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Sensitivity analysis for justification of utilizing special purpose machine tools in the presence of uncertain parameters

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Decision makers in manufacturing area frequently face machine tool selection problem under uncertainty due to competitive market changes. Special purpose machines (SPMs), a relatively new class of reconfigurable machine tools (RMTs), are used to react quickly to changes. Justification of utilizing these machines versus other machine tools requires a technique to investigate the sources of uncertainties. In this work sensitivity analysis (SA) is utilized to investigate the sources of these uncertainties and errors which may reveal new insights for evaluating a machine tool. An illustrative example is provided to show the sensitivity of parameters on the economic performance of SPMs compared to the other alternatives. The results show that this analysis provides additional information and moves the decision closer to the optimum alternative.

Keywords: Decision analysis; Machine selection; Uncertainty; Special purpose machine (SPM); Sensitivity analysis (SA)

Nomenclature

$f_1(x)$	Total material cost per year (*$*)
$f_2(x)$	Annual start demand
$f_3(x)$	Number of produced parts per hour
$f_4(x)$	Number of required machine tools
$f_5(x)$	Total machine tool cost (*$*)
$f_6(x)$	Total machining operation cost per year(*$*)
$f_7(x)$	Total tooling cost per year (*$*)
$f_8(x)$	Tool life of cutting tools (*min*)
$f_9(x)$	Total machining cost per year (*$*)
$f_{10}(x)$	Total maintenance cost per year (*$*)
$f_{11}(x)$	Total overhead cost per year (*$*)

$f_{12}(x)$	Salvage value (*$*)
$f_{13}(x)$	Total production cost (*$*)
$F(x)$	Unit profit (*$/pc*)
$f_{st}(x)$	Saw-tooth frequency function
$f_{upr}(x)$	Unit profit range function
x_1	Required demand
x_2	Scrap rate
x_3	Availability of machine tool (*%*)
x_4	Machining time (*min*)
x_5	Labour rate (*$/hour*)
x_6	Operator fault rate (*%*)
x_7	Cutting time (*min*)
x_8	Cutting speed (*mm/min*)
x_9	Maintenance coefficient (*%*)
x_{10}	Overhead rate (*$/hour*)
x_{11}	Sale price (*$*)
C	Taylor tool life constant
C_1	Cost of material unit (*$*)
C_2	Working hours per year
C_3	Cost of machine tool unit (*$*)
C_4	Number of drilling heads
C_5	Number of spindles per head
C_6	Tool cost (*$*)
C_7	Salvage coefficient
C_8	Constant value
C_9	Number of production years
i	Annual interest rate
j	Each year of production
k	Index of number of utilized spindle heads
n	Taylor's tool life exponent

T	Tool life (*min*)

1. Introduction

Market demand has led manufacturing technologies to quickly be adapt current production requirements and market changes (Abdi 2009; Battaïa, Dolgui, and Guschinsky 2016). The former paradigms of manufacturing methods for medium- and high production quantities are dedicated (DMS) and flexible manufacturing system (FMS) (Katz 2006). DMSs are designed to produce a specific part at a constant production volume through applying dedicated machine tools (DMT). This type of manufacturing system cannot be changed cost effectively to accommodate new requirements. FMSs are designed to produce a variety of unforeseen parts in undefined required quantities and often utilize general purpose machines (GPMs) (Koren and Shpitalni 2010) which may include unrequired capabilities. However, the current market forces manufacturers to be flexible enough to produce various specific parts in different quantities on the same system without the need for high investments.

Unlike DMSs and FMSs, reconfigurable manufacturing systems (RMSs) are designed to be rapidly and cost-effectively reconfigured to the required capacity to meet market demand (Wang and Koren 2012). Reconfigurable machine tool (RMT) is one of the primary components of these systems which is designed for a customised range of machining operations (Bensmaine, Dahane, and Benyoucef 2014). Special purpose machines (SPMs), is one type of these machine tools which is designed for a specific machining operations and include the advantages of both DMT and GPM. These machines can produce a family of parts in different quantities. This is a considerable capability comparing to the DMT. Furthermore, SPMs have limited reconfigurability or modularity to produce a number of parts with lower capital investment cost than GPMs.

