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Technical feasibility analysis of utilizing special purpose machine tools

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ABSTRACT

Special purpose machine tools (SPMs) are primarily used for performing drilling-related operations and are widely used in mass production including automotive component manufacturing. Utilization of SPM is considerably widespread; however, this technology is relatively new and expensive. The important problems facing manufacturing industries wishing to utilize this technology is feasibility analysis to decide whether a SPM can be utilised for production of the given part and if it is feasible which SPM components would be appropriate. Since the cost of utilizing SPM is high, feasibility analysis must be performed before any investment on detailed design. This paper proposes a technical feasibility analysis method which assists in deciding whether SPM is applicable for machining a given part to achieve the highest productivity. The method is based on the framework which consists of relations between the desired part properties to the characteristics of the SPM components. These relations are captured as rules and constraints in an intelligent system which is implemented in Visual Basic. Applying the proposed method to a number of industrial parts shows that it is a very useful tool in deciding when SPMs should be utilized.

Keywords Special purpose machines. Reconfigurable manufacturing systems. Drilling-related operations. Feasibility analysis.

1. Introduction

Increasing manufacturing competition market and rapidly changing consumer demand have led many industries to use flexible and responsiveness manufacturing systems. ElMaraghy [5] classified manufacturing systems into three major categories: Dedicated Machining Systems (DMSs), Flexible Manufacturing Systems (FMSs) and Reconfigurable Manufacturing Systems (RMSs) which have different characteristics (Table 1). DMSs are designed to produce a single part at a fixed volume over the life production time and involve dedicated machine tools which cannot be changed cost effectively to accommodate new requirements. FMSs are designed to machine a variety of undefined parts in changeable volumes and often involve General Purpose Machines (GPMs) which are typically not designed for a set defined of machining operations. Therefore, the manufacturer has to pay for unrequired capabilities and the cost of extensive efforts for meeting machine requirements. RMSs are designed to meet a specific range of machining production requirements. The capacity and functionality of RMSs, unlike DMSs and FMSs, are not fixed and may have been designed for a special purpose. Special purpose machine tool (SPM) as the major components of this type of manufacturing system can be applied to produce family parts for a specific range of volumes over the production life time. Notably, customized flexibility of SPMs makes them less expensive than GPMs [6].

These machines are designed based on current and future requirements of manufacturing systems and market demands [1, 8]. Their modularity allows them to manufacture various products by applying minor changes to the machine's configuration by rearranging units and accessories [9, 10]. These economic and productive machines are often used for drilling-related operations such as drilling, reaming and tapping which are typical hole-making operations and have large contribution to produce industrial parts [11]. Studies of modular machine tools have mainly focused on milling machines [12-14], While those performing drilling operations receiving less attention from researchers. The example of a SPM configuration performs drilling-related operations on the required part (Fig. 1). It consists of three working stations incorporating three machining units, a control unit, assembly components and

Table 1 A comparison of manufacturing systems [7]

	DMS	FMS	RMS
Part mix	Single	Various	Family
Volume	Fixed	Changeable	Changeable

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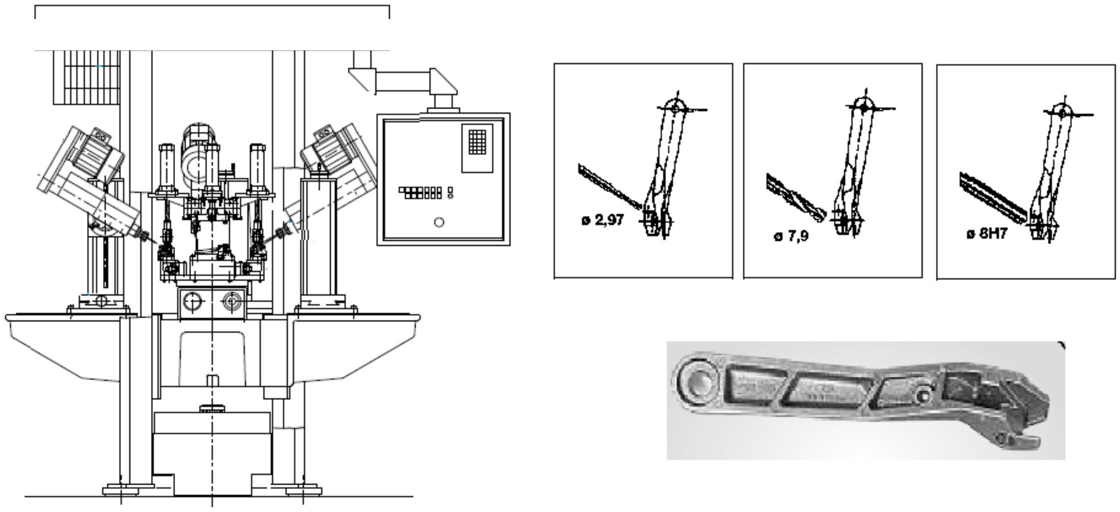

Fig. 1. SPM configuration and required working stations for producing parts with drilling-related operations [1, 2]

accessories.

While many advantages may be obtained by applying SPMs for producing industrial parts, the extent of application of these machines is not proportional to the achieved benefits. Furthermore, the design and manufacturing of SPM has relatively high cost and a proper justification of utilizing SPM and related components should be made before any decision to design and manufacture one [8, 10]. Clearly, this process requires appropriate and effective evaluation which necessitates substantial data analysis and identification of the major factors affecting at the correctness of analysis [15]. To do so an appropriate feasibility analysis is needed to decide whether a SPM should be used for the required production. While several studies on the design of reconfigurable machines exist systems [9, 16-19], they focus on designing the configuration with feasible components; however, the technical feasibility analysis has not received much attention.

Feasibility analysis is one of the necessary steps for any engineering problem which evaluates the viability of a proposed system. This analysis facilitates enterprise decisions for a detailed system design and then its manufacture [9]. While, researchers have explored feasibility analysis in different areas of manufacturing [20-22], but few addressed SPMs. Tolouei-Rad and Zolfaghari [8] presented an economic method for feasibility analysis of utilizing SPMs. There is a need to improve feasibility analysis method; particularly from a technical point of view for SPM utilization.

