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New cost model for feasibility analysis of utilizing special purpose machine tools

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Special purpose machine tools (SPMs) have been widely used to perform drilling-related operations in high volume production including within automotive component industries. The first step in designing and manufacturing a SPM is a feasibility analysis. Since SPMs have relatively higher investment cost than other machine tools, this task must be performed before any investment on the preparation of detailed design. The present paper explores an economic feasibility analysis strategy which aims to make logical decision by assessing the strengths and limitations of an SPM in comparison with other machine tools. The mathematical product cost model for SPMs is proposed for estimating important economic factors and then financial indicators are calculated to evaluate the SPM's economic performance. A case study is used to examine the proposed model and results are compared with other machine tools. The proposed model provides a decision support approach for selecting an SPM for manufacturing a given part from an economic perspective.

Keywords: Cost estimating; Machine selection; Life cycle costing; Special purpose machines; Economic feasibility analysis

1. Introduction

Today's competitive environment has led many industries to utilize advanced machine tools to meet the current and future requirements of manufacturing systems and market demands (ElMaraghy 2006). Youssef, El-Hofy, and Ahmed (2011) classified machine tools into two major categories: special purpose machine tools (SPMs) and general purpose machine tools (GPMs). SPMs are specially designed and manufactured for the particular machining operations and the manufacturer only pays for the required

capability. Whereas, GPMs are typically not designed for a set defined of machining operations. GPMs may involve additional unrequired capabilities and greater uncertainty over whether machine requirements will be met.

Some SPMs may have limited re-configurability and such machines consist of a set of machining and sliding units and accessories (Figure 1). The re-configurability character allows these machines to manufacture a number of similar products by rearranging the positions of units and accessories. Hence SPMs are useful however they impose high investment costs. Several publications deal with reconfigurable machine tools (Bensmaine, Dahane, and Benyoucef 2014; Gwangwava et al. 2014), but few address SPMs. Moreover studies of reconfigurable machine tools mainly focus on milling (Azulay, Mills, and Benhabib 2014; Aguilar, Roman-Flores, and Huegel 2013), rather than drilling.

While SPMs are often superior to GPMs in the case of high volume production, the extent of utilization of these machines is not proportional to the potential benefits. Few research publications have been focused on the utilization SPMs in manufacturing. Tolouei-Rad (2011) proposed a Knowledge-based (KB) system for analysing utilizing SPMs when dealing with qualitative and quantitative information. Tolouei-Rad and Zolfaghari (2009) introduced SPMs and the relevant components and proposed a method for improving productivity with SPMs. There is a need for better feasibility analysis, particularly from an economic perspective.

Selecting the most appropriate machine tool from among available machine tools is a difficult decision making process for companies (Yurdakul et al. 2013). Improper machine tool selection may reduce productivity and cause many problems (Quintana and Ciurana 2011). A key challenge in initial decision making is the lack of reliable information for SPM and other machine tool alternatives and access to an expert

with considerable knowledge of SPM properties. The selection of manufacturing systems and machine tools has been investigated from different points of view. For example Chan et al. (2001) categorized justification methodologies of manufacturing selection into three main groups: analytic, strategic and economic. A majority of researchers rely on the application of analytical methods such as the analytical hierarchy process (AHP) (Ic, Yurdakul, and Eraslan 2012; Abdi and Labib 2003), technique for order of preference by similarity to ideal solution (TOPSIS) (Ayağ and Gürcan Özdemir 2012), integrated linguistic multi decision making method (Xue et al. 2016), fuzzy ranking method (Abdi 2009; Singh, Khilwani, and Tiwari 2007) and a hybrid of the ranking methods (Samvedi, Jain, and Chan 2012). Several strategic methods have been applied in manufacturing research. Some of them applied expert systems (ES) for machine tool evaluation problem to consider qualitative factors (Battaïa et al. 2013; Guldogan 2010). Vafadar et al. (2016) proposed a strategic method for performing the technical feasibility analysis of utilizing SPMs and selecting efficient SPM components. The technical analysis framework is based on the relations between the part and SPM components, captured as rules and constraints, in an intelligent system. Several studies focused on economic feasibility analysis as an effective and accepted assessment tool for selecting suitable machine tools. Specially, Klocke et al. (2013) compared face milling versus surface grinding by considering the cost of machine depreciation, labour and consumable items such as cutting tools. Quintana and Ciurana (2011) developed a cost estimation method, for utilizing vertical high speed machining centres which is based on multiple regression analyses. Klocke et al. (2013) performed a cost analysis, for utilizing unconventional manufacturing systems such as electro discharge machining (EDM) and electrochemical machining (ECM) technologies, based on material removal rate for rough milling of titanium- and nickel-based alloys. From the above it can be