While SPMs constitute a relatively novel manufacturing technology, few researchers have focused on this technology (Tolouei-Rad and Zolfaghari 2009; Vafadar et al. 2016).

Appropriate utilization of SPMs can significantly enhance the productivity of manufacturing industries. Their efficiency is based on modularity which enables them to be cost effective and adaptable in rapidly changing markets. Indeed, SPMs are leading economic manufacturing solutions in the field of drilling, reaming and tapping operations (Tolouei-Rad and Zolfaghari 2009). These machines do not have a rigid bulky configuration and may comprise several of machining and slide units, and their accessories, such as single or multiple spindles, indexing tables and unit support columns (Vafadar et al. 2016). Because of their modularity, SPMs can be rearranged in different configurations to produce other parts. Many advantages may be obtained by applying SPMs for producing industrial parts, but their adoption is not proportional to the potential benefits. Thus an appropriate methodology is needed to justify SPM utilization in a competitive environment.

One method used for manufacturing system selection is cost analysis (Dai and Lee 2012; Quintana and Ciurana 2011). These developed methods are utilized for evaluating the productivity of different material handling systems and advanced manufacturing systems, respectively. Hazir, Delorme, and Dolgui (2015) believed that the number of publications which apply cost- or profit- methods in the manufacturing field is increasing. Economic analysis provides important information of a manufacturing system selection process and avoids costly and timely studies; a key challenge is the lack of sufficient and reliable data at the preliminary stage of designing or purchasing a machine tool. The estimation of input parameters and assumptions of any economic mathematical model are made under uncertainty which complicates the evaluation of investment decisions (Kim, Realff, and Lee 2011). Rönnberg Sjödin, Frishammar, and Eriksson (2016) believed that uncertainty is one of the key challenges at the early stages of projects which can have large consequences in project performance. Furthermore, when the behaviour of a system is described by a mathematical model a poor decision may be made due to uncertainty can occur in the parameters of the model (Abdo and Flaus 2016). Accordingly, the economic model may not be sufficiently robust for the decision making process, thus a supplementary technique is needed with the cost model for investigating the inputs of the model under uncertainty.

Sensitivity analysis (SA) investigates the inputs of the model and tests the robustness of the results in the presence of uncertainty. Generally, SA methods may be categorized into two main groups: local and global sensitivity analyses. Local sensitivity analysis studies the sensitivity of one input variable, while keeping the values of other input variables constant. Global sensitivity analysis operates in a random or systematic way to explore the global input space of variables (Van Griensven et al. 2006). There is a large literature about SA. Wainwright et al. (2014) compared the local and global sensitivity analyses. They demonstrated that both methods gave similar results and concluded that a local sensitivity analysis should be performed first, because it may provide sufficient information to identify influential variables. Furthermore, they concluded that global sensitivity analysis provides additional information to provide robust measures in the presence of nonlinearity among variables. Whereas, Foglia et al. (2009) explored different types of SA and found out that local SA provides sufficient information to justify the results and global SA methods do not provide additional information.

Pannell (1997) divided the objectives of SA into four main groups: Decision making purposes or development of justifications and information for decision makers, communication, quantification of the system, and model development. Considerable studies applied SA methods in different areas of engineering (Karaoğlu and Secgin 2008; Amidpour et al. 2015; Mazo et al. 2015; Pastore et al. 2015). However, SA on machine tool selection and manufacturing area has received less attention from the researchers. From the above it can be concluded although there are some publications on economic analysis of manufacturing processes; sensitivity analysis has not yet been adequately addressed in these publications for justifying machine tool selection.

This paper focuses on using sensitivity analysis to provide recommendations for decision making on utilizing SPMs. Important issues addressed in this paper are developing an economic model of production with SPMs, identifying critical independent variables, and applying SA to the economic model.

2. Application of SA in the justification of utilization of SPMs

The SA method is widely used when the input parameters of a mathematical model are uncertain. Since sufficient reliable information is not available for decision making of utilizing SPMs at the initial stage, calculations and estimations of the economic factors are subject to uncertainties (see Section 2.2). This is one of the primary reasons why SA is necessary for justifying the utilization of SPMs from an economic perspective. Fig. 1 shows the scheme of performing SA of utilizing SPMs versus other alternatives. First, all the independent variables are identified in the developed model. Some of these variables naturally change over time and some may be estimated incorrectly. Accordingly, based on the engineering knowledge and production life cycle requirements appropriate threshold for each identified uncertain variable are defined. Then, by estimating the sensitivity index (Section 2.1) effective variables are identified which are required for further evaluation. Section 3 presents a case study in detail which clarify the methodology.

