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An integrated model to use drilling modular machine tools

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An integrated model to use drilling modular machine tools

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Keywords Integrated decision making model; Manufacturing systems, Drilling-related operations; feasibility analysis; Machine tool selection.

Abstract Modular machine tools provide a platform for drilling-related operations within automotive companies. The use of these machine tools is widespread; however, manufacturers wishing to use this technology frequently face the challenge of selecting the most appropriate manufacturing system. Accordingly, a comprehensive feasibility analysis procedure is required to assist decision makers before any investment is made on the preparation of detailed machine design or purchase one. This paper presents a model, which collects the previous works of the authors. To do this, an integrated framework for decision-making of using machine tools is developed. The aim of this model is to enable users to make a logical decision by assessing the strengths and limitations of machine tools. To do this, the parameters which have a key influence on the decision making process and relevant procedures are identified and integrated into a model. A case study is presented to illustrate the application of proposed model, and results are discussed. The results show that the proposed model is useful in assisting manufacturers in evaluating the performance of a modular machine tool in comparison with other alternatives.

1. Introduction

Manufacturing industries have to cope with turbulent market environments which influence production requirements [1]. To take competitive advantages, manufacturing industries should respond quickly to the demand for customized production [2]. When industries invest manufacturing systems with limited flexibility, industries face a high risk that the investment may not pay off. In response to these identified requirements and to stay competitive, Koren et al. [3] proposed a new manufacturing system, reconfigurable manufacturing systems (RMSs) with technology advances which are designed with adjustable components, effectively responds to the market variations. These systems can be reconfigured from one configuration to another based on market requirements [4]. The main components of these systems are reconfigurable machine tools (RMTs) which may be designed for specific operations to be cost effective tools [5].

Recently, manufacturing industries have come up with modular machine tools. These machines are only modular and configurable and cannot be reconfigured at after design and purchase [6]. Tolouei-Rad and Zolfaghari [7] introduced modular drilling machine tools which are designed for performing drilling operations. These machines are leading economic production solutions by considering current and future market requirements. The structure of these machines is compact and modular' including different components such as machining and sliding units, table and chassis, rotary or sliding add-ons for table, spindle heads, supporting components, and other accessories (Figure 1). Because of their modular properties, they can produce similar or family products by rearranging their modular components [8, 9]. The productivity and profitability of industries may considerably increase by using such machines [7]. However, a proper tool is required to evaluate modular machine tools versus other available choices.

The machine tool selection is a key decision-making process which could lead to achieving market requirements and high competitiveness [10]. Inappropriate machine tool may significantly influence the profitability and the overall performance of the industry. Moreover, the machine tool selection problem is a sophisticated and a time-consuming process which requires expertise and advanced engineering knowledge [11]. This process becomes more complicated

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because of the lack of standard procedures, a large number of parameters should be considered. In addition, the competitive market offers a wide range of machine tools and new advanced technologies. These machine tools may have conflicting objectives from different perspectives which require more investigation. Samvedi et al. [12] concluded that the machine tool selection influences profitability and is a significant early investment decision for manufacturers.

The selection of machine tools has been studied from different perspectives. Samvedi et al. [12] categorized the decision-making procedures involved in selecting a machine tool into three main categories: analytic, strategic and economic. Many researchers apply analytical methods such as the analytical hierarchy process (AHP) [13, 14], technique for order of preference by similarity to ideal solution (TOPSIS) [15], and hybrid methods [18]. Some researchers also use strategic methods in different manufacturing research fields. For instance, Battaïa et al. [17] applied expert systems (ES) to the machine selection problem to evaluate qualitative factors. Vafadar et al. [8] used an expert system for technical feasibility analysis. Several research projects focused on cost analysis as a useful assessment method for selecting an appropriate choice among different alternatives [18-20]. From the above it can be concluded that there is some research on the machine tool selection problem; but up to now a comprehensive decision making approach has not been adequately considered in these publications.

The aim of this paper is to integrate the previous works of the authors into a whole decision-making process model that would support decision-makers in using modular drilling machines for a given production. The proposed method in this study deals with evaluating the performance of the machine tool from different points of view. Vafadar's previous analyses underpin this work and are explained as fully as possible given space limitations. Detailed information can be found in the author's works which are published elsewhere [8, 21, 22].