To perform this analysis an expertise and experience with in depth understanding of SPMs is required. Thus, this process can be difficult and time consuming as many critical technical qualitative and quantitative factors have to be figured out and analysed prior to design and implementation. Kou, Ergu and Shi [23] concluded that without intelligent systems, collecting the expert knowledge needed to make final decisions would be too costly and protracted. Clearly, an intelligent system is required for manufacturing industries to successfully perform feasibility analysis and decision making of utilizing SPMs by considering part(s) specifications and SPM characteristics.

Several intelligent systems have been applied in manufacturing research. Tan, Lim, Platts and Koay [24] proposed fuzzy ARTMAP (FAM) neural network model and a hybrid intelligent case-based reasoning (CBR) to assist users in manufacturing investment decision making. Culler and Burd [25] demonstrated a framework in which computer-aided process planning (CAPP) and activity based costing (ABC) are incorporated into a decision making system for documentation and cost control. Some studies applied Decision Support Systems (DSS) which majority of existing DSSs are limited to selecting machine tools and manufacturing systems by applying optimization tools [26]. Several publications reported use of expert systems for machine tool assessment to consider qualitative information [10, 27]. From the above it can be concluded that there are some research about machine tools evaluation for decision making of utilizing them by using intelligent systems; yet performing feasibility analysis of utilizing SPMs by using intelligent system based on the expert and experience knowledge has not been adequately addressed.

The main objective of this paper is to present a feasibility analysis method for evaluating SPM utilization and selecting efficient SPM components for a given part to be drilled. To achieve this, the properties of part should be evaluated in conjunction with SPM component's characteristics. The paper proposes a method for feasibility analysis of utilization SPM. To do so, critical effective factors of part and SPM are determined and a feasibility analysis framework is defined. Based on the framework the relevant feasibility relations between the part and SPM components are extracted and captured as rules and constraints in a knowledge-based intelligent system. Applying the proposed method would be useful for decision making process at the preliminary stage of designing a SPM.

2. Problem formulation

To achieve the objective, critical factors of part and SPM are identified and the importance of them for performing feasibility analysis and selecting appropriate SPM components are explained. Figs. 2, 3, and 4 show the framework for technical feasibility analysis for utilization of SPM. These figures clearly represent the relation between part and SPM characteristics and the important steps of technical feasibility analysis.

2.1. Part characteristics

Properties, shape, and dimensions of the workpiece, surfaces and properties of holes in each machining surface are effective factors in selecting feasible SPM components.

- Part properties: Part properties should be extracted from the part's design information. These items are weight, strength and machinability of the workpiece as they affect drilling performance. Weight is effective factor in selecting or designing fixture and chassis (Figs. 2 and 4). Strength is considered when selecting machining units and fixtures (Figs. 2 and 4). Since this factor is the ability of material to withstand an applied force without any failure, inappropriate strength makes the drilling process more difficult to perform reliably. Machinability is the ease with which the metal can be machined and depends on many variables such as heat treatment, strength, hardness, microstructure and work hardening [28].
- Shapes and dimensions: In this research, the shape of the workpiece has been divided into main four groups: round, prismatic, plane and odd-shaped. The shape of the workpiece and its overall dimensions are basic information of part which should be considered selection or design of fixture (Figs. 2 and 4).
- Surfaces: Fig. 2 shows that numbers, features, dimensions and accessibility of machining surfaces are effective items to identify whether all the holes can be drilled. They also determine which SPM components are suitable for performing this task. Furthermore, clamping and locatable surfaces are key issues for designing or selecting fixtures (Figs. 2 and 4). A surface which can be used for locating a workpiece is a locatable surface and clamping surface is one which can be used to clamp a workpiece.
- Holes per surface: Fig. 3 shows that holes are divided into two main groups: identical and different holes. Each group may have simple, countersink and counterbore holes. All key variables such as number, diameter, depth and tolerance of holes per machining surface should be analysed. Type of pattern and related information are important items with identical holes. These items are important for the selection of the cutting tool, spindle head, machining units, and sliding units (Figs. 3 and 4).

2.2. SPM characteristics

Considering the critical SPM characteristics greatly influences on the proper technical feasibility analysis. SPM characteristics are listed as below:

- Cutting tool: Proper feasibility analysis depends on selecting appropriate drilling tools at the early stage of feasibility analysis. Proper selection of drilling tools reduces tool changing time and cost, tool consumption and loss of production. Therefore, to decrease time and cost and increase production quantities, long-lasting hard material tools such as HSS and carbide drills are recommended for utilizing SPM [1, 8]. Selection of drilling tools depends on many factors such as material of the workpiece, hole diameter, hole depth, condition of drill press, required tolerance and thrust force (Figs. 2 and 4).
- Multiple spindle head: Proper selection of multiple spindle heads results in reduced machining time and production cost. The most important factors in finding a feasible multiple spindle head are required thrust and drive power. As shown in Eqs. (1) and (2) the required thrust and drive power for multiple drilling heads are the function of number of spindles, strength and hole diameter (Fig. 4) [1].

$$F_f = f(N_s, S, D) \tag{1}$$

$$P = f(N_s, S, D) \tag{2}$$

Where F_f is required thrust, P is required drive power, N_s is number of spindles, S is strength and D is hole diameter. To have appropriate rigidity and reliability, the multiple spindle heads should always be selected with a safety margin.

Machining unit: The most important components of SPMs are the machining units which should be selected after selecting the cutting tool and multiple spindle head (Fig. 4). Machining operation types, drilling size range, drive power, maximum feed, accuracy and maximum thrust are relevant factors of machining units when finding feasible machining units. Additional attributes of machining units should be considered for selecting other feasible SPM components (Fig. 4):

1. Weight: It is required to assist with designing and selecting a feasible chassis and sliding units.
2. Dimensions: They are required for designing and selecting feasible sliding units and a chassis.