2.1 Sensitivity analysis method

Generally, SA investigates how the input variables influence the output of a mathematical model or system. A common SA method is to repeatedly change one independent variable by a given percentage while leaving all other variables fixed and observing the behaviour of the model. This type of SA is referred to as a "local sensitivity analysis" (Hamby, 1994) or one-at-a-time (OAT) technique (Campbell et al., 2008). OAT is a popular technique to investigate the effect of one parameter on an economic function that the modellers can immediately find out which input parameter is responsible for the uncertainty. Furthermore, OAT enhances the comparability of the outcomes. Therefore, this technique may be a useful tool for monitoring the behaviour of an SPM and other alternatives simultaneously for each input parameter. This approach assists decision makers to find the optimum machine tool under different circumstances.

OAT involves taking the partial derivative of a function (F) of several input variables with respect to an input parameter ($x = \{x_1, \dots, x_n\}$) (Cacuci, Ionescu-Bujor, and Navon 2005)

$$\left| \frac{\partial F}{\partial x} \right|_{x^*} \qquad (1)$$

where x^* denotes the derivative taken at some fixed point in the input space.

As the information generated by performing SA can be voluminous the modeller should summarize the results to facilitate decision making process. Hence, sensitive and important parameters should be identified. To do so, the sensitivity index method can provide appropriate vision of variables and model variability and can be calculated by

$$SI = \frac{F(x)_{max} - F(x)_{min}}{F(x)_{max}} \tag{2}$$

where $F(x)_{max}$ and $F(x)_{min}$ are the maximum and minimum output values of the model, respectively, resulting from changing the independent variable over its range (Hamby 1994).

2.2 Development of economic function of utilizing SPMs

Vafadar, Tolouei-Rad, and Hayward (2016) proposed a cost model of utilizing SPMs and other machine tools. This cost model is utilized to develop a sensitivity analysis model which includes several dependent variables $f(x)$, and several independent variables $x = (x_1, \ldots, x_n)$. For the sensitivity analysis model developed below, the following assumptions are specified:

- Annual demand, scrap rate, availability of machine tool, machining time, labour rate, operator fault rate, maintenance coefficient, sale price, and overhead rate are considered as independent uncertain variables.
- Unit profit is considered as the main dependent variable.
- This model can be utilized for justification of different machine tools.
- Based on the market demand, the thresholds of independent variables may differ.
- This model can be extended for the case a part or family parts are required to be produced.
- The model can be utilized for all machine tools and SPM configurations, the only difference is the calculation of machining time which is dependent on the designed layout of the SPM or utilizing multiple spindle heads on the available machine tools.

- This research does not address the calculation of machining time. But it should be noted that the number and order of machining operations may affect the dependency of variables.
- The rational structure of the machining process of SPM (and its layout) can be varied depending on demand. Moreover, the designed layout can be designed for a family of products. In this case, it is assumed the designed SPM remains constant regardless of demand variations.
- Machining time is the sum of cutting, tool changing, loading/unloading, adjustment, and free travelling times for all machine tools. All these times are independent variables which have less effect on the output than machining time. Accordingly, in this study machining time is regarded as an uncertain independent variable.

The developed sensitivity analysis model includes following equations for analysing the sensitivity of utilization SPMs versus other alternatives under uncertainty, which cost factors are described as follows:

(1) Material cost: Total material cost for each production year can be estimated by

$$f_1(x) = C_1 \, f_2(x) \tag{3}$$

where annual demand can be estimated by

$$f_2(x) = \frac{x_1}{1 - x_2} \tag{4}$$

where scrap rate is an independent variable and is defined as the proportion of defective machined products. This variable depends on the type of machine tool and usually decreases slightly from the conventional machines to CNC and SPM.