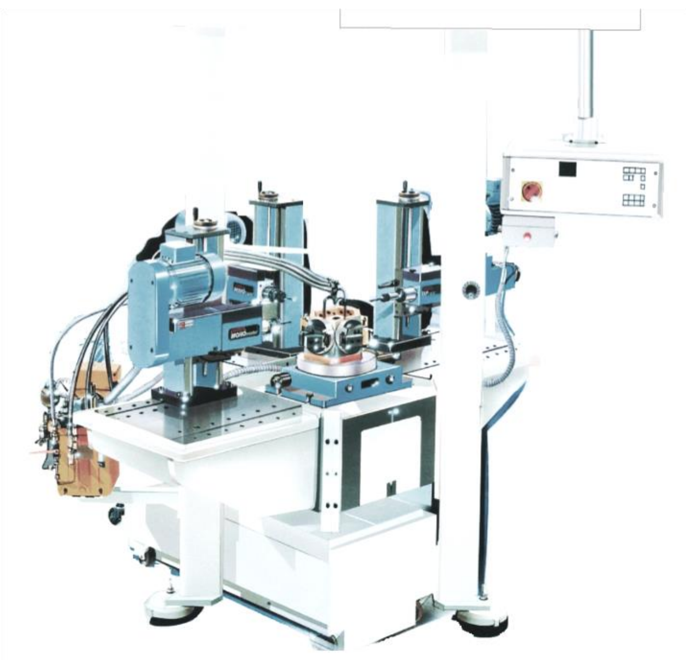


Figure 1: Drilling machine tool structure [23].

2. Methodology

In order to make an informed selection of a modular machine, the designer should have access to the following items:

- Part characteristics
- List of feasible modular machine tool components
- Optimised modular machine configurations
- Sensitivity results of economic factors.

To achieve the above, the critical phases for performing a comprehensive feasibility analysis are identified. These are shown in Figure 2.

2.1. Part analysis

By performing a part analysis, the following items can be extracted from the part's design. This information is essential for performing a technical feasibility analysis.

- Workpiece properties (weight, strength, machinability, shape, and dimension)
- Machining surfaces (number and direction)
- Holes (type, number, diameter, depth, tolerance, and pattern)

2.2. Machine tool analysis

This analysis results in the critical modular machine tool characteristics listed below which significantly affect the technical analysis output.

- Cutting tool (material, diameter, length, type, and cost)
- Spindle head (number of drilling heads, drilling size range, thrust and drive power, and cost)
- Machining unit (operation type, drilling size range, drilling type, feed and cutting speed range, drive power, cost, weight, and dimensions)

$$T_m = T_c + T_i + T_{tc} + T_{L/U} + T_f + T_s \quad (1)$$

- Sliding unit (size, sliding range, required machine tool, weight, and cost)
- Indexing or sliding table (type, speed, number of stations, and cost)
- Table and chassis (dimension, weight range, and cost)
- Accessories (dimension, cost, and so on).

2.3. Technical analysis

Technical feasibility analysis assists users in finding potential feasible components and configurations of modular machines for producing the given part(s). This evaluation includes different relations between the workpiece and the characteristics of machine tool components obtained from the previous analyses. This step can be performed by using rules and constraints which interconnect the workpiece and the characteristics of machine tool components. The properties of the workpiece which are retrieved from the first analysis are checked against the characteristics of the modular machine tool using some rules and constraints, and consequently feasible components are found. The process is the same for the other machine tools. To perform technical feasibility analysis, different types of rules and constraints can be used, as shown in Table 1. These rules can be defined based on the engineering facts and expert knowledge to impose constraints and limitations on finding feasible components/machine tools.

2.4. Developing a cost model

A cost analysis is required to perform machine tool selection using different analyses (optimization, economic and sensitivity analyses) for evaluating a modular machine tool in comparison with other machine tools. To do this, a mathematical product cost model for modular machine tool is developed for estimating time and cost factors and then financial indicators are calculated to evaluate the performance of the machine tool.

2.4.1. Machining time

Machining time is an important factor in estimating cost factors. The following equation explains how to calculate the machining time of modular machine tools. These machines can be designed into two main groups: single- and multi-station [8].

A single-station modular machine tool consists of one working station with different setups and in each setup drilling operations may be performed simultaneously or sequentially. All the actions in this configuration, such as loading, drilling, tool changing, and setup and are performed sequentially. In this case, the equation below is used for calculation of the machining time.

Where T_m is machining time, T_c defines cutting time, T_i is indexing time, T_{tc} is tool changing time, $T_{L/U}$ indicates loading/unloading time, T_f free travel tooling time, and T_s is setup time. All times are calculated in minutes.

A multi-station modular machine tool consists of different working stations with rotary or sliding indexing tables where one or more drilling operations may be performed simultaneously or sequentially in each working station. In this configuration, the longest cutting time of each working station is considered in the machining time calculation as all the operations in each working stations are performed simultaneously. Furthermore, loading, unloading and machining operations are performed simultaneously in different working stations. Thus, the maximum longest time period is considered in the machining time calculation as follows [21].

When loading and unloading activities are performed in one working station, the machining time is calculated as below

$$T_m = max\{T_c + T_f, T_{L/U}\} + T_{tc} + T_i \quad (2)$$

When loading and unloading activities are performed in the two different working stations, then the machining time equation is calculated as below

$$T_m = max\{T_c + T_f, T_L, T_U\} + T_{tc} + T_i \quad (3)$$

Table 1: Different types of rules and constraints which are required to perform technical feasibility analysis.

