporation of the proposed approach in a full application, it is used to assemble a complete layout of an SPM for machining holes and taps on the workpiece shown in **Figure 4-29**.

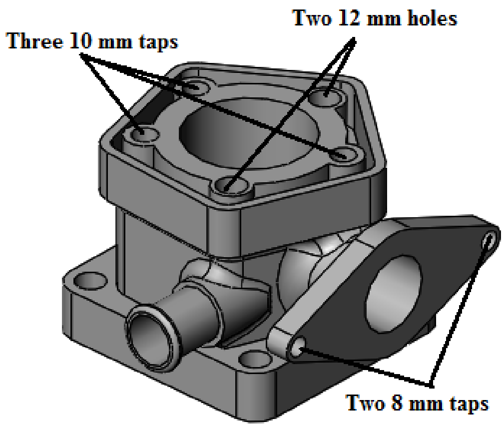


Figure 4-29. A designed cylinder of motorbike engines with holes and taps required for machining by an SPM.

The time required for the assembly process is reduced by more than 90% compared to the traditional assembly process: more than 9 minutes were required for the traditional process, while around 50 seconds only are needed when the developed approach is used. The complete SPM layout for machining the required hole and taps is shown in **Figure 4-30**.

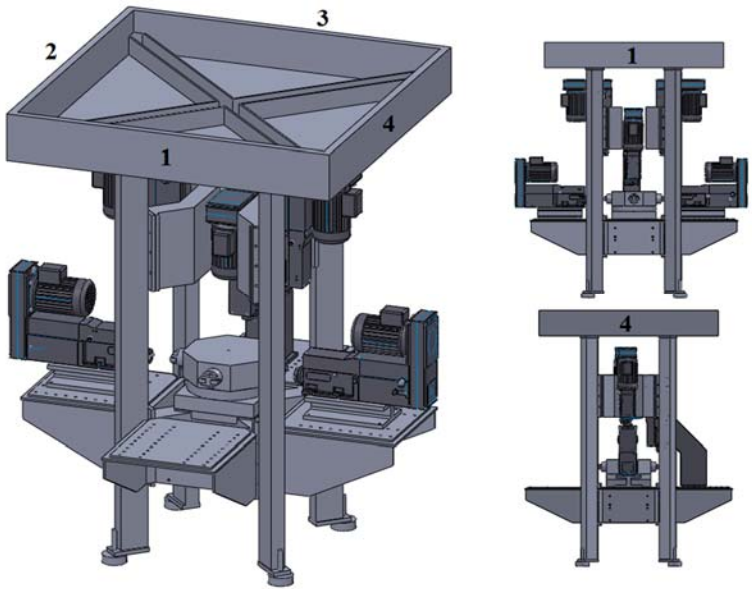
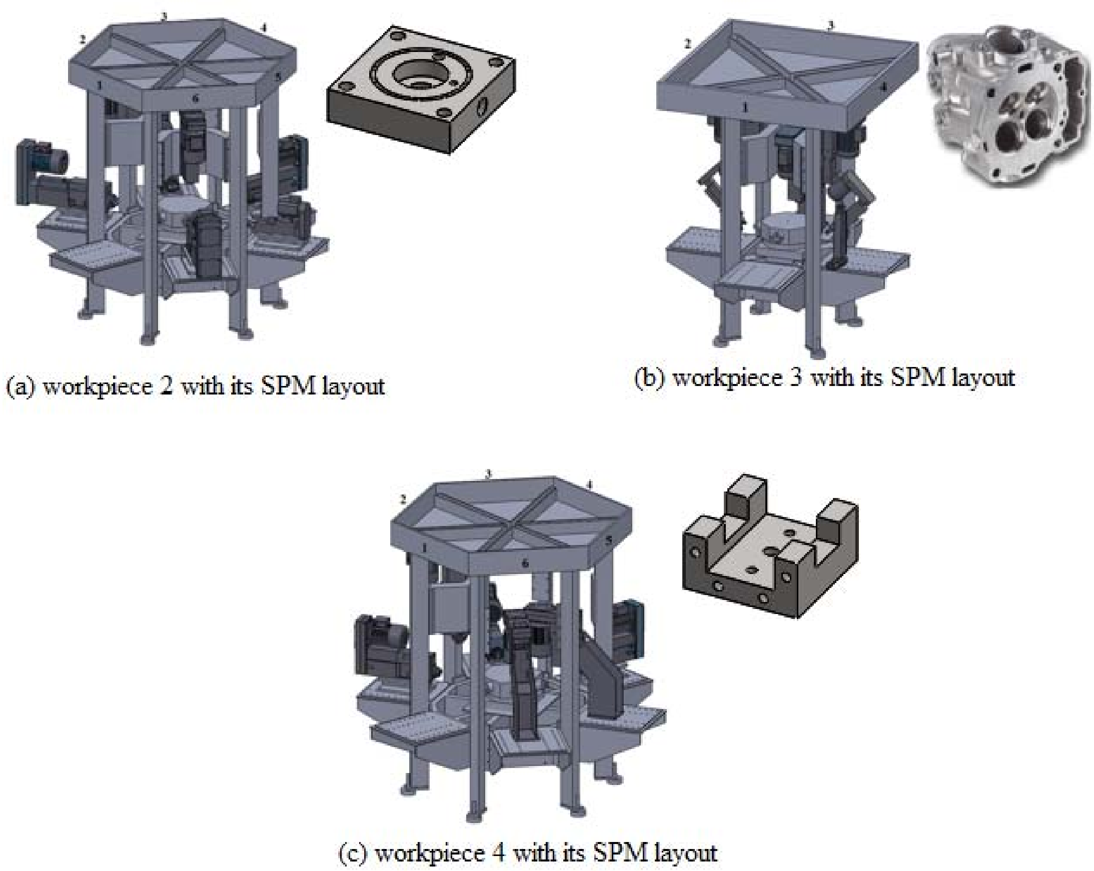


Figure 4-30. The complete SPM layout after applying the assembly approach for the selected workpiece shown in Figure 4.29. The layout has four stations as numbered to perform the required machining operations.

The assembly approach that has been developed in this chapter is also applied to other workpieces which are illustrated in **Figure 4-31** with their relevant SPM layouts. The size and number of the machining features (holes and taps) are different for these workpieces. In addition, the machining direction is also varied; therefore, this has affected the type and number of SPM elements as well as the type of the layout (four or six stations). The time required for the assembly of all workpieces by the traditional process versus the proposed approach is represented in **Figure 4-32**. Applying the proposed approach has reduced the assembly time significantly, and on average, a time reduction of 89% is achieved for these workpieces. Although the number of stations affects the assembly process and time, the number and type of SPM elements also have an impact. For example, and by comparing workpiece 2 with workpiece 4, fewer SPM elements are needed for assembling the layout of workpiece 4 with the same number of stations for both workpieces. In addition, the layouts for workpieces 1 and 3 have the same number of stations and SPM elements; however, more time is required for workpiece 3 than workpiece 1. This is because different types of SPM

elements with different interfacing features are used in the layout of workpiece 3, and this resulted in a longer assembly time.



(a) workpiece 2 with its SPM layout

(b) workpiece 3 with its SPM layout

(c) workpiece 4 with its SPM layout

Figure 4-31. Different workpieces and their SPM layouts, which were assembled by the proposed approach.

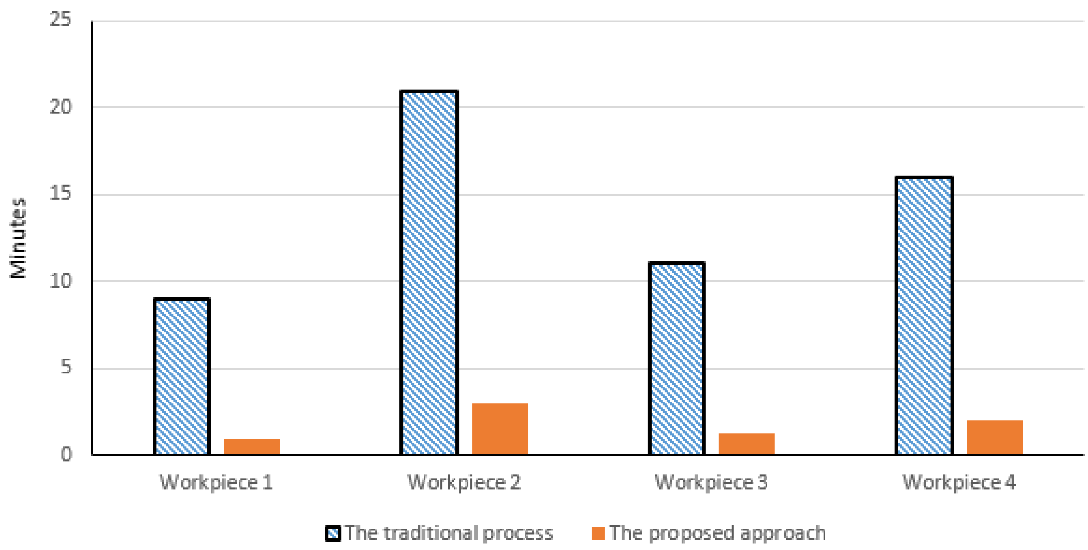


Figure 4-32. Assembly time for various workpieces in the traditional process versus assembly time in the proposed approach.

4.5 Summary

This chapter has explained the development of an assembly modelling approach for SPM layouts. This development included creating a database and a design library for SPM elements. An assembly relationships graph was also used to define the assembly relationships between SPM elements. A framework for assembly modelling was developed and implemented in SolidWorks API. The developed approach was applied to a practical workpiece in order to assemble the required SPM layout. The application of the approach developed in this work resulted in a significant reduction in the assembly time for the SPM layout, and this would help to reduce the overall design time for SPMs.

Chapter Five

5. Automation of layout selection for SPMs

This chapter introduces the CBR approach for SPMs developed during this research project and the integration of this approach with SolidWorks. This integration includes the other components that were developed in the previous chapters: the SPM knowledge-base, the SPM database, and the assembly modelling approach. A new menu called SPM system was created in the SolidWorks design environment, and this menu was extended to sub-menus related to each of the above components. The integration was completed using SolidWorks API features. As a result, an integrated system for SPMs was developed in this work, as shown in **Figure 5-1**, to automate the selection of SPM layouts and reduce the design time for the SPM layouts in overall.

5.1 Case-based reasoning for SPMs

There are three main stages of the CBR method to be used in SPM: indexing, retrieval, and modification. Indexing is important for the identification of similar cases by using indices in order to create a code for the target case. This code is used in the retrieval stage of similar cases. These indices, which are converted to a code, are related to the specifications of and information about the target case, and they differ from one application to another. Different approaches have been implemented for indexing the target cases and retrieving similar cases in the case-base [60, 157, 198-201]. For SPMs, it is important to consider design and machining information as indices in the indexing of the target case. These indices are referred to here as attributes (design and machining information attributes). These attributes are divided into two levels: the first level is related to the workpiece attributes, and the second level is related to the machining information of SPMs. The reason for dividing the attributes is to make the retrieval stage simple and more effective. Therefore, two levels of the retrieval stage are used for SPMs, as shown in **Figure 5-1**.

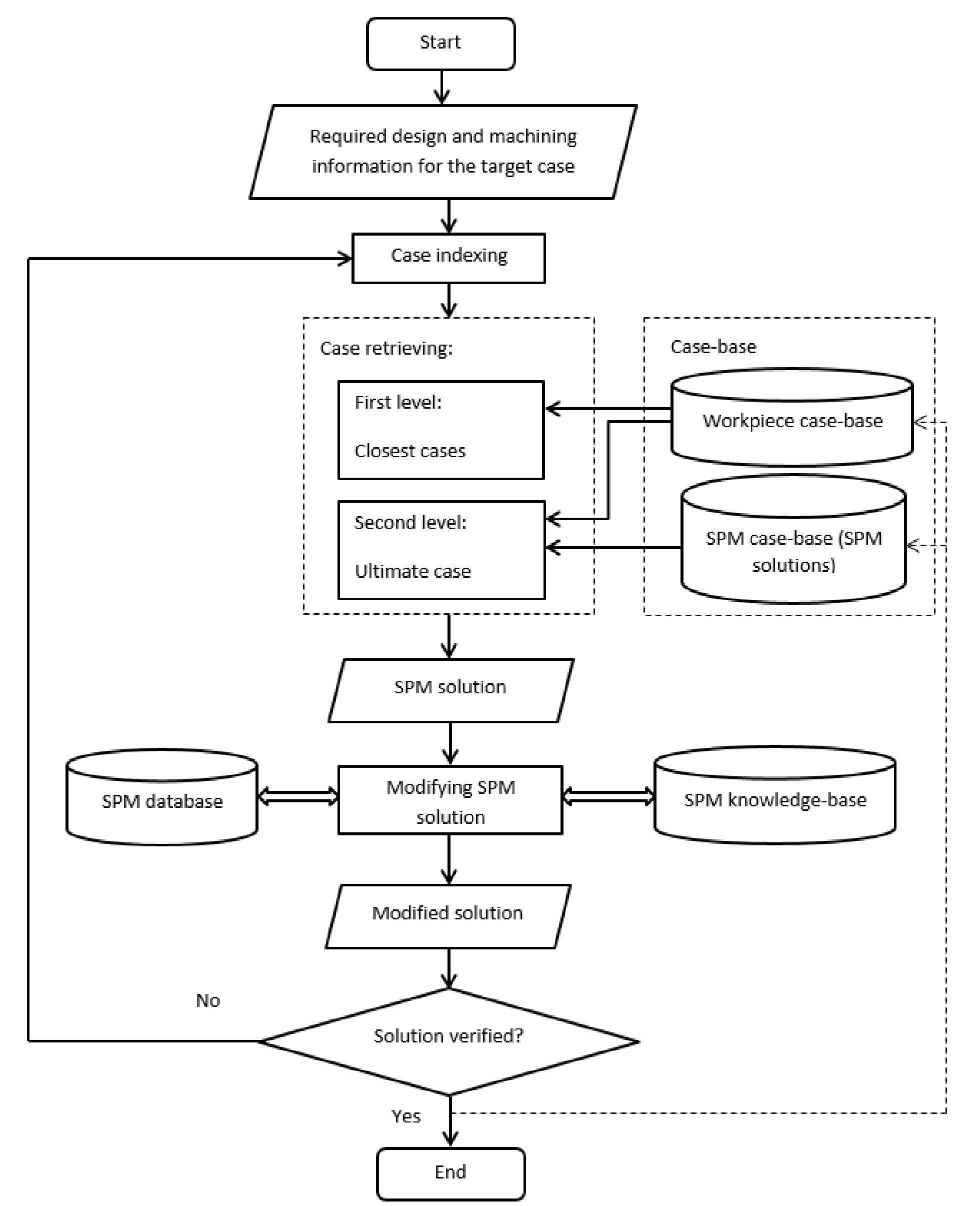


Figure 5-1. The framework of the integrated system for SPMs.

5.1.1 The indexing system

The first level of indexing is applied to the design attributes of the target workpiece. This is performed by an indexer that generates a code for the target workpiece to be used in retrieving similar cases from the workpiece case-base as a first retrieving level. After that, the second level of retrieval is applied to the machining attributes to match similar workpieces with the SPM cases stored in

the SPM case-base in order to identify the closest case. For this purpose, workpiece design attributes were identified based on design perspectives and standard classification systems. The indexing for these attributes was developed in this work as shown in **Table 5-1**. In addition, the machining attributes were also identified and their indexing is shown in **Table 5-2**. The case-base in this CBR approach is divided into two levels: a workpieces case-base and an SPM case-base. The workpiece case-base contains the codes for the stored workpieces as well as their specifications and design information. The SPM case-base includes the codes and the necessary information for SPM cases.

Table 5-1. The indexing for the workpiece attributes.

Workpiece attributes	Code	Description
Workpiece class	1 2	Flat components Cubic components
Workpiece shape	1	Plane, rectangular
Workpiece size	1 2 3	Small size Medium size Large size
Number of machined surfaces	1 2 3	Only one plane surface is machined Plane stepped surfaces – one holding position Plane stepped surfaces at right angles, inclined and /or opposite
Number of holes / holes pattern	1 2 3 4	One hole drilled in one direction One hole drilled in more than one direction Hole patterns in one direction Hole patterns in more than one direction
Workpiece material	1 2 3 4	Cast iron Steel Brass Aluminium

Table 5-2. The indexing for the machining attributes.

Machining attributes	Code	Description
Machining type	1 2 3	Drilling Tapping Drilling and Tapping
Number of machined workpieces	1 2	One workpiece at the time Two workpieces at the time
Machining axis	1 2 3 4 5 6	Horizontal Vertical Horizontal and vertical Inclined Horizontal and inclined Vertical and inclined
Number of machined surfaces	1 2	Only one surface is machined Two surfaces are machined
Workpiece holding mechanism	1 2	Workpiece fixed Workpiece moving
Type of workpiece transfer	1 2 3 4	Self-centring clamping- SPB Double self-centring clamping-DSC Special transfer- ST No transfer
Holes or taps pattern on one surface	1 2 3 4 5 6 7	One hole or tap Two holes or taps- same size Two holes or taps- different size Three holes or taps- same size Three holes or taps- different size Four holes or taps – same size Four holes or taps- different size

By applying this indexing system, a code of 13 digits is generated by the indexer module. The first six digits are for the workpiece attributes that are used for the first level case retrieval, and the following seven digits are for the machining attributes that are used for the second level case retrieval as well as the matched attributes from the first level. After the indexing of the new target case and the generation of the code, the retrieval process is started. Both indexing and retrieval are included in a principle stage of the CBR method called Recall, as illustrated in the model shown in **Figure 5-2**.

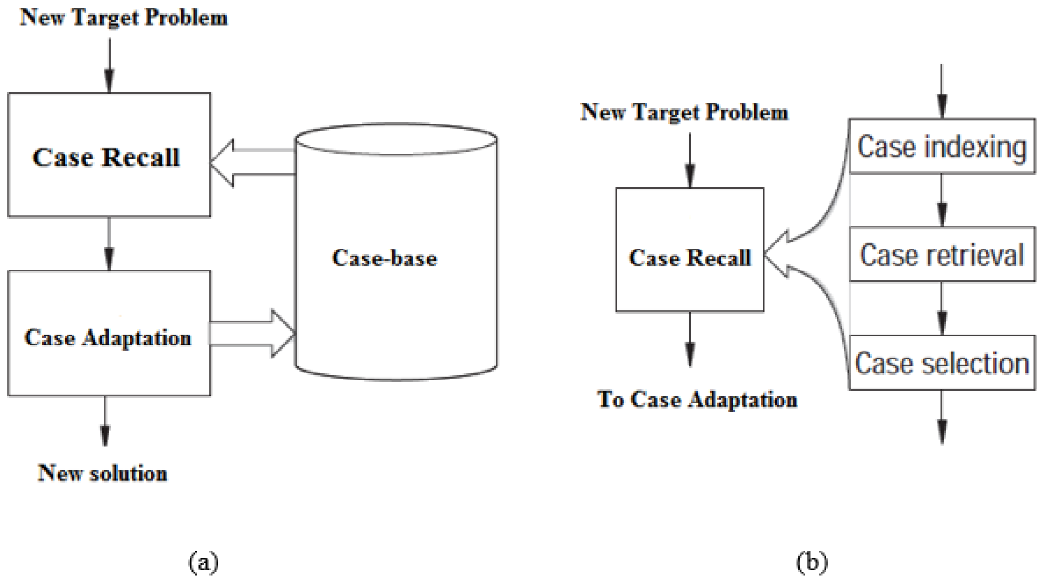


Figure 5-2. (a) The overall CBR model, and (b) the steps of recall process.

The recall stage is divided into indexing, retrieval, and selection. Indexing is related to identifying the attributes, as explained in the previous section, and to generating the code for the target case. Retrieval is a process of determining the cases in the case-base that have attributes in common with the target case. Selection is a computation of the degree of similarity of these cases and their ranking [202].

The indexing system introduced in Section 5.1.1 can be implemented by simply asking the user to enter the specifications of the target case and use these specifications as indexing attributes. These specifications are transformed into a code pattern to be matched with the cases in the case-base. A general approach that can be used for generating a code pattern to index the target case is given below:

- Start
  - Identify specifications of the target case
  - Organise specifications as attributes
    - Specify required attributes for indexing
    - Enter attributes
  - Generate a code pattern for matching
- End

5.1.2 Retrieval Cases

The task for the retrieval process in CBR is to search for matches between the target case and the cases in the case-base by using the generated code pattern in the indexing. The retrieval process can lead to a perfect match with the code pattern or to a partial match. In the case of a partial match, a threshold needs to be determined to refine the matched cases. A general approach for this process is given below:

- Start
  Get the code pattern to match
    Compare with all relevant cases
    Determine how close the matching is
    If matching > = threshold
    Then add case to the retrieved list
  Output list of retrieved cases
- End

The target case can be described as an attribute-code schema as follows:

< Target case >
< Attribute (1)> : < code (1)>
< Attribute (2)> : < code (2)>
< Attribute (3)> : < code (3)>
. .
< Attribute (j)> : < code (j)>

For each attribute (j), a code (j) is determined and a code pattern is generated as:

Code pattern = [code (1) | code (2) | code (3) | ………. | cod (j)]

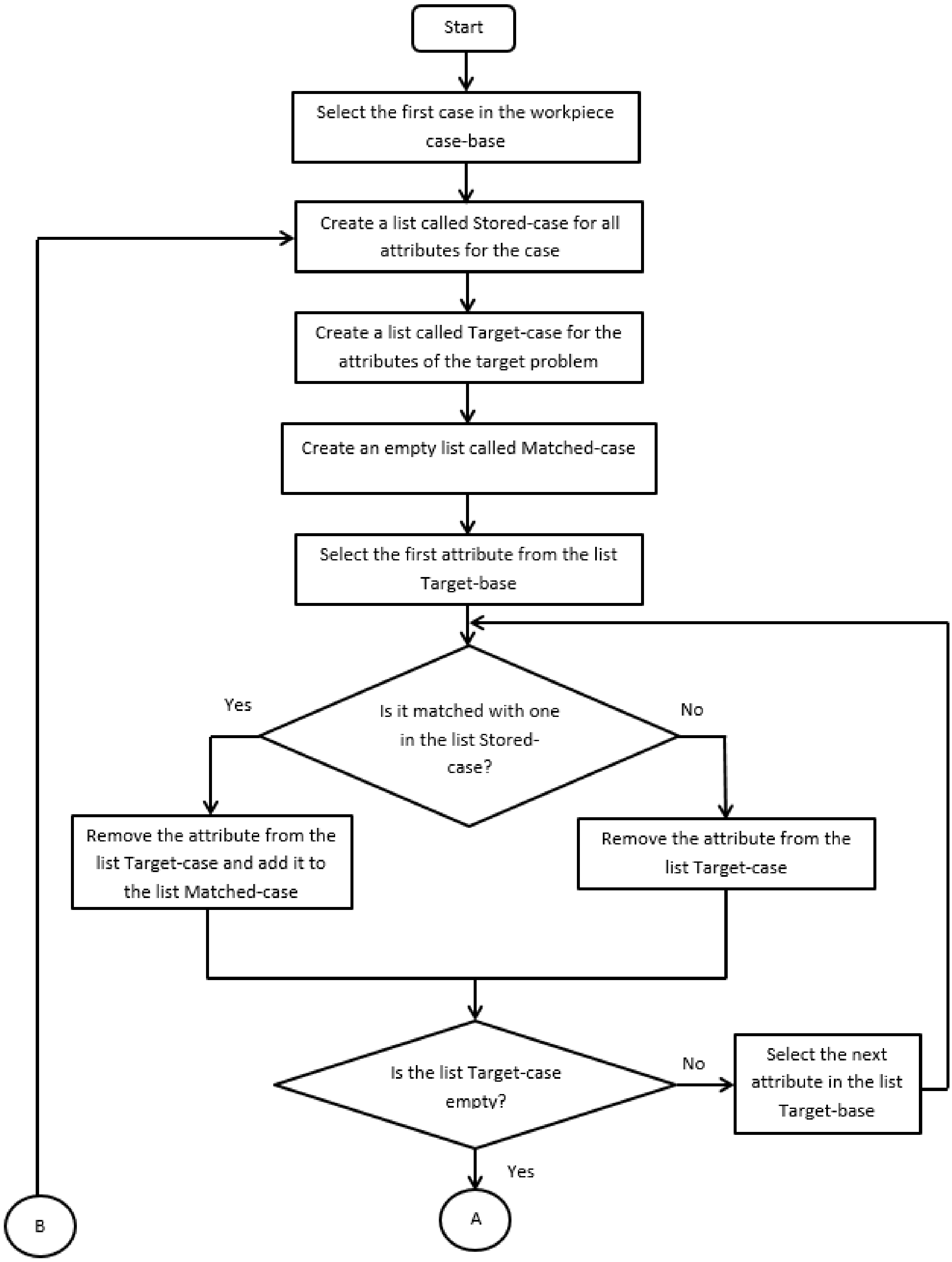
Each of these codes is compared with each case (i) in the case-base and the matched cases are retrieved. Therefore, the above retrieval approach can be revised as follows:

- Start
  Get the code pattern of the target case to match
    Compare each code (j) of the target case with each case (i) in the case-base
    If code (j) = code (i)
    Then add case (i) to the matched list

Determine how close the matched case (i) is
If matching > = threshold
Then add case (i) to the retrieved list
Output list of retrieved cases

- End

The retrieval process for SPMs is divided into two levels. The first level involves retrieving a list of the most similar cases from the workpiece case-base to the target workpiece. The retrieval approach explained above was applied and a complete algorithm of the first level retrieval in this work was developed as shown in **Figure 5-3**.



Start
Select the first case in the workpiece case-base
Create a list called Stored-case for all attributes for the case
Create a list called Target-case for the attributes of the target problem
Create an empty list called Matched-case
Select the first attribute from the list Target-base
Is it matched with one in the list Stored-case?
Yes
No
Remove the attribute from the list Target-case and add it to the list Matched-case
Remove the attribute from the list Target-case
Is the list Target-case empty?
No
Select the next attribute in the list Target-base
Yes
B
A

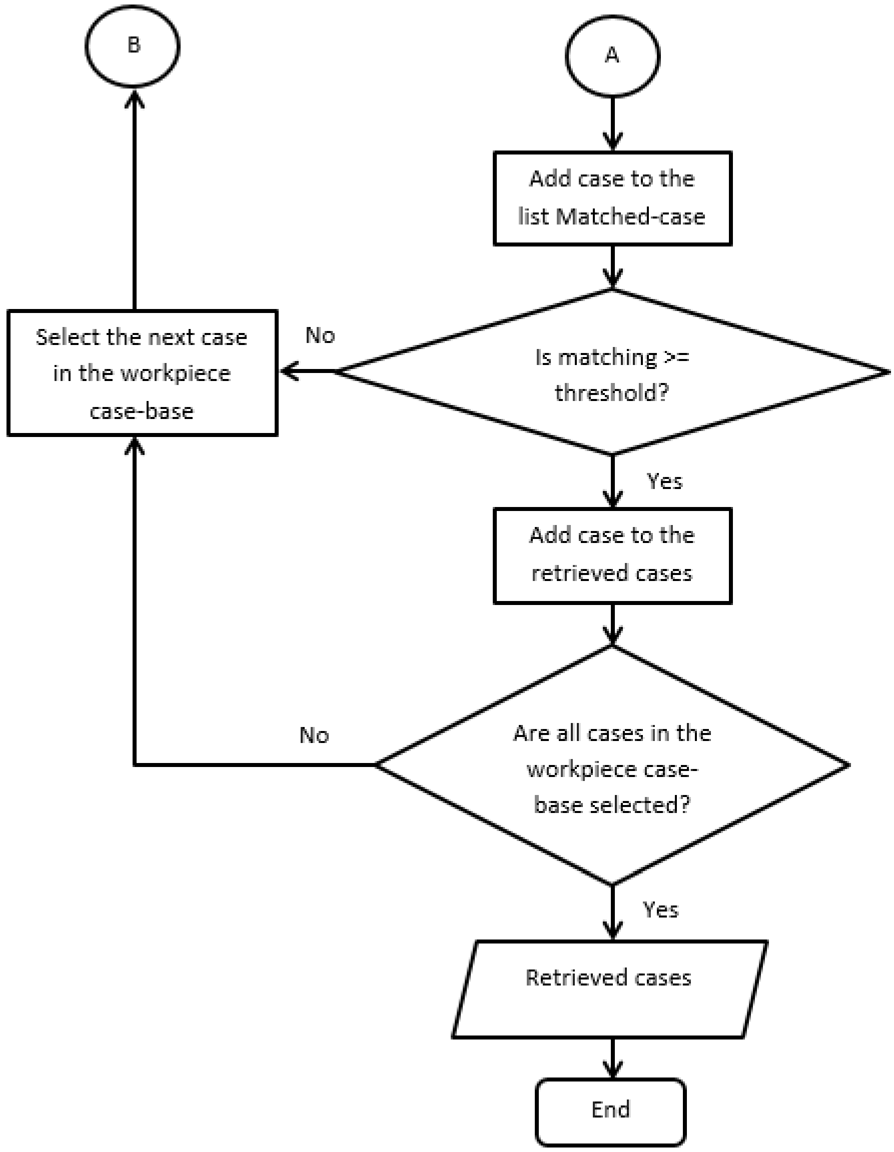


Figure 5-3. A complete algorithm for the first level of the retrieval process for SPMs.