(2) Machine tool cost: Total machine tool cost includes the number of required machine tools which can be calculated by the following equations and the cost of machine tool unit.

$$f_3(x) = \frac{60 \, x_3}{100 \, x_4} \tag{5}$$

$$f_4(x) = roundup(\frac{f_2(x)}{C_2\, f_3(x)}) \tag{6}$$

$$f_5(x) = C_3\, f_4(x) \tag{7}$$

where availability is the percentage of time period that the machine tool is available for use.

(3) Machining cost: Total machining cost per year is the sum of total machining operation cost and total tooling cost as below

$$f_6(x) = \frac{f_2(x)\, x_4\, x_5}{60} \tag{8}$$

$$f_7(x) = f_2(x)\ (1 + x_6) \sum_{k=1}^{C_4} ((\frac{x_7}{f_8(x)})_k C_{5_k} C_{6_k}) \tag{9}$$

$$f_8(x) = \sqrt[n]{\frac{C}{x_8}} \tag{10}$$

$$f_9(x) = f_6(x) + f_7(x) \tag{11}$$

where the constant values C_5 and C_6 considers the number of spindles per head, the cost of tools of each head, respectively, and x_6 also refers to operator fault rate which takes into account tool failures. It should be noted that Taylor exponent (C) and tool life constant (n) are defined by Groover (2014).

(4) Maintenance cost: Total maintenance cost per year can be estimated by the following equation and is defined as the percentage of machining operation cost (Campbell and Reyes-Picknell 2015).

$$f_{10}(x) = \frac{x_9\, f_6(x)}{100} \tag{12}$$

(5) Overhead cost: Total overhead cost per year can be estimated by the following equation. This cost factor does not include a particular expenditure and considers heating, rent, lighting, and so on.

$$f_{11}(x) = \frac{f_2(x)\, x_4\, x_{10}\, (1 + x_9)}{60} \tag{13}$$

(6) Salvage value: This item is defined as the value of machine tool at the end of its useful life. It can be estimated by a defined percentage of the machine tool price as below

$$f_{12}(x) = 0.01\, C_7\, f_5(x) \tag{14}$$

The above cost items are used to develop an economic indicator as a decision support tool for justifying the utilization of SPMs. Initially, it is required to calculate the total production cost at present time as below

$$f_{13}(x) = f_5(x) + \sum_{j=1}^{C_9}(1+i)^{-j}\,(f_1(x)_j + f_9(x)_j + f_{10}(x)_j + f_{11}(x)_j) - C_8 f_{12}(x) \tag{15}$$

where the constant value can be calculated by the following equations.

$$C_8 = (1+i)^{-C_9} \tag{16}$$

Unit profit is the main dependent variable which is estimated by sales minus total production cost (Hitomi 1996) and is given by

$$F(x) = \frac{\sum_{j=1}^{C_9}(1+i)^{-j}\; x_{11\,j} x_1 - f_{13}(x)}{x_1\, C_9} \tag{17}$$

3. Case study

An SA approach is applied for justification of utilizing SPMs for production of an automotive part (Fig. 2) versus CNC and conventional machine tool. Table 1 represents the properties of the part to be drilled. In Fig. 2 it can be seen that holes are divided into different groups where similar holes can be drilled with one multiple spindle head. Production information for manufacturing this part with SPM, CNC, and conventional machine tools as presented in Table 2. Fig. 3 shows the SPM designed for drilling the automotive part. The configuration of this machine includes six stations; four for drilling operations and two for loading and unloading activities. The SPM consists of different type of machining units and spindle heads, an indexing table and other accessories.

Based on Fig.1 independent variables are identified in the economic model. Then, for making a reasonable comparison the same thresholds for each variable for all identified alternatives are considered. Since machining time of machine tools is different, the same percentage of machining time is considered (Table 3). A sensitivity index for each individual variable is then calculated as shown in Table 3. Finally, input vectors are generated for sensitive variables and sensitivity analysis is performed for six sensitive variables, as explained in the following sections.

4. Results and discussion

In this section detailed OAT is conducted on the identified sensitive variables to represent the potential benefits and limitations of utilizing SPMs versus other alternatives. Following items explain the result of SA for five sensitive variables which are selected based on Table 3 also extracted from the manufacturer's catalogue (Suhner general catalogue 2012).