concluded that there are some publications on economic analysis of manufacturing processes; yet SPM has not been adequately addressed in these publications.

This paper provides an economic feasibility analysis strategy to support companies when deciding whether to utilize SPM for special production purposes. Important issues addressed in this work are building a cost estimation model for SPMs, based on the part and SPM characteristics and production requirements. Critical effective factors are determined and relevant mathematical models are developed. Applying the proposed model would be useful for decision makers at the early stages of designing SPMs.

2. Mathematical cost model development

Identified critical factors and developed mathematical models are explained below.

Nomenclature

A	Approach allowance (*mm*)
a	Availability of machine tool (*%*)
C	Constant value
C_{ac}	All costs related to accessories such as rotary indexing table and control unit (*$*)
$C_{downtime}$	Cost of annual production losses (*$/year*)
C_{fix}	Fixturing costs (*$*)
C_{ic}	Installation and commissioning costs (*$*)
C_l	labour cost (*$/hour*)
C_m	Annual machining operation cost (*$/year*)
$C_{machining}$	Annual machining cost (*$/year*)
$C_{maintenance}$	Annual maintenance cost (*$/year*)
C_{mat}	Cost of material unit before processing (*$*)
$C_{material}$	Annual material cost (*$/year*)
C_{mt}	Machine tool investment cost (*$*)
C_{mu}	Cost of required machining units (*$*)
C_o	Hour overhead cost (*$/hour*)
$C_{overhead}$	Annual overhead cost (*$/year*)
C_{su}	Cost of the required sliding units (*$*)
C_t	Annual tool cost (*$/year*)
C_{total}	Total life cycle production cost (*$*)
c_t	Cost of each tool of the spindle head (*$*)
D	Annual production volume
D_h	Hole diameter (*mm*)
d	length of cut (*mm*)
FV	Future value

f	Feedrate (*mm/min*)
H	Average working hours per year
i	Annual interest rate
j	Year of operation or production
k	Index of utilized drilling heads
m	Number of work-stations
N_d	Number of drilling heads
N_m	Number of required machine tools
N_{nso}	Number of sequential operation groups of single-station SPM
N'_{nso}	Number of sequential operation groups of multi-station SPM
N_p	Number of produced parts per hour
N_s	Number of spindles per drilling head
N_{so}	Number of cutting tools that perform a single operation or multiple operations in each sequential group of single-station SPM
N'_{so}	Number of cutting tools that perform a single operation or simultaneous operations in each group per station of multi-station SPM
N_t	Tool consumption per part
n	Taylor's tool life exponent
n'	Number of setups of single-station
o	Index of cutting tool performing a single operation or multiple operations in each sequential group
PV	Present value
p	Index of the sequential operation groups of single-station SPM
p'	Index of the sequential operation groups of multi-station SPM
q	Scarp rate
S	Salvage value (*$*)
S_p	Sale price of the product (*$*)
T	Tool life for cutting tools of each drilling head (*min*)
T_c	Longest cutting time of all work-stations (*min*)
$T_c(w)$	Longest cutting time of each work-station (*min*)
$T_c(u)$	Cutting time of each setup (*min*)
T_f	Free tool travelling time (*min*)
T_i	Indexing time (*min*)
$T_{L/U}$	Loading and unloading time (*min*)
T_m	Machining time (*min*)
T_{mo}	Maintenance time (*min*)
T_s	Setup time (*min*)
T_{tc}	Total tool changing time per part (*min*)
t	Number of production years
t_c	Cutting time for each drilling head per part (*min*)
$t_{c_p}(o)$	Cutting time for each of sequential operation groups of single-station SPM (*min*)
$t_{c_{p'}}(o)$	Cutting time for sequential operation groups of multi-station SPM (*min*)
t_{tc}	Tool changing time for each cutting tool of the spindle head
u	Index of setup of single-station ($u = 1, \dots, n'$)
v	Cutting speed (*mm/min*)
w	Index of work-station
α	Operator fault rate
β	Maintenance coefficient (%)
φ	Salvage coefficient (%)