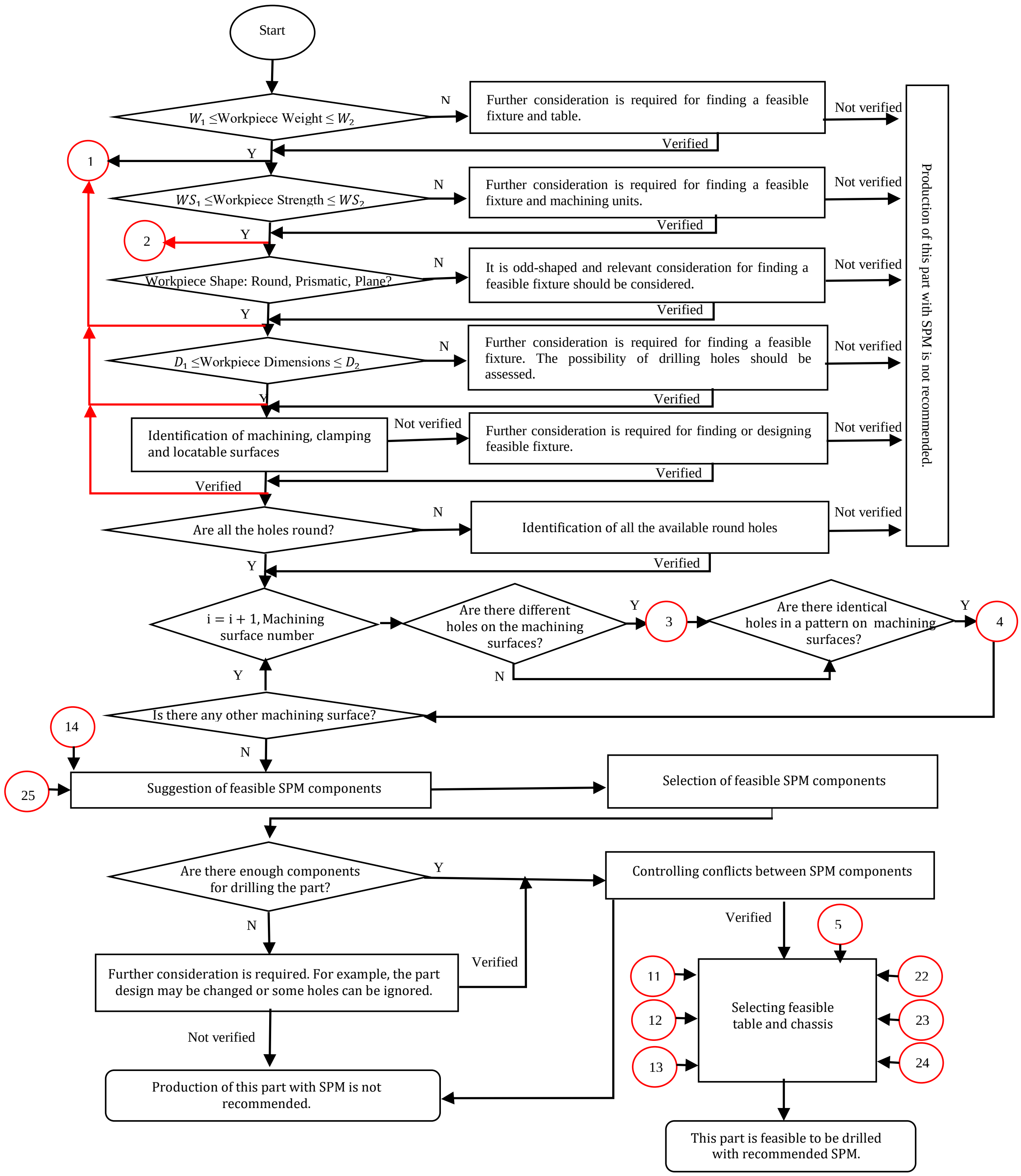

Fig. 2. Technical feasibility analysis framework

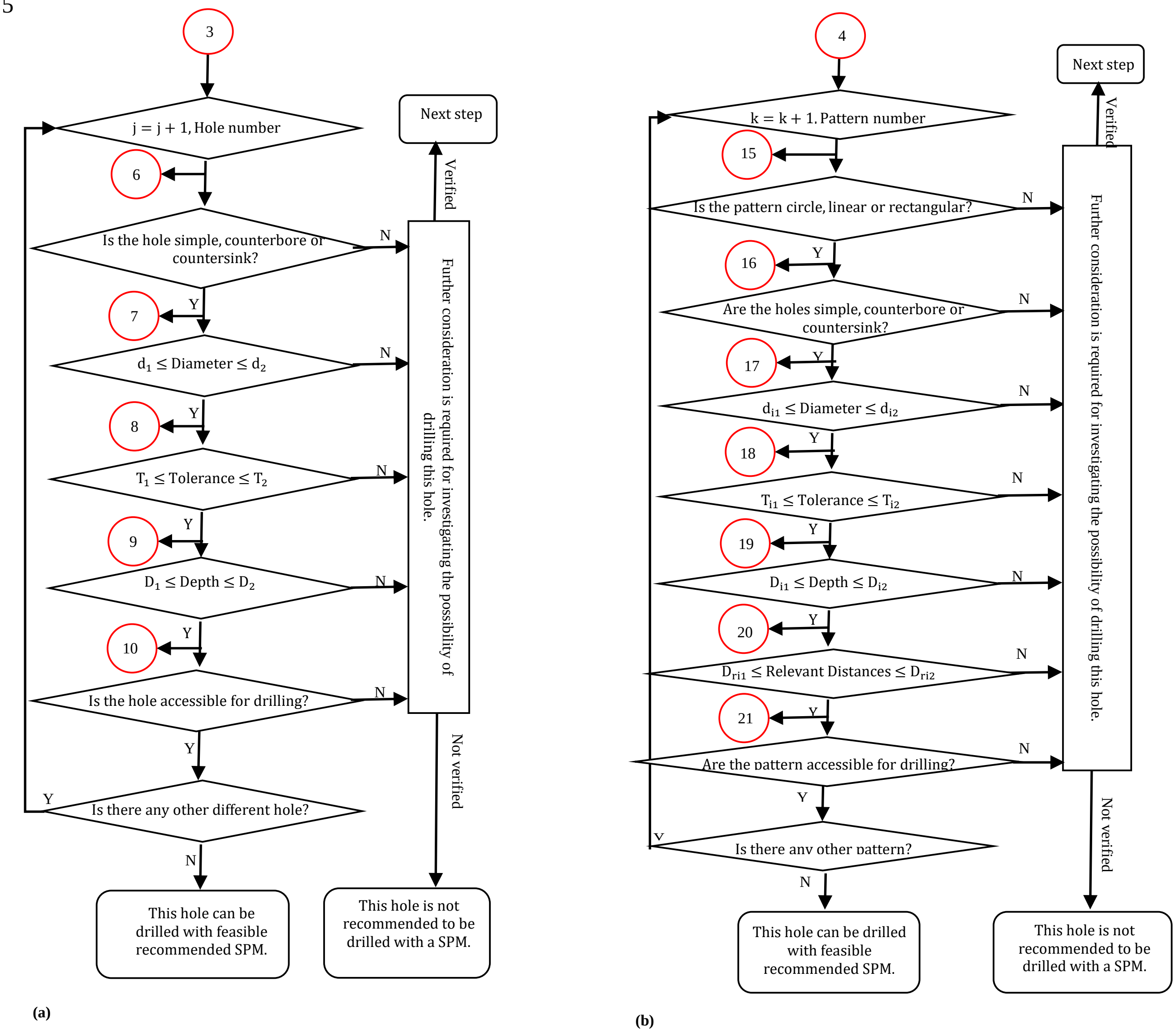

Fig. 3. Holes analysis framework. **a** Different holes analysis framework. **b** Identical holes analysis framework