	Rules/Constraints type	Required operator	Explanation
1	Logical constraints	AND, OR, ...	These constraints combine different rules and allow the user to reach the next rule.
2	Conditional rules	IF ... THEN ...ELSE IF	These rules evaluate the actions or computations which the results may be true or false (yes or no).
3	Equation rules	Mathematical operator such as plus, minus, ...)	These rules consider different variables in a calculation process.
4	Domain rules	Check.... conclusion....	Such rules search the used database to provide a conclusion(s) to the user.

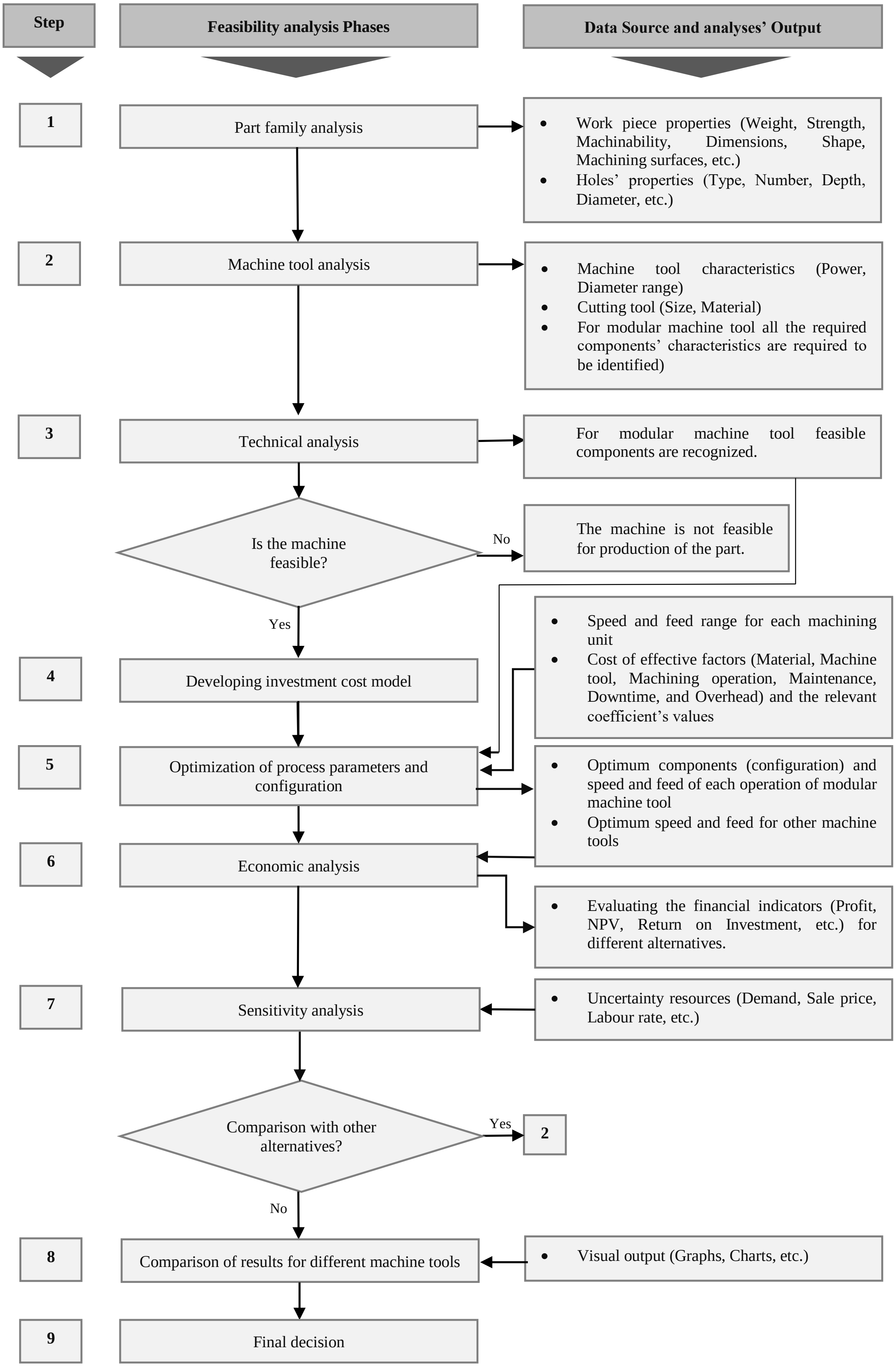


Figure 2: The schematic representation of the integrated model for feasibility analysis

2.4.2. The investment cost model

To justify machine tool investment the following equations are developed to estimate the unit profit during the life cycle of production at the present time [21]. This model can be used for evaluating all machine tools.

$$C_{total} = C_{mt} + \sum_{j=1}^{t} C_{material_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{machining_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{maintenance_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{overhead_j}(1+i)^{-j} - S(1+i)^{-t} \quad (4)$$

Where C_{total} is total cost of production, C_{mt} defines machine configuration cost, $C_{material}$ indicates material cost per year, $C_{machining}$ machining cost per year, $C_{maintenance}$ maintenance cost per year, $C_{overhead}$ overhead cost per year, S defines salvage value, i is annual interest rate, j is index of production year, and t is the number of production years.