4.1 Demand

Demand variable substantially influences the economic justification for choosing a machine tool and may change over time due to market influences. Accordingly, analysis of the sensitivity of machines tools to demand changes is required. This study assists the decision making process by considering the profit and loss of production which may rise by changing demand over the production time. Fig. 4 shows the sensitivity of each individual alternative for demand changes. It can be seen that there are four points in these graphs which should be considered when justifying the use of each machine tool.

Fig. 4 shows that conventional machine provides greater unit profit than both CNC and SPM until demand graphs reach Point 1. Prior to this point the machine tool cost and consequently total cost of conventional are less than both CNC and SPM. Accordingly, the unit profit of conventional machine is considerably greater than other alternatives. Point 1 also indicates that the unit profit of CNC exceeds that of SPM and conventional machine for 5,000 units and demand of less than 6,000 units, respectively. At this point, the number of required conventional machines, CNCs, and SPMs is still one. Since total cost of CNC is less than other alternatives, the unit profit of CNC is greater than SPM and conventional machine. Therefore, for lower demand the utilization of SPM is not recommended. For this level of demand conventional machine and CNC provide greater profits, respectively.

Point 2 shows that the unit profit of SPM overtakes that of both CNC and conventional machines above 6,000 units. To produce this part six stations are considered and one of the stations is the bottleneck which has the maximum operating time. This time is considered as the machining time of SPM which in this case it is less than that of CNC and conventional machines. In addition, SPM and CNC machining operations are parallel and sequential, respectively. Accordingly, machining time of SPM is less than that of CNC. Since machining and maintenance costs are the functions of machining time, as demand increases machining time is dominant in the cost model. Accordingly, the unit profit of SPM overtakes that of other alternatives.

As the unit profit is also a function of the number of required machines, when demand exceeds 31,000 units, the number of required conventional machines increases from 1 to 2 (see point 3). Point 4 also indicates that when demand reaches 58,000 units the number of requires CNCs increases from 1 to 2. In this case, the machine tool cost increases considerably whereas the salvage value increases slightly and other costs increase with the same ratio; therefore, the unit profit drops. The curves show that for larger demands SPM results in greater unit profit and savings. In this case, the utilization of SPM is recommended.

Fig. 5 shows that the unit profit versus demand behaves as a saw-tooth function. Each sharp drop indicates a point where another machine tool is required. The two following properties of this function can provide additional information for the decision making process especially for cross-over points (Point 2 of Fig.4 is discussed further in Section 4.7). The following should be noted:

(a) Saw-tooth frequency goes upward and then drops sharply. This is determined by Eq. 6 which is dependent on scrap rate, availability, and machining time as below

$$f_{st}(x) \propto \; x_2 , x_3^{-1}, x_4 \qquad (18)$$

where decreasing availability boosts frequency. Conversely, decreasing scrap rate and machining time reduce saw-tooth frequency.

(b) Unit profit range contains upper and lower bounds of the unit profit of a machine tool. This is determined by Eqs. 5, 6, 8, and 12 which are dependent on scrap rate, availability, machining time, labour rate, maintenance coefficient, sale price, and overhead rate as below

$$f_{upr}(x) \, \alpha \;\; x_2^{-1}, x_3 , x_4^{-1}, x_5^{-1}, \; x_9^{-1}, x_{10}^{-1}, x_{11} \qquad (19)$$

where decreasing scrap rate, machining time, labour rate, maintenance coefficient, and overhead rate increase unit profit range. Conversely, increasing availability and sale price boosts it.

Table 4 shows that the saw-tooth frequency of SPM is lower than CNC and conventional machines, respectively. Clearly, more stable performance can be provided by SPM. Furthermore, the saw-tooth frequency period for all machine tools remains constant (Fig. 5). These issues assist in finding critical demands which require more investigation for machine tool selection. Table 4 also represents that the maximum achieved unit profit of SPM is larger than that of CNC and conventional, respectively. Therefore, when a high unit profit is required, SPM may be an appropriate choice as long as the requested demand is high.

Fig. 5a indicates the ceiling unit profit points of SPM are the same, whereas by increasing demand the flooring points are enhanced with a constant slope. The reason is that by increasing the number of required machines boosts the salvage value and consequently the value of flooring points increases (Eq. 15). Fig. 5b shows that the value of ceiling points of CNC increase with higher demand. By increasing demand, the number of required machines and machine tool, machining, maintenance, overhead, and material costs increase; however sales and salvage value increase more than the costs (Eq. 15).