2.1 Time factors

The following items describe effective time factors and their mathematical equations. All time components given in this section are measured in minutes.

(1) Cutting time

Groover (2014) proposed the following equation for calculating the cutting time of one hole which has also been used in this work.

$$t_c = \frac{\pi D_h (d + A)}{vf} \tag{1}$$

where approach allowance represents the distance that the drill must be fed into the part before reaching full diameter.

Based on the above equation the cutting time for single-station or multi-station operations can be calculated as below.

A single-station SPM consists of n' setups and each setup may include one or more operations that will be performed simultaneously or sequentially. Therefore the cutting time of each setup and total cutting time can be calculated by the following equations, respectively.

$$T_c(u) = \sum_{p=1}^{N_{nso}} max\left\{t_{c_p}(o)\middle|o = 1, \dots, N_{so}\right\} \tag{2}$$

$$T_c = \sum_{u=1}^{n'} T_c(u) \tag{3}$$

Sometimes, multiple spindle heads can be used, and in this equation, they are treated as a single tool. Total cutting time of multi-setup can be calculated as below.

A multi-station SPM consists of rotary or sliding indexing tables and includes m work-stations and each work-station may include one or more operations performed simultaneously or sequentially. Since all the stations of this table perform operations simultaneously, the longest cutting time of each the work-stations will be considered in

the machining time calculation. The longest cutting time of each work-station can be calculated by

$$T_c(w) = \sum_{p'=1}^{N'_{nso}} max\left\{t_{c_{p'}}(o)\middle| o = 1, \dots, N'_{so}\right\} \tag{4}$$

Sometimes multiple spindle heads can be used and in this equation they are treated as a single tool.

The longest cutting time of all the work-stations can be calculated by

$$T_c = max\{T_c(w)\,|\,w = 1, \dots, m\} \tag{5}$$

(2) Indexing time

Single-station SPM may include one or more setups. Rotary and sliding indexing tables can provide indexing for multi-station SPMs. A rotary indexing table includes processing and loading/unloading stations. Often one of the stations is allocated for loading/unloading (*L/U*) (Figure 2(b)). Since all the stations process the part simultaneously, only one indexing time is required for calculating the machining time. Sliding indexing tables include processing, loading/unloading stations. In the example shown in Figure 2(b) one of the stations is allocated for loading and other for unloading. For both sliding and rotary SPMs, all the stations perform the required operations simultaneously; thus only one indexing time is required for calculating the machining time.

(3) Tool changing time

Total tool changing time per part can be calculated by

$$T_{tc} = \sum_{k=1}^{N_d} N_{t_k} N_{s_k}\ t_{tc_k} \tag{6}$$

where tool consumption calculation is explained in Eq. (18).

(4) Machining time

This section describes the calculation of required time to machine each part using single- and multi-station SPMs, computer numerical control (CNC) machine, and human-operated drill press which for simplicity is referred to drill press.