The matched cases are evaluated by the threshold. The cases that have values equal to or higher than the threshold are added to the Matched-case list. The threshold is considered in this algorithm to be a similarity measure to obtain the closest cases to the target case.

There are several approaches that have been applied to determine the threshold or the similarity measure in CBR. One of these approaches is calculating the similarity using the following equation [203]:

$$\text{SIM (X,Y)} = count + \sum_{i}^{n} 2^{li} \qquad (1)$$

Where X is the target case, and Y is the old case, "*count*' refers to the number of attributes that match between X and Y, and *li* is the length of each region consisting of two or more matches. As an example of this approach is considering the following workpiece attributes from **Table 5-1** to be matched between X and Y:

Type of attributes:	class	shape	size	material	number of machined surfaces	
Target case (X):	flat	plane	small	steel	one	
Old case (Y):	cubic	plane	small	steel	two	
count:	0	1	1	1	0	= 3

In this method, 1 is given for the matched attributes and 0 is given for the unmatched attributes as shown above. By applying equation (1), the similarity measure is calculated as:

$$\text{SIM (X,Y)} = 3+2^3 = 11$$

The similarity measure for the old case (Y) in comparison to the target case (X) is 11, and the rest of the cases are evaluated in the same way. This is a good method if the attributes are coded as strings, but it is not suitable if an indexing (coding) system is used for the target and old cases, and some errors have been recorded while using this approach [200].

Another approach is using Euclidian distance which calculates the similarity measure by the following equation [198]:

$$\text{SIM (X,Y)} = 1 - D_{(X,Y)} = 1 - \sqrt{\sum_{i=1}^{n} d\,(xi, yi)^2} \qquad (2)$$

Where d is the distance between an attribute of the target case and the similar attributes of the old case. This method is more complicated than the previous one

and often requires assigning weights to the attributes; however, more accurate results have been achieved by using this method [198]. It is a very useful method when parameters such as diameter, length, or hardness are set to the attributes.

The approach that is most often used to define the similarity measure is the Hamming method, which uses the following equation [157]:

$$\mathrm{SIM}\ (X,Y) = \frac{n_{xy}}{n} \tag{3}$$

Where n_{xy} indicates the number of identical attributes between the target case and the old case, and n refers to the total number of attributes to be compared. It is a simple and appropriate method to be used in integration with the indexing system to calculate the similarity of the matched cases. Therefore, the Hamming approach was used in this work to define the threshold for the matched cases in the first level of the retrieval process using the following equation:

$$\text{Threshold} = \frac{n_{m1}}{n_t} \tag{4}$$

Where n_{m1} indicates the number of matched attributes in the first level, and n_t is the total number of compared attributes. In the first retrieval level, only the workpiece attributes are compared. By referring to **Table 5-1**, the value of n_t is equal to 6, and the threshold ranges from 0.0 to 1.0 (0.0 for no match, and 1.0 for complete match). A value of >= 0.5 is set up to retrieve the closest cases from the matched cases. The closest cases are evaluated in the second retrieval level in order to find the optimum case with regard to the target case. At this level, the total similarity of the closest cases is calculated. For this purpose, equation (4) is modified as follows:

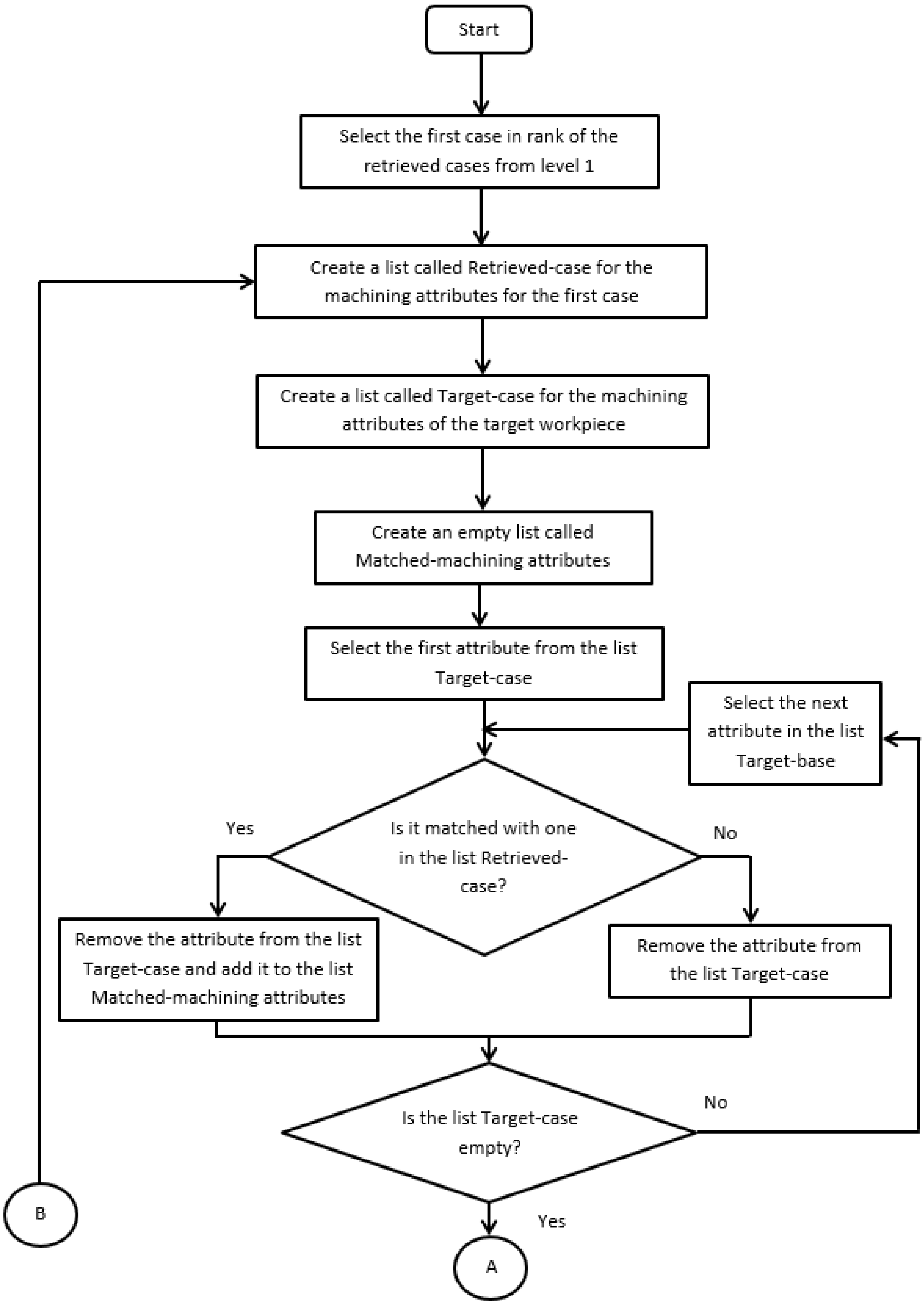
$$\mathrm{SIM}_t = \frac{n_{m1}+n_{m2}}{n_t} + \mathrm{SIM}_{Hardness} \tag{5}$$

Where n_{m2} is the number of the matched attributes in the second level. $\mathrm{SIM}_{Hardness}$ is the similarity degree of the hardness between the target case and the old case, and it is included in the equation because of the imporatnce of this

attribute in machining operations. The value of n_t in equation (5) is equal to 13, which is the total number of attributes .The value of $SIM_{Hardness}$ is calculated by applying a modified Euclidian distance equation, as follows [199]:

$$SIM_{Hardness} = 1 - D = 1 - \left|\frac{H_{target} - H_{old}}{H_{target} + H_{old}}\right| \qquad (6)$$

By applying eqaution (5), the total similarity value is calculated for the retrieved cases, and the case with the highest value is considered to be the optimum case. The system then suggests the best solution for the SPM design, which is associated with the optimum case from the the SPM case-base. **Figure 5-4** shows the algorithm that was developed in this work for the second level of the retrieval process, and the calculation of the total similarity SIM_t for the retrieved cases from the first level to define the optimum case.


Start
Select the first case in rank of the retrieved cases from level 1
Create a list called Retrieved-case for the machining attributes for the first case
Create a list called Target-case for the machining attributes of the target workpiece
Create an empty list called Matched-machining attributes
Select the first attribute from the list Target-case
Select the next attribute in the list Target-base
Is it matched with one in the list Retrieved-case?
Yes
No
Remove the attribute from the list Target-case and add it to the list Matched-machining attributes
Remove the attribute from the list Target-case
Is the list Target-case empty?
No
Yes
A
B

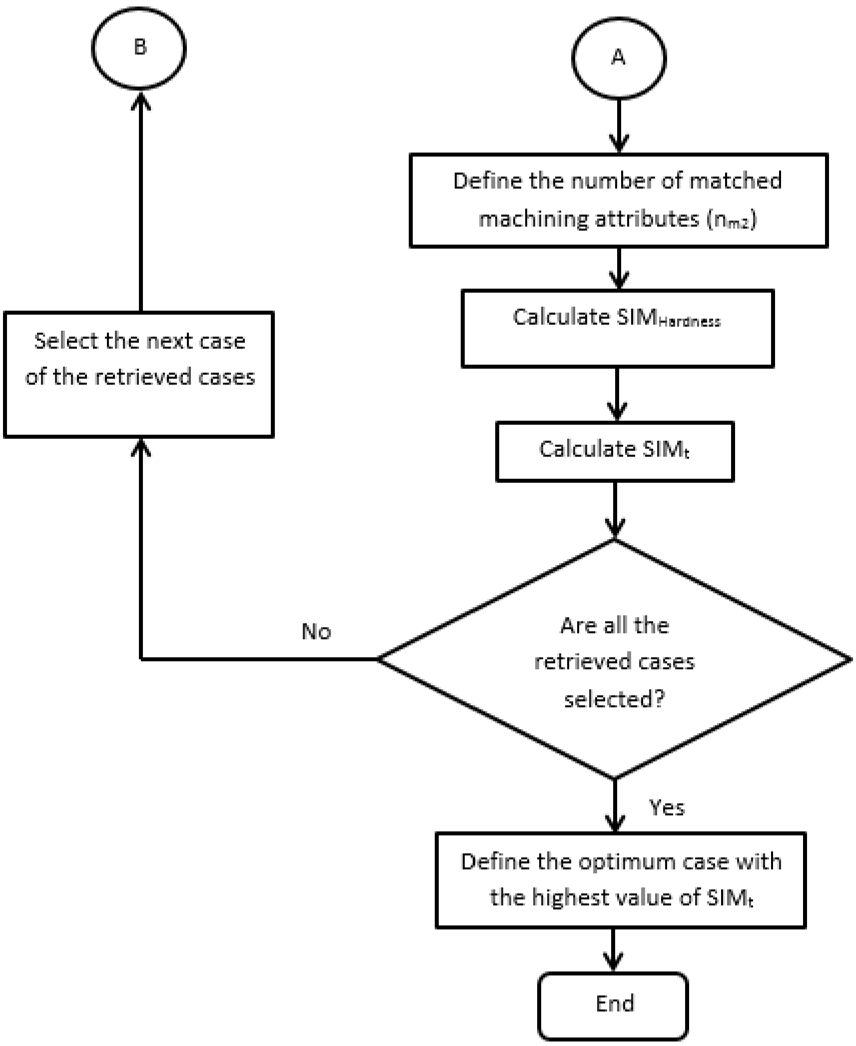


Figure 5-4. A complete algorithm for the second level of the retrieval process for SPMs with a calculation of the total similarity value.

5.1.3 Representation of the case-base

The case-base in this work is divided into a workpiece case-base and an SPM case-base: the former includes previous cases of workpieces, and the latter includes past SPM solutions that can be re-used in a new design case. To represent the cases in the case-base, three issues should be considered [204]:

- The content of the stored cases.
- The representation paradigms for the case-base organization.
- The presentation of the stored cases for the user.

The content of a stored case can be defined as a description of a previous design situation. Different approaches have been used to identify the content of a stored case, such as drawings, design requirements with solutions, or function-behaviour-structure descriptions.

In this work, design and machining attributes are used as the basis of the case-base. The approach that is used to store the information for a case is attribute-value pairs. In addition to the attributes, 3D models of the stored cases can be attached to the content of the case-base. This approach represents the stored cases in a way that can be easily and efficiently retrieved. A general example of this approach is given below:

Case-1
attribute-1: value-1
attribute-2: value-2
attribute-3: value-3
……
attribute-n: value-n

The values for the attributes are based on the indexing system or can be parameters of some specific attributes such as hardness. An example of this approach is shown in **Figure 5-5**.

Case-01

Category-1: workpiece attributes

Workpiece class: 2

Workpiece shape: 1

Workpiece size: 2

Number of machined surfaces: 2

Workpiece material: 2

Caregory-2: machining attributes

Machining type: 1

Number of machined workpieces: 2

Machining axis: 3

Number of machined surfaces: 2

Workpiece holding mechanism: 2

Workpiece transfer: 1

Hole/tap pattern: 1

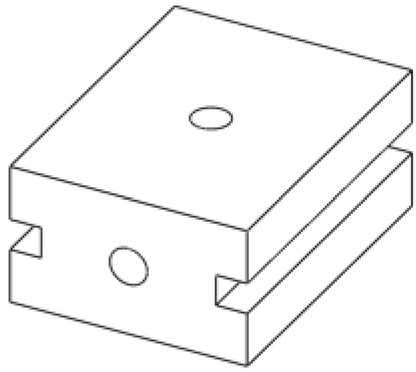


Figure 5-5. An example of the representation of a case content in the case-base.

5.1.4 The organisation of the case-base

The organisation of the cases in the case-base can be represented as a sequential data structure, which is also known as a Flat structure [204]. This can be represented as a linear list of cases, as follows:

Case-1   Case-2   Case-2   Case-3 ……. Case-n

In this type of structure, each case is searched and matched against a given new problem. The case-base can be easily updated using this structure because the new case can be stored sequentially in the existing list of cases. **Figure 5-6** shows how the cases are organised in the case-base.

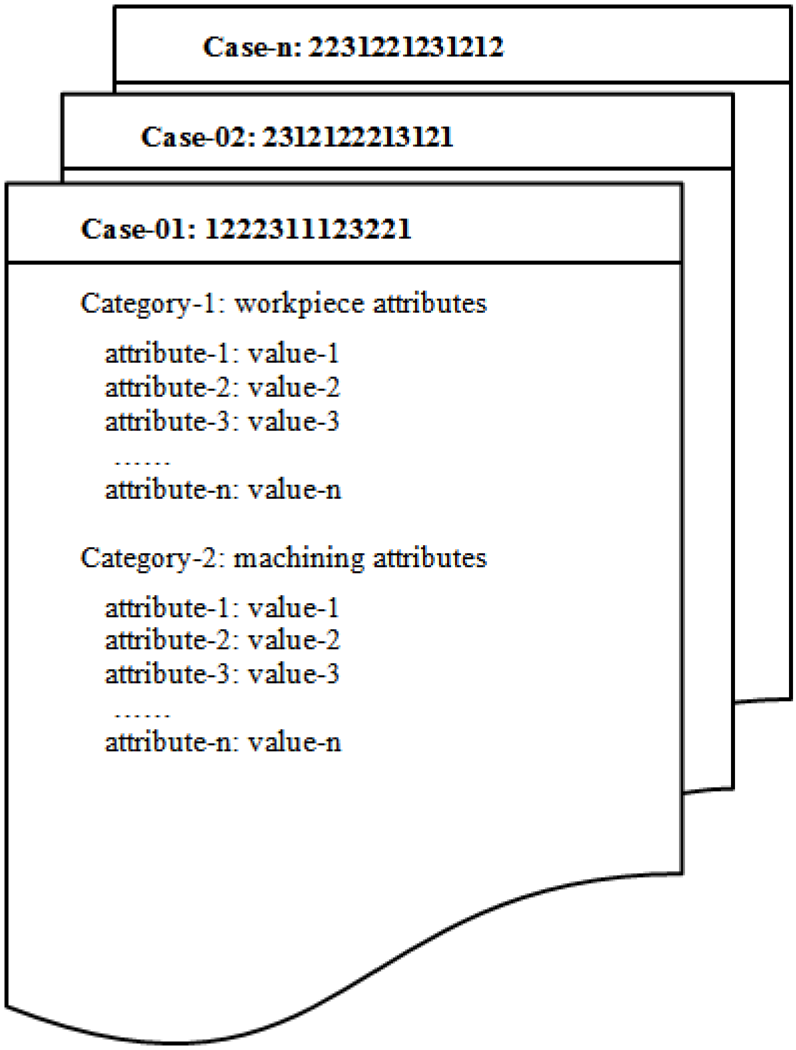


Figure 5-6. The organization of the stored cases in the case-base.

5.2 The implementation of the CBR approach

In order to apply the CBR approach and retrieve the optimum case, a number of workpieces used in this research as target workpieces. The first workpiece is shown in **Figure 5-7**. The following procedure was followed to implement the CBR approach:

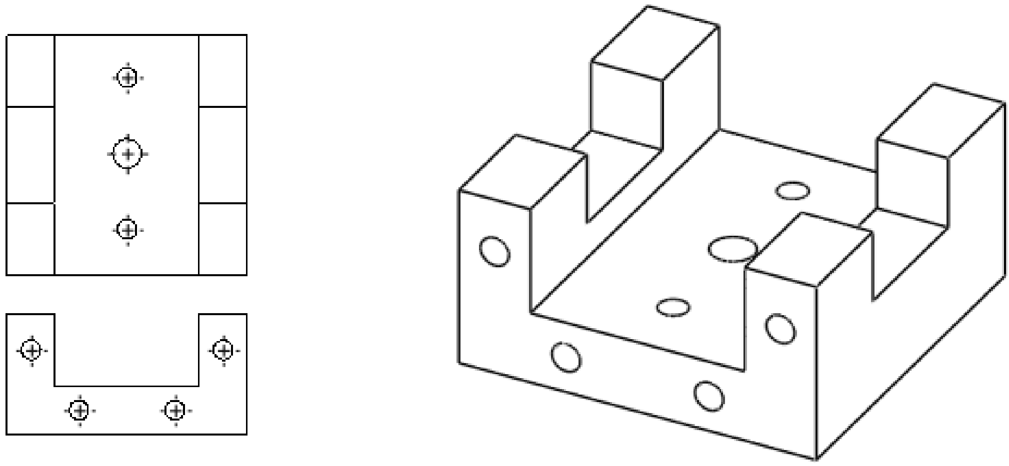


Figure 5-7. A target workpiece.

Step 1: The information of the target workpiece was analysed. This information contains the attributes of the workpiece and machining which can be extracted form the 3D CAD model and the design sheet. **Table 5-3** shows some of this information.

Table 5-3. Information of the target workpiece.

Information	Description
Wrokpiece Type	Prismatic
Workpiece size	Medium-size
Machining operation	Drilling and Tapping
Axis of machining	Horizontal and vertical
Number of machined surfaces	Two surfaces
Number of holes / hole patterns	Hole patterns in two directions
Diameter of the holes / taps	12 mm one hole and 8 mm six taps
Workpiece material	Carbon steel (H = 200 Brinell)

Other information, related to the machining operation and type of machine tool, should also be provided or defined. Here, the machine tools used are SPMs, and the following machining conditions were required for the target case:

- One workpiece is machined at each station;
- One holding position for the workpiece;

- The workpiece is moving from one station to another;
- There is a hole pattern at the same size on one direction, and there is a hole pattern at a different size on the other direction.

Step 2: The information provided above was used in applying the indexing system developed in this work as shown in **Table 5-1** and **Table 5-2**, and the code of the workpiece and machining attributes for the target workpiece was generated as shown in **Figure 5-8**.

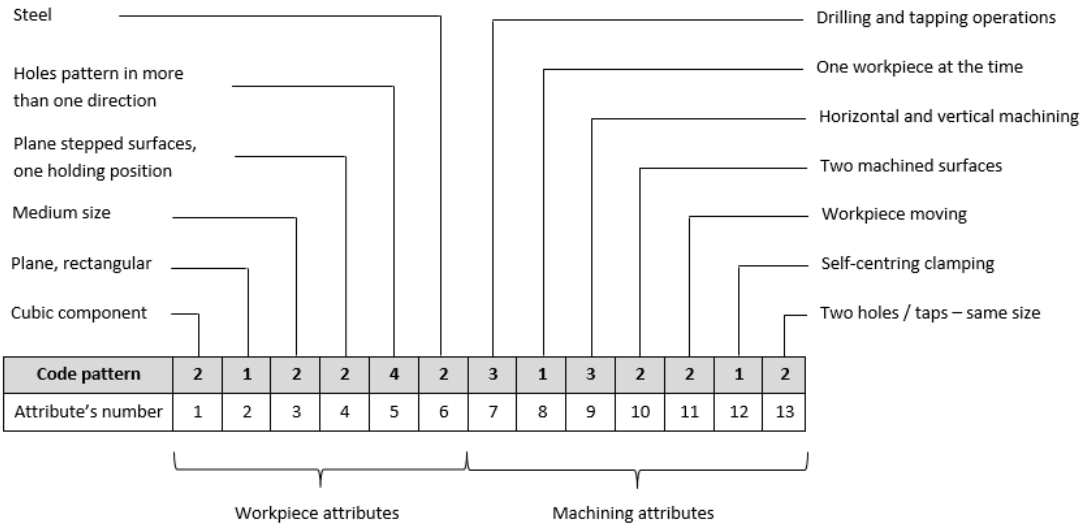


Figure 5-8. The code pattern generated by the developed indexing system. Each number refers to a specific attribute of the target workpiece.

Step 3: The first six digits of the code were taken first to compare the target workpiece to the stored cases in the first level retrieval process. The results for this level were five cases retrieved, as shown in **Figure 5-9**. The value of the threshold for each of the cases was calculated using equation (4), as shown in **Table 5-4**.

Table 5-4. The value of the threshold for the retrieved cases.

Case number	Threshold
Case-01	0.667
Case-03	0.5
Case-04	0.5
Case-07	0.833
Case-08	0.5

These cases were retrieved as the closest cases because the threshold value is ≥ 0.5 as a requirement for this retrieval level.

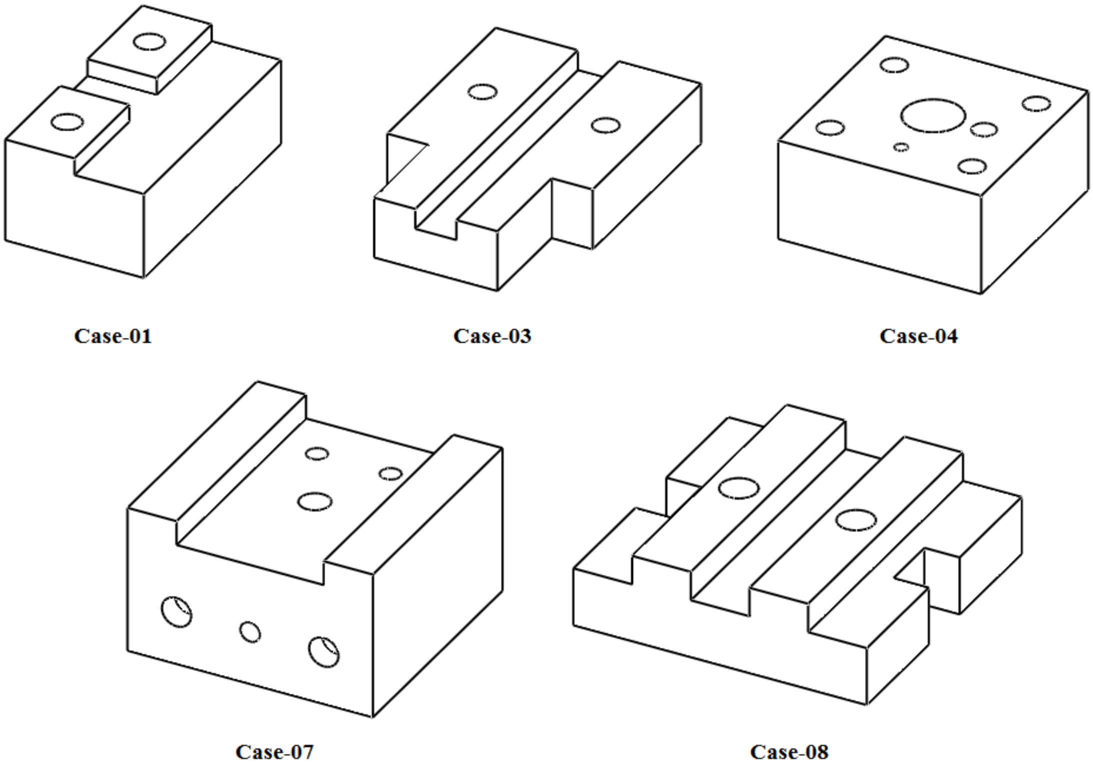


Figure 5-9. The five closest cases to the target workpiece from the first retrieval process.

Table 5-5 shows the comparion of the target workpiece to the stored cases. In this table, the number of the matched attributes of the stored cases is calculated compared to the target. The values 1 or 0 are given for matched or unmatched attributes, respectively.

Table 5-5. Defining the number of matched attributes for the stored cases with regard to the first six digits of the target workpiece code.

Stored cases	Target workpiece / first six digits					
	2	1	2	2	4	2
Case-01	1	1	1	0	0	1
Case-02	0	0	0	0	0	1
Case-03	0	1	1	0	0	1
Case-04	1	1	0	0	0	1
Case-05	1	0	0	1	0	0
Case-06	0	0	1	0	0	0
Case-07	1	1	1	1	1	0
Case-08	0	1	1	0	0	1
Case-09	0	0	0	0	0	0
Case-10	0	0	1	0	0	1

Step 4: The optimum case from these retrieved cases was identifed by applying the second level retrieval process. In this process, the last seven digits of the target workpiece code were compared to the machining attributes of the retrieved cases as well as the matched attributes from the first level (Step 3). The total similarity of the retrieved cases was calculated using equation (5). The value of the first part of this equation was calculated for each case as follows:

Case-01: 0.538
Case-03: 0.308
Case-04: 0.615
Case-07: 0.846
Case-08: 0.385

The second part of this equation relates to the hardness similarity ($SIM_{Hardness}$) and was calculated using equation (6). The hardness is related to the material and the machinability of the workpiece. The target workpiece is considered to be carbon steel with 200 Brinell hardness. The retrieved cases have the same material and hardness except foe Case-07, which is considered to be Brass with 192 Brinell hardness [205]. The values of $SIM_{Hardness}$ for the retrieved cases were calculated as:

Case-01: 1

Case-03: 1

Case-04: 1

Case-07: 0.98

Case-08: 1

The total similarity SIM_t of the retrieved cases was then calculated using equation (5) as shown in **Table 5-6**.

Table 5-6. The values of SIMt of the retrieved cases.

Case number	SIM_t
Case-01	1.538
Case-03	1.308
Case-04	1.615
Case-07	1.826
Case-08	1.385

From **Table 5-6**, Case-07 has the highest value of SIM_t (1.826), and it was therefore selected as the optimum case. The system then provided the SPM design solution that is associated with Case-07 from the SPM case-base as the best solution, as shown in F**igure 5-10**. The details of this solution are:

- Number of stations: 6
- Machining operation sequence: D – D – T – D – T (D for drilling and T for tapping).
- Station 1: Loading and unloading the workpiece.
- Station 2: drilling in two directions, horizontal and vertical, one hole in each direction.
- Station 3: drilling two holes, horizontal direction.
- Station 4: tapping two taps, horizontal direction.
- Station 5: drilling two holes, vertical direction.
- Station 6: tapping two taps, vertical direction.

The types of machining units required for each station are:

- Number of machining units required: 6
- Two BEM 25 units in station 2.
- One BEM 28 unit in station 3.
- One BEM 28 unit in station 4.
- One GEM 20 unit in station 5.
- One GEM 20 unit in station 6.