Fig. 5c indicates ceiling points are decreasing for conventional machine. This performance continues until the unit profit again approaches the maximum unit profit line. The reason for this behaviour is that increasing demand boosts the costs; however the increase in sales plus salvage value is less than the costs (Eq. 15). Therefore, the value of ceiling points decreases and when the ceiling point reaches close to the maximum unit profit line the increase of sales plus salvage value is more than the costs.

It can also be seen in Figs. 5b and c that the value of flooring points increases. The reason is that, by increasing demand, the costs and sales increase with a constant ratio except salvage value which increases with different rate. Indeed, by increasing the number of machine tools salvage value increases remarkably.

As presented in Table 4, the maximum unit profit of SPM can be achieved for several demands whereas CNC and conventional machines only exhibit it once. The maximum unit profit of CNC and conventional machines can be achieved in high demands (Table 4) although it is still less than that of SPM (Fig. 5). Table 4 also provides the number of produced parts per hour for maximum unit profit. The other important issue is that the unit profit range of CNC is larger than for SPM and conventional machines. Clearly, CNC has more flexibility than other alternatives and can cover a wider unit profit range than other alternatives while SPM has better performance as long as demand increases.

4.2 Machining time

In the early stage of utilizing a machine tool, accurate estimation of machining time is difficult since reliable and sufficient data is not available. Machining time substantially influences the economic performance of the machine tool and should be subjected to sensitivity analysis. Fig. 6 shows the sensitivity analysis results for SPM, CNC and conventional machines for machining time changes from -30% to 30%. It should be noted that for performing this analysis, demand was set at 100,000 units. For this demand SPM outperforms CNC and conventional machines and its unit profit is much less sensitive and stable than other alternatives.

Fig. 6 also shows that increasing the machining time reduces the unit profit of CNC. It can be observed a non-linearity for the CNC at 22%. Which is due to the increase in the required number of machine tools. The reason is that, some costs such as machining, overhead and downtime increase while salvage value and machine tool cost remain the same (see Eq. 15). It can be seen that when machining time increases by 15% there is a decline because as the number of machine tools increases (see Eqs. 5 and 6), costs increase remarkably whereas salvage value increases slightly. After this decline, the unit profit continues to decrease for CNC; because, machining, maintenance, and overhead costs increase slightly while salvage value and machine tool costs are unchanged.

It can be also seen that conventional machine's unit profit exhibits an overall strong decline as machining time changes. Because, machining and maintenance costs are the functions of machining time; accordingly, by increasing machining time these costs increase and consequently the unit profit decreases. It should be noted that non-linearity may occur when the number of required machine tools changes; however, in the defined thresholds the number of required conventional machine tools remains constant. It can be concluded that as machining time increases, the unit profit decreases for all alternatives. In addition, sensitivity of SPM is less than CNC and conventional machine, respectively. Indeed, the estimation of unit profit of SPM is not significantly affected by machining time underestimation or overestimation and decision making of utilizing SPM is more reliable.

4.3 Labour rate

The labour rate depends on factors such as production period, place of production, machine tool type, and the skill level required. Indeed, the qualification of machine operators and their relevant salaries changes for different machine tool types. Increasing and decreasing labour rates may strongly influence the economic performance of different machine tools. Therefore, machine tool performance should be assessed for a range of labour rates. Fig. 7 shows the sensitivity analysis for different labour rates. In this study, labour rate is considered constant for all skills but in reality SPM requires low skilled labour comparing to CNC and SPM, respectively. When labour rate changes from \$10 to \$40 per hour, the unit profit for SPM decreases much less than for CNC and conventional machine, respectively. Machining and maintenance costs are the function of the labour rate and the coefficient of labour rate in the equations of these costs is the function of machining time (see Eqs. 8 and 12). Therefore, when the coefficient of labour rate is greater, the sensitivity for that machine tool is higher. Since conventional machine and SPM have maximum and minimum machining time for this case, conventional machine and SPM are the most and least sensitive to labour rate changes, respectively.