All the required functions in a single-station SPM, such as loading, machining, setup and unloading, will be performed sequentially. Thus, the machining time can be calculated by

$$T_m = T_c + T_i + T_{tc} + T_{L/U} + T_f + T_s \tag{7}$$

Since several spindle heads can be utilized sequentially for a machining unit, setup time for changing all spindle heads should be considered in the machining time calculation.

Multi-station SPMs can perform loading, unloading and machining operations simultaneously in different work-stations. Therefore, only the maximum longest time component will be considered in the machining time calculation.

If loading and unloading are performed in one station while remaining work-stations perform machining operations, the machining time equation becomes

$$T_m = max\{T_c + T_f, T_{L/U}\} + T_{tc} + T_i \tag{8}$$

If loading and unloading are performed in the two separate stations while the rest of work-stations perform machining operations, then the machining time equation becomes

$$T_m = max\{T_c + T_f, T_L, T_U\} + T_{tc} + T_i \tag{9}$$

The machining time for producing the part with CNC and human-operated drill press can be calculated by the following equation.

$$T_m = T_c + T_{tc} + T_{L/U} + T_f \tag{10}$$

2.2 *Cost factors*

The following items describe effective cost factors and their mathematical models which are based on the equations introduced by Tolouei-Rad (2012).

(1) Material Cost

Material cost includes the cost of raw material plus added values of associated prior processing operations. Annual material cost can be estimated by

$$C_{material} = \frac{D\ C_{mat}}{1-q} \tag{11}$$

where scarp rate refers to the proportion of defective produced parts.

(2) Machine tools' cost

This is the capital investment cost which includes the number of required SPMs and the cost of one SPM configuration including components as below

$$C_{mt} = N_m(C_{mu} + C_{su} + C_{fix} + C_{ac} + C_{ic}) \tag{12}$$

The number of required machine tools can be estimated by

$$N_m = Roundup\left(\frac{D}{N_p H\ (1-q)}\right) \tag{13}$$

where the number of produced parts per hour can be calculated by

$$N_p = \frac{60\ \times\ a}{100 \times T_m} \tag{14}$$

where the machining time in minutes is explained in Subsection 2.1, and the availability of machine tool is the percentage of scheduled time which the machine tool is available for production.

(3) Machining cost

Annual machining cost is the most critical element which includes annual machining operation cost and annual tool cost as below

$$C_{machining} = C_t + C_m \tag{15}$$

Machining operation cost is the cost of the time the operator spends loading, unloading, or monitoring cutting processes of bottle neck, tool changing, and waiting to index the rotary table to receive the part for loading and unloading purposes. This cost component can be estimated by the following equation per year.

$$C_m = \frac{D\ T_m C_l}{60 \times (1-q)} \tag{16}$$

where the labour cost covers the cost of operation, tool changing, part handling, loading, and unloading. Annual tooling cost is the cost of consumed tools per year and is given by

$$C_t = \frac{D\ (1+\alpha)}{1-q} \sum_{k=1}^{N_d} N_{t_k} N_{s_k}\ c_{t_k} \tag{17}$$

where it is assumed that all the tools of the multiple spindle head of each of utilized drilling heads are the same. Generally, in drill press tool consumption is higher due to inefficient utilization of cutting tools and it can be calculated by

$$N_t = \frac{t_c}{T} \tag{18}$$

where tool life can be calculated by the Taylor's equation as below (Groover 2014)

$$v\ T^n = C \tag{19}$$

(4) Maintenance cost

Maintenance cost is the cost of the time the operator spends performing maintenance activities such as inspection, process monitoring, troubleshooting, problem solving and other relevant activities. Since, estimation of this cost component at the early design stage is inaccurate; it is estimated as a percentage of machining cost. Therefore, annual maintenance cost can be estimated by

$$C_{maintenance} = \frac{\beta\ C_m}{100} \tag{20}$$

where maintenance coefficient is maintenance cost as percentage of operating cost; and for manufacturing it is assumed to be 5%-15% (Campbell and Reyes-Picknell 2015).

