A multi–objective decision making model for machine tools selection

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Abstract: The metal machining sector plays an important role in the Italian economy, with numerous small and medium sized companies usually grouped in clusters. In recent years, machine tools have gone through remarkable technological innovations which, on one side, have widened their possible context of use. On the other side, the selection of the machine technology to be adopted within the production processes has become more complex and riskier. The paper proposes a structured Analytic Hierarchy Process decision–making model for supporting the machine tools selection in the machining sector. The model has been developed in collaboration with several machine tools producers located in Northern Italy and has been validated through its application in several real case studies.

Keywords: MADM, AHP, NPV, Machine tools selection, Rotary transfer machine, Machining center.

1. Introduction

The machine tools manufacturing sector and the machining sector play a very important role in the Italian economy and a leading role also on the international scene. Italian machine tool manufacturing companies are mainly small enterprises, with a strong propensity to export and high–quality standards. In 2018, 48.3% of machine tool manufacturing companies had a turnover of less than 12.5 million € and 62.3% employed less than 100 workers (UCIMU, 2020). The main user of machine tools is the metal products industry – which includes for instance the production and first transformation of metals and the production of metal construction elements (36.7%) – followed by the automotive industry (25.9%) (UCIMU, 2020).

Many gradual but revolutionary changes have affected machine tool sector over the years, leading to the adoption of flexible manufacturing system (FMS), robotic systems, rapid prototyping, artificial intelligence, Industrial Internet of Things (IIoT), and other Industry 4.0 enabling technologies. In parallel, offering new products in ever shorter time frames and leveraging on quality, reliability, costs, life cycle duration and organisational ability are key issues for competing in an open economy on a global scale. In order to meet global challenges, companies must choose quickly and efficiently the best production, design, and machining strategies. A wrong choice in terms of the production technology to be adopted can not only compromise the profitability of the company but particularly in the case of the small ones, also jeopardize its survival. To support such a choice, Multi–Attribute Decision Making (MADM) methods could be applied; for example:

- TOPSIS – Technique for Order Preference by Similarity to Ideal Solution (Sen and Yang, 1998),
- AHP – Analytic Hierarchy Process (Saaty, 1980),
- DEA – Data Envelopment Analysis (Tabucanon, 1988),
- GRA – Grey Relational Analysis (Ju–Long, 1982; Morán et al., 2006; Kuo, Yang and Huang, 2008),
- ELECTRE – Elimination and Et Choice Translating REality (Chatterjee, Athawale and Chakraborty, 2010),
- VIKOR – VIsekriterijumsko KOmpromisno Rangiranje (Chatterjee, Athawale and Chakraborty, 2010),
- PROMETHEE – Preference Ranking Organization METHod for Enrichment of Evaluations (Babic and Plazibat, 1998),
- MOORA – Multi–Objective Optimization on the basis of the Ratio Analysis (Brauers et al., 2008; Chakraborty, 2011).

Regarding machine tool selection, the first studies using MADM methods date back to the early 1990s. Since then, several approaches have been proposed, many of them adopting the AHP technique (e.g. Lin and Yang, 1996; Yurdakul, 2004; Çimren, Çatay and Budak, 2007; Paramasivam, Senthil and Rajam Ramasamy, 2011) or a hybrid approach in which AHP is combined with other techniques, such as VIKOR (e.g. Ilangkumaran et al., 2012), GRA (e.g. Samvedi, Jain and Chan, 2012), PROMETHEE (e.g. Dağdeviren, 2008), TOPSIS (e.g. Önüt, Kara and Efendigil, 2008; Lashgari et al., 2012) or Fuzzy logic (e.g. Ayağ and Özdemir, 2006, 2011; Durán and Aguilo, 2008; Ilangkumaran et al., 2012; Taha and Rostam, 2012).

Although these models are quite numerous, to the best of our knowledge, none of them are specifically designed for machines such as rotary transfer machines and flexible transfer machines, which are among the most common in the companies in Northern Italy.

This paper proposes a decision support model to compare different manufacturing technologies – and consequently different manufacturing systems – with particular reference to conventional rotary transfer machines, flexible transfer machines, machining centers and conventional machine tools. It takes into account the performance of each machine and the operating performance of the production system in which the machines are inserted, giving special attention to the cost dimension. By means of a multi–objective choice system, a synthetic indicator of preferability is therefore provided for each machine. Defining this decision making model, particular attention has been placed to the ease of use in real contexts, to the possibility of adapting to the specific needs of the decision maker, as well as to the availability of the data that need to be gathered on field for its application. The decision making model has been tested through different case studies – one of which is presented in this paper – that have allowed to verify in practice the procedure to follow, the input data to evaluate, as well as how to interpret the results in output.

2. Machine tools technologies

In the following, we present the main technological alternatives for the realisation of machining by chip removal. The model presented in this paper is specifically dedicated to the selection of one of these alternatives.

- *Conventional machine tools* are based on conventional technologies, such as lathe, drill, milling machine, etc.. These machines generally entail a low initial investment, high flexibility, low productivity – which requires the purchase of several machines to meet high production capacity requirements – and a high cost for the eventual automation of the system, which is not natively able to operate without supervision. This category also includes conventional machines adopting more advanced features (CNC, automatic tool changer, multi–spindle solutions, etc.) and organised through automated production cells.
- *Machining centers* are considered the pillars of flexible production, as they allow the production of small batches, although they are also used in the case of production with large batches (e.g. in the case of automotive supplies). The type of parts processed can therefore be characterised by high variability in volume and mix, and by very stringent quality specifications. The economic value of the machined components can be very high. The high flexibility of the machining center affects its production potential, because the installation of a large number of machines can be required.
- *Conventional transfer machines* are rotary transfer machines as conventionally intended: rigid machines specifically designed for the production of a single family of pieces. Typically, this choice is made in case of make–to–stock production and/or very large lots, even following multi–year production plans. When fully operational, these machines allow a production capable of competing with complex production systems, with all the advantages of compactness and ease of management. They lack flexibility and expandability, and require a huge initial outlay.
- *Flexible transfer machines*: these machines appeared on the market more recently than the above alternatives and, from the performance point of view, represent a hybrid between machining centers and conventional transfer machines. These machines are created to be more flexible than conventional transfer machines, although they maintain the typical high productivity of rotary transfer configurations, as well as a high degree of automation.