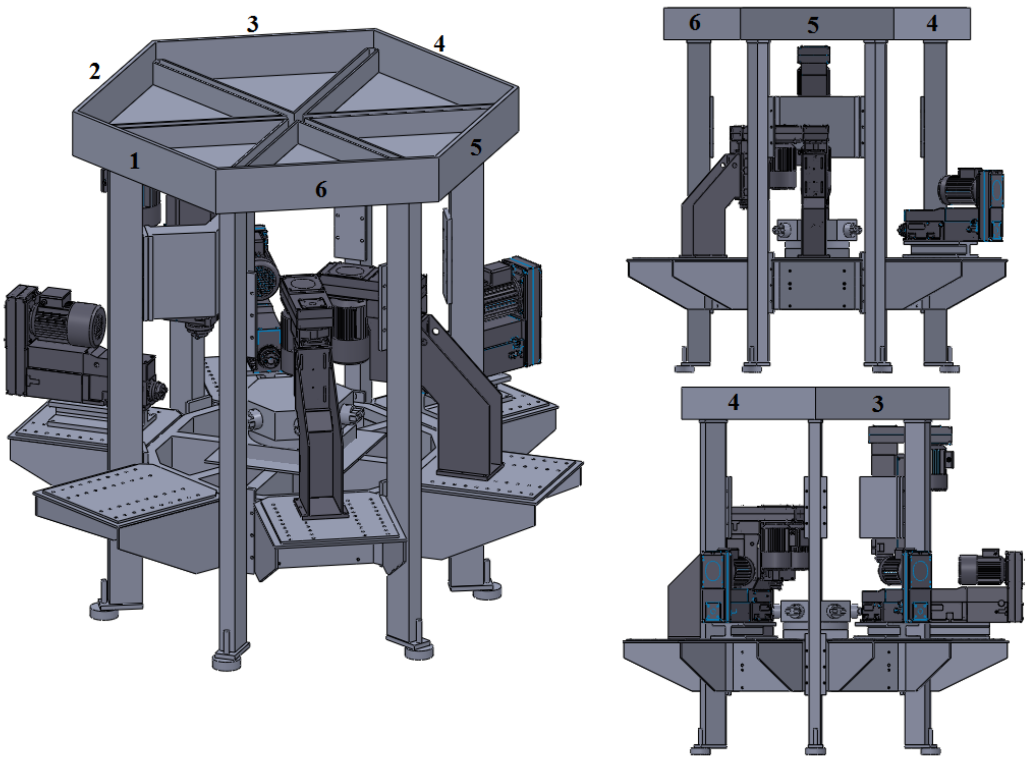


Figure 5-10. The suggested SPM solution of Case-07. The numbers are references to the stations of the layout.

This solution was then modified to meet the requirements of machining the target workpiece. This is because the target workpiece has one hole and six taps in two directions (the selected solution is for two holes and four taps). The number of holes/taps and the technical information for the target workpiece are provided in **Table 5-3**, and the modifications were made by consulting the knowledge-base and the SPM database. These modifications are shown below:

- Number of stations: 6
- Machining operation sequence: D – D – T – T – D.
- Station 1: Loading and unloading the workpiece.
- Station 2: drilling in two directions, horizontal and vertical, two holes in each direction.
- Station 3: drilling two holes, in a horizontal direction.
- Station 4: tapping two taps, in a horizontal direction.
- Station 5: tapping four taps in two directions, horizontal and vertical; two taps in each direction.
- Station 6: drilling one hole, vertical direction.

The types of machining units required for each station are:

- Number of machining units required: 7
- Two BEM 28 units in station 2.
- One BEM 20 unit in station 3.
- One GEM 20 unit in station 4.
- Two GEM 20 units in station 5.
- One BEM 20 unit in station 6.

The modified solution of the SPM design for the target workpiece is shown in **Figure 5-11**.

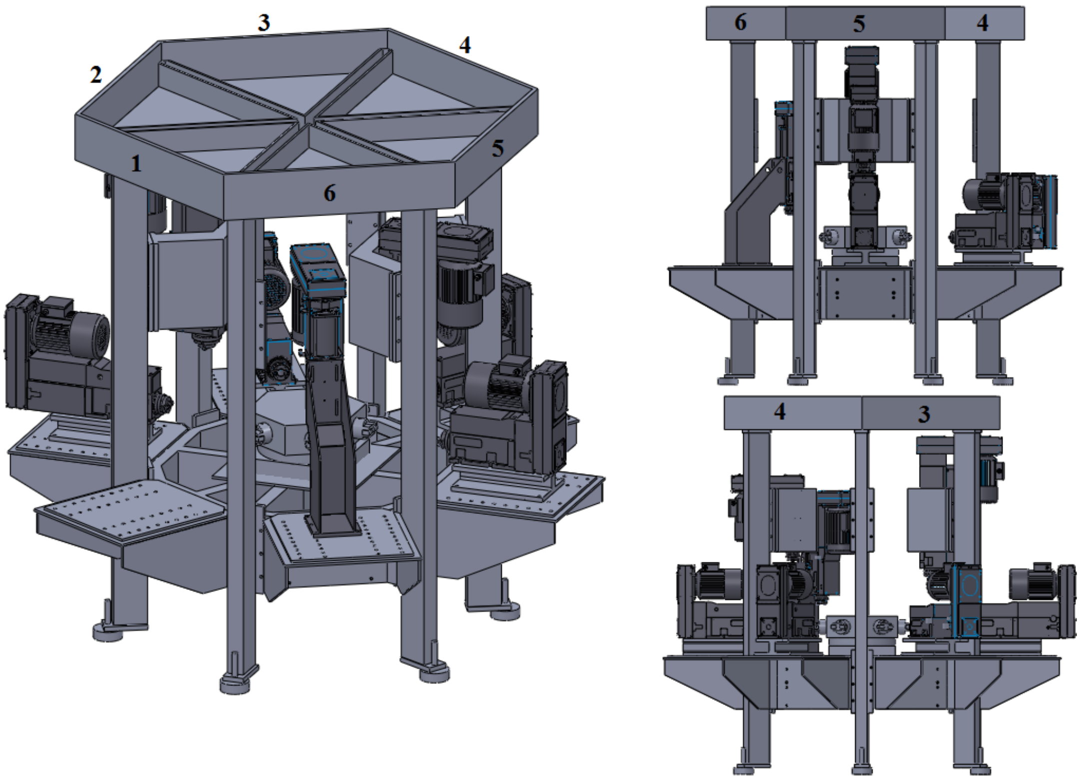


Figure 5-11. The modified solution for the target workpiece.

The modifications and differences between the selected and the modified solution are as follows:

- Only one more machining unit is needed in the modified solution.
- Tapping in two directions is needed in the modified solution in station 5, a vertical support (VBG 6) is therefore used to replace the previous support (VST 12), keeping the horizontal support SH.
- The type of machining units is modified for stations 2, 3, and 4 keeping the other supporting components unchanged.

The target workpiece and the modified solution are then stored as a new case in the case-base.

The second target workpiece used in this implementation is shown in **Figure 5-12**.

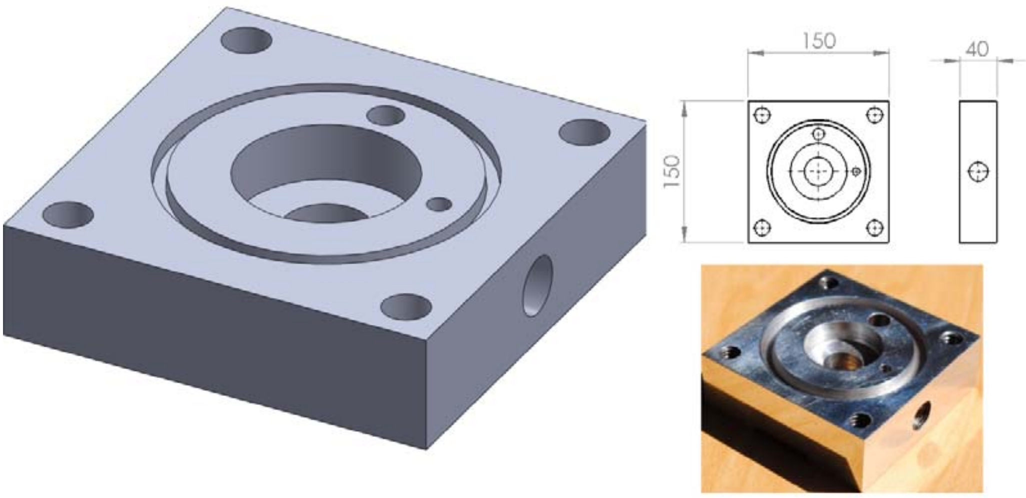


Figure 5-12. An example of a mechanical workpiece used in a hydraulic mechanism [206].

The specifications for this target workpiece were given below:

Workpiece Type : Prismatic

Workpiece size: Medium-size

Machining operation: Drilling and Tapping

Axis of machining: Horizontal and vertical

Number of machined surfaces: Two

Number of holes / hole pattern: Hole patterns in two directions

Diameter of the holes / taps: 12 mm one hole, 8 mm one hole, 30 mm one hole, 16 mm four taps, and 20 mm one tap.

Workpiece material: Carbon steel (H = 200 Brinell)

The code pattern for this workpiece was generated as follows:

Code pattern: 2 1 2 3 4 1 3 1 6 2 2 3 7

The steps outlined in the previous example were repeated. First, the first level retrieval process was applied to retrieve the closest cases. The results were as follows:

Case-01: 0.833
Case-02: 0.833
Case-04: 0.667
Case-07: 0.667
Case-09: 0.5

The second level of the retrieval process was then applied to calculate the total similarity SIM_t for the retrieved cases by applying equation (5). The results for the first part of this equation were as follows:

Case-01: 0.538
Case-02: 0.385
Case-04: 0.769
Case-07: 0.769
Case-09: 0.308

The second part of equation (5) was then calculated ($SIM_{Hardness}$), and the results were as follows:

Case-01: 1
Case-02: 1
Case-04: 1
Case-07: 0.98
Case-09: 1

The total similarity SIM_t was then calculated for the retrieved cases as follows:

Case-01: 1.538
Case-03: 1.385
Case-04: 1.769
Case-07: 1.749
Case-08: 1.308

Case-04 and Case-07 had the same output from the first part of equation (5); however, the value of $SIM_{Hardness}$ was different and played an important role in calculating the total similarity of the stored cases. As a result, Case-04 had the highest value of SIM_t and was selected as the optimum case for the target workpiece. The SPM solution for Case-04 is shown in **Figure 5-13**. This solution was then modified to meet the requirements for the target workpiece. By

following the steps outlined in the previous example, the modified solution is shown in **Figure 5-14**.

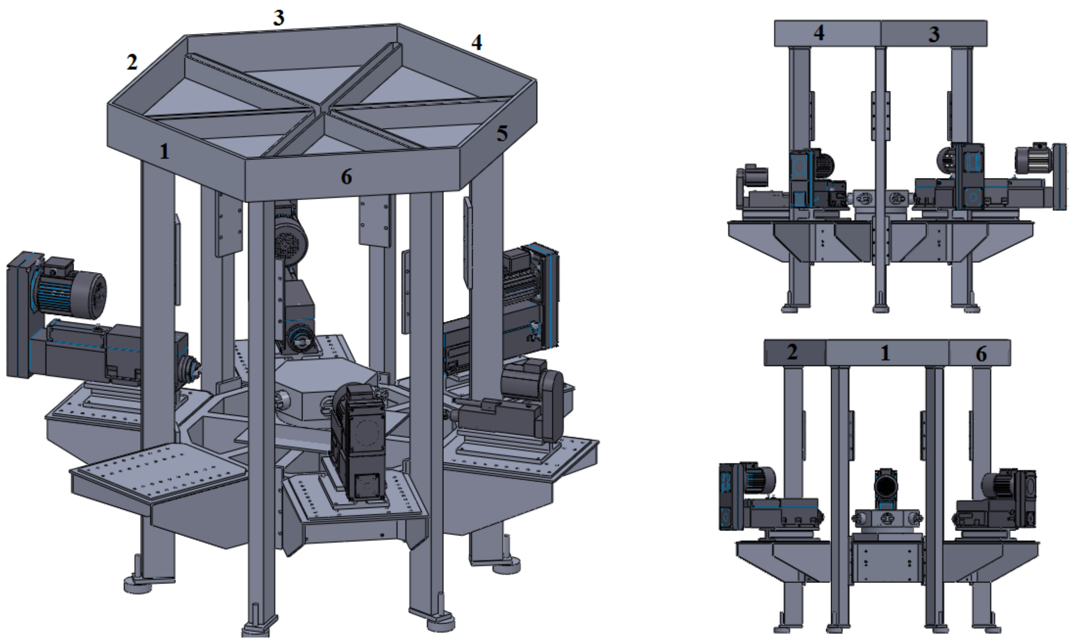


Figure 5-13. The suggested solution of the SPM design for the Case-04.

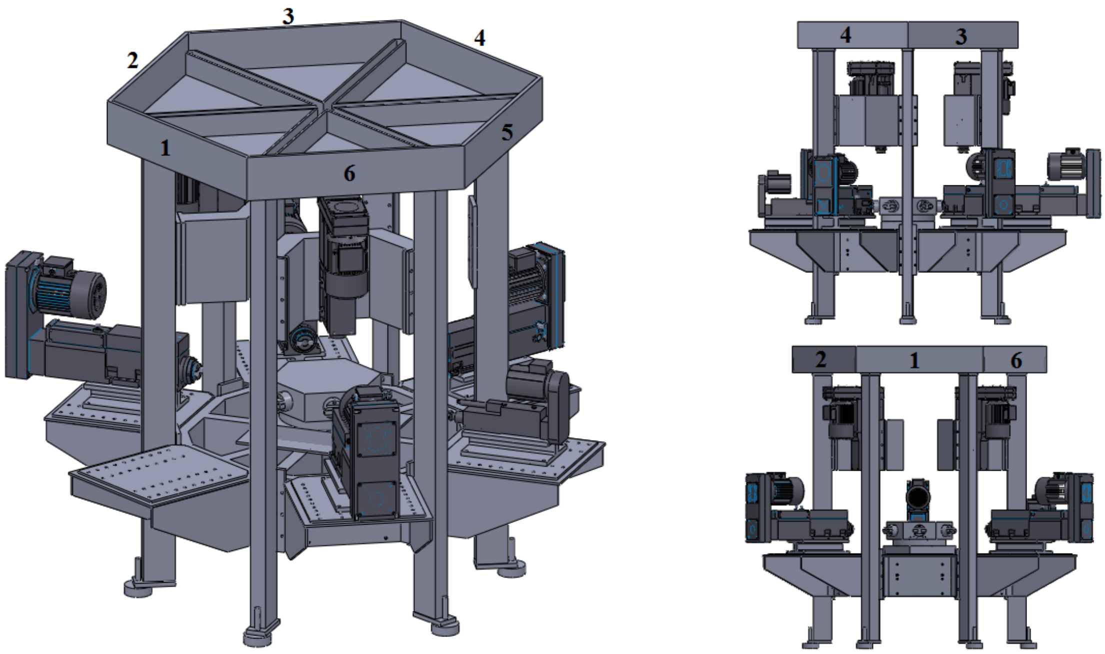


Figure 5-14. The modified solution of the SPM design for the target workpiece.

The most significant modifications made to this solution are in stations 2 and 6. The vertical support VGB 6 and machining unit BEM 25 were added to both stations in order to perform drilling and tapping in two directions at the same time. The remaining stations were kept with the same machining directions, and the type of the machining units, with some adjustments, could be applied to the final set up.

The third target workpiece used is shown in **Figure 5-15**, and its specifications were as follows:

Workpiece Type : Prismatic

Workpiece size: Medium-size

Machining operation: Drilling and Tapping

Axis of machining: Vertical and inclined

Number of machined surfaces: Two

Number of holes / hole patterns: Hole patterns in two directions

Diameter of the holes / taps: 12 mm four holes, 8 mm two taps, and 8 mm two holes, and 6 mm one hole.

Workpiece material: Cast iron (H = 293 Brinell)

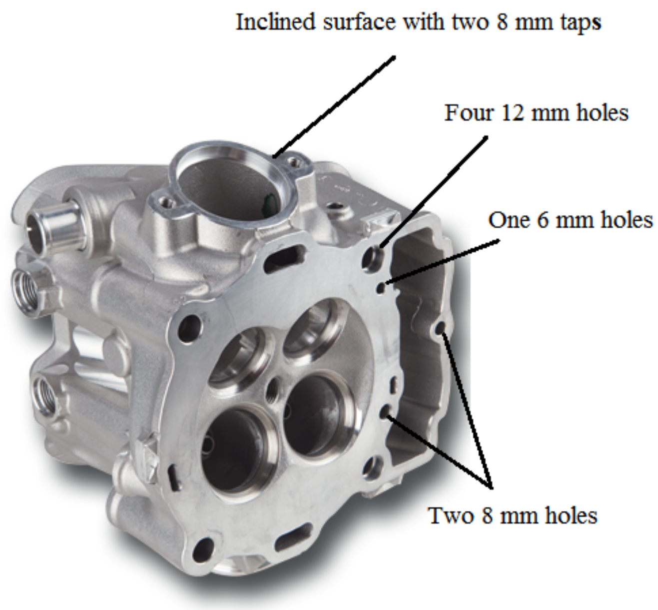


Figure 5-15. A cylinder head for motorcycle engine [207].

The code pattern for this workpiece was generated as follows:

Code pattern: 2 1 2 3 4 1 3 1 6 2 2 3 7

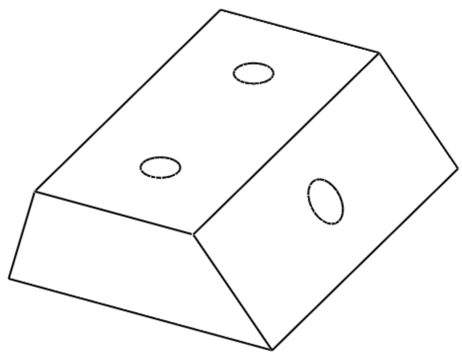
The results of the first level retrieval process were:

Case-02: 0.5, Case-04: 0.5, Case-07: 0.667, Case-09: 0.667

These retrieved cases were then used in the second retrieval process to select the ultimate case, and the results from this process were:

Case-02: 1.311
Case-04: 1.311
Case-07: 1.432
Case-09: 1.503

These values were obtained by applying equations (5) and (6) of the SIMt in the second level process, and Case-09 was selected as the ultimate case, as shown in **Figure 5-16**. The SPM solution for this case is shown in **Figure 5-17**.



Case-09

Figure 5-16. Case-09 in the case-base.

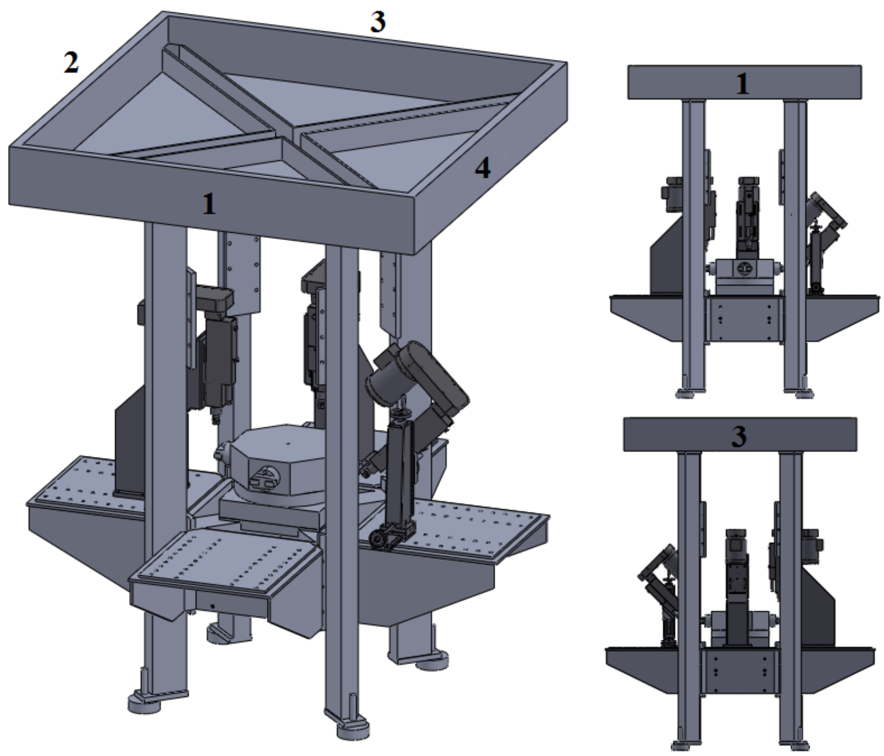


Figure 5-17. The solution for case-09.

This solution was then modified to meet the requirements for the target workpiece. A summary of the modification made to this solution is as follows:

- Station 2: adding vertical support (VGB 4) and a machining unit BEM 20 for vertical machining and to replace the previous support (VST 12). A universal support (UST) was also added for inclined machining.
- Station 4: adding vertical support (VGB 4) and a machining unit BEM 20 for vertical machining while keeping the universal support.
- Station 3: replacing the machining unit with BEM 20 and keeping the vertical support (VST 12).

The modified solution for the target workpiece is shown in **Figure 5-18**.

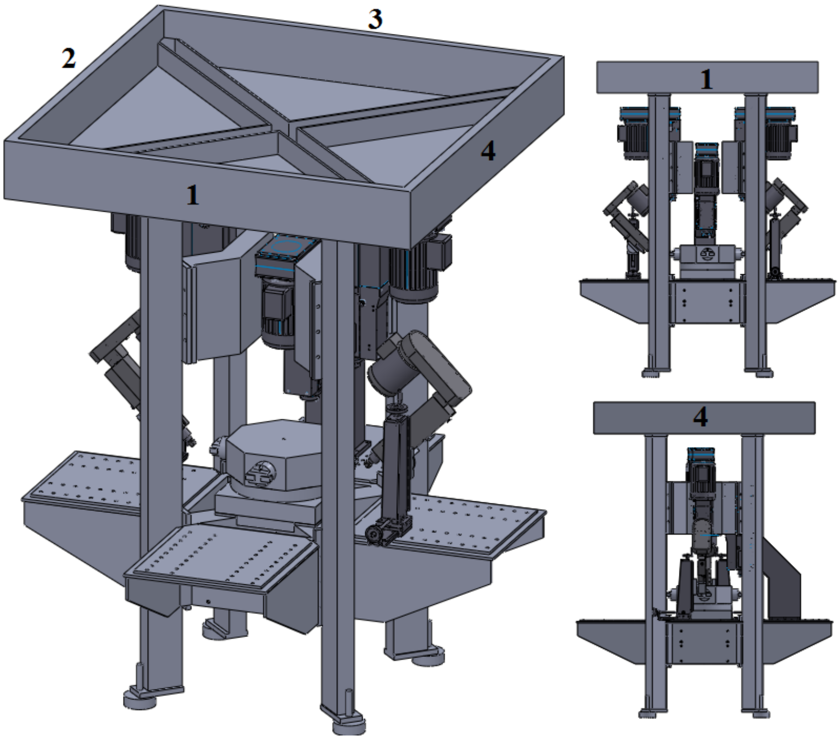


Figure 5-18. The modified solution of Case-09.

The fourth target workpiece used is shown in **Figure 5-19**, and its specifications for were as follows:

Workpiece Type : Prismatic

Workpiece size: Medium-size

Machining operation: Drilling and Tapping

Axis of machining: Vertical and inclined

Number of machined surfaces: Two

Number of holes / hole patterns: Holes patterns in two directions

Diameter of the holes / taps: 10 mm three taps, 8 mm two taps, and 12 mm two holes.

Workpiece material: Cast iron (H = 293 Brinell)

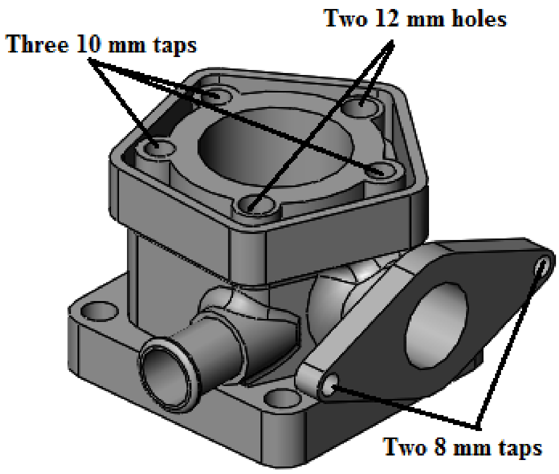


Figure 5-19. A motorbike engine cylinder design with holes and taps required for machining by an SPM.

The code pattern for this workpiece was generated using the indexing system as follows:

Code pattern: 2 1 2 3 4 1 3 1 6 2 2 3 7

This code was used in the first level retrieval process and the results were:

Case-02: 0.5, Case-04: 0.5, Case-07: 0.834, Case-09: 0.667

These retrieved cases were used in the second retrieval process, and the values of the total similarity SMt for these cases were:

Case-02: 1.311
Case-04: 1.311
Case-07: 1.657
Case-09: 1.503

Case-07 was the ultimate case and the SPM solution for this case is shown in **Figure 5-10**. This solution was modified, and the summary of the modifications is as follows:

- Number of stations was reduced to 4.
- Station 2: replacing the vertical support (VGB 6) with a vertical support (VGB 4).
- Station 3: replacing the horizontal support (SH) with a vertical support (VST 12) for vertical drilling (two holes).
- Station 4: adding a vertical support (VGB 4) while keeping the horizontal support (SH) for tapping two directions.

The modified solution is shown in **Figure 5-20**.

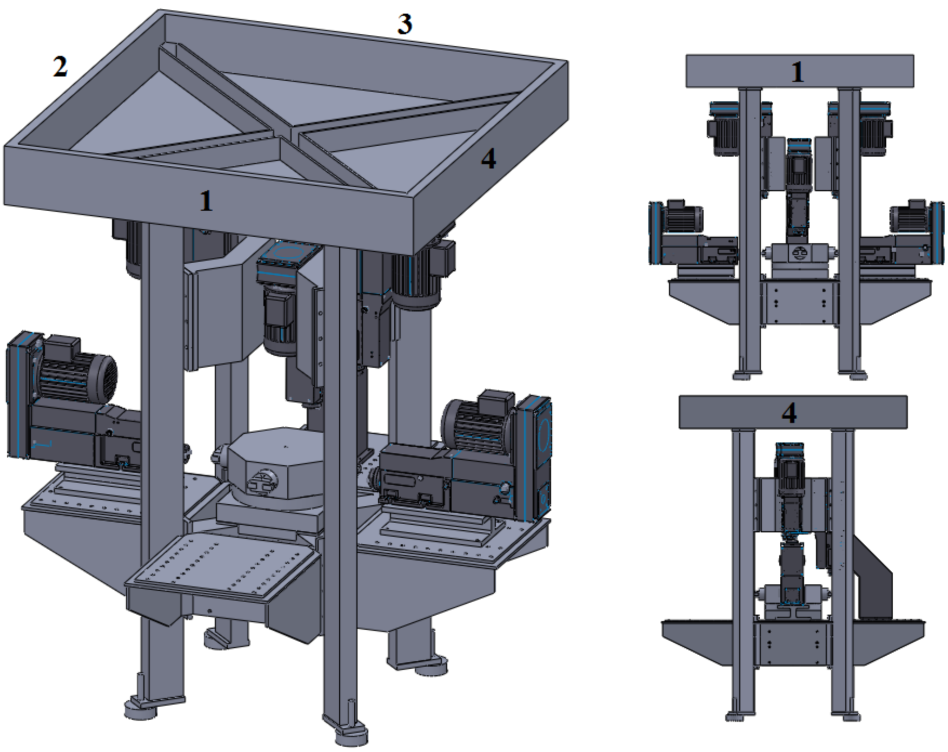


Figure 5-20. The modified solution for the fourth workpiece.

5.3 The integration process

The CBR approach developed in this work was implemented and integrated in SolidWorks. The other components that were developed in the previous chapters were also included in this integration. Visual Basic programing language and SolidWorks API features were used to develop a new menu, called SPM system, in the SolidWorks design environment. This menu provides direct and flexible access to the CBR method, SPM knowledge-base, SPM database, and SPM assembly. The integrating of these components has led to the development of an integrated system for SPMs, which represents the main object of the work presented in this thesis and a novel contribution to the field of the SPM layout design.

5.3.1 Add-in project development

The creation of this new menu was achieved by developing Add-in project in Visual Basic and implementing this project in SolidWorks. **Figure 5-21** shows the new menu in the SolidWorks environment.

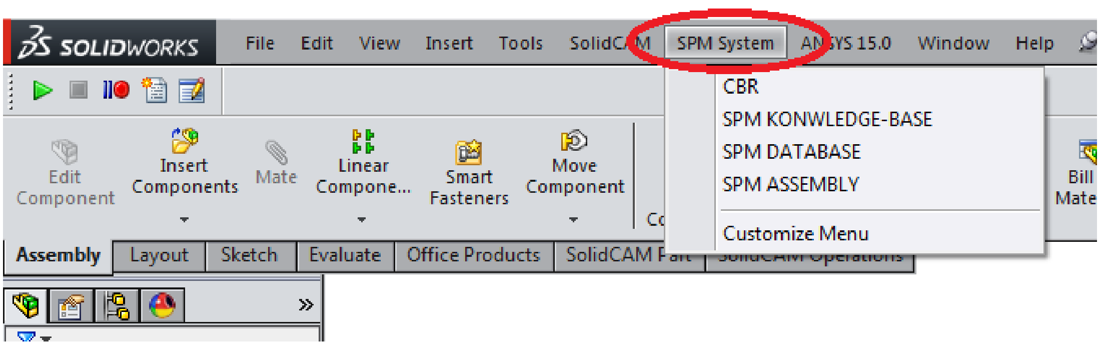


Figure 5-21. The new menu, SPM system, and the sub-menus the in SolidWorks environment.

This new menu has sub-menus for each of the SPM system components. When selecting CBR from the sub-menu, a new window – the indexing system for SPMs as shown in **Figure 5-22** – is opened. From this window, the designer can specify the workpiece and machining attributes for the target workpiece

based on its specifications, and then start the retrieval process. Examples of the results of the retrieval process and SPM solutions suggested by the system are shown in **Figure 5-23** and **Figure 5-24**.