(5) Downtime cost

Downtime refers to periods of time when the SPM is not being utilized or is unavailable due to technical issues. It may be due to technical failure, an unplanned event, maintenance, or non-availability of labour, tooling and power. Downtime cost refers to the annual loss of production due to a downtime or outage period and it can be estimated as

$$C_{downtime} = \frac{\left(1 - \left({}^{a}/_{100}\right)\right) D\ S_p}{1 - q} + \left(Roundup\left(\frac{D}{(1-q)\ N_p H}\right) - \left(\frac{D}{(1-q) N_p H}\right)\right) \times C_{mt} \tag{21}$$

(6) Overhead cost

Overhead is important cost element which cannot be allocated to a particular expenditure and includes rent, gas, staff wages, heating, and lighting expenses of the factory and so on. Annual overhead cost can be estimated by considering overhead rate and production time of one part which includes maintenance and machining time.

$$C_{overhead} = \frac{D\ (T_m C_o + T_{mo} C_o)}{60 \times (1-q)} \tag{22}$$

where maintenance operation time per part can be calculated by

$$T_{mo} = \frac{\beta\ T_m}{100} \tag{23}$$

2.3 Salvage value

Salvage is the estimated value at the end of machine tool's useful life. It is usually calculated by a given percentage of the capital investment which is calculated by

$$S = \frac{\varphi \; C_{mt}}{100} \tag{24}$$

where salvage coefficient is usually 5-10% of machine tool cost (Bethel 2006).

2.4 SPM work-stations

SPMs have two main types of work-station layouts: single-station and multi-station (Figure 2). Single-station SPMs (Figure 2(a)) are divided into two groups: one-setup and multi-setup. In a one-setup single-station all the operations are performed in a single-setup. A multi-setup single-station needs more than one setup each of which may be used to perform one or more drilling-related operations. Since the positions of the machining units in the single-station are fixed, the part should be repositioned to make different setups possible for performing other operations.

Multi-station SPMs include two major categories: rotary and sliding (Figure 2(b) and (c)), respectively. These SPMs consist of m work-stations and each work-station may include one or more drilling-related operations which work simultaneously or at different times.

2.4 Cost decision model

Financial indicators for justifying investment decisions include total life cycle production cost, unit profit and return on sales (ROS). Financial indicators for justifying investment decisions include total life cycle production cost, unit profit and return on sales (ROS). In order to use these indicators, it is required to calculate the costs during the life cycle of production at present time. Accordingly, the concept of the value of money over time is utilized for developing these indicators. Brigham and Houston (2011) calculated the present value by considering future value, year of operation or production, and annual interest rate as below

$$PV = FV_j \; (1 + i)^{-j} \tag{25}$$

Therefore, the total life cycle production cost C_{total} can be estimated by the sum of the present values of the individual cost elements as below

$$C_{total} = C_{mt} + \sum_{j=1}^{t} C_{material_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{machining_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{maintenance_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{downtime_j}(1+i)^{-j} + \sum_{j=1}^{t} C_{overhead_j}(1+i)^{-j} - S\,(1+i)^{-t} \tag{26}$$

The machine tools are purchased and installed at present time before beginning the production and no interest is required to be added to the value of the machine tools. The costs are assumed to incur in each year of production which will be paid at the end of the corresponding year. To convert material, machining, maintenance, downtime, and overhead costs over the life cycle of production to present time, the costs are multiplied by the discounting coefficient which considers interest rate and the year of production. It is also assumed that the value of salvage is estimated in the last year of production. Therefore, it is multiplied by a discounting coefficient which represents the value of salvage at present time.