2.5. Optimization process

Optimization processes at the feasibility analysis stage of using a modular machine tool may influence the final decision considerably. To do this, the list of feasible components and the range of feeds and cutting speeds achieved from the part and machine tool analyses are used. The aim of the optimization process is to find the optimum process parameters and a machine configuration to cope with the competitive market requirements at an early stage of decision-making by using a GA-based approach. The main advantage of using GA is that the cutting parameters and configuration can be optimized concurrently Xu et al. [24]. To fulfil this, the following steps are performed to maximize the potential profit:

Defining the objective function: The above cost model is used to develop the objective function to find the maximum unit profit.

Defining decision variables: The following variables are considered in the optimization process:

- Cutting speed of each drilling operation or operation group
- Feed of each drilling operation or operation group
- Machining unit allocation to each drilling operation or operation group
- Configuration type
- Number of stations
- Assignment of loading and unloading to the working stations.

Defining constraints: Different constraints are applied to the optimization model as below.

- Machine configuration cost should be equal or less than the predefined budget (B).

$$B \geq C_{mt} \quad (5)$$

- The drilling power for each operation or operation group should be equal or greater than the required power which can be estimated by considering number of spindles per head (N_s), hole diameter (D_h), and part material (M_p) [23].

$$P\left(N_{s\,k}, D_{h_k}, M_p\right) \leq P_{m\,k} \quad (6)$$

$$\forall \quad k = 1, \ldots, N_d \quad \& \quad m = 1, \ldots, M$$

Where k is index of drilling head, N_d defines the number of drilling heads, m is the index of the machining unit, M indicates the number of machining units.

- Allowable cutting speed range is defined based on the drilling tool type and workpiece material which are recommended by manufacturers [25].

$$v_{km\,min} \leq v_{km} \leq v_{km\,max} \quad (7)$$

$$\forall \quad k = 1, \ldots, N_d \quad \& \quad m = 1, \ldots, M$$

Where $v_{km\,min}$ and $v_{km\,max}$ are minimum and maximum cutting speeds of each drilling head, respectively.

- Allowable feed is defined based on the drilling tool type, workpiece material, and hole diameter [26].

$$f_{km\,min} \leq f_{km} \leq f_{km\,max} \quad (8)$$

$$\forall \quad k = 1, \ldots, N_d \quad \& \quad m = 1, \ldots, M$$

Where $\mathbf{f_{km\,min}}$ and $\mathbf{f_{km\,max}}$ are minimum and maximum feeds of each drilling head, respectively.

2.6. Economic analysis

Economic analysis is required to assess the strengths and limitations of a modular machine tool in comparison with other machine tools. To perform this analysis, the optimum process parameters and configuration resulting in the highest profit are used. Economic analysis can evaluate machine performance by using one or more financial indicators as presented below.

Profit and unit profit are important indicators which can be used for the evaluation, and they can be estimated by considering sales revenue, total life cycle production cost, and , and demand volumes [26]. The detailed equations can be found in [21].

Return on sale (ROS) is another useful tool which can be

$$Profit = D \sum_{j=1}^{t} S_{p_j} (1+i)^{-j} - C_{total} \tag{9}$$

$$Unit\ profit = \frac{Profit}{D \times t} \tag{10}$$

used to compare the performance of modular machines with other alternatives. The following equation is developed to calculate this indicator. This equation is based on the formula introduced by Hitomi [26].

$$ROS = \frac{Profit}{D \times \sum_{j=1}^{t} S_{p_j} (1+i)^{-j}} \tag{11}$$

Where D is demand volume and S_p defines sale price.

2.7. Sensitivity analysis

The optimum configuration and process parameters are utilized in the economic analysis which may lead manufacturers to make an appropriate decision; however, in any competitive market, manufacturers face uncertainties over the life of production which should be analysed in order to make a reliable selection at the preliminary stages. Accordingly, a sensitivity analysis (SA) is required to evaluate future or unpredicted situations, which determines the range of possible outputs. To do so the financial indicators of economic analysis are subjected to uncertain input parameters. Figure 3 shows the steps required for this analysis of this analysis. To perform this analysis, all individual variables which are uncertain are repeatedly changed by allocating a distribution while leaving all other variables constant and monitoring the machine's performance.

2.8. Final decision making

The proposed integrated system can be used for modular machine tools and other alternatives. As Figure 2 shows the results of part and machine tool analyses are used for technical analysis. This analysis provides a list of feasible modular machine tool components if they exist. The feasible components and feed and cutting speed ranges which are achieved by machine tool and part analyses, respectively, are used for the optimization process.