An effective factor for selecting feasible machining units is required machine power. It can be calculated as below [1]

$$P_M = \frac{P}{\eta_m} \tag{3}$$

Where P_M is required machine power, P is calculated power and $\eta_m < 1$ is machine efficiency [1].

- Sliding unit: Fig. 4 shows that sliding units can be selected after the machining unit. If the machining unit does not provide enough feed, sliding units can be used. Selecting feasible sliding units requires consideration of machining unit type and the maximum feed, accuracy, maximum thrust and weight of the sliding unit, the last of which influences chassis selection.
- Accessories:

1. Set up: The utilizing of appropriate set up components improves production quality and decreases production time and costs. Accordingly, the finding and designing of feasible set up components have key roles in the technical feasibility analysis. One of the common set up components in drilling operations is the rotary table. Indexing accuracy, diameter and other dimensions of the indexing table and the type of required control system should be considered in selecting a rotary table. The other set up component is fixture. The following information is required to be identified in selecting or designing of a feasible fixture (Figs 2 and 4):

- Part geometry such as shape and dimensions.
- Operational information such as workpiece material and required accuracy.
- Fixturing information such as machining surfaces, locatable and clamping surfaces.

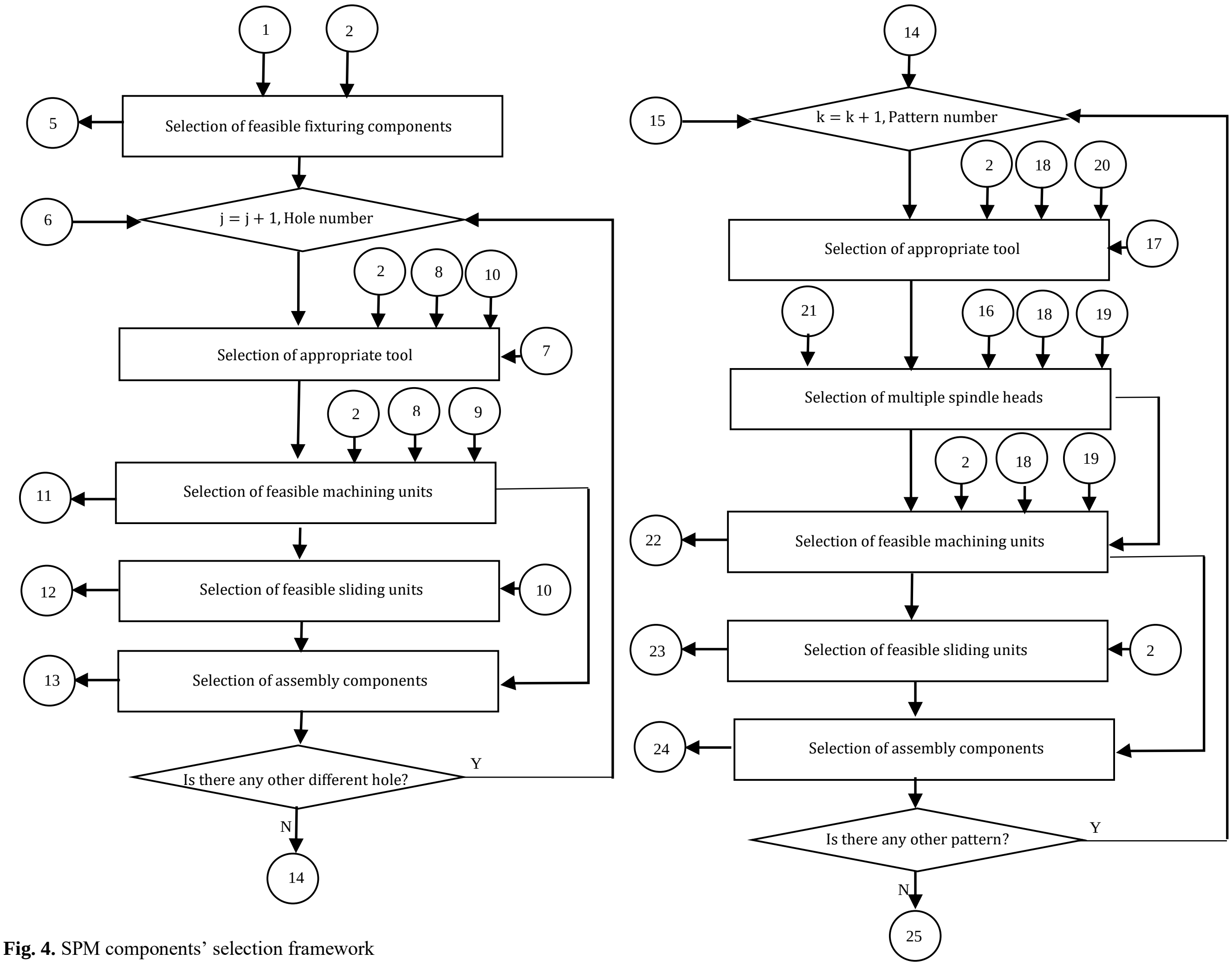

Fig. 4. SPM components' selection framework

2. Assembly components: Assembly components may be selected after set up components, machining and sliding units' selection (Fig. 4). Information required for selecting or designing feasible assembly components includes type of utilized machining and sliding units, dimensions of machining and sliding units, dimensions of set up components, position of workpiece and set up components, dimensions of assembly components, required stroke and allowable directions of sliding assembly components.

3. Table and chassis: After selecting all of the above components, a table and chassis can be selected or designed to position all the SPM components and provide sufficient rigidity (Fig.2). Outcomes of proper selection of table and chassis are improved production quality and reduced production losses. The following factors have great influence on the selection of a feasible table and chassis: weight and dimensions of all required components and table and chassis material and their dimensions (Figs 2 and 4).