Profit can be obtained by sales revenue minus total life cycle production cost (Hitomi 1996). Therefore, overall production profit and unit profit for this study can be calculated as below which is based on the above mentioned work.

$$Profit = D \sum_{j=1}^{t} S_{p_j}(1+i)^{-j} - C_{total} \tag{27}$$

$$Unit\,profit = \frac{Profit}{D \times t} \tag{28}$$

ROS can be used to evaluate machine tool’s operating performance and can be used as a tool to compare SPM’s performance against one another machine tool. The

following equation is defined for ROS calculation which is based on the equation introduced by Hitomi (1996).

$$ROS = \frac{Profit}{D \times \sum_{j=1}^{t} S_{p_j}(1+i)^{-j}} \quad (29)$$

3. Case study

This section describes a case study using the economic analysis model developed for a SPM and compares the results with a CNC and a drill press. The part to be produced is a throttle body (Figure 3) . This automotive component is made of aluminium alloy 5083 with magnesium and traces of manganese and chromium. It is highly resistant to attack by industrial chemicals.

By focusing on the final production requirements and part properties, the tool type, and Taylor tool life exponents (Groover 2014), the appropriate cutting speed and feedrate are selected. Uncoated HSS tool has been selected for throttle body production. Since aluminium alloy 5083 includes 0.4% of Si, the cutting speed is selected within a range of 80 to 140 m/min (HSS Forum 2014). The value of a Taylor tool life constant C for this part is 120 and n is selected to be 0.125 (see Eq.(19)).

This part consists of fourteen holes with different diameters, depths, and positions. Based on the holes' properties, spindle heads and machining unit characteristics; similar holes are grouped into different categories to be drilled by a single or multiple drilling head (Table 1). Then the required power is calculated for drilling each operation group and the appropriate single- or multiple-spindle head and machining unit are selected (Suhner general catalogue 2012). Results are presented in Table 2.

The SPM layout designed for producing throttle body has six stations as shown in Figure 4 The rotary multi-station SPM has six stations; one for loading, one for

unloading whereas the remaining four stations are devoted to drilling operations. In each station, machining units are arranged to perform two simultaneous drilling operations. Based on the designed SPM, all the required factors are estimated by the developed mathematical equations (Section 2) and some data are also extracted from the manufacturer's catalogue (Suhner general catalogue 2012).

4. Results and discussion

In this study the required cost and time factors are estimated by developed mathematical models (Section 2). The unit of all cost components given in this section is Australian dollar ($). Table 3 represents the outputs of the economic feasibility analysis for throttle body production and the results are compared with other machines tools. The demand considered for this analysis is 100,000 units per year. Results show that the profit per unit for drilling the throttle body production with SPM, CNC and drill press machine tools are $7.67, $6.35 and $1.78, respectively. During five years cycle time of throttle body production, use of SPM results in $662,858 and $2,949,014 savings in comparison with CNC and drill press machines, respectively. It should be taken into account that the total life cycle production cost, profit, and unit profit are a function of demand, and therefore, the profit and savings are enhanced by increasing the production volume.

To make an appropriate investment decision, analysing the risk of market demand over production life cycle time may be useful. Figures 5, 6, and 7 provide details for the economic performance of the SPM, CNC and drill press machines versus demand uncertainties. Figures 5 and 6 show the unit profit and ROS of these machine tools versus demand changes (from 10,000 to 300,000 units per year), respectively. The curves show that for lower demands drill press and CNC machines result in greater unit profit and ROS. The capital investment of SPM is higher than conventional and CNC, respectively. Accordingly, for lower demands the sale profit resulting from SPM is less

than CNC and conventional machines. By increasing demand the unit profits and ROSs of all machines increase at different rates; and when annual demand exceeds 60,000 units, SPM unit profit and ROS overtake those of CNC and drill press machines, and saving is even bigger for larger demands. Since the unit profit is a function of the number of required machines, at this level of demand the number of required CNC machines increases from 1 to 2. Accordingly, the investment and associated costs increase resulting in a sudden decrease in the unit profit. Clearly, such an increased demand makes SPM more profitable than other alternatives.

It can also be seen in Figure 5 that the unit profit of SPM increases progressively until it stabilities. However, the drill press machine tool and especially the CNC do not provide a stable economic performance; because, the unit profit, total life cycle production cost and ROS all depend on the loss of production which is a function of demand and the numbers of required machines, these last two variables do not have a rigidity fixed relationship.