4.4 Sale price

Due to competitive markets and the need to enhance profitability, manufacturing companies must estimate a suitable sale price. Pricing the product is a major profit driver and is related to many parameters. Therefore, machine tool performance should be studied under different sale prices for the product. Fig. 8 shows the sensitivity analysis of the sale price for three machine tools. If the sale price changes by the same ratio when SPM, CNC, and conventional machines are used, the unit profit curves increase with a constant slope and SPM generates a greater profit at this demand (100,000 units).

4.5 Overhead rate

Overhead rate includes the costs which are not directly related to part production and is usually difficult to precisely estimate for each production process. Furthermore, the overhead rate usually differs for long term production. However, as increasing or decreasing the overhead rate may considerably affect the economic performance of different machine tools and should be assessed. Overhead cost is a function of overhead rate (see Eq. 14). For greater machining and maintenance times, overhead cost is more sensitive to the overhead rate changes. As Fig. 9 shows, conventional machines are more sensitive to overhead rate changes and make greater difference in the unit profit because the sum of machining and maintenance times is higher than for CNC and SPM. Accordingly, since the sum of machining and maintenance times of SPM is lower than the other machines, it is less sensitive to the overhead rate variation. Therefore, SPM outperforms CNC and conventional machines versus overhead rate changes for the set demand (100,000 units).

4.6 Effective variables

Clearly, three variables, overhead rate, machining time, and annual demand strongly influence the economic performance of machine tools. To provide a greater insight and facilitate logical decisions these variables are evaluated versus annual demand changes. To do so, OAT is applied to investigate each of these variables and then the results are utilized to create the figures which show the effect of two variables on the unit profit simultaneously. Moreover, this process assist manufacturer to observe interactions between the input variables and possible non-linearity behaviours of variables which may influence the economic output and final decision. Discontinuities are a function primarily of demand which is why this is always an axis.

Figs. 10 and 11 present sensitivity analysis graphs that highlight the optimum combinations for each alternative. Two-dimensional graphs are provided to clarify three-dimensional graphs. For this purpose, two curves, for machining time changes in a1, b1, and c1 of Fig. 10 and overhead rate changes in a1, b1, and c1 of Fig. 11 versus demand changes, are used. Three-dimensional graphs are also used in a2, b2, and c2 of Figs. 10 and 11 to provide more information for decision makers. The surfaces of these graphs show unit profit areas when two variables change simultaneously. The range of variables which meet the desired unit profit can also be extracted from these figures. Furthermore, some curves and areas, which may exist in the performance graph of each machine tool, should be considered in the decision making process but cannot be presented in two-dimensional graphs.

Fig. 10a shows that by increasing demand and decreasing machining time the unit profit of SPM progressively increases. Since the machining time of SPM is less than CNC and conventional, machining time changes do not strongly affect the economic performance of SPM. Conversely, CNC has an unstable and different performance response to demand and machining time changes. For example, when demand changes between 40,000 to 85,000 units and machining time changes between -30% to -20% CNC has a better performance (Fig. 10b). The best result can be achieved when demand is 85,000 units and machining time change is -30%. Fig. 10b also shows that CNC provides reasonable profits and stable performance for 55,000 and 75,000 units while machining time changes from -30% to 30%. The reason for this unstable performance is that unit profit depends on the number of required machines which is a function of demand and machining time (see Eqs. 4, 5, and 6). By increasing machining time the unit profit decreases whereas increasing demand boosts unit profit. Furthermore, the machining time of CNC is greater than SPM and capital investment required for CNC is relatively high. Therefore, by increasing and decreasing the number of machines the unit profit of CNC changes greatly. Fig. 10c shows that the unit profit of conventional machine increases remarkably when the underestimation of machining time is increased. It can also be seen that increasing demand for conventional does not strongly affect unit profit.

Fig. 11 shows the sensitivity analysis for demand and overhead rate. SPM provides a stable performance that improves for larger demand and lower overhead rate (Fig. 11a). CNC has a different performance for different overhead rates and demands (Fig.11 b). The most unit profit may be achieved when the demand changes between

45,000 to 55,000 units and lower overhead rates (1 to 10 $/hour). This unstable behaviour occurs because of the changing number of required CNC which is related to the demand (see Eqs. 4 and 6) and overhead cost which is a function of overhead rate (see Eq. 13). It can also be seen that the conventional machine gives better results for lower overhead rates (1 to 15 $/hour). The reason is that, by decreasing overhead rates the overhead cost decreases and consequently the unit profit increases.