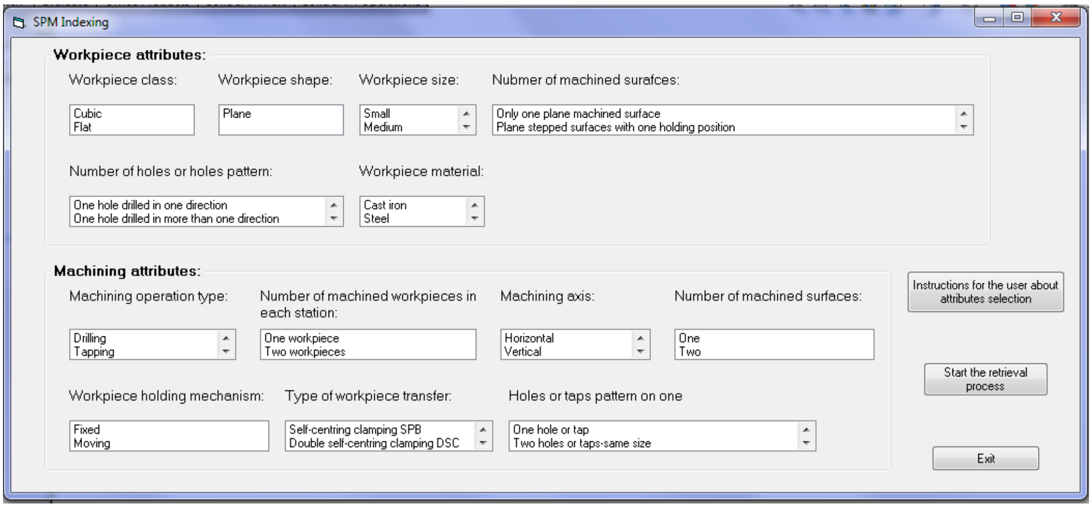


Figure 5-22. SPM indexing window.

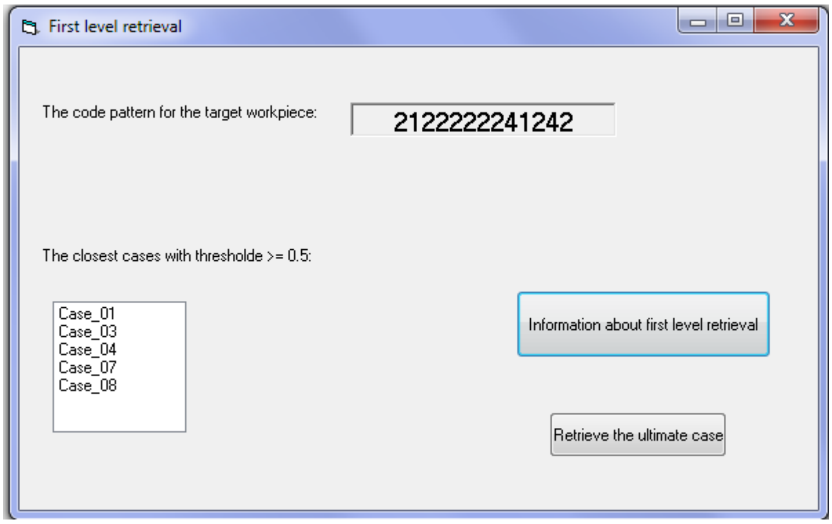


Figure 5-23. The result of the first level retrieval.

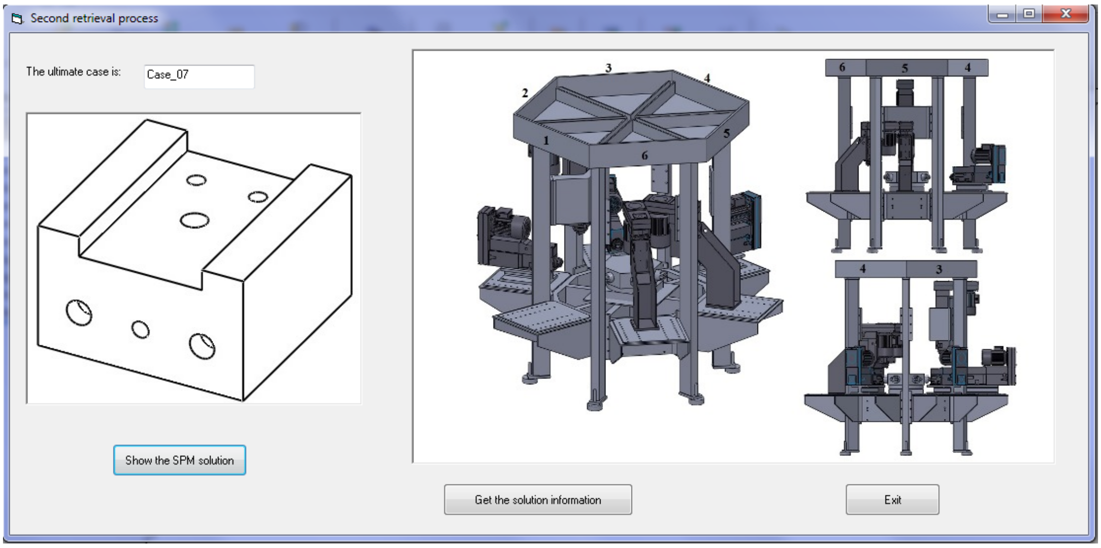


Figure 5-24. The result of the second retrieval process and the SPM solution suggested by the system.

More windows were developed in the Add-in project in this thesis for this integration in order to facilitate the selection of the SPM elements and make the integrated systems developed flexible and easy to use. Examples of these windows are shown in **Figure 5-25**, **Figure 5-26**, and **Figure 5-27**.

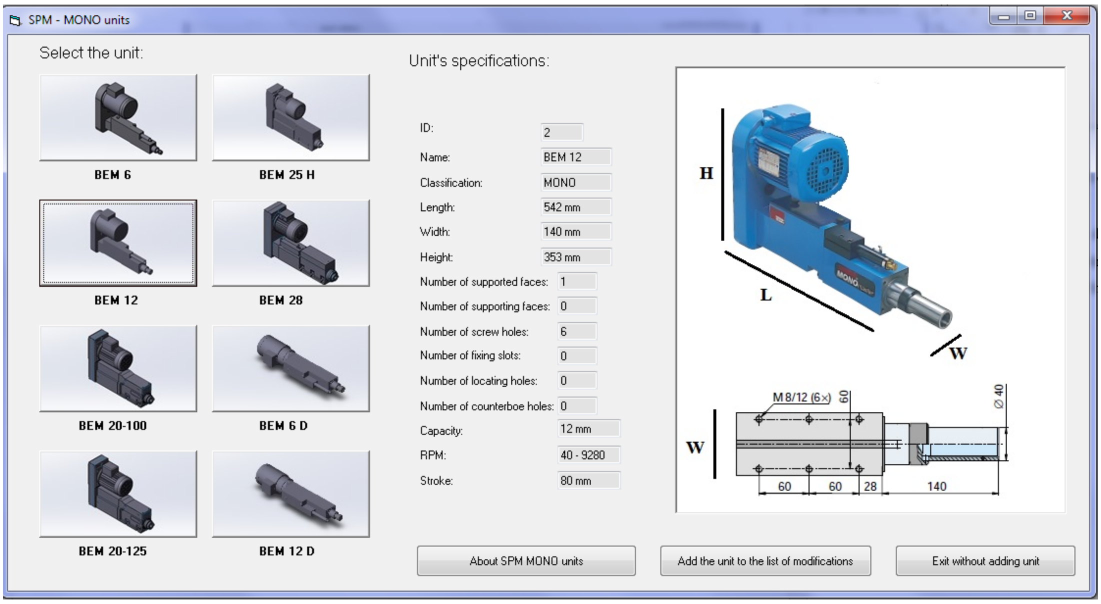


Figure 5-25. Selecting MONO drilling units from the SPM database.

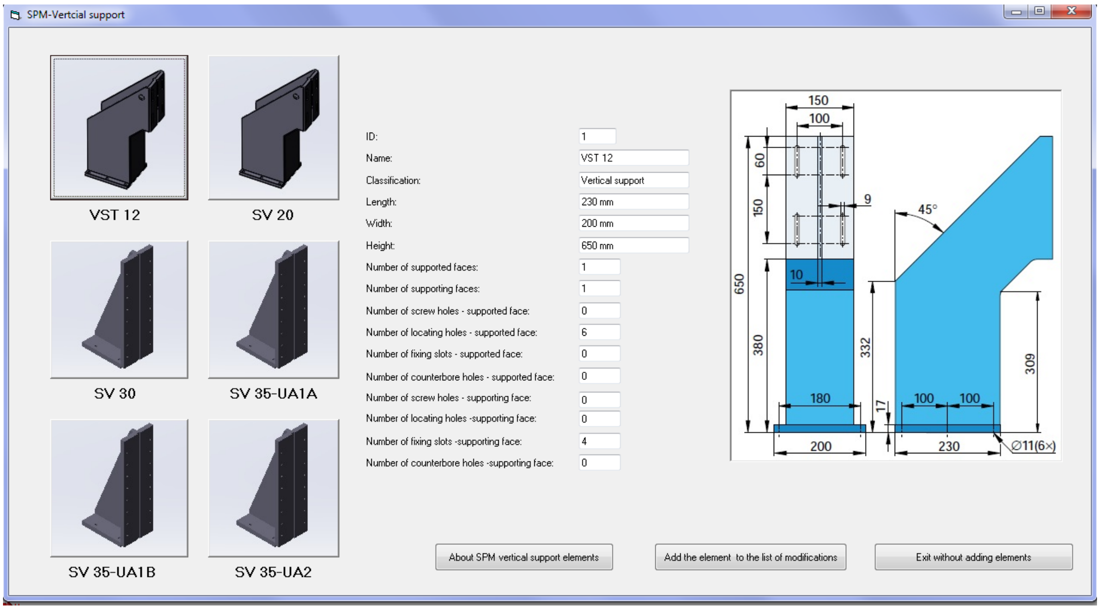


Figure 5-26. Selecting the vertical support elements.

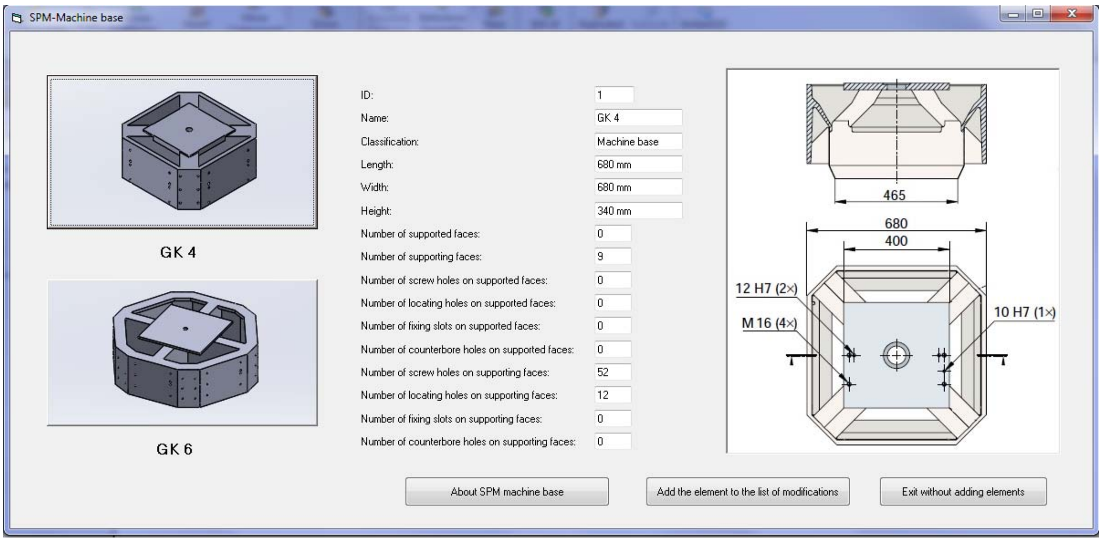


Figure 5-27. Selecting the machine base element.

The development of the Add-in project in this work included developing a comprehensive code in VB for integrating the CBR approach and the other components developed in the previous chapters in this thesis. As a result, the code was converted to a file with .dll format, and this file was implemented in

SolidWorks. Part of the code developed in this work for the integration process can be found in Appendix 9.8.

5.4 Results and discussion

This reaserch project has intergrated the CBR approach and the other SPM components with SolidWorks API, and as a result has created an integrated system that can facilitate the selection of SPM layouts. The user of this system has the flexibility to assign the attributes, view the results, and select the most appropriate SPM solutions. The implementation of the CBR method and the intergation process will significantly reduce the time taken to design SPM layouts compared to the standard SPM design process. Section 5.4.1 and Section 5.4.1 set out the key difference betwween the standard design approach and the new integrated system.

5.4.1Standard deisng process

The standard design process involves design SPM layout from scratch by consulting the knowledge-base first and selecting the appropriate elements, and then checking the specifications of the elements in the database before placing and assembling them in the SolidWorks design enviroment. Taking the target workpiece shown in **Figure 5-7**, it took approximately three hours to complete the SPM layout for this workpiece using the standard approauch. First, the expert system tool (VisiRule) was consulted in order to identify the required number and types of SPM components (machining units and other elements); it took approximately 15 minutes for this workpiece. After that, the specifications and the availability of SPM components need to be checked with the SPM database, and their connections to each other should also be chekced in order to establish the SPM layout. This step took approximately 65 minutes for this workpiece. The final step is to assemble the SPM elements, and it took approximately 120 minutes to complete the SPM layout and apply interference detections in order to verify it in SolidWorks.

5.4.2 The new integrated system

In contrast to the standard design process, it took only a matter of minutes to retrieve the ultimate case using the new integarted system developed in this work, and the modifications for the suggested SPM solution tool approximately 1 hour only. The intergrated system that was developed enabled the time for the assembly process to be reduced. This reduction was achieved because the user only needs to modify a similar SPM layout (solution) proposed by the retrieval process. Although the modifications were made manually, it took approximately 60 minutes to modify the suggested SPM layout for the workpiece. **Figure 5-28** shows the time saved by applying the integrated system developed in this reaserch.

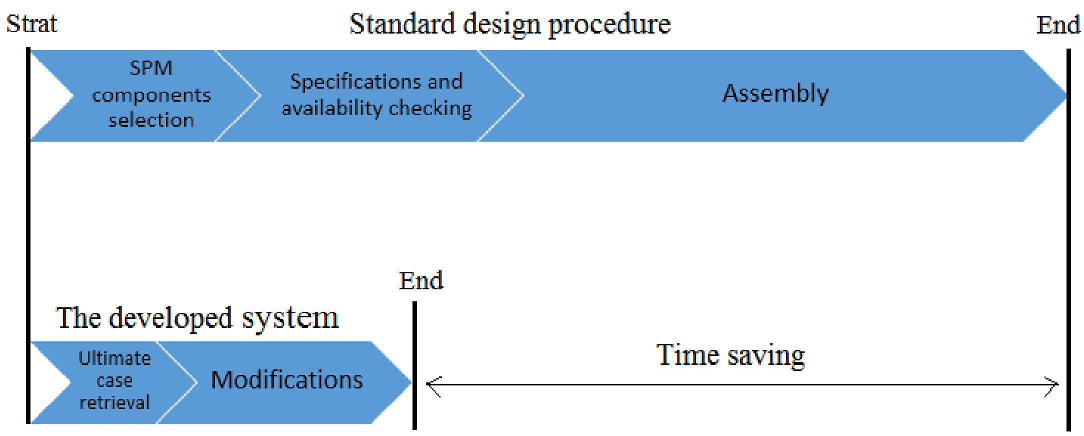


Figure 5-28. The time saving achieved by the system developed in comparison to the standard SPM design process.

The CBR method reduces the time involved by providing similar solutions. The start from scratch design process can therefore be avoided and an effective and time-efficient design process can be achieved. The modifications to the SPM solution can be made using the SPM knowledge-base and the SPM database. The results of this chapter eliminate one of the major limitations that were stated in Section 2.6.1 about SPM design process which is the lack of automated approach using AI methods in SPM design and lack of integration between different

components of the design process such as CAD software, database, and knowledge-base of SPMs. These results fulfil the outcomes for the novel approach that has been developed in this chapter as was stated in Section 2.6.1.

5.5 Summary

This chapter has introduced a new integration of the CBR method with SolidWorks API for SPMs, focusing on the indexing and retrieval processes of design cases. This integration also includes SPM knowledge-base, SPM database, and SPM assembly in order to develop an integarted system for SPMs. An indexing mechanism was developed based on the workpiece and machining attributes. As a result, an indexer was created in a flexible way to facilitate the indexing process. A dual-step retrieval process was used to search and retrieve the ultimate case. The system provides the SPM solution associated with the ultimate case, and this solution can be modified based on the requirements of the target workpiece. This integration helps engineers and designers to select suitable SPM layouts for a variety of workpieces and reduces the overall design time for SPMs.

Chapter Six

6. Further techniques in SPM design

This chapter introduces the use of two techniques in the SPM design process. The first technique is a new model of analytical hierarchy process (AHP) that can help in selecting the most appropriate configurations of SPM layouts. The second technique is a proposed approach using a mechanical adapter to develop an adapter system that can enhance the process of reconfiguring of SPM layouts.

6.1 AHP for SPMs

The advantages of AHP are summarised as follows:

- The evaluation process of AHP can take both certain and uncertain factors.
- Complex evaluation processes can be easily made by AHP because of the benefits of the hierarchy concept.
- The mathematical process of AHP gives numerical values for non-quantified elements (criteria and alternatives), eventually indicating how decisions should be prioritised.
- Decision-makers can reach a suitable solution in a short time without requiring precise information.

The implementation of AHP has revealed that this method can be integrated with different programming tools and techniques. This is a very important feature in order to achieve better decisions and enhance the decision-making process [106]. Because of the advantages of AHP and its unique feature, a new model of this method was developed in this work to support the selection of the most suitable configurations of SPM layouts. This model addresses two types of machining operations, drilling and tapping, and can be extended to include other machining operations such as reaming or milling.

6.1.1 Implementation of AHP for SPMs

Two basic SPM configurations were used to implement AHP as shown in **Figure 6-1**. These configurations were based on the following factors: how the workpiece would be held during the machining operations, the size of the workpiece, and the types of machining operations. From these factors, criteria and sub-criteria were identified. Three main criteria were determined: workpiece size (C1), workpiece transfer (C2), and operation type (C3). For workpiece size, the sub-criteria were the size range of the workpiece that can be machined by the standard-design of SPM layouts (S1), and specific part sizes needing special considerations in the SPM layout design (S2). For workpiece transfer, three sub-criteria were determined: self-centring clamping (abbreviated SPB by the manufacturer), double self-centring clamping (abbreviated DSC by the manufacturer), and special transfer (ST). SPB is used when one workpiece is machined in each station at one time, while in DSC, two workpieces are machined in each station at the same time, as shown in **Figure 6-2**. The sub-criterion ST is applied for the specific design and size of a workpiece that cannot be machined by the standard SPM layout design. For the operation type, drilling and tapping were considered as sub-criteria in this work and referred to as D and T, respectively.

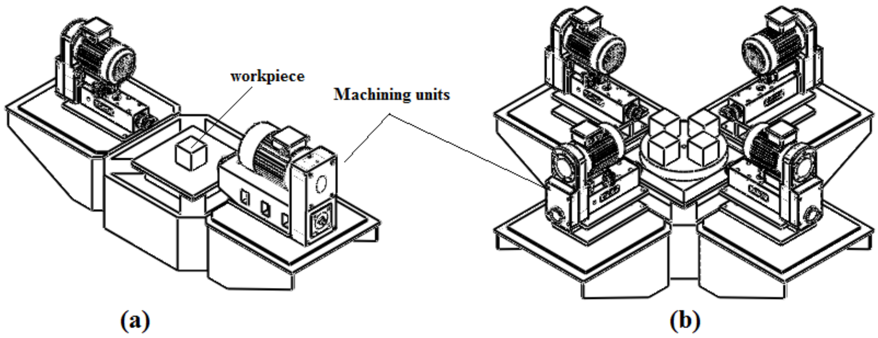


Figure 6-1. Two basic SPM configurations: (a) the workpiece is fixed in a position and manufactured by the machining units, (b) the workpiece is transferred from a station to another to perform several machining operations.

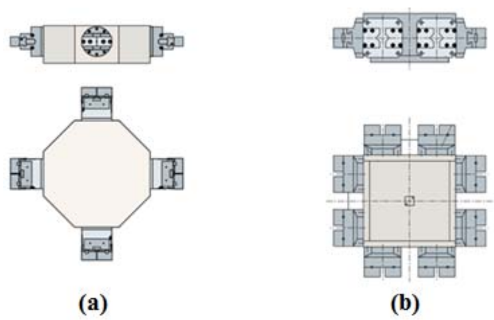


Figure 6-2. (a) The SPB workpiece transfer and (b) the DSC workpiece transfer [124].

The above criteria and sub-criteria were considered to have a direct contribution to the selection of SPM configurations and to the overall design process. Extended configurations were determined in this work and used as alternatives to complete the AHP model as follows:

A1: Standard design, single machining type, workpiece fixed.
A2: Special design, single machining type, workpiece fixed.
A3: Standard design, single machining type, workpiece moving.
A4: Special design, single machining type, workpiece moving.
A5: Standard design, multiple machining types, workpiece moving.
A6: Special design, multiple machining types, workpiece moving.

The term "standard design" refers to the use of standardised components to design new SPM layouts. Conversely, the term "special design" indicates that the standardised components cannot be used to design new layouts because the workpiece size is large or special. An example of a special design of SPMs is given in **Figure 6-3**.

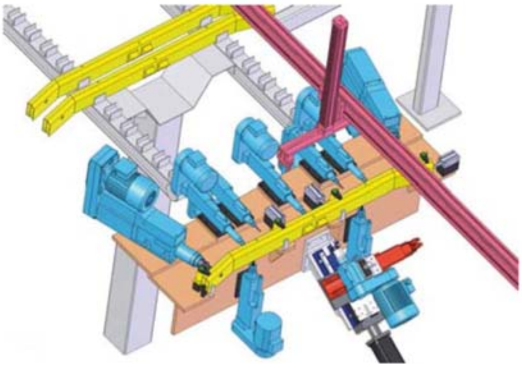


Figure 6-3. A special design of SPMs [166].

A decision hierarchy was constructed for the identified criteria, sub-criteria, and alternatives as shown in **Figure 6-4**. The next step was creating pairwise comparison matrices for the elements in one level with respect to the upper level. The criteria C1, C2, and C3 are compared with respect to the main goal. The sub-criteria were compared with respect to the related main criteria, and alternatives were compared with respect to each of the sub-criteria. The workpiece that was taken in Chapter 3 and Chaplet 4 (as shown in **Figure 6-5**) was also considered in this model to apply the assessment process.

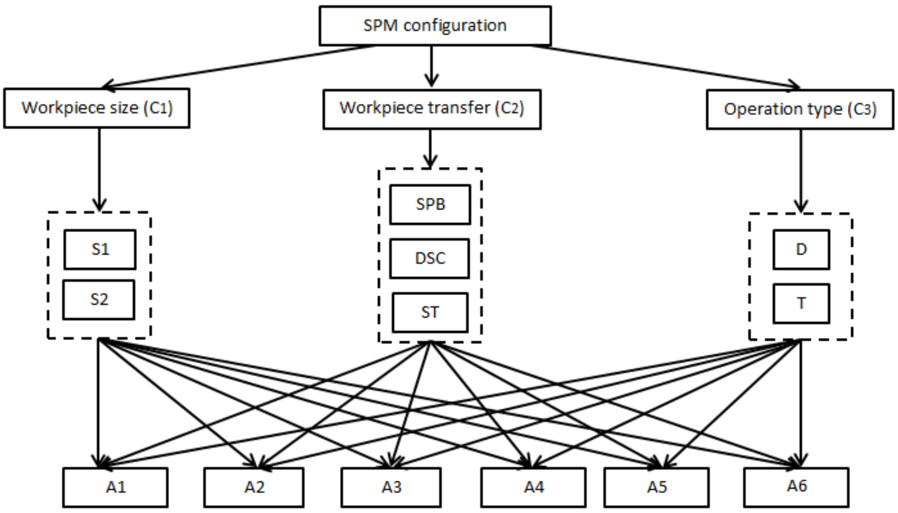


Figure 6-4. The decision hierarchy for the identified elements for the given criteria, sub-criteria, and alternatives.

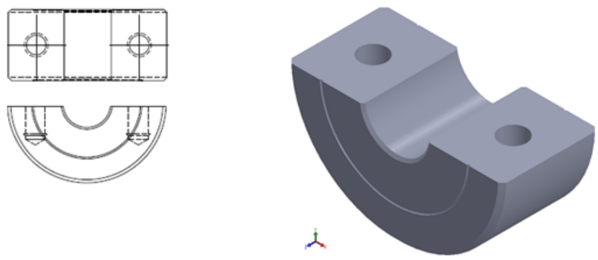


Figure 6-5. The design for the selected workpiece (half-collar).

6.1.1.1 Comparison matrices for criteria, sub-criteria, and alternatives

The assessment process was conducted to compare the elements in the hierarchy and then find the priorities of the criteria, sub-criteria, and alternatives. Subsequently, the priorities were synthesised to determine the weights of alternatives. The workpiece design information, manufacturing preferences, and industry recommendations were considered when associating the relevant importance of the elements in the hierarchy in the pairwise comparison based on the scale in **Error! Reference source not found.**. In addition, the experience and knowledge of the decision-makers play an important role in converting tangible and intangible factors into numerical data, and the decision-making process can therefore be enhanced. Designers, engineers, and managers in a company can use their knowledge and expertise to assign relevant importance in the pairwise comparison of the elements [106]. The assessment process in this work began by constructing a comparison matrix of the main criteria with respect to the main goal, as shown in **Table 6-1** below:

Table 6-1. The comparison matrix for criteria.

	C1	C2	C3
C1	1	1	1
C2	1	1	1
C3	1	1	1

The criteria were considered to have equal importance in the decision-making process for SPM configurations since they all contributed to the ultimate configuration. The normalised matrix for criteria is shown in **Table 6-2**.

Table 6-2. The normalised matrix for criteria.

	C_1	C_2	C_3
C_1	0.333	0.333	0.333
C_2	0.333	0.333	0.333
C_2	0.333	0.333	0.333

The column vector is given as (0.999, 0.999, 0.999) for this matrix, and the priority vector for this matrix is given as (0.333, 0.333, 0.333), which indicates the strength of importance (or priority) of each criteria C1, C2, and C3. The largest eigenvalue λ_{max} is calculated by taking the sum of the column vector which is 0.999 + 0.999 + 0.999 ≈ 3, and this is equal to the size of the matrix. This means that this matrix is consistent. The same process was applied to compare the sub-criteria with respect to the relative main criteria in the hierarchy. Examples of the generated matrices for the criteria and sub-criteria are given in **Table 6-3** and **Table 6-4**.

Table 6-3. The comparison matrix for sub-criteria with respect to workpiece transfer.

	SPB	DSC	ST
SPB	1	1/9	1
DSC	9	1	9
ST	1	1/9	1

Table 6-4. The comparison matrix for sub-criteria with respect to operation type.

	D	T
D	1	1/9
T	9	1

The priorities of sub-criteria from the pairwise comparison matrices were considered as local and they needed to be weighted regarding to the relative main criteria in order to calculate the global priorities for sub-criteria with respect to the main goal. This was completed by taking the percentage of the priority for

each sub-criterion to the priority of its relative main criteria. **Table 6-5** represents the local and global priorities for the sub-criteria.

Table 6-5. The local and global weights for the sub-criteria.

Sub-criteria	Local priorities	Global priorities
S1	0.900	0.270
S2	0.100	0.030
SPB	0.091	0.027
DSC	0.818	0.245
ST	0.091	0.027
D	0.100	0.030
T	0.900	0.27

The same assessment was applied to compare alternatives with respect to each sub-criterion. **Table 6-6** shows an example of these comparisons.

Table 6-6. The comparison matrix for the alternatives with regard to S1.

	A1	A2	A3	A4	A5	A6
A1	1	9	1	9	1	9
A2	1/9	1	1/9	1	1/9	1
A3	1	9	1	9	1	9
A4	1/9	1	1/9	1	1/9	1
A5	1	9	1	9	1	9
A6	1/9	1	1/9	1	1/9	1

The priorities of alternatives from the pairwise comparison matrices with respect to the sub-criteria are shown in **Table 6-7** which also contains the priorities for the criteria and the global priorities for sub-criteria. The consistencies of the matrix shown in **Table 6-6** and all the other matrices of alternatives were validated with Equations (3) and (4), and the values of CR were less than 0.1.

Table 6-7. The priorities from the comparison matrices of the alternatives with regard to the sub-criteria.