5. Conclusion

This paper presents an economic model for justifying SPM utilization. Inappropriate adoption of SPM technology may affect the productivity. This analysis evaluates SPM economic performance for the required production tasks. The effective factors are identified and the relevant mathematical equations are developed to estimate total life cycle production cost (based on the part properties, SPM characteristics and production requirements). The proposed model has been successfully applied to the case study presented in this paper. Results show that, based on the part properties, SPM performance can improve with increasing production volume.

The cost model presented can be improved by identifying and considering risk factors such as underestimation or overestimation. Furthermore, detailed sensitivity

analysis can be conducted on the level of uncertainty with the potential benefits of utilizing SPM. Applying the proposed economic model will help companies to assess SPM economic performance and estimate machining time and cost in the preliminary stages of designing and manufacturing a SPM.

References

Abdi, M. R. 2009. "Fuzzy multi-criteria decision model for evaluating reconfigurable machines." *International Journal of Production Economics* 117 (1):1-15. doi: 10.1016/j.ijpe.2008.06.009.

Abdi, Mohammad Reza, and Ashraf W. Labib. 2003. "A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): A case study." *International Journal of Production Research* 41 (10):2273-99. doi: 10.1080/0020754031000077266.

Aguilar, Alejandro, Armando Roman-Flores, and Joel C. Huegel. 2013. "Design, refinement, implementation and prototype testing of a reconfigurable lathe-mill." *Journal of Manufacturing Systems* 32 (2):364-71. doi: 10.1016/j.jmsy.2013.01.003.

Ayağ, Zeki, and Rifat Gürcan Özdemir. 2012. "Evaluating machine tool alternatives through modified TOPSIS and alpha-cut based fuzzy ANP." *International Journal of Production Economics* 140 (2):630-6. doi: 10.1016/j.ijpe.2012.02.009.

Azulay, Hay, James K. Mills, and Beno Benhabib. 2014. "A Multi-Tier Design Methodology for Reconfigurable Milling Machines." *Journal of Manufacturing Science and Engineering* 136 (4):041007. doi: 10.1115/1.4027315.

Battaïa, Olga, Alexandre Dolgui, Nikolai Guschinsky, and Genrikh Levin. 2013. "Integrated configurable equipment selection and line balancing for mass production with serial–parallel machining systems." *Engineering Optimization* 46 (10):1369-88. doi: 10.1080/0305215x.2013.841904.

Bensmaine, A., M. Dahane, and L. Benyoucef. 2014. "A new heuristic for integrated process planning and scheduling in reconfigurable manufacturing systems." *International Journal of Production Research* 52 (12):3583-94. doi: 10.1080/00207543.2013.878056.

Bethel, Stephan. 2006. "Asset Valuation (Equipment)." In *The Business Valuation Resource Guide*, 197-227. Mattatall Press.

Brigham, Eugene, and Joel Houston. 2011. *Fundamentals of financial management*: Cengage Learning.

Campbell, John D, and James V Reyes-Picknell. 2015. *Uptime: Strategies for Excellence in Maintenance Management*. 3rd ed: Productivity Press.

Chan, FTS, MH Chan, H Lau, and RWL Ip. 2001. "Investment appraisal techniques for advanced manufacturing technology (AMT): a literature review." *Integrated Manufacturing Systems* 12 (1):35-47.

ElMaraghy, Hoda A. 2006. "Flexible and reconfigurable manufacturing systems paradigms." *International Journal of Flexible Manufacturing Systems* 17 (4):261-76. doi: 10.1007/s10696-006-9028-7.

Groover, Mikell P. 2014. *Automation, production systems, and computer-integrated manufacturing*. 4th ed: Prentice Hall Press.

Guldogan, Evrim Ursavas. 2010. "An integrated approach to machine selection and operation allocation problem." *The International Journal of Advanced Manufacturing Technology* 55 (5-8):797-805. doi: 10.1007/s00170-010-3063-y.