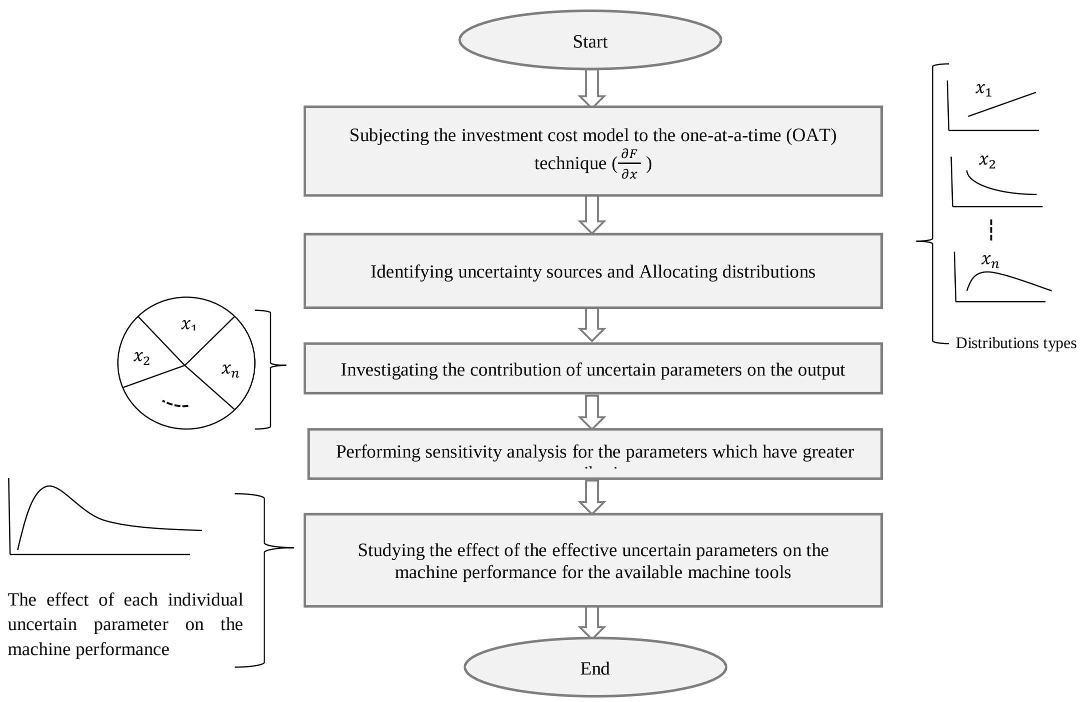


Figure 3: The required steps for sensitivity analysis.

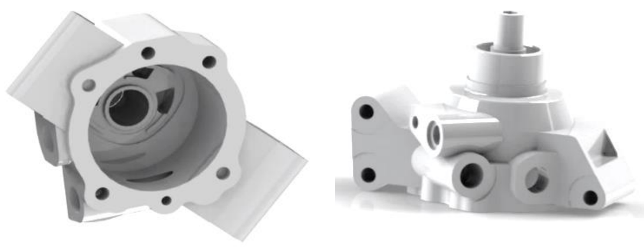


Figure 4: Power steering pump body from different views downloaded by Nathan [28].

The aim of the optimization process is to maximize the profit by finding the optimum machine tool configuration and process parameters (feed and cutting speed). The results of this process are applied to the economic feasibility and sensitivity analyses. The outcome of the feasibility analysis can be presented by calculating financial indicators which can be compared with other machine tools. Since manufacturers face uncertainties and errors during the life cycle of production, financial indicators should be investigated versus variations in uncertain parameters. Schmitz et al. [27] believed that considering uncertainty in the decision-making process may provide substantial economic benefit which enhances the competitiveness of the manufacturer. These results can be represented by visual outputs which facilitate comparing the performance of different machine tools. Indeed, the decision-maker can easily investigate the benefits and limitations of using of any machine tools under different conditions.

3. Case study

The proposed feasibility analysis system is examined for the selection of a modular machine tool versus computer numerical control (CNC) and conventional machines for production of an automotive component (Figure 4). This part is made of Aluminium alloy which includes Si (less than 5%). This part has different holes which are analysed and categorized into several operation groups, and each group can be drilled by a drilling head which may have one or more spindles (Table 2).