	C1: 0.333		C2: 0.333			C3: 0.333	
	S1: 0.270	S2: 0.030	SPB: 0.027	DSC: 0.245	ST: 0.027	D: 0.030	T: 0.270
A1	0.300	0.167	0.167	0.045	0.167	0.167	0.071
A2	0.033	0.167	0.167	0.045	0.167	0.167	0.071
A3	0.300	0.167	0.167	0.409	0.167	0.167	0.071
A4	0.033	0.167	0.167	0.045	0.167	0.167	0.071
A5	0.300	0.167	0.167	0.409	0.167	0.167	0.643
A6	0.033	0.167	0.167	0.045	0.167	0.167	0.071

After the priorities of all alternatives are obtained, the weight of each alternative was calculated using Equation 5, as follows [107]:

$$W_j = \sum_i u_i \times p_j \quad (5)$$

Where Wj is the weight of the alternative, u_i is the global priority of sub-criteria, and p_j are the priorities of the alternatives with respect to each sub-criterion. For example, the weight for A1 is:

$W_{A1} = 0.300 \times 0.270 + 0.167 \times 0.030 + 0.167 \times 0.027 + 0.045 \times 0.245 + 0.167 \times 0.027 + 0.167 \times 0.030 + 0.071 \times 0.270 = 0.131$

Table 6-8 shows the results of multiplying the priorities of the alternatives with the relative priorities of the sub-criteria, and the final weights of the alternatives as were calculated from Equation 5. These results were also represented in **Figure 6-6**.

Table 6-8. The final weights of the alternatives from the synthesis process.

	S1	S2	SPB	DSC	ST	D	T	Final weights
A1	0.081	0.005	0.005	0.011	0.005	0.005	0.019	0.131
A2	0.009	0.005	0.005	0.011	0.005	0.005	0.019	0.059
A3	0.081	0.005	0.005	0.100	0.005	0.005	0.019	0.220
A4	0.009	0.005	0.005	0.011	0.005	0.005	0.019	0.059
A5	0.081	0.005	0.005	0.100	0.005	0.005	0.174	0.375
A6	0.009	0.005	0.005	0.011	0.005	0.005	0.019	0.059

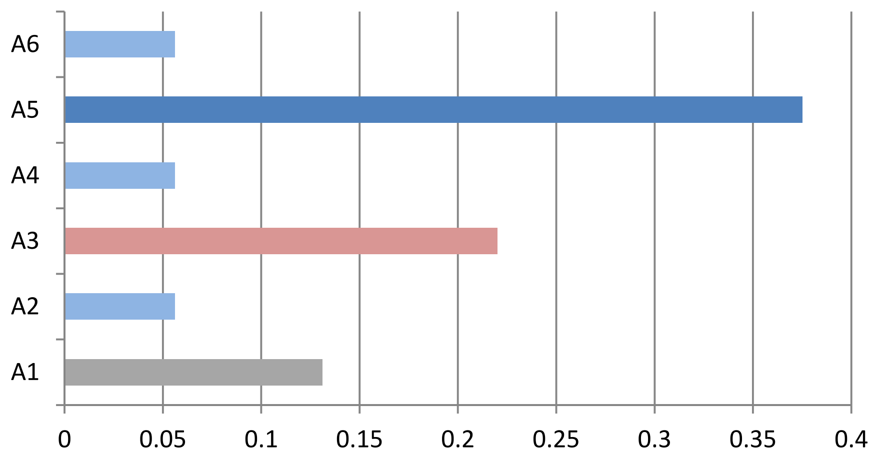


Figure 6-6. The weights of alternatives.

Alternative A5 had the highest value among the weights, followed by A3 and A1. Alternatives A2, A4, and A6 had the equal lowest weights. This is because the size of the workpiece was considered as standard, which led to a lower priority being given for these alternatives during the pairwise comparison process. These results depend on the design information of the workpiece, on the preferences of the decision-maker, and on industry recommendations which eventually affect the assessment process. For the same workpiece given in **Figure 6-5**, other scenarios were identified as shown in **Figure 6-7**.

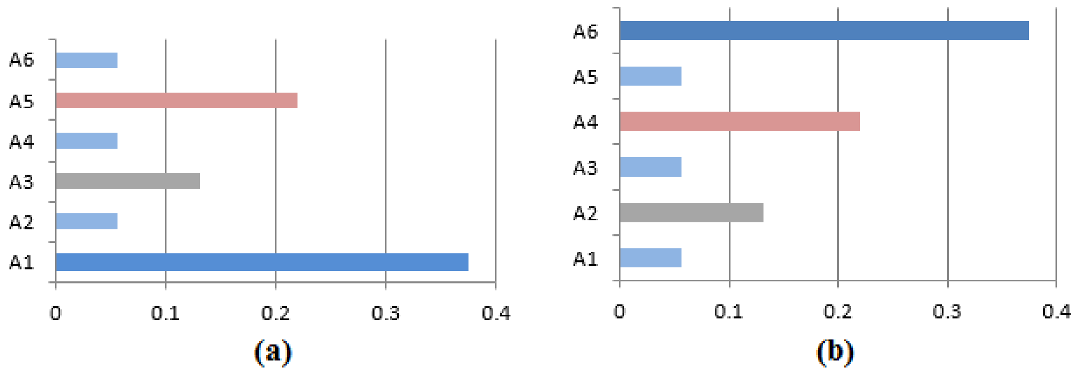


Figure 6-7. Other scenarios from the AHP model for the same workpiece; (a) one machined workpiece with no transfer (fixed), and (b) two special-size workpieces machined at each station.

Selection of configuration A5 results in a high production rate because DSC transfer was considered in the decision preferences, and two workpieces are therefore machined in each station at the same time. However, the same configuration can be used by considering SPB transfer, but with a lower production rate as there is only one workpiece machined at each station. This yields a less complicated configuration because the number of machining units and the other elements is reduced with the use of SPB transfer. The use of workpiece transfer (both SPB and DSC) brings automation features to the SPM layout design in regards to the feeding, clamping, and ejection procedures of the workpiece. Therefore, a high production rate with taking less time can be achieved by considering these features. When a lower importance was considered for the production rate and workpiece transfer in the design process, then configuration A1 is more appropriate in this case (as shown in scenario (a), **Figure 6-7**). In this configuration, only one workpiece is fixed and machined by the machining units at a time with manual feeding, clamping, and removing procedures. This configuration is less complicated than A5 (with both SPB and DSC); however, more time is needed to complete the machined workpiece with a lower production rate.

The implementation of the AHP model for SPMs was completed by Excel and Visual Basic software. This implementation helps the decision-makers to determine the appropriate configurations of the SPM layouts for a variety of workpieces and their group families. Therefore, the time for the SPM design process would be decreased and the decision process would be more effective. **Figure 6-8** shows the entry window of the developed AHP model, and **Figure 6-9** shows the result window for the first scenario.

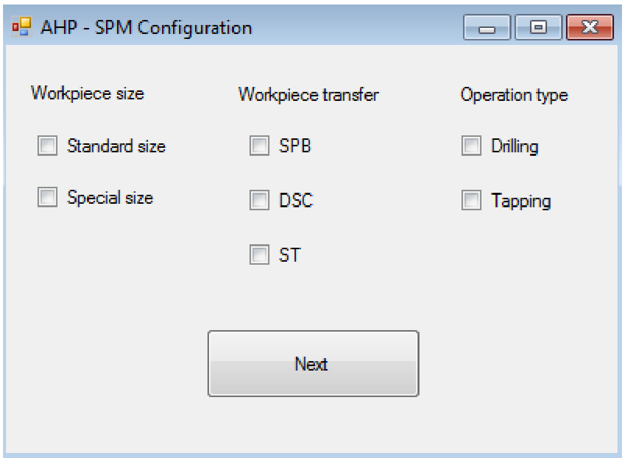


Figure 6-8. The entry window of the AHP model for the required criteria.

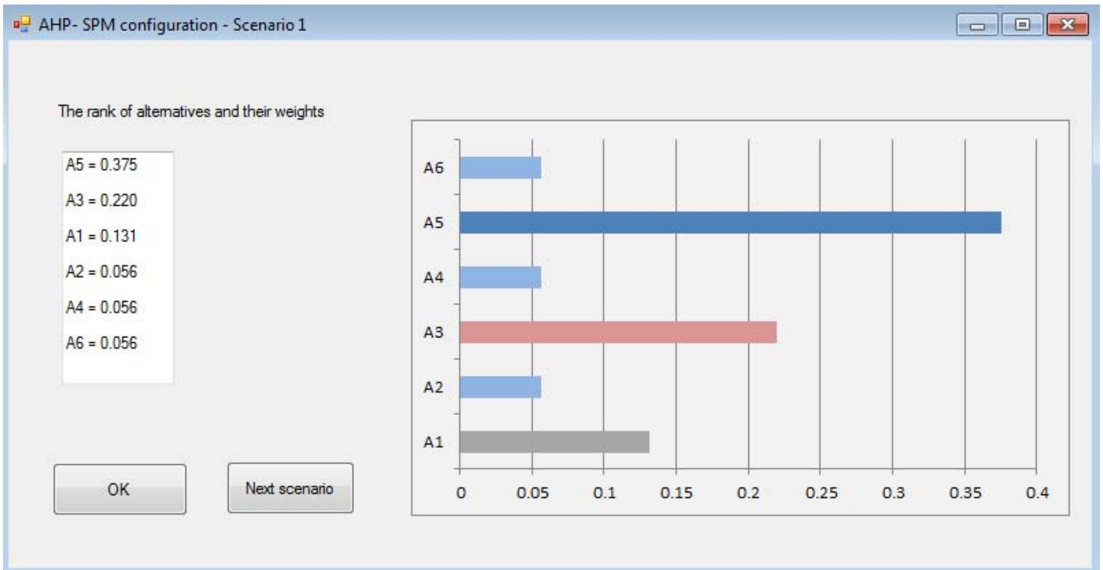


Figure 6-9. The results window for the first scenario after the pairwise compression.

6.2 Enhancing the reconfigurability of SPMs

The reconfigurability of machine tools has been an issue of interest to the manufacturing industry in order to meet changes in market demands. Manufacturing companies must have the ability to deliver products to the market quickly and to respond effectively to fluctuations in demand. Therefore, there is a need for machine tools with a scalable output and adjustable functionality that are available with minimum lead time. These machine tools should be modular and the interaction between their elements, or modules, should be minimised to prevent the effects of changes, with enhanced ability to add, remove, or rearrange the modules quickly providing adjustable functionality and capacity [208]. SPMs have a modular mechanical structure which allows machine elements to be removed and added based on changes in machining requirements. The main feature of SPMs is their ability to perform multiple operations simultaneously, unlike traditional machine tools such as a machining centre (which uses computer numerical control (CNC) machines) where only one operation can be performed in the same cycle time. This can reduce the machining time significantly [209]. As for reconfigurable machine tools (RMTs), the reconfiguration for SPMs depends on the design and machining requirements and must be performed quickly in addition to placing the machine elements accurately. This results in a minimisation of the build-up cost of the machine tools. Generally, the degree of reconfigurability of machine tools is measured in terms of the following characteristics:

- Integrability: the ability to integrate the modules quickly.
- Convertibility: the ability to modify the machine’s functionality.
- Scalability: the ability to adapt the machine’s capacity.

However, increasing the degree of reconfigurability will not bring flexibility to the machine tools as they will be customised to a part family which can be produced on these machine tools. The reconfiguration of a machine tool can be done in two ways: replacing machine modules, or integrating reconfiguration functions into the machine tool modules [210]. The first technique requires

disassembly and reassembly of the machine modules including calibration and other operations. In this regard, machine modules should be modular with standard interfaces which allow for the generation of several machine tool configurations. This will lead to a shorter set-up time and avoid the purchase of new machine tools. The reconfiguration of an SPM is defined as a change of size, type, and number of modules and their interconnections, in an attempt to quickly accommodate new and unanticipated changes in the product design. Therefore, the modules should be able to integrate quickly, and positional accuracy must be maintained when replacing the modules with respect to the machine coordinate system. **Figure 6-10** shows the construction of SPMs and their modules, sub-modules, and some possible configurations. End-users often buy a machine tool with a specific configuration, and when they need a different configuration, they have to buy a new machine or ask the machine's manufacturer to reconfigure their existing machine tool. End-users may buy more elements with the machine tool so they can reconfigure the machine tool for predicted or unpredicted changes in the market. In both cases, this incurs additional costs for parts and labour [211].

As the number of errors increase when more modules are used for the reconfiguration, the goal of this work is to propose a solution that would reduce the number of modules as much as possible while maintaining accuracy. It is important to design hardware and software so that the machine tool can be economically reconfigured for a part family with customised functionality and capacity (producing a variety of products with different production volumes). Previous studies recommended that end-users should be able to replace machine modules quickly and accurately, and more comprehensive techniques and mechanical connections between the modules should be investigated and developed [210]. The next section will propose a possible solution to overcome the errors that result from the reconfiguration process of SPMs.

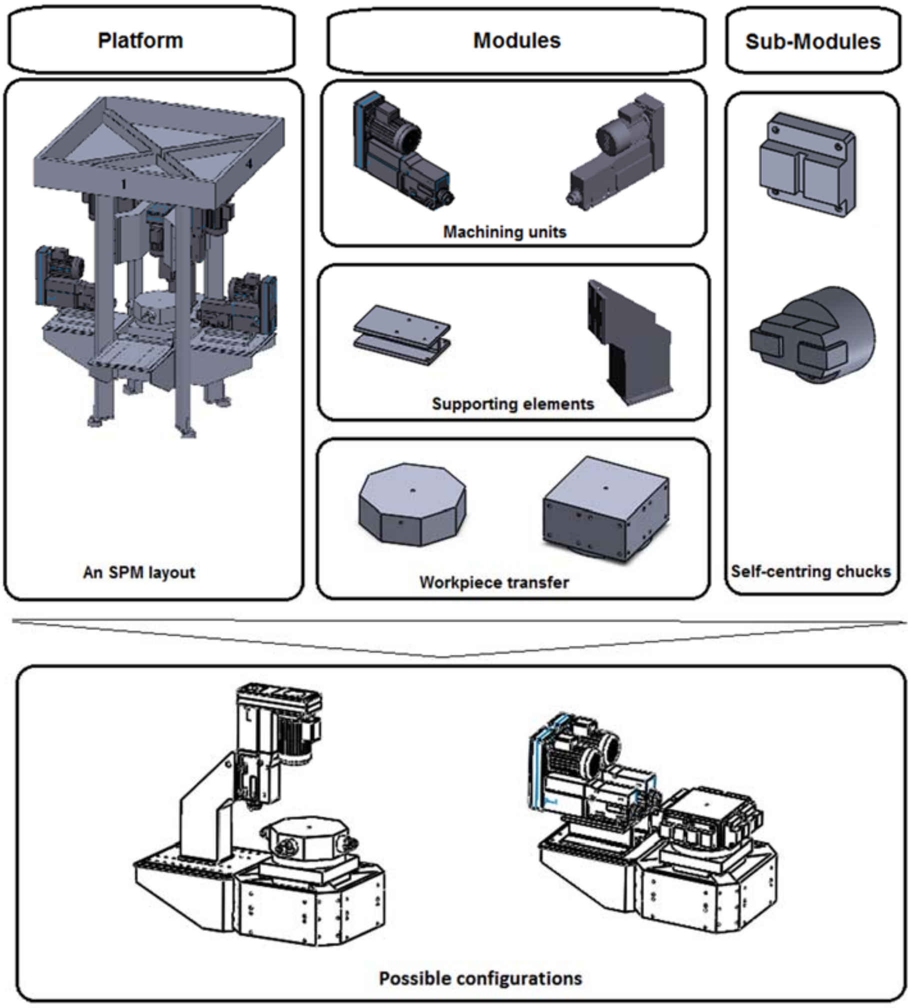


Figure 6-10. The construction of SPMs and some possible configurations.

6.2.1 The proposed solution

In SPMs, the characteristics that were mentioned above depend mainly on the properties of the interfaces of the SPM elements (modules). These elements are divided into categories, and it is important to minimise functional congruence and interference when installing them in order to reduce the primary machining processing time. To achieve this, the degree of re-configurability and modularity should be increased. **Figure 6-11** shows the frequency of replacement for SPM elements with operation and replacement times.

There are two types of interfacing: mechanical and transmission. Mechanical interfaces are of interest in this study because they can not only provide a quick and easy connection between SPM elements, but also improve the overall performance of the machine tool due to their ability to transmit forces and align the elements precisely [212]. To meet the objectives stated above, a mechanical adapter system for joining SPM elements is proposed and analysed.

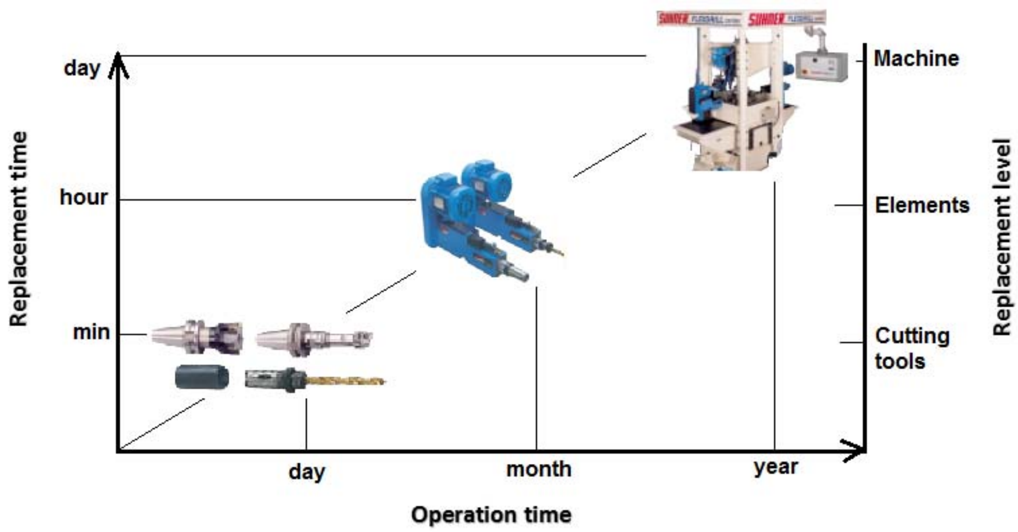


Figure 6-11. The three levels of replacement for SPMs.

The mechanical interface discussed in this work is a type of multi-coupling (MC), and its functionality is based on “Plug and Produce” [213]. This type of interface provides important features, such as function transfer across the joined planes of the elements, locking and releasing mechanisms, locating and positioning elements, and also reconfiguration capabilities. Previous studies introduced and discussed several types of mechanical interfaces for reconfigurable machine tool elements [214]. It is important to design these interfaces based on the maximum system requirements, taking into account the function tolerance area. In SPMs, the design of the mechanical adapter system should be carried out carefully to select the elements that can be implemented in the system. In this regard, there are some factors that should be considered in the design of this system: changing the type of machining (drilling, tapping, and

reaming), changing the capacity of machining (dimensions of the holes/taps), changing the holding mechanism for the workpiece, and changing the workpiece transfer mechanism. When these factors are considered in the context of the degree of reconfigurability measures discussed above, the SPM elements that are selected to apply this proposed interface are the clamping systems DSC and SPB (or also called the workpiece transfer systems) as shown in **Figure 6-2**.

The SPB workpiece transfer is used when one workpiece is machined at each station at the same time, while DSC is used when two workpieces are machined at each station at the same time. The end-user should decide which one of these systems to buy as this affects the configuration of the machine tool. In case a reconfiguration is needed later, then the end-user should buy the other system with the relevant machine elements. Both DSC and SPB are customised systems, as they are made at the request of the end-user. Two types of chucks are used with these systems: MF chucks are used with the DSC system and ML chucks are used with the SPB system. **Figure 6-12** shows these chucks with their respective systems. Overall, there are four available configurations for each system based on the size of the workpiece.

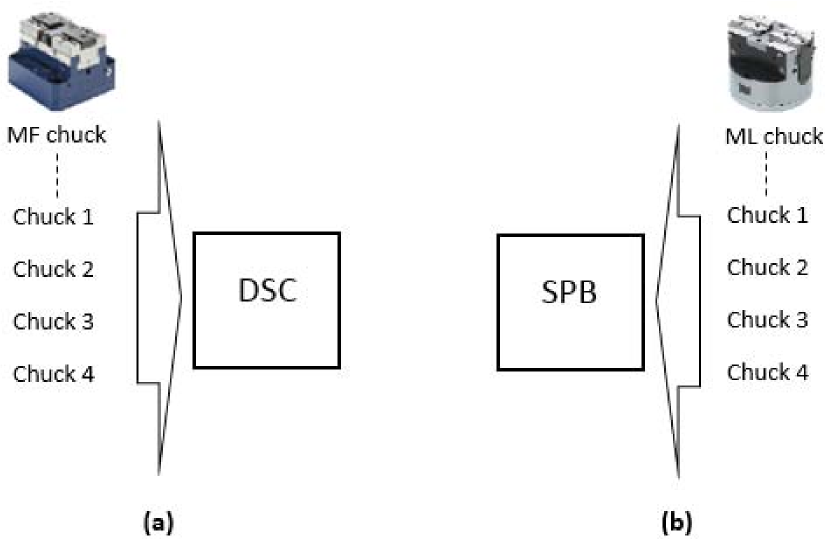


Figure 6-12. (a) The DCS system and its MF chucks, and (b) the SPB system and its ML chucks.

The reconfiguration from DSC to SPB or vice versa requires the end-user to buy more elements and also requires a considerable amount of time. To meet the characteristics of reconfigurability and the factors mentioned above, a new workpiece transfer is proposed in this work to combine both DSC and SPB in one system. A quick-coupling mechanism is used to develop the new transfer system for a quick and accurate reconfiguration. The reconfiguration will only include replacing the chucks for machining one or two workpieces at a station. **Figure 6-13** shows how DSC and SPB systems can be combined in one workpiece transfer device that can accommodate both types of chucks associated with DSC and SPB. This new proposed solution will reduce the number of modules for a reconfiguration. Therefore, the build-up cost of the machine tool and the reconfiguration time can be reduced. This solution will increase the reconfiguration characteristics of the existing modules in order to respond to changes in produced workpieces. In addition, it will enhance the integrability, convertibility, and scalability of SPMs.

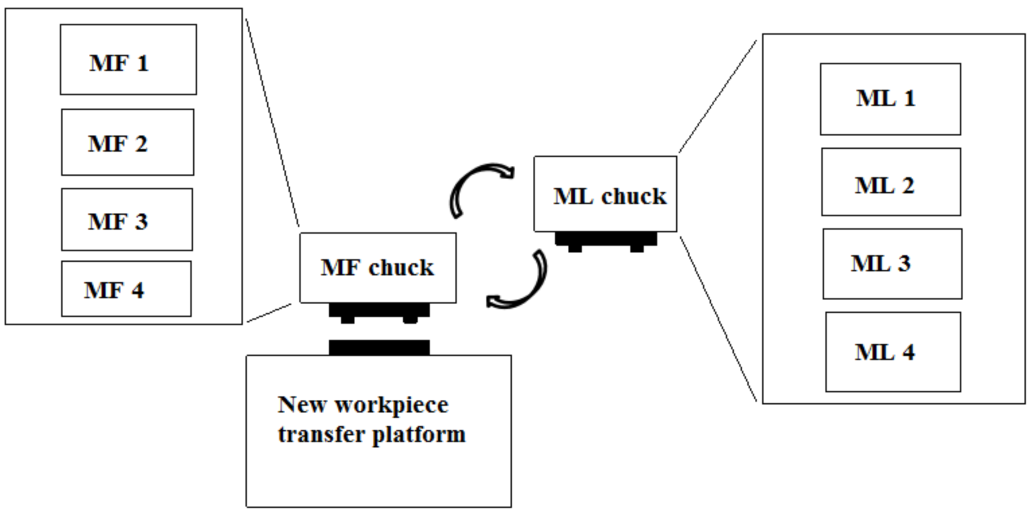


Figure 6-13. Both SPB and DSC systems can be combined in one platform to accommodate both types of chucks without the need to change the whole system.

6.2.2 The design concept

The proposed approach is to develop a platform that can accommodate both types of chucks, ML and MF, without changing the workpiece transfer. To achieve this goal, a mechanical adapter is used between the chucks and the workpiece transfer so they can be easily assembled and disassembled without bolts (the default joining type for these chucks). However, the mechanical adapter must not only join the chucks with the workpiece transfer but must also meet specific criteria to ensure the optimum performance of SPMs. In this regard, a quick-change pallet system is used to modify the existing workpiece transfer system (DSC) so it can accommodate both types of chucks for machining one or two workpieces. The original DSC is shown in **Figure 6-14**.

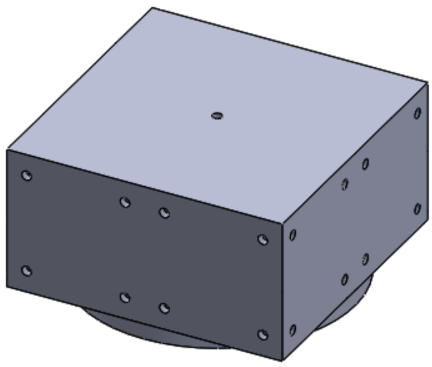


Figure 6-14. The original DSC.

The DSC is designed to assemble MF chucks for machining two workpieces at the same time. There are four types of MF chucks with different dimensions. Therefore, four DSC systems are provided by the manufacturer upon the request of the end-user. The choice of DSC depends on the type and size of MF chuck that is required for the specific workpiece. In this work, the DSC is modified by a specially-designed adapter system consisting of a quick-change module and a clamping pallet as shown in **Figure 6-15**. The quick-change module is attached to the original DSC workpiece transfer while the clamping pallet is attached to the chucks (ML or MF chucks). The joining method of this adapter involves a

clamping pin on the clamping pallet and sliding pins on the quick-change module (as shown in **Figure 6-15**).

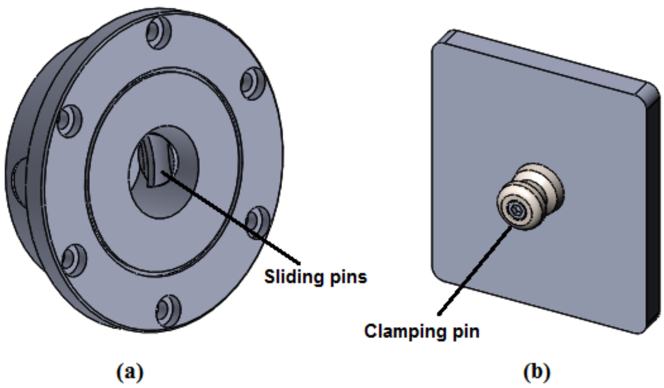


Figure 6-15. (a) A quick-change module, and (b) a clamping pallet.

Figure 6-16 shows how this adapter is attached to SPMs and how different configurations can be generated.

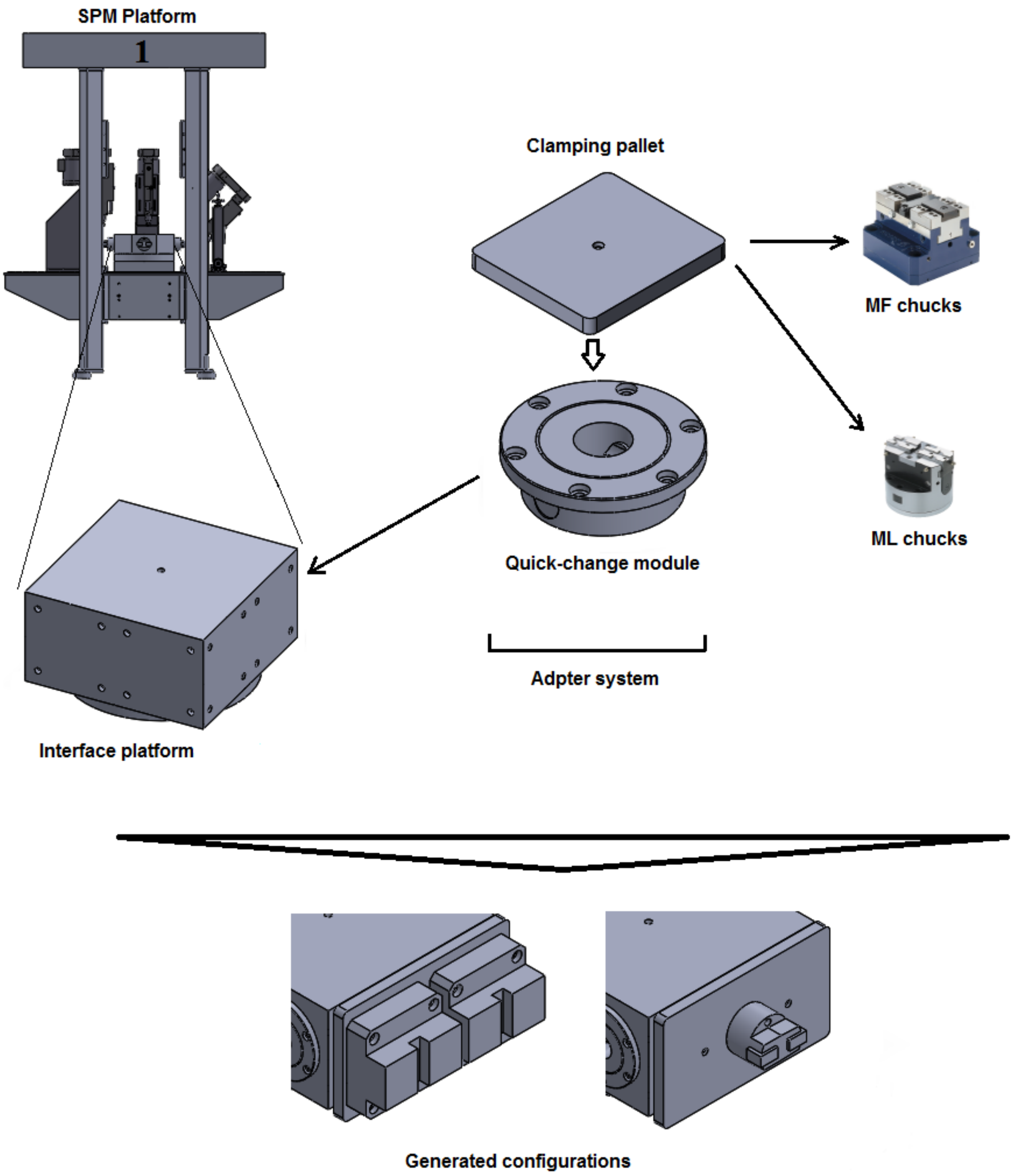


Figure 6-16. The attachment of the adapter to four stations SPM and possible configurations.