3. Development of technical feasibility analysis framework

The relation between identified factors of part and SPM in the technical feasibility analysis framework is based on the experience and engineering knowledge and facts. The framework is developed via rules and constraints which impose limitations on design of SPM. To perform the feasibility analysis several interconnected groups of rules and constraints have been developed for finding feasible SPM components that meet the requirements. For example, one group of rules is developed for controlling workpiece properties in conjunction with fixtures, rotary tables and chassis characteristics. Some rules control holes and machining surface properties in conjunction with machining unit and sliding unit characteristics.

Each characteristic of part has its own rules and constraints and the limits have been retrieved from the SPM components' database. Hence the conclusion of one rule may result in living another. The analysis continues until all the part parameters are checked through the relevant rules and constraints and the feasible components are found.

Various types of constraints and rules are used in this research as follows:

a. Logical constraints: Logical constraints are yes/no expressions which can combine constraints by mean of combination operators such as *and*, *o*r and conditional rules. This allows the programmer/ analyser to combine different constraints as one step and the user can input the data to reach the next step.

Conditional rules (*if…, then…*) are utilized for actions or computations which should be evaluated to be true or false (yes/no). An example of logical constraints and conditional rules is given below (Fig.2)

[*Is the weight of workpiece in the defined limitation range? (YES or NO)*]

This constraint can be expressed by the following rule:

[*If* *(the weight of workpiece is in the defined range)*

then *(Go to the next step)*

and *(use of the weight of workpiece for feasible fixturing selection)*

else if *(Further consideration is required for finding a feasible fixture and table)*

End]

b. Equations rules: Equation rules are functions which consider several variables in calculations. This type of rules is applied for computations such as thrust and drive power calculations. An example of equation rules is given below

[$machine\ power\ P_M = \frac{P}{\eta_m}$]

c. Domain rules: Domain rules require that the database be used to check the conditions and provide conclusions. Furthermore, it lets the programmer/ analyser define the way that the database can be automatically searched. These rules can be applied for finding feasible components (Fig. 4) such as machining units, sliding units, cutting tools and etc. An example of domain rules is given below

[*Check (machining unit power is =< 0.37 kWh)*

and

Conclusion= BEM6 and BEM3 can drill this part and go to the next step]

4. Intelligent feasibility analysis system

To perform technical feasibility analysis an intelligent feasibility analysis system is developed which comprises a user interface, inference engine, rule-base, database and database management. This system is a computer-based system which integrates different sources of data, provides intelligent access to the knowledge and information, and supports the decision makers to perform feasibility analysis in what would otherwise be large-scale, time-consuming, and complex problems. It also reduces the analysis time and improves the reliability of the outcome of the decision

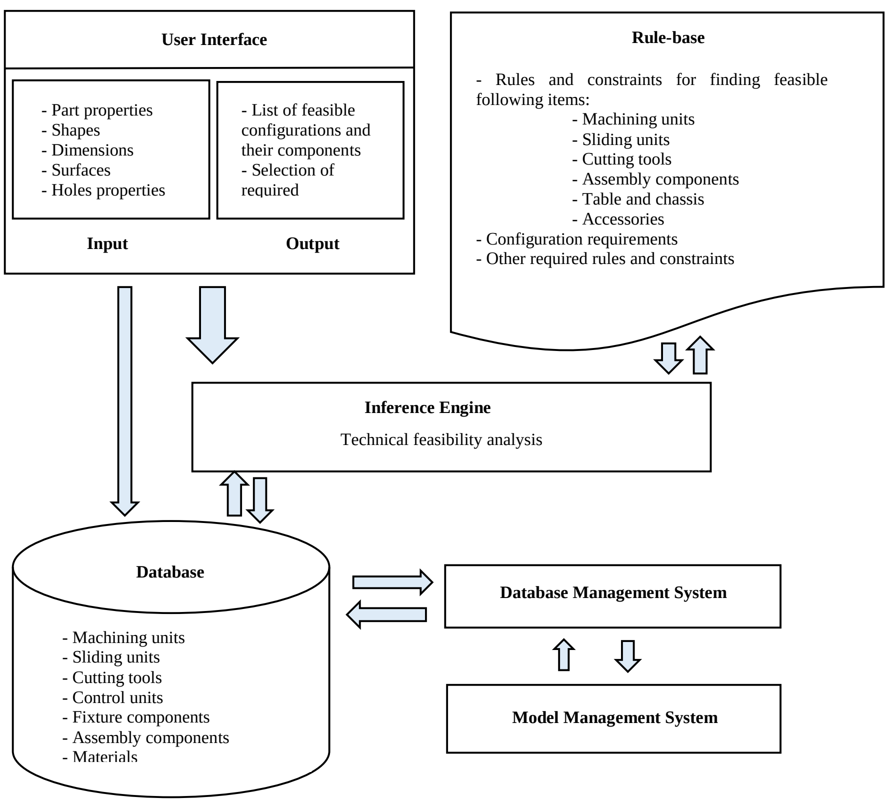

Fig. 5. Overall structure of the proposed intelligent feasibility analysis system

process and gives a comparative benefit over the competitors.

A developed system uses the following items to perform a feasibility analysis for producing a part with a SPM:

1. User interface: Firstly, the required properties of the part should be entered into the system via a user interface. The feasible components are recommended based on the properties of part and relevant rules and constraints. Then, the user can select the required feasible components for designing a SPM configuration which is then verified in terms of some constraints such as geometrical interface, components positioning and components matching due to their properties. If the configuration is not verified, it must be modified with other feasible components. This process continues until all feasible components are identified. The user interface displays the recommended feasible SPM component lists as output for displaying the recommended feasible and infeasible components.
2. Database: As presented in Fig. 5, the system contains a database module which is comprised of SPM components such as machining and sliding units, cutting tools, assembly components, tables and chassis. Each database comprises the relevant properties which will be controlled with the relevant rules and constraints by considering the input data for the part.
3. Database management system: Fig.5 shows this module of the system stores, organizes and retrieves the required data for the feasibility analysis process.
4. Model management system: For storage, organizational and retrieval activities, this system transfers data from the database management system into the inference engine (as shown in Fig.5).
5. Rule-based system: Fig.5 shows that the rule-based module includes rules for controlling part properties, holes properties, machining operations and machining surfaces (as discussed in Section 3).
6. Inference engine: As any other computer-based information system, this is a key reasoning module. An inference engine of the proposed system derives the required information from relevant database, follows the required rules in the rule-base segment, and performs the analysis by considering the relevant input data.