3.1. Results and feasibility analysis

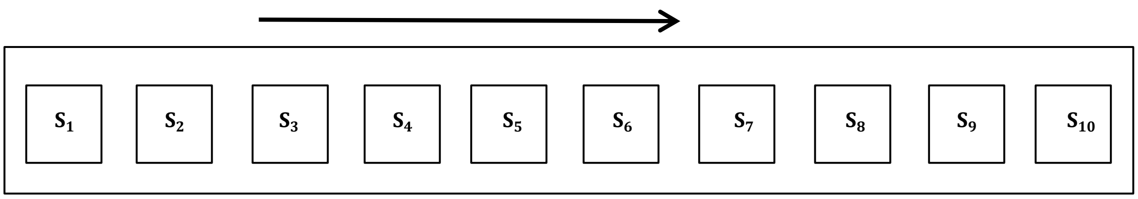
According to the flowchart (Figure 2), part properties are achieved from the part analysis (Step 1) and the characteristics of machine tool components are obtained from machine tool analysis (Step 2). Based on the results the feasible components of modular machine tools are identified from the technical feasibility analysis (Step 3). Moreover, based on the results of part analysis uncoated HSS tools are selected to perform drilling operations (Step 1). Following this, the mathematical investment cost model developed in Step 4 is used for defining an objective function of the optimization process (Step 5). By considering tool material and part properties feasible cutting speed and feed ranges for each machining unit are established for the optimization process (Step 5). The optimization process is performed to select the near optimum configuration of the modular machine tool. As explained before, the objective function of the optimization model involves maximizing the unit profit by using the developed mathematical cost model. Table 3 shows the optimum process parameters and optimum spindle heads and machining units selected for designing the modular machine configuration. Figure 5 also represents the optimum layout of the modular machine tool for drilling the given part. The sliding multi-station machine has ten stations; one for loading, one for unloading, and the remaining eight devoted to the drilling operations. Two stations perform two simultaneous drilling operations by using multiple spindle heads. In each of the remaining six stations, machining units are arranged to perform two simultaneous drilling operations from different directions.

Then economic and sensitivity analyses are applied to the optimized configurations (Steps 6 and 7). Figure 6 represents the result of the economic analysis of using the optimum modular machine and two other alternatives (CNC and conventional drilling machines) versus different production demands. It is noteworthy that the optimum process parameters are considered in the analysis of CNC and conventional machines. It can be seen that for lower demands (less than 7,500 units) the conventional drill machine results in a greater unit profit. Since the capital investment in modular and CNC machines is higher than the capital investment in conventional machines, respectively, the sale profit of the conventional machine is greater than other alternatives. Figure 5 also shows that when demand is less than 2,500 units, the modular machine and CNC do not provide any profit. Accordingly, it can be concluded that the conventional drill machine is an appropriate choice for lower demands. By increasing demand, the unit profit of all machines increases; however, the unit profit achieved by a modular machine is considerably higher than the unit profit achieved by other machines. It is noteworthy that these results may be influenced by uncertainties in the initial stages of decision-making.

In the feasibility analysis stage, the accurate estimation of parameters is a difficult task as sufficient data is not available. Accordingly, a sensitivity analysis should be performed before making the final decision. In this study, four uncertain parameters – demand, labour rate, machining time, and labour rate – are investigated and are shown in Figure 7. Demand, labour rate, and overhead rate are variables which inherently vary over time and machine time is a variable which may be estimated inaccurately. To make a reasonable comparison, the same thresholds are considered for all machine tools.

Table 2: The properties of holes.

Operation Group number	Diameter (mm)	Length of cut (mm)	Number of holes	Allowance (mm)	Required power (kW)
1	7	27	1	1.63	0.6
2	5.6	52.2	2	1.30	0.7
3	11	20	1	2.50	1.5
4	14.5	20	1	3.38	2.2
5	16.5	2.5	1	3.84	2.5
6	15	13.5	1	3.49	2.4
7	8.6	52.5	1	2.00	0.8
8	11	6.5	2	2.56	1.5
9	11	6.5	1	2.56	0.9
10	7	13.5	2	1.63	0.9
11	7	4	1	1.63	0.6
12	7	13.5	1	1.63	0.6
13	5	15.5	1	1.16	0.45
14	7	5.36	1	1.63	0.6



S_1: Loading

S_2: Drilling operation group 1 and operation group 3

S_3: Drilling operation group 4 and operation group 6

S_4: Drilling operation group 5 and operation group 8

S_5: Drilling operation group 7 and operation group 9

S_6: Drilling operation group 11 and operation group 12

S_7: Drilling operation group 13 and operation group 14

S_8: Drilling operation group 2

S_9: Drilling operation group 10

S_{10}: Unloading

Figure 5: Optimum configuration of modular machine tool for power steering pump body production.

Table 3: The optimum process parameters and modular machine components.

Operation Group number	Cutting speed (m/min)	Feed (mm/rev)	Selected Spindle head [1]	Selected machining unit [1]
1	72	0.22	Single spindle	BEM 12
2	80	0.17	multiple spindles (MH20/7)	BEM 12
3	78	0.31	Single spindle	BEM 20
4	71	0.35	Single spindle	BEM 28
5	100	0.41	Single spindle	BEM 28
6	70	0.30	Single spindle	BEM 28
7	71	0.25	Single spindle	BEM 12
8	74	0.31	multiple spindles (MH20/7)	BEM 20
9	82	0.31	Single spindle	BEM 12
10	74	0.23	multiple spindles (MH20/7)	BEM 12D
11	70	0.23	Single spindle	BEM 12
12	79	0.23	Single spindle	BEM 12
13	75	0.16	Single spindle	BEM 6
14	72	0.23	Single spindle	BEM 12

1: The optimum machining units and spindle heads are selected from a range of drilling machining units which are extracted from Suhner general catalogue [23].