The adapter shown in **Figure 6-15** restricts two degrees of freedom (DOF), the translational DOF of the clamping pallet. However, the clamping pallet can still rotate, and this movement should also be restricted to achieve maximum positioning accuracy of the workpiece. In order to do this, two modules are added to each side of the DSC. In this case, the clamping pallet is modified to include

two clamping pins in order to fit precisely with the quick-change modules. The modified DSC and the clamping pallet are shown in **Figure 6-17**.

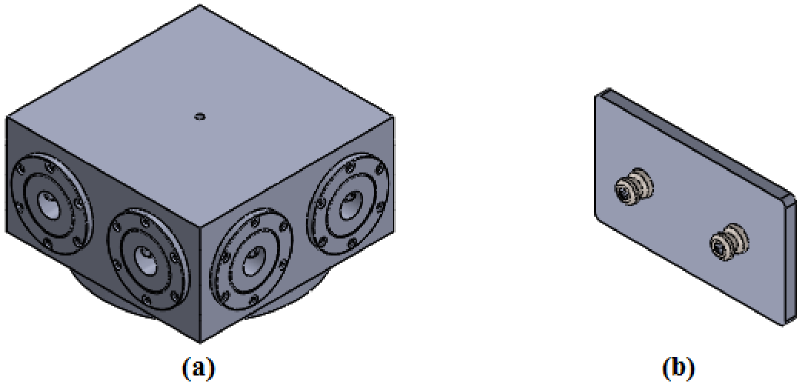


Figure 6-17. (a) The modified DSC workpiece transfer, and (b) the modified clamping pallet.

Therefore, all the DOF are restricted and machining accuracy is maintained. **Figure 6-18** shows how these DOF are being restricted since one of the clamping pins is considered as interface 1 and the other is interface 2 between the quick-change module and the clamping pallet. Interface 1 prevents two translational DOF, and interface 2 completes the full restriction of the DOF.

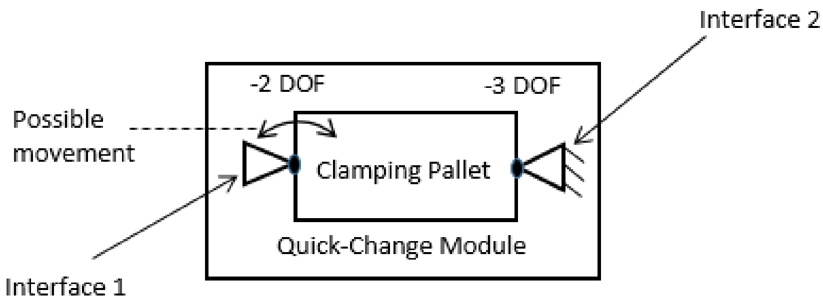


Figure 6-18. A model shows how DOF are restricted for the adapter (i.e. the quick-change module and the clamping pallet).

The clamping pallet is designed to accommodate MF and ML chucks. A complete arrangement of these components is shown in **Figure 6-19** for MF chucks.

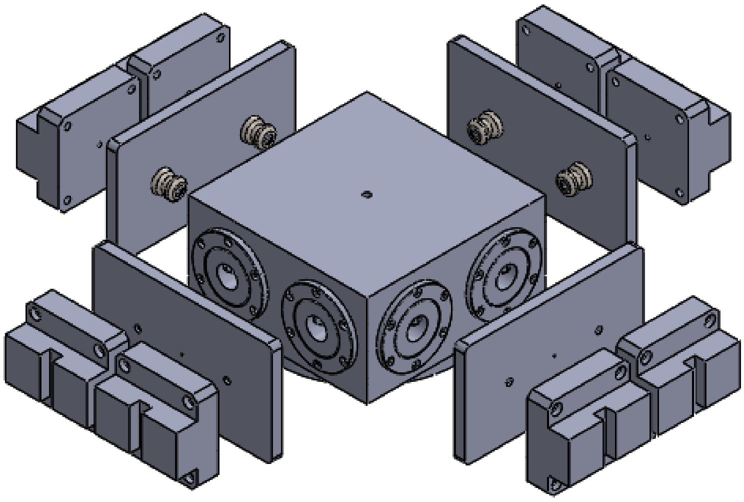


Figure 6-19. A complete arrangement of the modified DSC, clamping pallets, and MF chucks for 4 station SPMs.

The original arrangement for the same chucks using the original DSC workpiece transfer is shown in **Figure 6-20**.

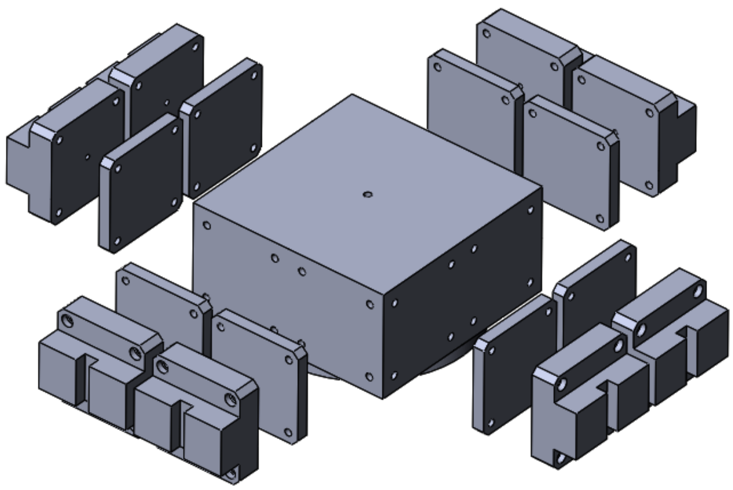


Figure 6-20. The original arrangement for the DSC and MF chucks.

In the original arrangement, the chucks are bolted to the DSC with the use of separate plates for each chuck, while in the modified system, the chucks are bolted to the clamping pallet, and the pallet is plugged into the DSC using the clamping pins. This action is performed by the sliding pins in the quick-change module, and in this case, the chucks are positioned without any preloads that exist in the original arrangement. Four types of the DSC workpiece transfer with its arrangements – including four types of MF chucks with different sizes – are provided by the manufacturer at the request of the end-user. In addition, five types of ML chucks, i.e. five types of the SPB workpiece transfer, are available upon request. The modified DSC proposed in this work with an adapter system will eliminate the need for these types of workpiece transfer, as it will be able to accommodate the four types of MF chucks and the five types of ML chucks. The only requirement is for a set of these chucks attached to a clamping pallet for the same modified DSC. Therefore, the number of machine tool elements (modules) can be reduced significantly and this can enhance the degree of reconfigurability of the SPMs. The separate plates in the original arrangement are replaced by the clamping pallets, and the original design of the DSC is adapted to attach the quick-change modules. As a results, the manufacturing cost of the modifications is minimal.

6.2.3 Performance criteria for the proposed adapter

There are a number of criteria that should be investigated for the design of the mechanical adapter in order to ensure the best performance. In this study, the following criteria for the proposed adapter were investigated and discussed: repeatability, accuracy, ram-up time, and natural frequencies.

6.2.3.1 Repeatability

This criterion refers to how well a device can deliver an outcome over a period of time. In the mechanical adapters, wear is the measure that can decrease repeatability, and this affects the machining quality of machine tools. Because the reconfiguration happens at the adapter interface only, therefore, the repeatability of the machine tool depends on the repeatability of the adapter system. The new

adapter system proposed in this work can increase repeatability by decreasing mechanical wear for the modules. This is achieved by using the quick-change module with clamping pins. The clamping pins are designed to bear the work forces as they are clamped by sliding pins in the quick-change module. The material for the clamping pins was selected to withstand the maximum loads and in the case of any mechanical wear, only the clamping pins will be replaced, with no need to change the quick-change module and the clamping pallet.

6.2.3.2 Accuracy

Accuracy in machine tools refers to the translational and rotational errors in their work volumes. These errors come from all components and adapters. Usually, these errors can be avoided by careful calibration or adjustment so accuracy can be achieved. The proposed adapter system provides a high level of accuracy. This is because clamping pins' tapered shape, which fits perfectly with the sliding pins inside the quick-change module. This provides an optimum centre positioning with no errors, and by using two clamping pins (as shown in **Figure 6-17**), the positional accuracy of the workpiece is secured by restricting the movement of the clamping pallet. As a result, no further adjustment and calibration are needed.

6.2.3.3 Ramp-up time

This criterion refers to the ease of use of a device. In regard to the adapter system, it can be defined as how quickly the adapter system is taken off and plugged in. The ramp-up time is a key measure of the reconfiguration process required to enable a machine tool to face new production changes. It is preferable that the assembly and disassembly of the machine tool components can be completed with less specialised tools and skills so the time for set up and take off can be reduced. The proposed adapter system in this work has considerable flexibility so it can be assembled and disassembled quickly without tools. It can be activated and deactivated mechanically and pneumatically. The type of interface used in this adapter system provides an easy method for plugging in and

taking off as no bounded components are used (such as bolts). As a result, the time for reconfiguration will be significantly reduced.

6.2.3.4 Natural frequency

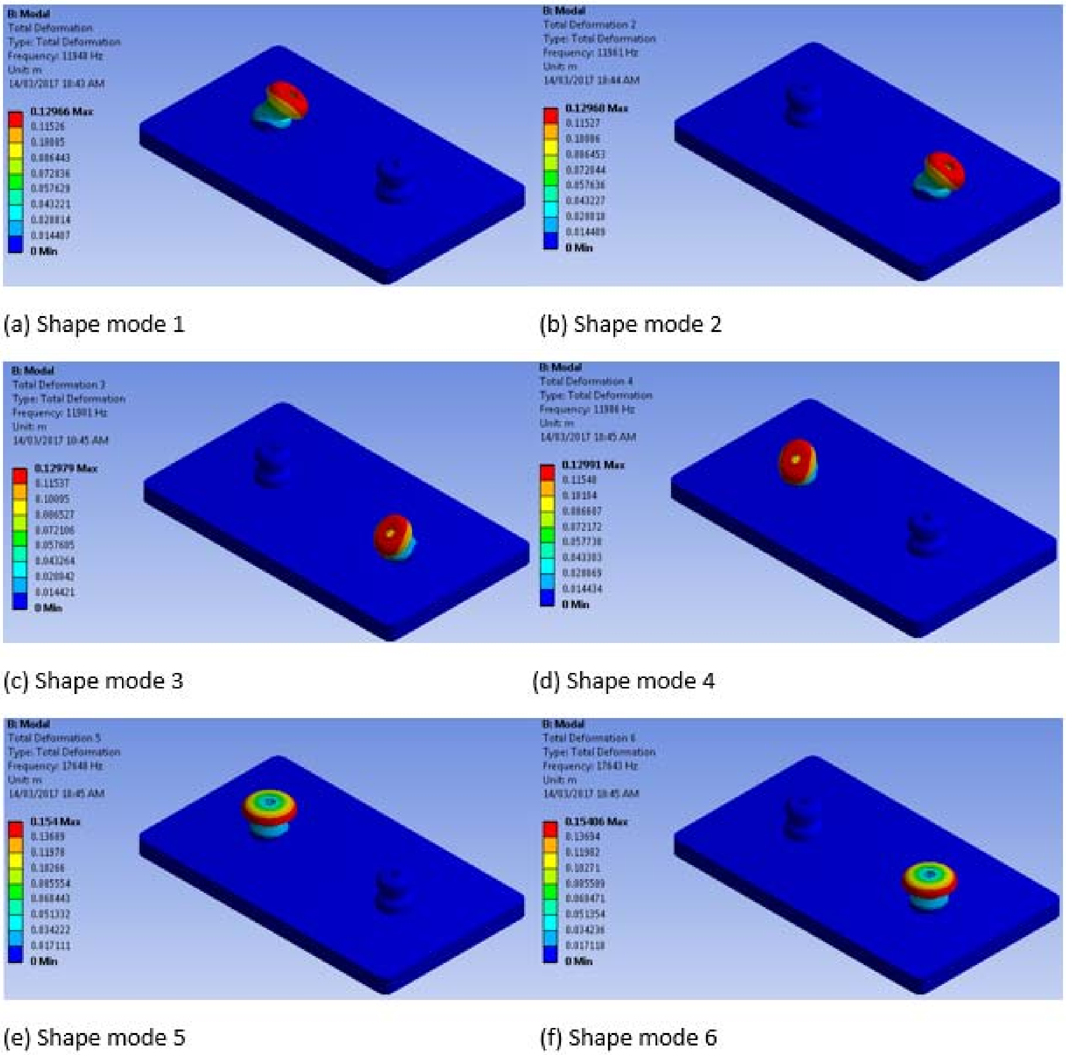
Natural frequency (NF) is an important criterion for any mechanical components. The natural frequency of the adapter system should not be equal to the frequencies of the applied loads in an SPM layout. This is to ensure the optimal performance of the adapter without resonance occurring. In order to define the natural frequencies of the adapter system, modal analysis was used by ANSYS in this study. This analysis predicts the vibration response of a structure to dynamic loads (applied loads). It is known that every component has natural frequencies, and resonance is encountered when the exciting forces coincide with one of the natural frequencies. This condition produces large amplitudes of displacement. Modal analysis was applied to the clamping pallet in this work because this component will withstand the maximum loads generated during the machining processes. It is crucial that its natural frequencies do not match the frequencies of the machine tool. Natural frequencies for the clamping pallet were defined as shown in **Figure 6-21** with maximum displacement.

The maximum and minimum NF for the clamping pallet were 17643 Hz and 11948 Hz respectively (see **Figure 6-21**). The value of the maximum NF should not be equal to the frequencies generated from the machining operations in SPMs. These frequencies can be determined from the speed of the machining units. In this study, it was assumed that each station accommodated two machining units, and there were four stations. The maximum speed of 15000 rpm was assumed for each unit, and therefore, the maximum frequency was calculated as follows:

15000 x 8 = 120000 rpm

Hertz = rpm/60 = 120000/60 = 2000 Hz

The value (2000 Hz) is much lower than the NF values of the clamping pallet defined by the modal analysis.



(a) Shape mode 1 (b) Shape mode 2

(c) Shape mode 3 (d) Shape mode 4

(e) Shape mode 5 (f) Shape mode 6

Figure 6-21. Natural frequencies and shape modes for the clamping pallet.

6.3 Summary

This chapter described the development of an AHP model which was implemented in the SPM layout design. The model will help engineers and designers to select the most appropriate configurations of SPM layouts from available alternatives. In addition, an approach to increase SPM reconfigurability was also proposed in this chapter. The approach includes developing an adapter system for SPM modules in which they would be easily added or removed in order to reconfigure SPM layouts. A design concept for a mechanical adapter was

introduced and explained. Related design criteria were discussed in order to justify the proposed approach. Both the AHP model and the mechanical adapter approach represent future trends for this research, as explained in Chapter 7.

Chapter Seven

7. Conclusions and Future Work

The main objective of the work presented in this thesis was to develop an integrated system to facilitate the design process for SPM layouts. The integration process includes the implementation of four components: the SPM knowledge-base, an assembly modelling approach, a CBR method, and SolidWorks. The required SPM knowledge-base was developed in this work, and it was coded using VisiRule expert system tool as explained in Chapter 3. An assembly modelling approach for SPMs was developed using a data structure method, an assembly relationships graph, an SPM database, and a design library as explained in Chapter 4. A CBR method was used to develop a new indexing and retrieval approach for SPMs using workpiece and machining attributes as explained in Chapter 5. Chapter 5 also presents how the integration process was completed using SolidWorks API by creating a new menu and sub-menus for the SPM system in the SolidWorks environment. Although the primary aim of this work was to develop the integrated system, other techniques and methods regarding the design of SPMs have been investigated as shown in Chapter 6. An AHP method was used to develop an approach using design criteria and available SPM alternatives. In addition, a new approach was proposed using a mechanical adapter to be attached to the SPM elements.

7.1 Research outcomes and contributions

The overall outcome from the development of the integrated system in this thesis is the potential to significantly reduce the time involved in the SPM design process; however, each of the components explained above has specific outcomes and make particular contributions to this research and to the literature. These outcomes and contributions are as follows:

(a) Make the selection process of the SPM elements quick and efficient.

This outcome was achieved by building the SPM knowledge-base. The domain knowledge for SPMs needed to be collected and presented in an

appropriate format. The required information about the SPM elements and all information related to the SPM design process formed the basis of the SPM knowledge-base. This information was collected from available resources such as manuals, industry recommendations, and machining operation requirements. Furthermore, engineering domain knowledge and experience were also used in developing this knowledge-base. As a result, the SPM knowledge-base was built using rules in IF-THEN format. In total, more than 350 rules were created in order to include as much information as possible about the SPM elements and two machining operations: drilling and tapping. After that, this knowledge-base was coded using the VisiRule expert system tool. This tool has significant flexibility in implementing different rule formats in a flowchart form. The first result of using this tool was a code generated for the knowledge-base. This code could be used with any software and can be converted to any programming language. Another result of using VisiRule is that users can run the code within this tool and they can therefore obtain results regarding the selection of the suitable SPM machining units and other elements. Therefore, the selection of SPM elements is fast and efficient.

The contribution of this outcome to literature is that it makes the domain knowledge of SPMs available for engineers in design and manufacturing fields. This knowledge has not previously been recorded, and this was therefore had to be the first step in this research. A new use of the VisiRule expert system tool was also introduced to the literature through this work. This tool has many advantages in decision-making processes and can be used in coding different types of rules effectively.

(b) Significantly reduce the assembly time for SPM layouts.

This outcome was achieved by developing an assembly modelling approach for SPMs. This approach included the creation of the SPM database, which was built using Microsoft Access. The database included technical information about various SPM elements. In addition, a design library for the SPM elements was built in the SolidWorks environment. 3D models of the SPM elements were used

in building the design library. The assembly relationships between the SPM elements were defined using the assembly relationships graph (ARG). The approach developed in this work also explained how the mating conditions between the SPM elements were identified. The result of the implementation of this assembly modelling approach was the automation of the assembly process of the SPM elements using SolidWorks API thanks to the predefined assembly relationships between the SPM elements. This automation resulted in a significant reduction in the assembly time for the SPM layouts.

The contribution of this outcome is building the SPM database and making it available for use. This database is a very important component in the integrated system because it provides the required technical information for the SPM elements. In addition, the assembly relationships between the SPM elements were defined by the assembly modelling approach and stored in the database. The other contribution of this outcome is introducing the use of SolidWorks API in assembly automation. This was achieved using the predefined assembly relationships from the assembly modelling approach in order to automate the assembly process of SPM layouts.

(c) Automate the selection process of the SPM layouts.

This outcome was achieved using a CBR approach. CBR is an artificial intelligence tool that is used in automating the design process for many engineering applications. In this thesis, CBR was used to select the most suitable SPM layouts for target workpieces from similar cases. These similar cases were stored in a case-base. The case-base was divided into the workpiece case-base, which included a range of workpieces, and the SPM case-base, which included SPM layouts as solutions for the workpieces in the workpiece case-base. An indexing system for SPMs was developed considering workpiece and machining attributes. A dual-step retrieval process was developed and used to search and retrieve the ultimate case. The CBR approach developed in this work was applied to different target workpieces and it was clear that this approach reduced the SPM layout design time considerably by reducing the time required for the SPM

layout assembly process. The users or designers need only to modify the suggested layouts using the developed approach and there is no need to start the layout design from scratch for the target workpieces.

The contribution of this outcome is a new use of the CBR method in the design of machine layouts. The CBR approach developed in this work brings many advantages to the SPM design process: SPM layouts were made available as solutions for new cases, quick and effective searches were possible for similar SPM cases, and an efficient SPM indexing and retrieval system was made available.

(d) Integrate the developed components for the SPM system with SolidWorks.

The integration of the CBR approach, the assembly modelling approach, the SPM database, and the SPM knowledge-base was completed in this work in the SolidWorks environment. This outcome was achieved by applying SolidWorks API features together with the Visual Basic (VB) programming language. An Add-in project was developed in VB and implemented in the SolidWorks environment. The result of this development was a new menu called SPM system which was added to the menu bar in the SolidWorks environment. This menu extended to sub-menus for the CBR approach, the SPM knowledge-base, the SPM database, and SPM assembly. Each of these menus leads to different windows that allow the user to start the process by selecting the most similar layout for a new case from the CBR menu. The user can then consult the SPM knowledge-base for the best decision about the SPM elements to modify the suggested layout, and check the specifications of these elements with the SPM database. Finally, the user can add the required SPM elements and complete the layout for the new workpiece.

The contribution of this outcome is a new approach to integrate different applications and software in SolidWorks. The new approach uses VB as a programming language due to its effective role in developing Add-in projects. In addition, VB is already implemented in SolidWorks API and this makes the integration process much easier and less time-consuming.

7.2 Future Work

Although the main objectives of the work presented in this thesis were achieved, there are aspects of the work that can be further investigated and enhanced. The future trends of this work are as follows:

(a) Automating the modifications step for the suggested SPM layouts in the CBR approach.

The CBR approach developed in this thesis has automated the selection process of similar SPM layouts for new target workpieces. However, the user still needs to make modifications to these SPM layouts in order to meet all the requirements for the new target workpieces. These modifications are made manually in the integrated system developed in this thesis. Therefore, an additional stage can be created and integrated with the CBR method to enable the integrated system to suggest the required modifications for the SPM layouts.

(b) Integrating the AHP method with the developed SPM system.

An AHP approach was developed as additional work in this thesis. The AHP approach was used to identify the most suitable configurations for SPM layouts based on criteria and available alternatives (solutions). This AHP approach can be further extended and integrated with the developed SPM system in SolidWorks. The benefits of this integration will be providing weights for the workpiece and machining attributes that are used in the CBR approach. This can enhance the retrieval process in the CBR approach and make the developed integrated system more effective.

(c) Undertaking additional tests and analysis for the mechanical adapter system proposed in Chapter 6.

A new approach, using a mechanical adapter, was proposed in Chapter 6 in order to enhance the reconfigurability of SPMs. This is a promising solution that can considerably reduce the reconfiguration time for SPM layouts. However, further investigation is needed, including more analyses and tests in ANSYS for

this adapter to make sure that it meets all the working conditions for the SPM elements. The approach was proposed for a specific SPM element (the workpiece transfer); however, further investigation is required in order to apply this adapter to other SPM elements and build a complete adapter system for SPMs.

8. References

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9. APPENDICES

9.1 Cutting information and parameters for SPMs

SUHNER® CUTTINGdata

● Werkzeug ▲ Tool ■ Outil	● Vorschubreihen-Nr. ▲ Feed column No. ■ Nº des avances								
	1	2	3	4	5	6	7	8	9
	● f: mm/U			▲ f: mm/R			■ A: mm/t		
Ø 2,00	**0,020**	**0,025**	**0,032**	0,040	0,050	0,063	0,080	0,100	0,125
Ø 2,50	0,025	0,032	0,040	0,050	0,063	0,080	0,100	0,152	0,160
Ø 3,15	**0,032**	**0,040**	**0,050**	0,063	0,080	0,100	0,125	0,160,	0,160
Ø 4,00	0,040	0,050	0,063	0,080	0,100	0,125	0,160	0,200	0,200
Ø 5,00	**0,040**	**0,050**	**0,063**	0,080	0,100	0,125	0,160	0,200	0,250
Ø 6,30	0,050	0,063	0,080	0,100	0,125	0,160	0,200	0,250	0,315
Ø 8,00	**0,063**	**0,080**	**0,100**	0,125	0,160	0,200	0,250	0,315	0,315
Ø 10,00	0,080	0,100	0,125	0,160	0,200	0,250	0,315	0,400	0,400
Ø 12,50	**0,080**	**0,100**	**0,125**	0,160	0,200	0,250	0,315	0,400	0,500
Ø 16,00	0,100	0,125	0,160	0,200	0,250	0,315	0,400	0,500	0,630
Ø 20,00	**0,125**	**0,160**	**0,200**	0,250	0,315	0,400	0,500	0,630	0,630
Ø 25,00	0,160	0,200	0,250	0,315	0,40	0,500	0,630	0,800	0,800
Ø 31,50	**0,160**	**0,200**	**0,250**	0,315	0,400	0,500	0,630	0,800	1,000
Ø 40,00	0,200	0,250	0,315	0,400	0,500	0,630	0,800	1,000	1,250

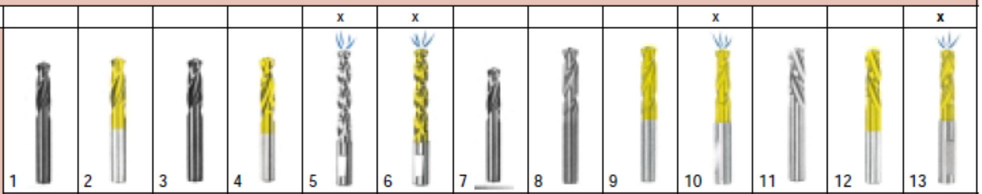
● Formel für min⁻¹ ▲ Formula for RPM ■ Formule pour t.min⁻¹ = $\frac{\text{Vc (m/min)} \times 1000}{\text{d (Ø mm)} \times 3{,}14}$

● Schneidstoff	▲ Tool material	■ Matières
● TiN-Beschichtung	▲ TiN-coated	■ Revêtu TiN
● DIN-Norm	▲ Norme DIN	■ Norme DIN
● Mit Kühlkanälen	▲ With coolant	■ Lubrification centrale

HSCO: S6-5-2,5
1.3243 (6,5 W/5% Mo/2% V/4,8% Co)
HM: ● Hartmetall
HM: ▲ Carbide
HM: ■ Carbure métallique

● Zerspanbarkeitsgruppe ▲ Material group ■ Groupe matière	● Werkstoffbeispiele (fett gedruckte Zahlen: nach DIN EN 10027) ▲ Material examples (bold printed numbers: according to DIN EN 10027) ■ Examples matière (selon DIN EN 10027 pour les chiffres en gras)	● Zugfestigkeit N/mm² ▲ Tensile strenght N/mm² ■ Résistance N/mm²
● Allgemeine Baustähle ▲ Common structural steels ■ Aciers de construction	1.0035 St 33, 1.0254 St 37.0, 1.0486 StE 285, 1.0345 H1, 1.0425 H2 1.0050 St 50-2, 1.0070 St 70-2, 1.8937 WStE500	≤500 >500–850
● Automatenstähle ▲ Free-cutting steels ■ Aciers de décolletage	1.0718 9SMnPb28, 1.0723 15 S20, 1.0736 9 SMn36 1.0727 45 S20, 1.0728 60 S20, 1.0757 45SPb20	≤850 850–1000
● Unlegierte Vergütungsstähle ▲ Unalloyed heat-treatable steels ■ Aciers d'amélioration non-alliés	1.0402 C22, 1.1178 Ck30 1.0503 C45, 1.1191 Ck45 1.0601 C60, 1.1221 Ck60	≤700 700–850 850–1000
● Legierte Vergütungsstähle ▲ Alloyed heat-treatable steels ■ Aciers d'amélioration alliés	1.5131 50MnSi4, 1.7003 38Cr2, 1.7030 28Cr4 1.5710 36NiCr6, 1.0735 41Cr4, 1.7225 42CrMo5	850–1000 >1000–1200
● Unlegierte Einsatzstähle ▲ Unalloyed case-hard steels ■ Aciers de cémentation non-alliés	1.0301 C10, 1.1121 Ck10, 1.1140 Cm15	≤750
● Legierte Einsatzstähle ▲ Alloyed case-hard steels ■ Aciers de cémentation alliés	1.5919 15CrNi6, 1.7012 13Cr2, 1.7015 15Cr13 1.5752 14NiCr14, 1.7131 16MnCr5, 1.7264 20CrMo5	850–1000 >1000–1200
● Nitrierstähle ▲ Nitriding steels ■ Aciers de nitruration	1.8504 34CrAl6, 1.8506 34CrAlS5, 1.8509 41CrAlMo7 1.8507 34CrAlMo5, 1.8519 31CrMoV9, 1.8550 34CrAlNi7	≥850–1000 >1000–1200
● Werkzeugstähle ▲ Tool steels ■ Aciers à outils	1.1750 C75W, 1.2067 100Cr6, 1.2307 29CrMoV 1.2080 X210Cr12, 1.2083 X42Cr13, 1.2419 105WCr6, 1.2767 X45NiCrMo4	≤850 >850–1000
● Schnellarbeitsstähle ▲ High-speed steels ■ Aciers rapide	1.3243 S 6-5-2-5, 1.3343 S 6-5-2, 1.3344 S 6-5-3	≥650–1000