5. Case studies

Databases containing alternative SPM components products and their important characteristics have been established. Required rules and constraints for feasibility analysis have been restored in the rule-base module in the intelligent feasibility analysis system. In this paper, parts can be contained within two main categories as below.

1. Feasible parts: As explained in the Section 3, each rule or constraint has its own limits. If all required part properties have been checked with the relevant rules and constraints and are within the lower and upper limits, the part is feasible to be manufactured with SPM.
2. Infeasible parts: When one or several properties exceed the lower and upper limits, it means that production of this part poses risks such as increasing cutting forces, increasing chatter and reducing tool life or cannot be machined by the available equipment. In this case, producing this part with SPM is not recommended. Two main subcategories have been defined for this category as below:
   a. Close-to-feasible parts: These parts have one or several properties which are close to the lower or upper limits. The defining of close limits relies on the experience and engineering knowledge for each rule or constraint. In this case, the part can be manufactured under new considerations and some revisions, for example, minor revision of a part’s design.
   b. Totally infeasible parts: Some properties of these parts significantly exceed the feasible limits and are not in the close-to-feasible limits. Therefore, they cannot be manufactured by any set of SPM components in the database.

6. Results and discussion

Fig. 6 presents case studies from automotive parts which require drilling operations. In this study the required part properties are extracted from the design of case studies (Table 2) and are entered into the system. The feasibility analysis method is applied to the case studies. Results show that all the required characteristics of part A for technical feasibility analysis are located in the feasible range (filled area). While, there are 3 characteristics of part B that are not in the feasible range (Fig.7). However, they are in the infeasible range; but they are located in the close-to-feasible range. Therefore, they may be able to be drilled with SPM under some revisions. For instance, part B may be drilled before heat treating. Furthermore, it has an odd shape which requires analysis and designing a specific fixture.

(a) **(b)**

Fig. 6. Case studies for automotive parts. **a.** Brake disk. **b.** Engine mounting. Models downloaded from [3]

Table 2 The properties of case studies

				Part A	Part B
Part Properties	**Weight (kg)**			8.1	1.2
	Strength (N/mm^2)			250	760
	Machinability/Material			Cast iron is machineable material.	Heat treated carbon steel
Shapes	-			Round	Odd-shaped
Dimensions (mm)	**Diameter**			235	-
	Length			44	110
	Width			-	81
	Height			-	125
	Thickness			-	5
Number of machining surfaces	-			2	2
Number of possible clamping surfaces	-			1	2
Number of possible locatable surfaces	-			1	2
Holes per machining surface	**Surface 1**			6	3
	Surface 2			30	1
Number of different holes per machining surface	**Surface 1**			0	3
	Surface 2			0	1
Properties of different holes (mm)	**Diameter**	Surface 1		-	Hole 1: 11.5 Hole 2: 12.5 Hole 3: 13
		Surface 2		-	6.10
	Depth	Surface 1		-	Hole 1: 3.54 Hole 2: 3.54 Hole 3: 3.54
		Surface 2		-	4.08
	Tolerance	Surface 1		-	± 0.02
		Surface 2			± 0.02
Number of pattern for identical holes per machining surface	**Surface 1**			2	0
	Surface 2			3	
Type of pattern for identical holes per machining surface	**Surface 1**	Pattern 1: 2 identical holes in linear pattern Pattern 2: 4 identical holes in rectangular pattern			-
	Surface 2	Pattern 1: 10 identical holes in circular pattern Pattern 2: 10 identical holes in circular pattern Pattern 3: 10 identical holes in circular pattern			-
Properties of different holes in patterns (mm)	**Diameter**	Surface 1	Pattern 1	8.8	-
			Pattern 2	12.7	-
		Surface 2	Pattern 1	5	-
			Pattern 2	5	-
			Pattern 3	5	-
	Depth	Surface 1	Pattern 1	7	-
			Pattern 2	7	-
		Surface 2	Pattern 1	22	-
			Pattern 2	22	-
			Pattern 3	22	-
	Tolerance	Surface 1	Pattern 1	± 0.02	-
			Pattern 2	± 0.02	-
		Surface 2	Pattern 1	± 0.02	-
			Pattern 2	± 0.02	-
			Pattern 3	± 0.02	-

Based on the entered part characteristics, a feasibility analysis process is executed to check possibility of utilization SPM and find feasible SPM components. This involves interaction between the inference engine and the rule-based module, databases and input data. First, hole properties and part material are checked to find a feasible tool. If the properties are in the infeasible range, the process is terminated. If they are in the close-to-feasible range the process may continue with some minor revisions. So a similar checking process for finding a feasible multiple spindle head is executed. Then, the analysis continues to find feasible sliding and machining units and accessories. Finally, the process is terminated with a list of feasible SPM configurations and their components as output (Table 3).

After recommending the feasible components, the proposed method controls the possible conflicts between recommended components via configuration rules in the rule-based module. Then, the feasible configurations of SPM with their components are recommended. The system allows the user to select and modify any suggested configuration or to generate a new one by adding and/or removing recommended components from the SolidWorks SPM components database integrated with DSS. Finally, an initial 3D model of the SPM is obtained (Fig. 8).

The results are required for performing the economic feasibility analysis which is the next step in the SPM design and manufacturing process. If the system does not suggest enough feasible components, the part may be modified. However, if that is not possible, the SPM cannot produce the part from technical perspective and the different production method should be used which is not addressed in this work.

7. Conclusion

This paper focused on the technical feasibility analysis which is a major step of design and manufacturing a SPM. This analysis evaluates the possibility of utilizing, design and manufacturing SPMs to product given parts. Parts and SPMs characteristics which influence the feasibility analysis have been identified and then the required rules and constraints have been defined and captured in an intelligent system. The proposed feasibility analysis method has been successfully applied to a number of industrial components included two automotive parts which are presented in this paper. Results show that feasibility analysis facilitates decision making on utilizing SPM and finding appropriate SPM components; taking into consideration the part and SPM characteristics, numerous factors, rules and constraints.

Future perspectives for feasibility analysis may involve extending it to include an economic feasibility analysis using optimization methods and improving the feasibility analysis for uncertainties within manufacturing.