Demand is an inherently uncertain parameter as market requirements change over time [29]. Accordingly, the contribution of this parameter in the selection of machine tool have to be assessed. Figure 7 (a) shows that demand changes has a considerable influence on the final decision. It can be seen that for lower demands, less than 7,500 units, the conventional machine is a suitable choice, whereas by increasing demand and when the demand is less than 10,000 units, CNC provides greater profit than the conventional machine but the profit is still lower than modular machine. Since the capital investment in a modular machine is high, the sale profit does not justify the investment cost when demand is low. This figure also shows that for higher demands, the modular machine provides a considerable profit compared to the two other alternatives. Indeed, the number of required machines remains constant when the modular machine is used whereas more conventional and CNC machines are required for higher demands. Accordingly, the capital investment costs of CNC and conventional machines increases and results in a low profit. It can be concluded that to produce this part, the modular machine is a suitable choice for high demand, while for lower demands, the conventional machine provides greater profit. CNC can also be a reasonable choice when demand is between 5,000 units to 10,000 units.

The labour rate is another important parameter which differs between places and changes over time due to market requirements. Accordingly, the influence of labour rate changes on the performance of the alternative machine tools should be studied. Figure 7 (b) shows that the sensitivity of conventional and CNC machines to the labour rate changes is much greater than that of modular machine. Machining and maintenance costs are functions of the labour rate and machining time. Since labour rate changes are assumed to be the same for all machine tools, and using the modular machine leads to a shorter period of machining time than the alternatives, the modular machine is not as sensitive as other options. Therefore, in this case the modular machine may be a reliable selection.

Machining time is an important parameter which may significantly influence the performance of a machine tool. Most of the cost factors of the developed cost model are functions of the machining time. Figure 7 (c) indicates that the conventional machine is more sensitive to the machining time variation than modular and CNC machines, as machining and maintenance times for the conventional machine are higher than other choices and these times effectively influence the unit profit. This figure shows a non-linearity in the CNC behaviour versus machining time changes. The reason is that the number of required machines changes as the machining time increases. It can also be seen that the modular machine provides a stable behaviour versus machining time changes and this machine provides a higher unit profit. Accordingly, the modular machine is the most appropriate choice.

Like the labour rate, the overhead rate changes over time and between countries. Accordingly, the analysis of the performance of machine tools versus overhead changes may provide useful information. Figure 7 (d) shows that again, the modular machine always outperforms the other alternatives and its performance is less sensitive to CNC and conventional machines. It can also be seen that the conventional machine has a strong decline as overhead rate varies. Therefore, the overall performance of the modular machine is not affected by the overhead rated changes and the use of the modular machine is more reliable in the case if this machine provides greater unit profit than other options.

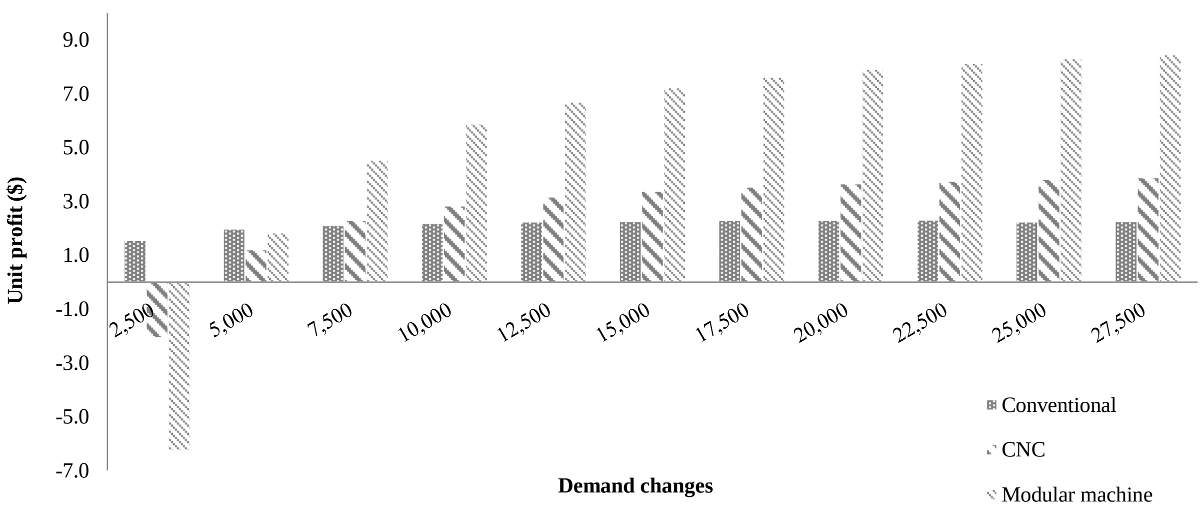


Figure 6: Economic feasibility analysis of using a modular machine versus CNC and conventional drilling machines.