● Auswahl und Empfehlungen für Bohrwerkzeuge, in HSS und HM, 3×D
▲ Selection and application recommendations for HSS and carbide drills, 3×dia.
■ Conseils d'utilisation et sélection des forêts en HSS et carbure, 3×D



	1		2		3		4		5		6		7		8		9		10		11		12		13	
	HSS		HSS		HSCO		HSCO		HSCO		HSCO		HM-K 20		HM-K 40		HM-K 40		HM-K 20		HM-K 20		HM-K 20		HM-K 20	
			TiN				TiN				TiN						TiN		TiN				TiN		TiN	
	1897		1897		1897		1897		6537		6537		6539		6539		6539		6537		6539		6539		6537	
									x		x								x						x	
● Kühlmittel ● Emulsion ● Öl ○ Luft ▲ Lubrification ● Emulsion ● Oil ○ Air ■ Lubrification ● Emulsion ● Huile ○ Air	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No	m/min	No
●	36	6	45	6					48	7	60	7	80	4			100	6	110	**6**			**100**	**5**	**110**	**5**
●	28	5	36	5					38	6	48	6	55	3			85	5	90	**5**			**85**	**4**	**90**	**4**
●	36	5	45	5					48	6	60	6	55	4			90	6	100	**7**			**90**	**5**	**100**	**6**
●	28	5	32	5	30	5	40	5	38	6	48	6	–	–			85	6	95	**6**			**85**	**5**	**95**	**5**
●	–	–	18	4	22	4	28	4	20	5	25	5	–	–			80	6	90	**6**			**80**	**5**	**90**	**5**

SUHNER® CUTTINGdata

● Auswahl- und Einsatzempfehlungen für Gewindebohrer in HSS, DIN 376

▲ Selection and application recommendations for tapping tools in HSS, DIN 376

■ Conseils d'utilisation et sélection des tarauds DIN 376 en acier HSS

● Durchgangsgewinde	▲ Through-holes	■ Trous débouchants
● Sacklochgewinde	▲ Hole deph	■ Profondeur de perçage
● TiN-Beschichtung	▲ TiN-coated	■ Revêtu TiN
● Gewindeformen	▲ Fluteless taps	■ Tarauds à former
● Mit Kühlkanälen	▲ With coolant	■ Lubrifcation centrale

● Formel für min⁻¹
▲ Formula for RPM
■ Formule pour t.min⁻¹

$$= \frac{Vc\ (m/min) \times 1000}{d\ (\varnothing\ mm) \times 3{,}14}$$

● Zerspanbarkeitsgruppe ▲ Material group ■ Groupe matière	● Werkstoffbeispiele (fett gedruckte Zahlen: nach DIN EN 10027) ▲ Material examples (bold printed numbers: according to DIN EN 10027) ■ Examples matière (selon DIN EN 10027 pour les chiffres en gras)	● Zugfestigkeit N/mm² ▲ Tensile strenght N/mm² ■ Résistance N/mm²
● Allgemeine Baustähle ▲ Common structural steels ■ Aciers de construction	1.0035 St 33, 1.0254 St 37.0, 1.0486 StE 285, 1.0345 H1, 1.0425 H2 1.0050 St 50-2, 1.0070 St 70-2, 1.8937 WStE500	≤500 >500–850
● Automatenstähle ▲ Free-cutting steels ■ Aciers de décolletage	1.0718 9SMnPb28, 1.0723 15 S20, 1.0736 9 SMn36 1.0727 45 S20, 1.0728 60 S20, 1.0757 45SPb20	≤850 850–1000
● Unlegierte Vergütungsstähle ▲ Unalloyed heat-treatable steels ■ Aciers d'amélioration non-alliés	1.0402 C22 1.1178 Ck30 1.0503 C45 1.1191 Ck45 1.0601 C60 1.1221 Ck60	≤700 700–850 850–1000
● Legierte Vergütungsstähle ▲ Alloyed heat-treatable steels ■ Aciers d'amélioration alliés	1.5131 50MnSi4, 1.7003 38Cr2, 1.7030 28Cr4 1.5710 36NiCr6, 1.0735 41Cr4, 1.7225 42CrMo5	850–1000 >1000–1200
● Unlegierte Einsatzstähle ▲ Unalloyed case-hard steels ■ Aciers de cémentation non-alliés	1.0301 C10, 1.1121 Ck10, 1.1140 Cm15	≤750

1	2	3	4	5	6	7	8	9	10	11	12	13
						≥2×D	≥2×D	>2×D	>2×D	>2×D	>2×D	>2×D
<2×D	<2×D	≥2×D	≥2×D	≥2×D	≥2×D							
	TiN		TiN				TiN		TiN		TiN	
				F								F
					X							
m/min	m/min	m/min	m/min	m/min	m/min	m/min	m/min	m/min	m/min	m/min	m/min	m/min
18 15	25 25	18 15	25 25	30 30	18 15	18 15		18 15	25 25			30 30
8 8 6	12 10 8	8 8 8	15 15 12	20 20 18	8 8 6	8 8 6		8 8 6	12 10 8			14 12 12
15	25		25	30				20	25	8		30

9.2 Additional rules of drilling one and multiple holes in SPMs

Rule 034D

If only one hole is required to be machined on the surface, then the material of the workpiece and the size of the hole are determined. Identifying the last two features is important to determine the cutting speed for each material and the suitable machining unit.

Rule 035D

If the material is cast iron and the hole size is less than or equal to 6 mm, and the cutting speed is ≥ 100 m/min, then BEX 35 CNC unit is used with HM-K20 Carbide drill bit. Sliding unit AU 30 is needed with BEX 35 CNC unit.

Rule 036D

If the material is cast iron and the hole size is less than or equal to 6 mm, and the cutting speed < 100 m/min then BEM 12 MONO unit is used with HSS drill bit.

Rule 037D

If the material is cast iron and the hole size is > 6 mm and ≤12 mm, and the cutting speed is >100 m/min, then BEM 28 MONO master is used with HM-K20 Carbide drill bit.

Rule 038D

If the material is cast iron and the hole size is > 6 mm and ≤12 mm, and the cutting speed ≤ 100 m/min, then BEM 20-100 MONO is used with HSS drill bit.

Rule 039D

If the material is cast iron and the hole size is > 12 mm and ≤ 20 mm, and the cutting speed is > 100 m/min, then BEX 60 CNC is used with HM-K20 Carbide bit. Slide unit UA 60 is needed with BEX 60 unit.

Rule 040D

If the material is cast iron and the hole size is > 12 mm and ≤ 20 mm, and the cutting speed ≤ 100 m/min, then BEM 28 MONO master unit is used with HSS drill bit if.

Rule 041D

If the material is cast iron and the hole size is > 20 mm and ≤ 40 mm, then BEX 60 with slide unit UA 60 are used for any ranges of the cutting speed and for both Carbide and HSS drill bits.

Rule 042D

If the material is steel and the hole size is less than or equal to 6 mm, and the cutting speed is > 25 m/min, then BEM 12 MONO unit is used with HM-K20 Carbide drill bit.

Rule 043D

If the material is steel and the hole size is less than or equal to 6 mm, and the cutting speed ≤ 25 m/min, then BEM 6 MONO unit is used with HSS drill bit.

Rule 044D

If the material is steel and the hole size is > 6 mm and ≤ 12 mm, and the cutting speed is > 25 m/min, then BEM 20-100 MONO unit is used with HM-K20 drill bit.

Rule 065D

If there are two holes on the surface to be machined with low cutting speed in ≤ 3 mm diameter size and S is between 9 mm minimum and 157.5 mm

maximum, then BEM 6 MONO unit is used with MH20 multiple spindle heads for any material.

Rule 066D

If there are two holes on the surface to be machined with high cutting speed in ≤ 3 mm diameter size and S is between 9 mm minimum and 157.5 mm maximum, then BEX 15 CNC unit is used with MH20 multiple spindle heads for any material. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 067D

If there are two holes on the surface to be machined with low cutting speed in ≤ 3 mm diameter size and S is between 7 mm minimum and 190 mm maximum, then BEM 6 MONO unit is used with MHF fixed multiple spindle heads for any material.

Rule 068D

If there are two holes on the surface to be machined with high cutting speed in ≤ 3 mm diameter size and S is between 7 mm minimum and 190 mm maximum, then BEX 15 CNC unit is used with MHF fixed multiple spindle heads for any material. Sliding unit UA 15 is needed with BEX 15 unit.

Rules 069D

If there are two holes on the surface to be machined with low cutting speed in a diameter > 3 mm and ≤ 6 mm and the material is plastics or thermoplastics, and S is between 9 mm minimum and 157.5 mm maximum, then BEM 6 MONO unit is used with MH20 multiple spindle heads.

Rules 070D

If there are two holes to be machined on the surface with high cutting speed in a diameter > 3 mm and ≤ 6 mm and the material is plastics or thermoplastics, and S is between 9 mm minimum and 157.5 mm maximum, then BEX 15 CNC

unit is used with MH20 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 093D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 12 MONO unit is used with MH33 multiple spindle head.

Rule 094D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MH33 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 095D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and straight line pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 096D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and straight line pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 097D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEM 20-100 MONO unit is used with MH33 multiple spindle heads.

Rule 098D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MH33 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 099D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and straight line pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 20-100 MONO unit is used with MHF multiple spindle heads.

Rule 100D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and straight line pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 101D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 10 mm and ≤ 16 mm and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 28 MONO unit is used with MH33 multiple spindle heads.

Rule 117D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 12 MONO unit is used with MH30 multiple spindle head.

Rule 118D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MH30 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 119D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 120D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 3 mm and < 6 mm and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 121D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 20-100 MONO unit is used with MH30 multiple spindle heads.

Rule 122D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MH30 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 123D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 20-100 MONO unit is used with MHF multiple spindle heads.

Rule 124D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 6 mm and < 10 mm and staggered pattern with S1 = 7 mm and S2 190 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 125D

If there are three holes to be machined with low cutting speed on the surface in a diameter ≥ 10 mm and ≤ 16 mm and staggered pattern with S1 = 14.5 mm and S2 = 174.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEM 28 MONO unit is used with MH30 multiple spindle heads.

Rule 126D

If there are three holes to be machined with high cutting speed on the surface in a diameter ≥ 10 mm and ≤ 16 mm and staggered pattern with S1 = 14.5 mm and S2 = 174.5 mm, and the material is cast iron, carbon steel, AL-Si alloy, or brass, then BEX 35 CNC unit is used with MH30 multiple spindle heads. Sliding unit UA 30 is needed with BEX 15 unit.

Rule 141D

If there are four holes to be machined with low cutting speed on the surface in a diameter ≤ 3 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEM 12 MONO unit is used with MH40 multiple spindle head.

Rule 142D

If there are four holes to be machined with high cutting speed on the surface in a diameter ≤ 3 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEX 15 CNC unit is used with MH40 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 143D

If there are four holes to be machined with low cutting speed on the surface in a diameter ≤ 3 mm with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 144D

If there are four holes to be machined with high cutting speed on the surface in a diameter ≤ 3 mm with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 145D

If there are four holes to be machined with low cutting speed on the surface in a diameter > 3 mm and ≤ 8 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEM 20-100 MONO unit is used with MH40 multiple spindle head.

Rule 146D

If there are four holes to be machined with high cutting speed on the surface in a diameter > 3 mm and ≤ 8 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEX 15 CNC unit is used with MH40 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 147D

If there are four holes to be machined with low cutting speed on the surface in a diameter > 3 mm and ≤ 8 mm with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEM 20-100 MONO unit is used with MHF multiple spindle heads.

Rule 148D

If there are four holes to be machined with high cutting speed on the surface in a diameter > 3 mm and ≤ 8 mm with S1 = 7 mm and S2 = 190 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 149D

If there are four holes to be machined with low cutting speed on the surface in a diameter > 8 mm and ≤ 16 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEM 28 MONO unit is used with MH40 multiple spindle head.

Rule 150D

If there are four holes to be machined with high cutting speed on the surface in a diameter > 8 mm and ≤ 16 mm with S1 = 22 mm and S2 = 195 mm, and the material is cast iron, carbon steel, Al-Si alloy, or brass, then BEX 35 CNC unit is used with MH40 multiple spindle heads. Sliding unit UA 30 is needed with BEX 35 unit.

9.3 Additional rules for tapping one and multiple holes in SPMs

Rule 034T

If only one tap is required to be machined on the surface, then the material of the workpiece and the size of the tap are determined. Identifying the last two features is important to determine the cutting speed and spindle speed for each material which will lead to define the driving power for tapping operation to select the suitable machining unit.

Rule 035T

If the material is cast iron, steel, brass, or aluminium alloys with M3, M4, M5, and M6 tap sizes, and the cutting speed is ≤ 10 m/min, then GEM 6 unit is used with HSS drill bit.

Rule 036T

If the material is cast iron or steel with M3 tap size, and the cutting speed is > 10 m/min, then GEM 16 unit is used with HSS drill bit.

Rule 037T

If the material is cast iron or steel with M4 tap size, and the cutting speed is > 10 m/min, then GEM 20C unit is used with HSS drill bit.

Rule 038T

If the material is cast iron or steel with M5 tap size, and the cutting speed is > 10 m/min, then BEM 20 drilling unit and GSX 50 tapping attachment are used with HSS drill bit.

Rule 039T

If the material is cast iron or steel with M6 tap size, and the cutting speed is > 10 m/min, then BEM 28 drilling unit and GSX 70 tapping attachment are used with HSS drill bit.

Rule 040T

If the material is cast iron, steel, brass, or aluminium alloys with M8, M10, M12, and M16 tap sizes, and the cutting speed is ≤ 10 m/min, then GEM 16 unit is used with HSS drill bit.

Rule 041T

If the material is cast iron or steel with M20 tap size, and the cutting speed is ≤ 10 m/min, then GEM 20C unit is used with HSS drill bit.

Rule 042T

If the material is cast iron or steel with M8 tap size, and the cutting speed is > 10 m/min, then BEM 28 and GSX 70 tapping attachment are used with HSS drill bit.

Rule 043T

If the material is cast iron or steel with M10, M12, M16, and M20 tap size, and the cutting speed is > 10 m/min, then BEX 60 CNC unit and GSX 90 tapping attachment with HSS drill bit.

Rule 044T

If the material is brass or aluminium alloys with M20 tap size, and the cutting speed is ≤ 10 m/min, then GEM 20C unit is used with HSS drill bit.

Rule 045T

If the material is brass or aluminium alloys with M3, M4, M5, and M6 tap sizes, and the cutting speed is > 10 m/min, then GEM 6 unit is used with HSS drill bit.

Rule 046T

If the material is brass or aluminium alloys with M8 or M10 tap sizes, and the cutting speed is > 10 m/min, then GEM 16 unit is used with HSS drill bit.

Rule 047T

If the material is brass or aluminium alloys with M12 or M16 tap sizes, and the cutting speed is > 10 m/min, then GEM 20C unit is used with HSS drill bit.

Rule 049T

If there are two taps on the surface to be machined with low cutting speed in M3, M4, or M5 sizes with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, brass or plastics, then BEM 6 MONO unit is used with MH20 multiple spindle heads.

Rule 050T

If there are two taps on the surface to be machined with high cutting speed in M3, M4, or M5 sizes with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, brass or plastics, then BEX 15 CNC unit is used with MH20 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 051T

If there are two taps on the surface to be machined with low cutting speed in M3, M4, or M5 sizes with S between 7 mm minimum and 190 mm maximum, and the material is steel, aluminium, brass or plastics, then BEM 6 MONO unit is used with MHF multiple spindle heads.

Rule 052T

If there are two taps on the surface to be machined with high cutting speed in M3, M4, or M5 sizes with S between 7 mm minimum and 190 mm maximum, and the material is steel, aluminium, brass or plastics, then BEX 15 CNC unit is

used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 053T

If there are two taps on the surface to be machined with low cutting speed in M6 or M8 sizes with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, or brass, then BEM 12 MONO unit is used with MH20 multiple spindle heads.

Rule 054T

If there are two taps on the surface to be machined with high cutting speed in M6 or M8 sizes with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, or brass, then BEX 15 CNC unit is used with MH20 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 055T

If there are two taps on the surface to be machined with low cutting speed in M6 or M8 sizes with S between 7 mm minimum and 190 mm maximum, and the material is steel, aluminium, or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 056T

If there are two taps on the surface to be machined with high cutting speed in M6 or M8 sizes with S between 7 mm minimum and 190 mm maximum, and the material is steel, aluminium, or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 057T

If there are two taps on the surface to be machined with low cutting speed in M10, M12, or M14 sizes with S between 9 mm minimum and 157.5 mm

maximum, and the material is steel, aluminium, or brass, then BEM 20 MONO unit is used with MH20 multiple spindle heads.

Rule 058T

If there are two taps on the surface to be machined with high cutting speed in M10 or M12 sizes with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, or brass, then BEX 15 CNC unit is used with MH20 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 059T

If there are two taps on the surface to be machined with high cutting speed in M14 size with S between 9 mm minimum and 157.5 mm maximum, and the material is steel, aluminium, or brass, then BEX 35 CNC unit is used with MH20 multiple spindle heads. Sliding unit UA 30 is needed with BEX 35 unit.

Rule 085T

If there are three taps to be machined with low cutting speed on the surface in M3 or M4 sizes and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is steel, aluminium or brass, then BEM6 MONO unit is used with MH33 multiple spindle head.

Rule 086T

If there are three taps to be machined with high cutting speed on the surface in M3 or M4 sizes and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MH33 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 087T

If there are three taps to be machined with low cutting speed on the surface in M3 or M4 sizes and straight line pattern with S1 = 7 mm and S2 = 190 mm, and

the material is steel, aluminium or brass, then BEM 6 MONO unit is used with MHF multiple spindle heads.

Rule 088T

If there are three taps to be machined with high cutting speed on the surface in M3 or M4 sizes and straight line pattern with S1 = 7 mm and S2 = 190 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 089T

If there are three taps to be machined with low cutting speed on the surface in M5 or M6 sizes and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is steel, aluminium or brass, then BEM 12 MONO unit is used with MH33 multiple spindle head.

Rule 090T

If there are three taps to be machined with high cutting speed on the surface in M5 or M6 sizes and straight line pattern with S1 = 9.5 mm and S2 = 97.5 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MH33 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 091T

If there are three taps to be machined with low cutting speed on the surface in M5 or M6 sizes and straight line pattern with S1 = 7 mm and S2 = 190 mm, and the material is steel, aluminium or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 092T

If there are three taps to be machined with high cutting speed on the surface in M5 or M6 sizes and straight line pattern with S1 = 7 mm and S2 = 190 mm,

and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 118T

If there are three taps to be machined with low cutting speed on the surface in M3 or M4 sizes and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is steel, aluminium or brass, then BEM 6 MONO unit is used with MH30 multiple spindle head.

Rule 119T

If there are three taps to be machined with high cutting speed on the surface in M3 or M4 sizes and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MH30 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 120T

If there are three taps to be machined with low cutting speed on the surface in M3 or M4 sizes and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is steel, aluminium or brass, then BEM 6 MONO unit is used with MHF multiple spindle heads.

Rule 121T

If there are three taps to be machined with high cutting speed on the surface in M3 or M4 sizes and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 122T

If there are three taps to be machined with low cutting speed on the surface in M5 or M6 sizes and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm,

and the material is steel, aluminium or brass, then BEM 12 MONO unit is used with MH30 multiple spindle head.

Rule 123T

If there are three taps to be machined with high cutting speed on the surface in M5 or M6 sizes and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MH30 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 124T

If there are three taps to be machined with low cutting speed on the surface in M5 or M6 sizes and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is steel, aluminium or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 125T

If there are three taps to be machined with high cutting speed on the surface in M5 or M6 sizes and staggered pattern with S1 = 7 mm and S2 = 190 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used with MHF multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 126T

If there are three taps to be machined with low cutting speed on the surface in M8 or M10 sizes and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is steel, aluminium or brass, then BEM 20 MONO unit is used with MH30 multiple spindle head.

Rule 127T

If there are three taps to be machined with high cutting speed on the surface in M8 or M10 sizes and staggered pattern with S1 = 14.5 mm and S2 = 172.5 mm, and the material is steel, aluminium or brass, then BEX 15 CNC unit is used

with MH30 multiple spindle heads. Sliding unit UA 15 is needed with BEX 15 unit.

Rule 151T

If there are four taps to be machined with low cutting speed on the surface in M3 or M4 sizes with S1 = 22 mm and S2 = 195 mm, and the material is steel, Al-Si alloy or brass, then BEM 6 MONO unit is used with MH40 multiple spindle head.

Rule 152T

If there are four taps to be machined with low cutting speed on the surface in M3 or M4 sizes with S1 = 7 mm and S2 = 190 mm, and the material is steel, Al-Si alloy or brass, then BEM 6 MONO unit is used with MHF multiple spindle heads.

Rule 153T

If there are four taps to be machined with low cutting speed on the surface in M5 or M6 sizes with S1 = 22 mm and S2 = 195 mm, and the material is steel, Al-Si alloy or brass, then BEM 12 MONO unit is used with MH40 multiple spindle head.

Rule 154T

If there are four taps to be machined with low cutting speed on the surface in M5 or M6 sizes with S1 = 7 mm and S2 = 190 mm, and the material is steel, Al-Si alloy or brass, then BEM 12 MONO unit is used with MHF multiple spindle heads.

Rule 155T

If there are four taps to be machined with low cutting speed on the surface in M8 or M10 sizes with S1 = 22 mm and S2 = 195 mm, and the material is steel,

Al-Si alloy or brass, then BEM 20 MONO unit is used with MH40 multiple spindle head.

Rule 156T

If there are four taps to be machined with low cutting speed on the surface in M8 or M10 sizes with S1 = 7 mm and S2 = 190 mm, and the material is steel, Al-Si alloy or brass, then BEM 20 MONO unit is used with MHF multiple spindle heads.

Rule 157T

If there are four taps to be machined with low cutting speed on the surface in M12 or M14 sizes with S1 = 22 mm and S2 = 195 mm, and the material is steel, Al-Si alloy or brass, then BEM 28 MONO unit is used with MH40 multiple spindle head.

Rule 158T

If there are four taps to be machined with low cutting speed on the surface in M12 or M14 sizes with S1 = 7 mm and S2 = 190 mm, and the material is steel, Al-Si alloy or brass, then BEM 28 MONO unit is used with MHF multiple spindle heads.

Rule 159T

If there are four taps to be machined with high cutting speed on the surface in M3, M4, M5, M6, or M8 sizes with S1 = 22 mm and S2 = 195 mm, and the material is steel, Al-Si alloy or brass, then BEX 15 CNC unit is used with MH40 multiple spindle head. Sliding unit UA 15 is needed with BEX 15 unit.