Finally, performing the proposed technical feasibility analysis offers industries the possibility of decreasing the decision making time and costs for utilizing SPM.

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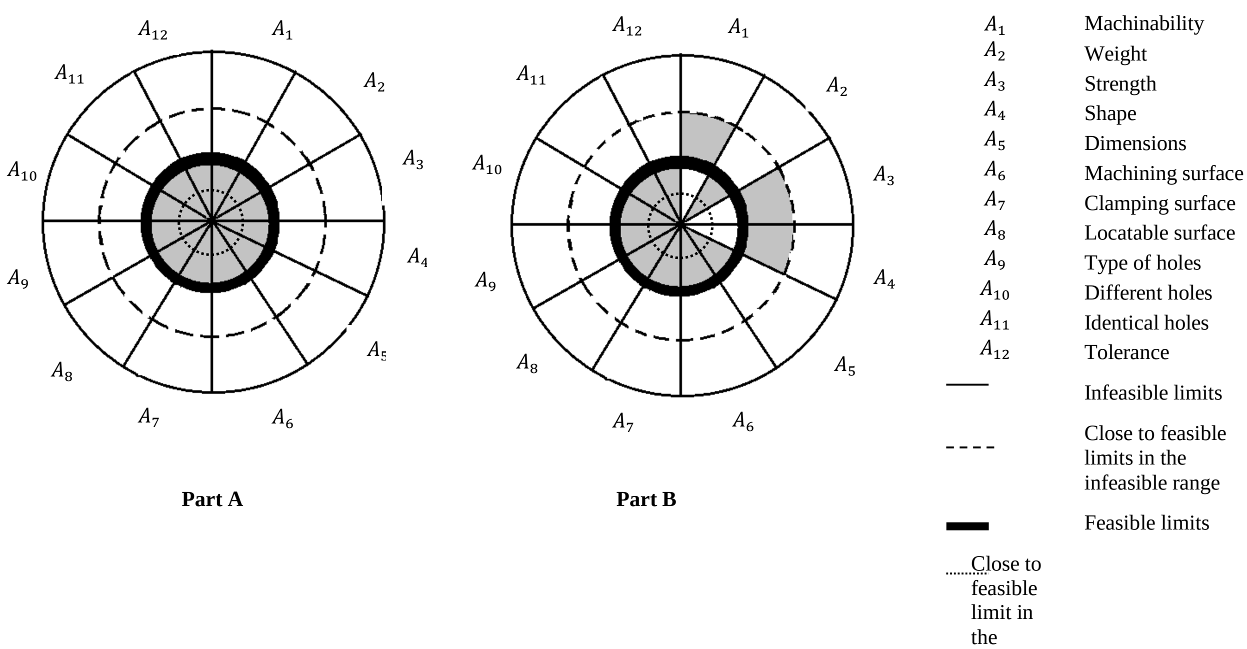

Fig. 7. Comparison results of case studies characteristics with SPM characteristics

Table 2 the output of feasibility analysis by proposed system

List of recommended components of feasible SPM configurations						
Feasible machining units	Drilling Capacity (mm)	Thrust (N)	Power (kW)	Capital Cost ($)	Operational Cost ($/hour)	Maintenance Cost ($/hour)
BEM 6	6	700	0.44	C_{c1}	C_{o1}	C_{m1}
BEM 12	12	1470	0.9	C_{c2}	C_{o2}	C_{m2}
BEM 20	20	4130	1.8	C_{c3}	C_{o3}	C_{m3}
BEM 28	28	8200	6.6	C_{c4}	C_{o4}	C_{m4}
Feasible multiple spindle heads	Drilling Capacity (mm)	Number of Spindles	Adjustment Range (mm)	Capital Cost ($)	Operational Cost ($/hour)	Maintenance Cost ($/hour)
MH 20/10	2.5-10	2	21-103	C_{c5}	-	C_{m5}
MH 33/5	2.5-5	3	14-44	C_{c6}	-	C_{m6}
MH 40/16	2.5-16	4	75-195	C_{c7}	-	C_{m7}
MH 30/5	2.5-5	3	20.5-80.5	C_{c8}	-	C_{m8}
Feasible indexing table	Indexing Diameter (mm)	Rotation Direction	Permission machining thrust (N)	Capital Cost ($)	Operational Cost ($/hour)	Maintenance Cost ($/hour)
RT 320	320	Clockwise	20000	C_{c9}	-	C_{m9}
RT 400	400	Clockwise	30000	C_{c10}	-	C_{m10}
Feasible fixturing	Size (mm)	Outside Jaw (mm)	Inside Jaw (mm)	Capital Cost ($)	Operational Cost ($/hour)	Maintenance Cost ($/hour)
Chuck 3 jaw	250	6-110	90-250	C_{c11}	-	C_{m11}
Feasible assembly components	Support Assembly with Machining unit			Capital Cost ($)	Operational Cost ($/hour)	Maintenance Cost ($/hour)
SH2	BEM 20- BEM 28- BEX 35			C_{c12}	-	C_{m12}
SH6	BEM 20- BEM 28- BEX 35			C_{c13}	-	C_{m13}
Feasible table and chassis	Material	Length (m)	Width (m)	Height (m)	Capital Cost ($)	Maintenance Cost ($/hour)
Table	Cast iron	1.6	0.7	1	C_{c14}	C_{m14}

List of SPM configurations and their components
SPM configuration
BEM 28
MH 20/10
MH 33/5
MH 40/16
RT 320
Chuck 3 jaw 250 mm
SH6
Table 0.7× 1.6 m^2× 1 m

C_c is capital cost of SPM components, C_o is operational cost and C_m is maintenance cost of SPM components