Gwangwava, Norman, Khumbulani Mpofu, Nkgatho Tlale, and Yan Yu. 2014. "A methodology for design and reconfiguration of reconfigurable bending press machines (RBPMs)." *International Journal of Production Research* 52 (20):6019-32. doi: 10.1080/00207543.2014.904969.

Hitomi, K. 1996. *Manufacturing Systems Engineering: A Unified Approach to Manufacturing Technology, Production Management and Industrial Economics*. 2nd ed: CRC Press.

HSS Forum. 2014. "Think reliability, Think HSS." In.

Ic, Yusuf Tansel, Mustafa Yurdakul, and Ergün Eraslan. 2012. "Development of a component-based machining centre selection model using AHP." *International Journal of Production Research* 50 (22):6489-98. doi: 10.1080/00207543.2011.653011.

Klocke, F., M. Zeis, A. Klink, and D. Veselovac. 2013. "Technological and economical comparison of roughing strategies via milling, sinking-EDM, wire-EDM and ECM for titanium- and nickel-based blisks." *CIRP Journal of Manufacturing Science and Technology* 6 (3):198-203. doi: 10.1016/j.cirpj.2013.02.008.

Quintana, Guillem, and Joaquim Ciurana. 2011. "Cost estimation support tool for vertical high speed machines based on product characteristics and productivity requirements." *International Journal of Production Economics* 134 (1):188-95. doi: 10.1016/j.ijpe.2011.06.013.

Samvedi, Avinash, Vipul Jain, and Felix T. S. Chan. 2012. "An integrated approach for machine tool selection using fuzzy analytical hierarchy process and grey relational analysis." *International Journal of Production Research* 50 (12):3211-21. doi: 10.1080/00207543.2011.560906.

Singh, R. K., Nitesh Khilwani, and M. K. Tiwari. 2007. "Justification for the selection of a reconfigurable manufacturing system: a fuzzy analytical hierarchy based approach." *International Journal of Production Research* 45 (14):3165-90. doi: 10.1080/00207540600844043.

Stamatopoulos, Dionysios. 2012. "NA inlet manifold and throttle bodies." In. https://grabcad.com/library/na-inlet-manifold-and-throttle-bodies.

Suhner general catalogue. 2012. "Automation Expert." In. Switzerland.

Tolouei-Rad, Majid. 2011. "An intelligent approach to high quantity automated machining." *Journal of Achievements in Materials and Manufacturing Engineering* 47 (2):195-204.

Tolouei-Rad, M., 2012. Intelligent Analysis of Utilization of Special Purpose Machines for Drilling Operations. INTECH Open Access Publisher.

Tolouei-Rad, Majid, and Saeed Zolfaghari. 2009. "Productivity improvement using Special-Purpose Modular machine tools." *International Journal of Manufacturing Research* 4 (2):219-35.

Vafadar, Ana, Majid Tolouei-Rad, Kevin Hayward, and Kazem Abhary. 2016. "Technical feasibility analysis of utilizing special purpose machine tools." *J Manuf Syst 39*:53-62. doi: http://dx.doi.org/10.1016/j.jmsy.2016.02.003.

Xue, Yi-Xi, Jian-Xin You, Xufeng Zhao, and Hu-Chen Liu. 2016. "An integrated linguistic MCDM approach for robot evaluation and selection with incomplete weight information." *International Journal of Production Research*:1-16. doi: 10.1080/00207543.2016.1146418.

Youssef, H.A., H.A. El-Hofy, and M.H. Ahmed. 2011. *Manufacturing Technology: Materials, Processes, and Equipment*: Taylor & Francis.

Yurdakul, Mustafa, Emre Arslan, Yusuf Tansel İç, and O. Selim Türkbaş. 2013. "A decision support system for selection of net-shape primary manufacturing processes." *International Journal of Production Research* 52 (5):1528-41. doi: 10.1080/00207543.2013.848489.