9.4 Part of the generated code in VisiRule

```
vv do ensure_loaded( system(vrlib) ) .

relation start1( Conclusion ) if
  'q_Number of the surfaces'( Conclusion ) .

relation 'q_Number of the surfaces'( Conclusion ) if
  the answer to 'Number of the surfaces' is _ and
  check( 'Number of the surfaces', =, one ) and
  'q_Type of machining operation'( Conclusion ) .

relation 'q_Number of the surfaces'( Conclusion ) if
  the answer to 'Number of the surfaces' is _ and
  check( 'Number of the surfaces', =, two ) and
  continue1( Conclusion ) .

relation 'q_Type of machining operation'( Conclusion ) if
  the answer to 'Type of machining operation' is _ and
  check( 'Type of machining operation', =, drilling ) and
  'q_The number of the holes '( Conclusion ) .

relation 'q_Type of machining operation'( Conclusion ) if
  the answer to 'Type of machining operation' is _ and
  check( 'Type of machining operation', =, tapping ) and
  'q_Rule 001T'( Conclusion ) .

relation 'q_The number of the holes '( Conclusion ) if
  the answer to 'The number of the holes ' is _ and
  check( 'The number of the holes ', =, one ) and
  'q_Number of the workstations - one hole'( Conclusion ) .

relation 'q_The number of the holes '( Conclusion ) if
  the answer to 'The number of the holes ' is _ and
  check( 'The number of the holes ', =, two ) and
  'q_Rule 013D'( Conclusion ) .

relation 'q_The number of the holes '( Conclusion ) if
  the answer to 'The number of the holes ' is _ and
  check( 'The number of the holes ', =, three ) and
  'q_Rule 026D'( Conclusion ) .

relation 'q_The number of the holes '( Conclusion ) if
  the answer to 'The number of the holes ' is _ and
  check( 'The number of the holes ', =, four ) and
  'q_Rule 48D'( Conclusion ) .

relation 'q_Number of the workstations - one hole'( Conclusion ) if
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    the answer to 'Number of the workstations - one hole' is _ and
    q_Material( Conclusion ) .

  relation q_Material( Conclusion ) if
    the answer to 'Material' is _ and
    check( 'Material', =, brass ) and
    'q_Rule 007'( Conclusion ) .

  relation q_Material( Conclusion ) if
    the answer to 'Material' is _ and
    check( 'Material', =, 'Cast_iron' ) and
    'q_Rule 001'( Conclusion ) .

  relation q_Material( Conclusion ) if
    the answer to 'Material' is _ and
    check( 'Material', =, aluminium ) and
    'q_Rule 004'( Conclusion ) .

  relation q_Material( Conclusion ) if
    the answer to 'Material' is _ and
    check( 'Material', =, steel ) and
    'q_Rule 010'( Conclusion ) .

  relation 'q_Rule 007'( Conclusion ) if
    the answer to 'Rule 007' is _ and
    check( 'Rule 007', >=, 100 ) and
    'q_Rule 008'( Conclusion ) .

  relation 'q_Rule 007'( Conclusion ) if
    the answer to 'Rule 007' is _ and
    check( 'Rule 007', <, 100 ) and
    'q_Rule 009'( Conclusion ) .

  relation 'q_Rule 008'( Conclusion ) if
    the answer to 'Rule 008' is _ and
    check( 'Rule 008', =<, 6 ) and
    Conclusion = 'USE BEX 15 CNC UNIT.~M~JSLIDING UNIT UA 15 IS
NEEDED~M~JWITH BEX 15 UNIT.' .

  relation 'q_Rule 008'( Conclusion ) if
    the answer to 'Rule 008' is _ and
    [
      check( 'Rule 008', >, 6 ) and
      check( 'Rule 008', =<, 12 )
    ] and
    Conclusion = 'USE BEX 15 CNC UNIT.~M~JSLIDING UNIT UA 15 IS
NEEDED~M~JWITH BEX 15 UNIT.' .

  relation 'q_Rule 008'( Conclusion ) if
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    the answer to 'Rule 008' is _ and
    [
      check( 'Rule 008', >, 12 ) and
      check( 'Rule 008', =<, 20 )
    ]  and
    Conclusion  =  'USE  BEX  35  CNC  UNIT.~M~JSLIDING  UNIT  UA  30  IS
NEEDED~M~JWITH BEX 35 UNIT.'  .

  relation 'q_Rule 008'( Conclusion ) if
    the answer to 'Rule 008' is _ and
    [
      check( 'Rule 008', >, 20 ) and
      check( 'Rule 008', =<, 40 )
    ]  and
    Conclusion = 'USE BEX 40 CNC UNIT~M~JAND AU 40 SLIDE UNIT'  .

  relation 'q_Rule 009'( Conclusion ) if
    the answer to 'Rule 009' is _ and
    check( 'Rule 009', =<, 6 ) and
    Conclusion = 'USE BEM 6 MONO UNIT'  .

  relation 'q_Rule 009'( Conclusion ) if
    the answer to 'Rule 009' is _ and
    [
      check( 'Rule 009', >, 6 ) and
      check( 'Rule 009', =<, 12 )
    ]  and
    Conclusion = 'USE BEM 12 MONO UNIT'  .

  relation 'q_Rule 009'( Conclusion ) if
    the answer to 'Rule 009' is _ and
    [
      check( 'Rule 009', >, 12 ) and
      check( 'Rule 009', =<, 20 )
    ]  and
    Conclusion = 'USE BEM 20-100 MONO UNIT'  .

  relation 'q_Rule 009'( Conclusion ) if
    the answer to 'Rule 009' is _ and
    [
      check( 'Rule 009', >, 20 ) and
      check( 'Rule 009', =<, 40 )
    ]  and
    Conclusion = 'USE BEX 40 CNC UNIT~M~JAND AU 40 SLIDE UNIT'  .

  relation 'q_Rule 001'( Conclusion ) if
    the answer to 'Rule 001' is _ and
    check( 'Rule 001', >, 100 ) and
    'q_Rule 002'( Conclusion ) .
```
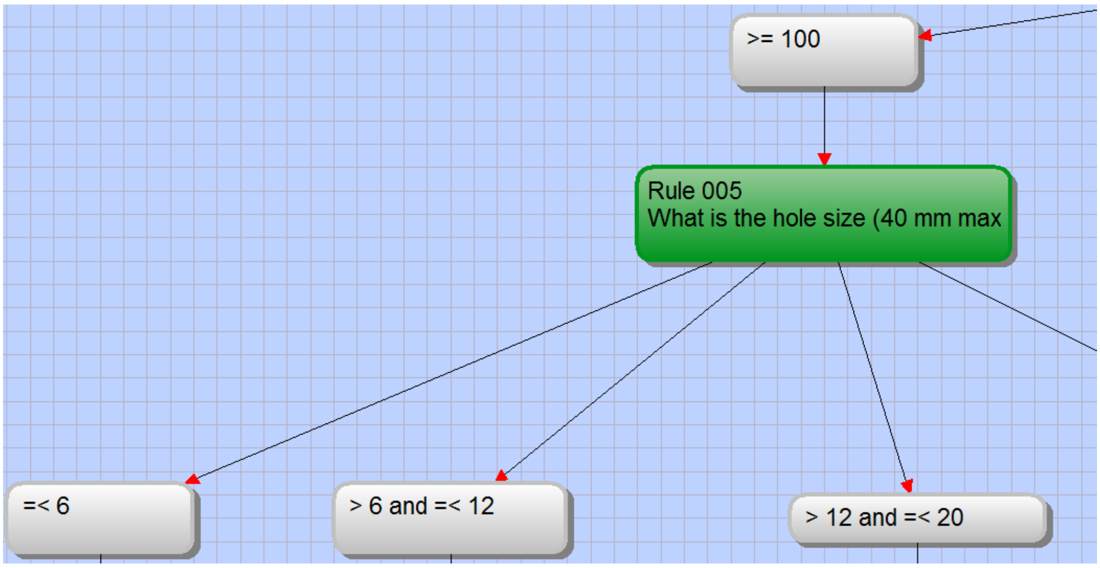
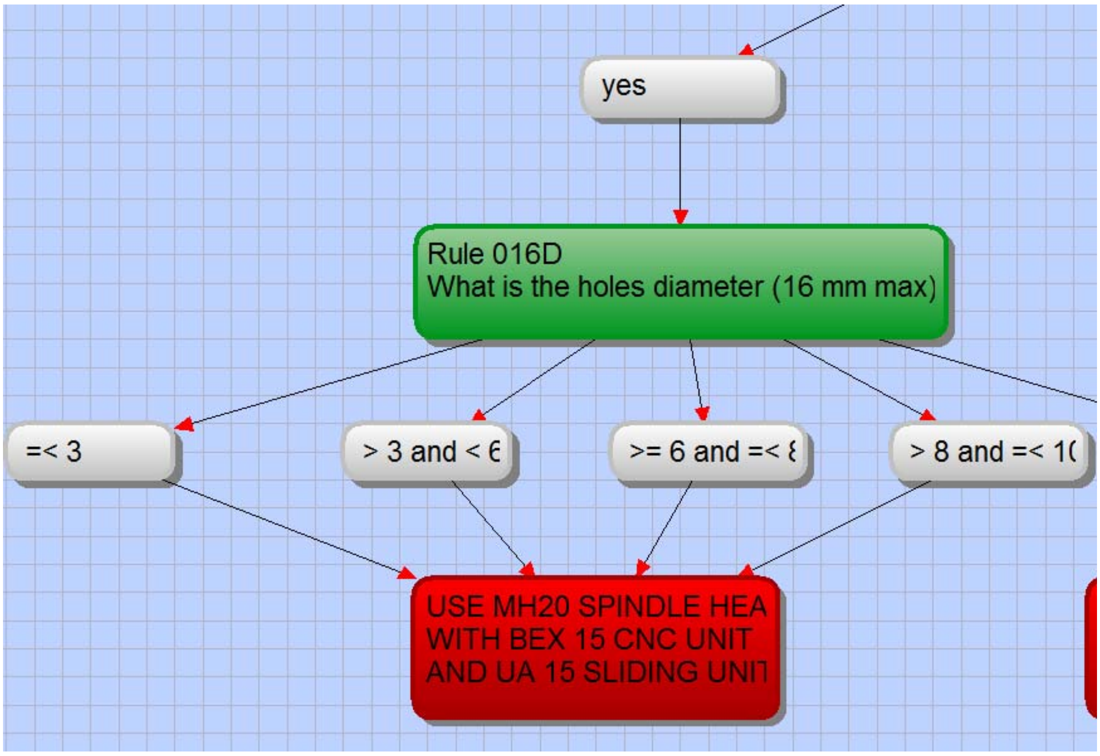
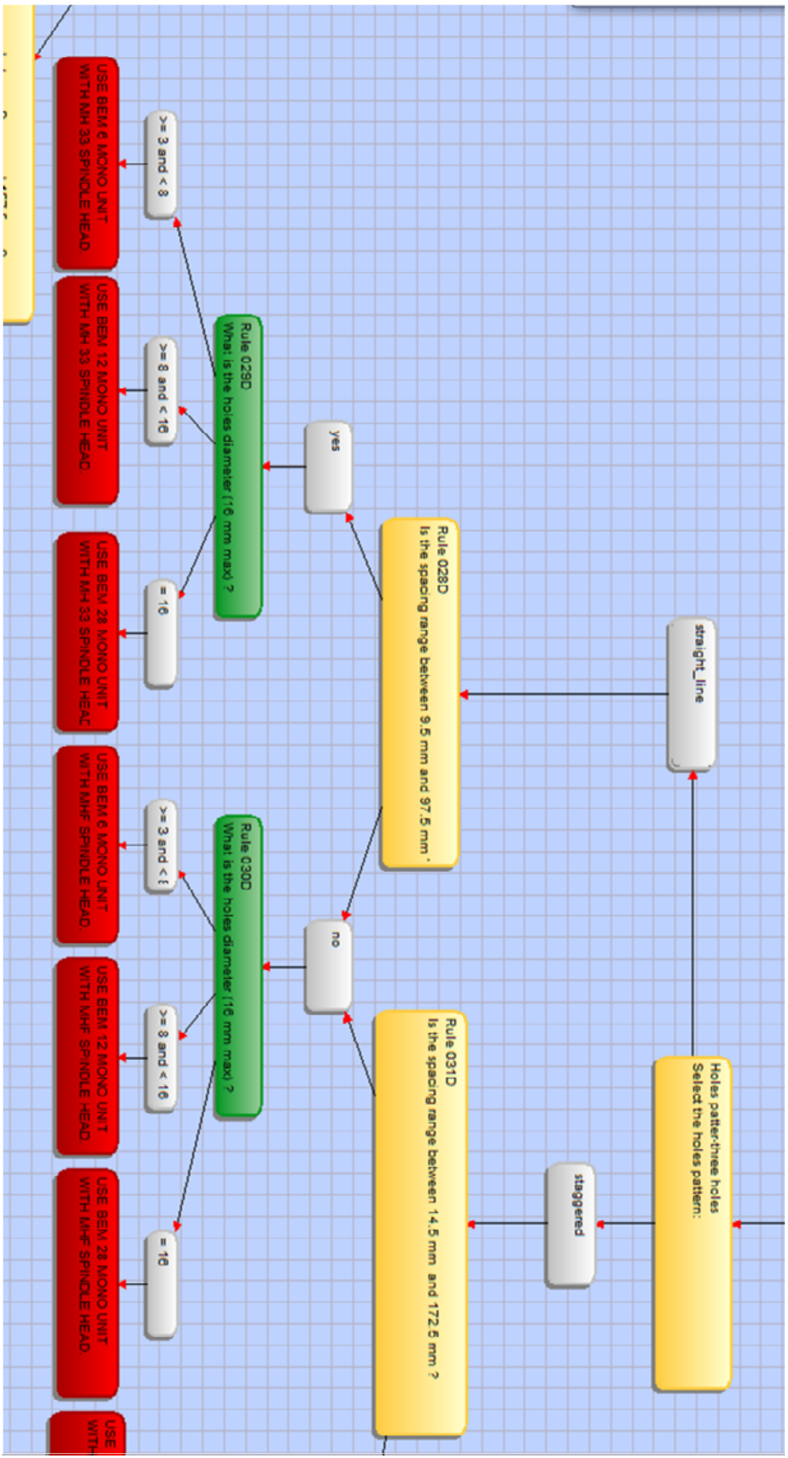

```
relation 'q_Rule 001'( Conclusion ) if
  the answer to 'Rule 001' is _ and
  check( 'Rule 001', =<, 100 ) and
  'q_Rule 003'( Conclusion ) .

relation 'q_Rule 002'( Conclusion ) if
  the answer to 'Rule 002' is _ and
  check( 'Rule 002', =<, 6 ) and
  Conclusion = 'USE BEX 35 CNC AND ~M~JAU 30 SLIDE UNIT'  .

relation 'q_Rule 002'( Conclusion ) if
  the answer to 'Rule 002' is _ and
  [
    check( 'Rule 002', >, 6 ) and
    check( 'Rule 002', =<, 12 )
  ] and
  Conclusion = 'USE BEM 28 MONO'  .

relation 'q_Rule 002'( Conclusion ) if
  the answer to 'Rule 002' is _ and
  [
    check( 'Rule 002', >, 12 ) and
    check( 'Rule 002', =<, 20 )
  ] and
  Conclusion = 'USE BEX 60 CNC AND ~M~JAU 60 SLIDE UNIT'  .

relation 'q_Rule 002'( Conclusion ) if
  the answer to 'Rule 002' is _ and
  [
    check( 'Rule 002', >, 20 ) and
    check( 'Rule 002', =<, 40 )
  ] and
  Conclusion = 'USE BEX 60 CNC AND ~M~JAU 60 SLIDE UNIT'  .

relation 'q_Rule 003'( Conclusion ) if
  the answer to 'Rule 003' is _ and
  check( 'Rule 003', =<, 6 ) and
  Conclusion = 'USE BEM 12 MONO'  .

relation 'q_Rule 003'( Conclusion ) if
  the answer to 'Rule 003' is _ and
  [
    check( 'Rule 003', >, 6 ) and
    check( 'Rule 003', =<, 12 )
  ] and
  Conclusion = 'USE BEM 20-100'  .

relation 'q_Rule 003'( Conclusion ) if
```

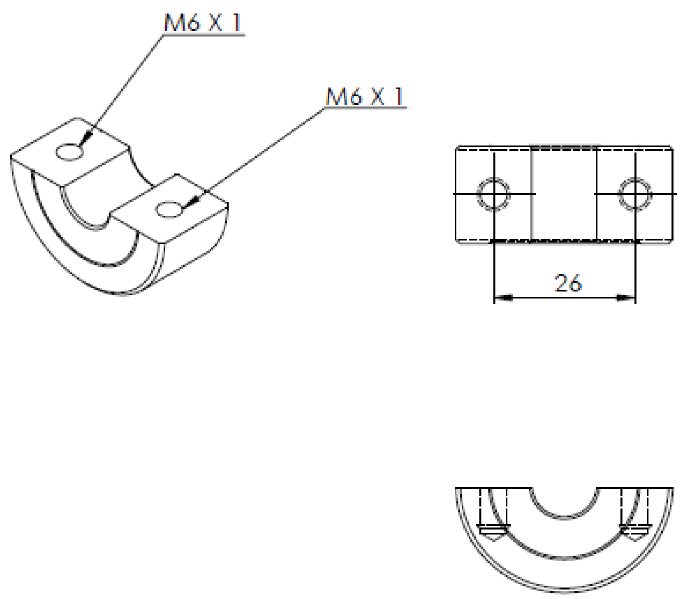
9.5 Additional charts developed in VisiRule



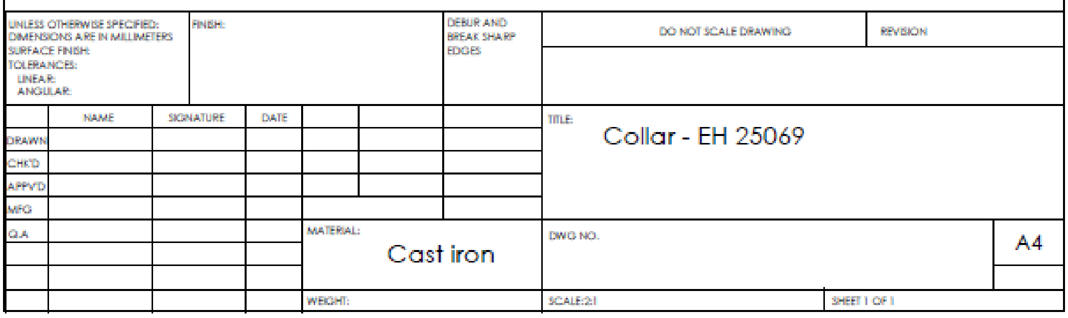



Holes patter-three holes
Select the holes pattern:
straight_line
staggered
Rule 028D
Is the spacing range between 9.5 mm and 97.5 mm ?
Rule 031D
Is the spacing range between 14.5 mm and 172.5 mm ?
yes
no
Rule 029D
What is the holes diameter (16 mm max) ?
Rule 030D
What is the holes diameter (16 mm max) ?
>= 3 and < 8
>= 8 and < 16
= 16
>= 8 and < 16
= 16
USE BEM 6 MONO UNIT WITH MH 33 SPINDLE HEAD
USE BEM 12 MONO UNIT WITH MH 33 SPINDLE HEAD
USE BEM 28 MONO UNIT WITH MH 33 SPINDLE HEAD
USE BEM 6 MONO UNIT WITH MHF SPINDLE HEAD
USE BEM 12 MONO UNIT WITH MHF SPINDLE HEAD
USE BEM 28 MONO UNIT WITH MHF SPINDLE HEAD

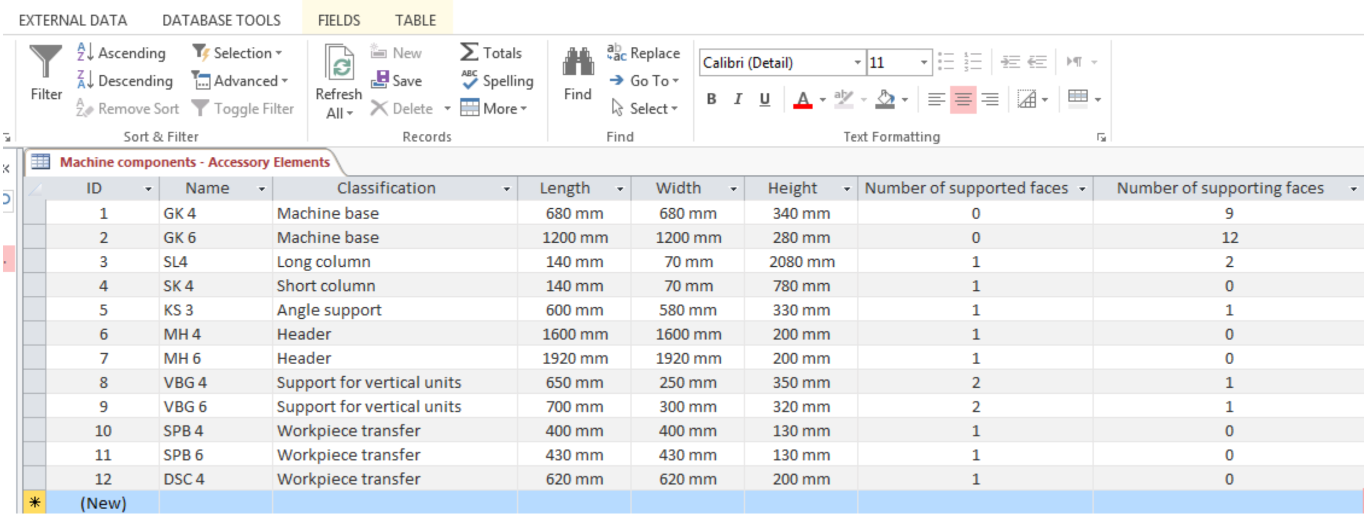
9.6 The design information for a half-collar workpiece



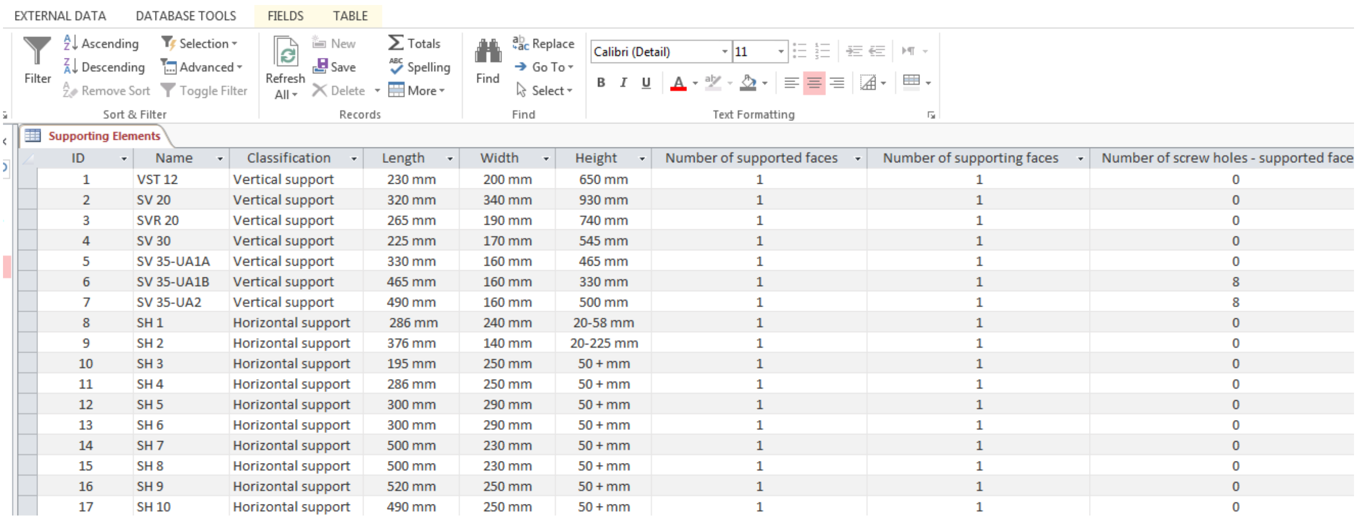
- Material: cast Iron
- Cutting speed = 15 m/min
- Number of taps: 2 (M6X1)
- The distance between the taps centre: 26 mm
- The depth pf taps: 8 mm
- Number of machined surfaces: 1
- Operation type: Tapping



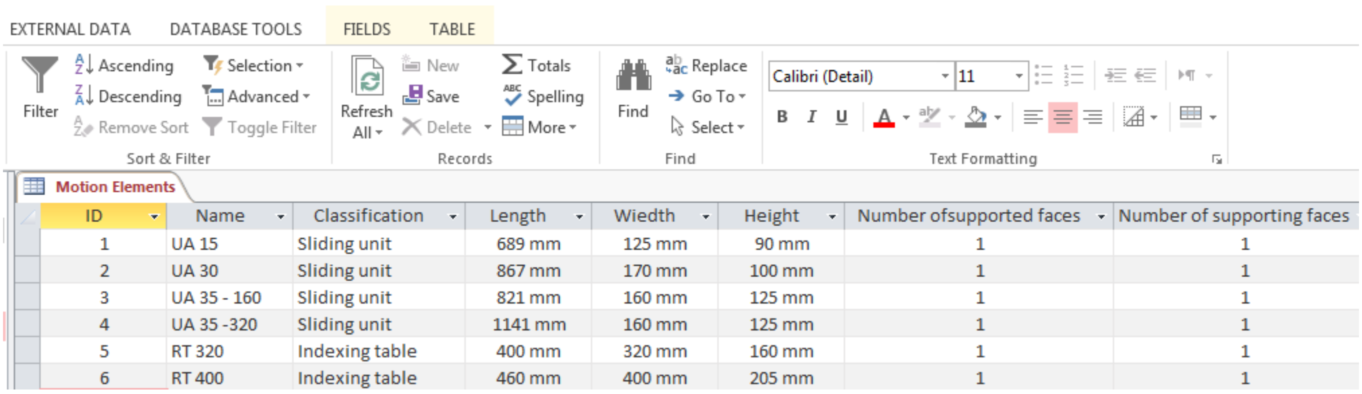
9.7 Additional figures for the SPM database



ID	Name	Classification	Length	Width	Height	Number of supported faces	Number of supporting faces
1	GK 4	Machine base	680 mm	680 mm	340 mm	0	9
2	GK 6	Machine base	1200 mm	1200 mm	280 mm	0	12
3	SL4	Long column	140 mm	70 mm	2080 mm	1	2
4	SK 4	Short column	140 mm	70 mm	780 mm	1	0
5	KS 3	Angle support	600 mm	580 mm	330 mm	1	1
6	MH 4	Header	1600 mm	1600 mm	200 mm	1	0
7	MH 6	Header	1920 mm	1920 mm	200 mm	1	0
8	VBG 4	Support for vertical units	650 mm	250 mm	350 mm	2	1
9	VBG 6	Support for vertical units	700 mm	300 mm	320 mm	2	1
10	SPB 4	Workpiece transfer	400 mm	400 mm	130 mm	1	0
11	SPB 6	Workpiece transfer	430 mm	430 mm	130 mm	1	0
12	DSC 4	Workpiece transfer	620 mm	620 mm	200 mm	1	0
(New)							



ID	Name	Classification	Length	Width	Height	Number of supported faces	Number of supporting faces	Number of screw holes - supported face
1	VST 12	Vertical support	230 mm	200 mm	650 mm	1	1	0
2	SV 20	Vertical support	320 mm	340 mm	930 mm	1	1	0
3	SVR 20	Vertical support	265 mm	190 mm	740 mm	1	1	0
4	SV 30	Vertical support	225 mm	170 mm	545 mm	1	1	0
5	SV 35-UA1A	Vertical support	330 mm	160 mm	465 mm	1	1	0
6	SV 35-UA1B	Vertical support	465 mm	160 mm	330 mm	1	1	8
7	SV 35-UA2	Vertical support	490 mm	160 mm	500 mm	1	1	8
8	SH 1	Horizontal support	286 mm	240 mm	20-58 mm	1	1	0
9	SH 2	Horizontal support	376 mm	140 mm	20-225 mm	1	1	0
10	SH 3	Horizontal support	195 mm	250 mm	50 + mm	1	1	0
11	SH 4	Horizontal support	286 mm	250 mm	50 + mm	1	1	0
12	SH 5	Horizontal support	300 mm	290 mm	50 + mm	1	1	0
13	SH 6	Horizontal support	300 mm	290 mm	50 + mm	1	1	0
14	SH 7	Horizontal support	500 mm	230 mm	50 + mm	1	1	0
15	SH 8	Horizontal support	500 mm	230 mm	50 + mm	1	1	0
16	SH 9	Horizontal support	520 mm	250 mm	50 + mm	1	1	0
17	SH 10	Horizontal support	490 mm	250 mm	50 + mm	1	1	0



ID	Name	Classification	Length	Wiedth	Height	Number ofsupported faces	Number of supporting faces
1	UA 15	Sliding unit	689 mm	125 mm	90 mm	1	1
2	UA 30	Sliding unit	867 mm	170 mm	100 mm	1	1
3	UA 35 - 160	Sliding unit	821 mm	160 mm	125 mm	1	1
4	UA 35 -320	Sliding unit	1141 mm	160 mm	125 mm	1	1
5	RT 320	Indexing table	400 mm	320 mm	160 mm	1	1
6	RT 400	Indexing table	460 mm	400 mm	205 mm	1	1

9.8 Part of the code for the Add-In project for the integration process

```
Implements SWPublished.SwAddin

'Declarations for addin SW connection
Dim axSldWorks As SldWorks.SldWorks
Dim axCookie As Long 'holds value created in SwAddin_ConnectToSW
'cookie needed for menus, toolbars, CallbackInfo
Dim axToolbarID As Long 'toolbar ID if toolbars used
Dim axActiveDoc As SldWorks.ModelDoc2
Dim axTargetDoc As SldWorks.ModelDoc2
Private Function SwAddin_ConnectToSW(ByVal ThisSW As Object, ByVal
Cookie As Long) As Boolean
Dim bRet As Boolean 'boolean return
Dim lRet As Long 'long return
Dim axMenuID As String
Dim lngToolbarDocTypes As Long

Set axSldWorks = ThisSW
axCookie = Cookie
bRet = axSldWorks.SetAddinCallbackInfo(App.hInstance, Me, axCookie)
    axMenuID = "SPM System"
  lRet = axSldWorks.AddMenu(swDocASSEMBLY, axMenuID, 5)

Dim axMenu1 As String, axMenu2 As String, axMenu3 As String, axMenu4
As String, axMenu5 As String, axMenu6 As String, axMenu7 As String, axMenu8
As String

  axMenu1 = "SPM ASSEMBLY@" & axMenuID
  axMenu2 = "SPM DATABASE@" & axMenuID
  axMenu3 = "SPM KONWLEDGE-BASE@" & axMenuID
  axMenu4 = "CBR@" & axMenuID

  bRet = axSldWorks.AddMenuItem2(swDocPART, axCookie, axMenu1, 0,
"CallAssembly", "EnableIfAssembly", "")
  bRet = axSldWorks.AddMenuItem2(swDocPART, axCookie, axMenu2, 0,
"CallForm1", "EnableIfAssembly", "")
  bRet = axSldWorks.AddMenuItem2(swDocPART, axCookie, axMenu3, 0,
"CallForm1", "EnableIfAssembly", "")


  bRet = axSldWorks.AddMenuItem2(swDocASSEMBLY, axCookie,
axMenu1, 0, "CallAssembly", "EnableIfAssembly", "")
  bRet = axSldWorks.AddMenuItem2(swDocASSEMBLY, axCookie,
axMenu2, 0, "CallUnitsandelements", "EnableIfAssembly", "")
```

```
bRet = axSldWorks.AddMenuItem2(swDocASSEMBLY, axCookie, axMenu3, 0, "Callknowledgebase", "EnableIfAssembly", "")
bRet = axSldWorks.AddMenuItem2(swDocASSEMBLY, axCookie, axMenu4, 0, "CallIndexing", "EnableIfAssembly", "")
bRet = axSldWorks.AddMenuItem2(swDocASSEMBLY, axCookie, axMenu5, 0, "CallWorkpiece", "EnableIfAssembly", "")

SwAddin_ConnectToSW = True

End Function
Private Function SwAddin_DisconnectFromSW() As Boolean
Dim bRet As Boolean
Dim axMenu0 As String 'for SW menu ID ("File", "Insert", "Tools", etc.)
Dim axMenu1 As String, axMenu2a As String, axMenu2b As String, axMenu2c As String, axMenu2d As String, axMenu2e As String, axMenu2f As String, axMenu2g As String, axMenu3 As String
Dim TargetMenu As String
Dim SubMenuCount As Long
Dim axFrame As SldWorks.Frame
axMenuID = "SPM System"
Set axFrame = axSldWorks.Frame 'needed for Frame.GetSubMenuCount
axMenu0 = axSldWorks.AddMenu(swDocASSEMBLY, axMenuID, 5)
axMenu1 = "SPM ASSEMBLY"
axMenu2 = "SPM DATABASE"
axMenu3 = "SPM KNOWLEDGE-BASE"
axMenu4 = "CBR"

TargetMenu = axMenu2a & "@" & axMenu1 & "@" & axMenu0
bRet = axSldWorks.RemoveMenu(1, TargetMenu, "CallAssembly") 'part
bRet = axSldWorks.RemoveMenu(2, TargetMenu, "CallAssembly") 'assembly

TargetMenu = axMenu2b & "@" & axMenu1 & "@" & axMenu0
bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly

TargetMenu = axMenu2c & "@" & axMenu1 & "@" & axMenu0
bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly

TargetMenu = axMenu2d & "@" & axMenu1 & "@" & axMenu0
bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly

TargetMenu = axMenu2e & "@" & axMenu1 & "@" & axMenu0
bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly
```

```
    TargetMenu = axMenu2f & "@" & axMenu1 & "@" & axMenu0
    bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
    bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly

    TargetMenu = axMenu2g & "@" & axMenu1 & "@" & axMenu0
    bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
    bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly

    TargetMenu = axMenu3 & "@" & axMenu0
    bRet = axSldWorks.RemoveMenu(1, TargetMenu, "") 'part
    bRet = axSldWorks.RemoveMenu(2, TargetMenu, "") 'assembly


Set axFrame = Nothing
Set axSldWorks = Nothing

SwAddin_DisconnectFromSW = True

End Function

Public Function EnableIfAssembly() As Long
EnableIfAssembly = 1
'Dim axActiveDoc As SldWorks.ModelDoc2
Dim axActiveType As Long
'Dim axTargetDoc As SldWorks.ModelDoc2
Dim axTargetType As Long
Dim SelfEdit As Boolean
Dim ButtonStat As Long

Set axTargetDoc = Nothing
axTargetType = 0
ButtonStat = 0
Set axActiveDoc = axSldWorks.ActiveDoc
axActiveType = axActiveDoc.GetType
If axActiveType = 2 Then
    ButtonStat = 1
    GoTo ClearObjects_EnableIfAssembly
End If
If axActiveType = 1 Then
ButtonStat = 0
    SelfEdit = axActiveDoc.IsEditingSelf
    Set axTargetDoc = axActiveDoc.GetEditTarget
    axTargetType = axTargetDoc.GetType
    If axTargetType = 1 Then ButtonStat = 1
    If SelfEdit Then ButtonStat = 0
End If
ClearObjects_EnableIfAssembly:
EnableIfPart = ButtonStat
```

```
Set axActiveDoc = Nothing
Set axTargetDoc = Nothing

End Function
Sub Callknowledgebase()
knowledgebase.Show
End Sub
Sub CallIndexing()
Indexing.Show
End Sub
Sub CallAssembly()
Assembly.Show
End Sub
Sub CallSPMdatabase()
SPMdatabase.Show
End Sub
Sub CallUnitsandelements()
Unitsandelements.Show
End Sub
```