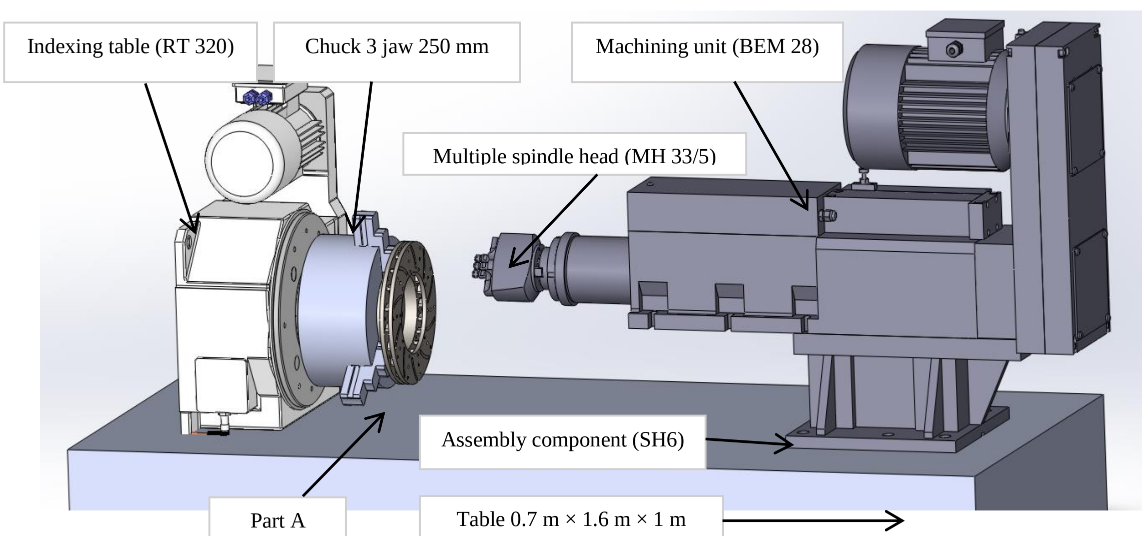

Fig. 8. Feasible SPM configuration for production part A. 3D models of individual parts downloaded from references [3, 4]

References

[1] G.c. Suhner Corporation, in: A. expert (Ed.), Suhner, Switzerland, 2012.

[2] J. Moncada, M.M. El-Halwagi, C.A. Cardona, Techno-economic analysis for a sugarcane biorefinery: Colombian case, Bioresource technology, 135 (2013) 533-543.

[3] Automotive parts, in, https://grabcad.com/library/category/automotive.

[4] Suhner, in, http://www.tracepartsonline.net/.

[5] H.A. ElMaraghy, Flexible and reconfigurable manufacturing systems paradigms, International Journal of Flexible Manufacturing Systems, 17 (2006) 261-276.

[6] M. Mehrabi, G. Ulsoy, Y. Koren, Reconfigurable Manufacturing Systems Key to Future Manufacturing, Journal of Intelligent Manufacturing, 11 (2000) 403-419.

[7] R.G. Landers, B.-K. Min, Y. Koren, Reconfigurable machine tools, CIRP Annals-Manufacturing Technology, 50 (2001) 269-274.

[8] M. Tolouei-Rad, S. Zolfaghari, Productivity improvement using Special-Purpose Modular machine tools, International Journal of Manufacturing Research, 4 (2009) 219-235.

[9] M.R. Abdi, A.W. Labib Feasibility study of the tactical design justification for reconfigurable manufacturing systems using the fuzzy analytical hierarchical process, International Journal of Production Research, 42 (2004) 3055-3076.

[10] M. Tolouei-Rad, Intelligent Analysis of Utilization of Special Purposes Machines for Drilling Operations, in: P.V.M. Koleshko (Ed.), InTech, croatia, 2012, pp. 297-320.

[11] M. Tolouei-Rad, An intelligent approach to high quantity automated machining, Journal of Achievements in Materials and Manufacturing Engineering, 47 (2011) 195-204.

[12] H. Azulay, J.K. Mills, B. Benhabib, A Multi-Tier Design Methodology for Reconfigurable Milling Machines, Journal of Manufacturing Science and Engineering, 136 (2014).

[13] J. Dulpia, B. Powalka, R. Katz, A. Ulsay, Dynamics of the arch-type reconfigurable machine tool, International Journal of Machine Tools and Manufacture, 47 (February 2007) 326-334.

[14] A. Aguilar, A. Roman-Flores, J.C. Huegel, Design, refinement, implementation and prototype testing of a reconfigurable lathe-mill, Journal of Manufacturing Systems, 32 (2013) 364-371.

[15] M. Dağdeviren, Decision making in equipment selection: an integrated approach with AHP and PROMETHEE, Journal of Intelligent Manufacturing, 19 (2008) 397-406.

[16] M. Tolouei-Rad, Intelligent design of reconfigureable machines, World Academy of Science, Engineering and Technology, 59 (2009) 278-282.

[17] M.R. Abdi, A.W. Labib, A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): A case study, International Journal of Production Research, 41 (2003) 2273-2299.

[18] Y. Koren, M. Shpitalni, Design of reconfigurable manufacturing systems, Journal of Manufacturing Systems, 29 (2010) 130-141.

[19] N. Gwangwava, K. Mpofu, N. Tlale, Y. Yu, A methodology for design and reconfiguration of reconfigurable bending press machines (RBPMs), International Journal of Production Research, 52 (2014) 6019-6032.

[20] J. Liu, D. Zhang, L. Qin, L. Yan, Feasibility study of the rotary ultrasonic elliptical machining of carbon fiber reinforced plastics (CFRP), International Journal of Machine Tools and Manufacture, 53 (2012) 141-150.

[21] C.-C. Wang, Y.C. Lin, Feasibility study of electrical discharge machining for W/Cu composite, International Journal of Refractory Metals and Hard Materials, 27 (2009) 872-882.

[22] M. Tolouei-Rad, An efficient algorithm for automatic machining sequence planning in milling operations, International Journal of Production Research, 41 (2003) 4115-4131.

[23] G. Kou, D. Ergu, Y. Shi, An integrated expert system for fast disaster assessment, Computers & Operations Research, 42 (2014) 95-107.

[24] K.H. Tan, C.P. Lim, K. Platts, H. Koay, An intelligent decision support system for manufacturing technology investments, International Journal of Production Economics, 104 (2006) 179-190.

[25] D.E. Culler, W. Burd, A framework for extending computer aided process planning to include business activities and computer aided design and manufacturing (CAD/CAM) data retrieval, Robotics and Computer-Integrated Manufacturing, 23 (2007) 339-350.

[26] O. Battaïa, A. Dolgui, N. Guschinsky, G. Levin, Integrated configurable equipment selection and line balancing for mass production with serial–parallel machining systems, Engineering Optimization, 46 (2013) 1369-1388.

[27] E.U. Guldogan, An integrated approach to machine selection and operation allocation problem, The International Journal of Advanced Manufacturing Technology, 55 (2010) 797-805.

[28] M.P. Groover, Automation, production systems, and computer-integrated manufacturing, 4th ed., Prentice Hall Press, 2014.