4.7 SPM versus other alternatives

The above analysis indicates that conventional machine is suitable for a low volume of production where it can provide greater profit than the other alternatives but it requires many machines for larger demands. Because of machining time SPM is not sensitive to labour rate and accordingly it provides a stable behaviour for high demand whereas CNC is somewhere between the two other alternatives and provides. Accordingly, for higher demands the decision to use SPM or CNC under uncertainty requires more investigation.

Figs. 10 and 11 provide additional information for machine tool selection. Figs. 10b1 and c1 indicate that increasing machining time strongly boosts the saw-tooth frequency of CNC and conventional machines and decreases the unit profit range of CNC, and conventional machines. These issues should be considered in the decision making process especially for crossover points. Point 3 of Fig. 4 is a crossover point which requires more investigation for CNC or SPM. Figs. 10b2 and c2 show that increasing machining time boosts the saw-tooth frequency period of CNC and conventional machine tools, respectively, which will influence the final decision. It should also be noted that by increasing the number of required machine tools more space factory is required. This issue may be a limitation and should be also considered in decision making process.

Figs. 11 b1 and c1 show that overhead rate change does not influence the saw-tooth frequency. Moreover, by decreasing overhead rate the unit profit range of CNC and conventional machines increases whereas it does not considerably influence the unit profit range of SPM (Fig.11a1). Therefore, for lower overhead rates, the unit profit of CNC may overtake that of SPM and provide greater unit profit. Figs. 11a2 and b2 show that the unit profit of CNC may overtake that of SPM for lower overhead rates. Indeed, by decreasing overhead rates the unit profit of SPM increases slightly whereas CNC increases strongly and may generate higher unit profit than SPM. Generally SPM provides more profit than CNC for the considered demand and may be a better selection especially for greater overhead rates. However, CNC may be an appropriate selection low overhead rate can be assured.

5. Conclusion

This paper studied the benefits and limitations, of utilization SPMs versus other alternatives in the presence of uncertainty by performing sensitivity analysis. This strategy evaluates the influence of uncertain inputs on the economic performance of SPM and provides a comprehensive understanding of the relationship between input variables and model's output.

In this study an economic mathematical model of performing SA on selecting SPMs is presented. The model is developed based on the independent input variables and dependent output variables. The model was subjected to OAT to analyze the effect of all individual independent variables on the developed economic function once at a time while, holding the other variables constant. The analysis has been successfully performed for an automotive part presented in this paper. Results show that in this case SPM is less sensitive than other alternatives in the presence of uncertainty. Moreover, for lower demands conventional and CNC are more appropriate than SPM. While for larger demands SPM usually provides better results than two other alternatives. However, this comparison can be applied for other machine tools and may result in different conclusions. Accordingly, to justify of decision making of utilizing a machine tool versus other alternatives SA should be performed. From the above it can be concluded that SPM can be better than other machine tools may be not. To generalize the model more case studies can be studied for future works.

Results show that demand is an important and sensitive variable which should be carefully evaluated in the decision making process before applying SA on the other variables. It can be concluded that generally for lower demands conventional and CNC are more appropriate than SPM. While for larger demands SPM usually provides better results than other alternatives. Preforming SA for other variables on a defined range of demand may provide more comprehensive and accurate information for decision making.

This model can be extended by considering industrial limitations and relevant constraints based on the production and organization limitations. In this study the variables are considered as independent. This a basis for future work where the independence is not assumed. The model can also be improved by fully exploring the input space of variables and considering the input changes of different variables simultaneously. Furthermore, potential interactions between input variables may be another source of uncertainty which can be studied. Moreover, this model can be extended to be used for a family of similar parts. Applying SA to the economic model of utilizing SPM will assist companies to have a better understanding of the benefits and limitations of SPM and other available alternatives. It should also assist with practical and logical decision making under uncertainty at the early stages of design and manufacturing of SPMs.

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(Suhner general catalogue 2012; Stamatopoulos 2012)

("ROMHELD AUTOMATION")

(Bethel 2006)

(Groover 2014)

(HSS Forum 2014)

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