4. Conclusion

One of the main challenges in the selection of a modular machine tool versus other alternatives is the lack of a reliable procedure for feasibility analysis. In this paper an integrated feasibility analysis model is presented through integrating the previous works of the authors into a whole decision-making process model. The part and machine tool have been analyzed and effective characteristics have been identified and the relevant relations have been created to perform a technical feasibility analysis. Following this a mathematical investment model is developed which is used as a basis for the optimization process. Then economic and sensitivity analyses are conducted which are defined based on the mathematical cost model. The final decision is made based on the output and this leads the manufacturer to a reliable solution. This process enables the limitations and benefits of using a modular machine for the given product are assessed and compared with other machine tools.

The proposed model has been applied to a number of case studies, one of which was presented in this paper. The results show that this model provides insightful information which helps in the assessment of other designing and manufacturing processes or purchasing an appropriate modular machine. The model presented is intended for the selection of modular machines; however, a similar approach can be developed for other decision-making problems such as material-handling system selection and cutting-tool selection. Finally, the model presented here is a useful tool for making a reliable decision at a preliminary stage and eliminating a costly and time-consuming process.

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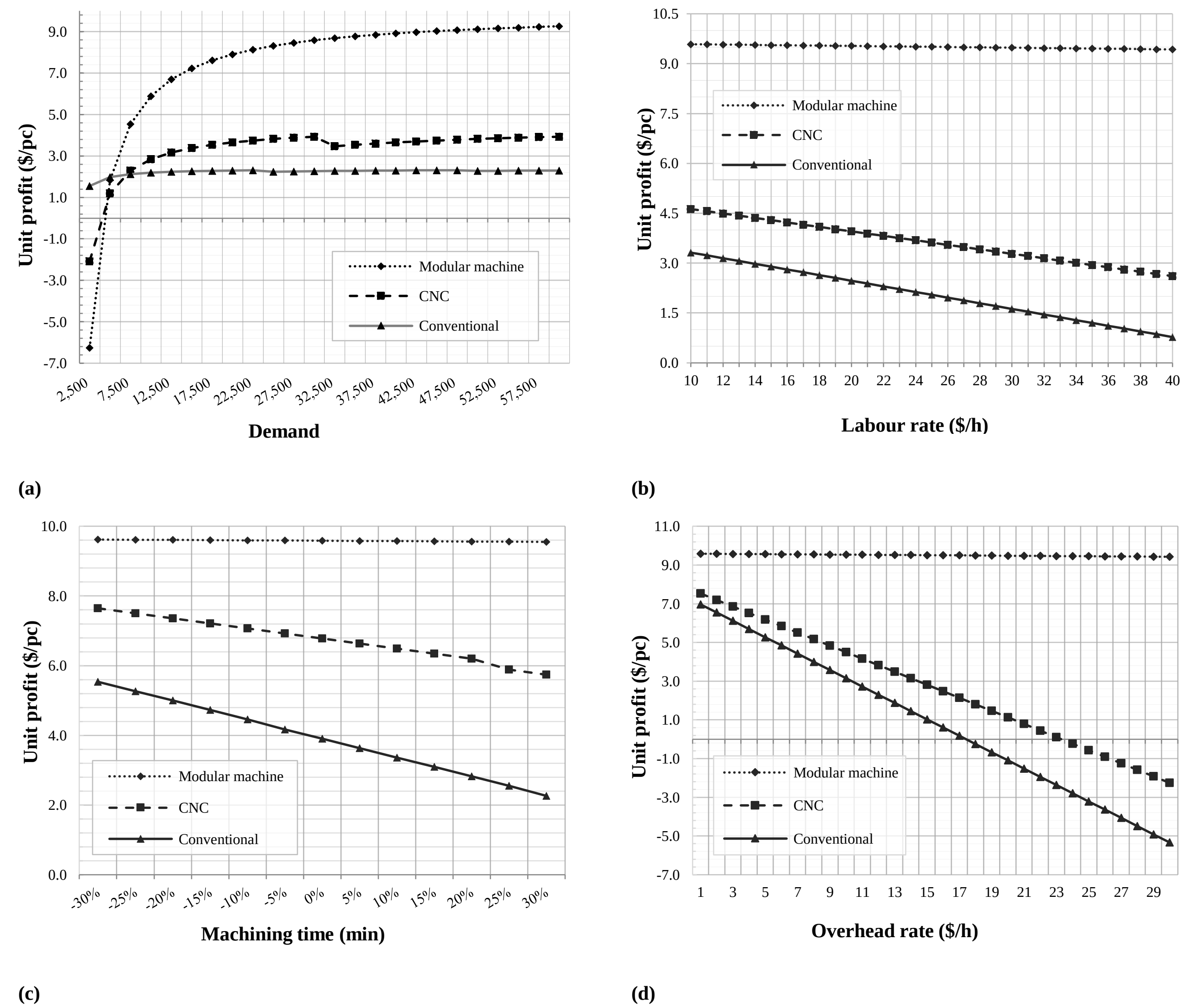

Figure 7: Sensitivty analysis of some uncertain parameters; (a) Demand, (b) Labor rate, (c) Machining time, (d) Overhead rate.

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