3. Analytic Hierarchy Process

The model presented in this paper has been developed in close collaboration with a group of machine tool manufacturers. Their contribution was of fundamental importance for their deep knowledge of the machines and their operating performance, and of the customer companies. In this way, it was also possible to take into account the point of view of the users. The developed decision making model for machine tool selection is based on a conventional economic profitability analysis of the investment realised through the calculation of the Net Present Value (NPV) indicator for each alternative considered, combined with the use of the AHP method for the consideration of non–financial evaluation criteria. To combine the two assessments, the scores obtained with the AHP and the NPV values are normalised, and the final ranking is obtained based on the normalized sum of the values of these normalised scores.

AHP was chosen because of its proven ability to consider numerous evaluation criteria and guide decision making. It is also a relatively simple method in which quantitative and qualitative criteria can be integrated at the same time. AHP was developed by Saaty (1980) in the 1970s and allows for the prioritisation of several alternative solutions considered for a specific problem. This technique involves decomposing the problem into a hierarchy of related elements. Such a structure clarifies the problem and presents the contribution of each of the elements to the final decision. Refer to Marciano et al. (2016) and Rossi et al. (2013) for the step–by–step procedure of AHP and examples of applications in industrial contexts.

4. Financial and non–financial evaluation criteria

The evaluation criteria were selected based both on literature studies and from the indications received from machine tool manufacturers. The contribution of machine producers also allowed us to take into account the point of view of machining companies. The criteria identified are therefore the following: costs, flexibility, quality, impact on the operations, reliability and maintenance and safety and environment.

With reference to these criteria, it should be noted that most models in the literature also include the productivity criterion, understood as the machine's ability to process a given number of pieces in a given time unit. In this case, however, productivity is not considered directly as an evaluation criterion, but is nevertheless taken into account in calculating the number of machines required to meet a given level of production capacity, which in turn conditions other criteria such as costs or flexibility.

4.1 Costs

This criterion consists of calculating the sum of the discounted cash outflows (NPV). Revenues are not considered as they do not differ between alternatives. In particular, the following items are taken into account.

- *Machine(s) purchase cost*: this takes into account the machine(s), the automation system and installation costs. The number of machines to meet certain production capacity requirements has to be calculated.
- *Cost of machine equipment*: this relates to the equipment costs of the machine, of tooling, of grips, and of equipping the automation system.
- *Direct labour and other direct costs*: this takes into account the number of operators required to operate the machine(s) and the cost of energy.
- *Indirect labour costs*: this includes indirect employees, such as toolmakers, warehousemen, quality control workers.
- *Maintenance cost* takes into account the costs of maintaining the machine, whether internal or external.
- *Cost of the storage*: it takes into account the quantity of stock, including buffer stocks warehouses.
- *Cost of rejects and rework* takes into account the quality yield of the plant.
- *Cost of machine downtime*: it considers the costs of failures and the costs due to the unavailability of faulty machines.

4.2 Flexibility

The importance of this factor has been highlighted particularly by conventional rotary transfer manufacturers because it is critical in this type of machine, especially in relation to the perception of flexibility by the customer. In the model developed in this work, flexibility is evaluated through the following dimensions.

- *Expandability*: it represents the ability to increase the installed capacity and the costs at which such expansion can be implemented. Expansion is typically high for systems based on conventional machines or stand–alone machining centers; it is medium for FMS–FMC production systems as it is necessary a re–configuration of the automated system and finally it is low for both conventional and flexible transfer systems.
- *Presence of CNC*: it is one of the most important variables in the choice of a flexible production system and it affects both process and product flexibility. This variable is a logical one (presence or absence) and may represent an important discriminating factor. Typically, less expensive conventional machines and conventional transfer machines do not have CNC, whereas machining centers and flexible transfer machines all have CNC installed.
- *Number of machining operations that can be carried out*: even this parameter both affects process and product flexibility. For production systems based on conventional machines, the number of machining operations carried out is a function of the types of machines that make up the system. For machining centers it will probably receive the maximum score, while for conventional transfer machines (which can only carry out the machining operations for which they have been designed) the minimum one; flexible transfer machines that can carry out a wide range of machining operations at each station, including milling and turning, will be assessed with a high score.
- *Maximum workpiece size*: This criterion is part of product flexibility and can often be quantitatively defined and measured in mm×mm×mm; it is evaluated starting from the maximum spindle strokes, the size of the work table or vice, the maximum size of the tools, etc.
- *Setup time*: setup time is a fundamental parameter in the context of process flexibility; it depends on some of the machine's features, such as the presence of quick tool couplings, automated tool change, the possibility of varying the work programs quickly in the CNC and the ease of replacing the workpiece holder equipment.

4.3 Quality

In this context, quality is to be understood as the conformity of the product to the design specifications in terms of compliance with dimensional, geometric and roughness tolerances. The aspects to be evaluated are therefore the accuracy of positioning and the repeatability, which, in the case of the machine tools, depend on characteristics such as static and dynamic stiffness, combined with high thermal stability of the machine.

The accuracy of positioning is a fundamental but not very discriminating parameter; it is typically very high in rigid transfer machines, high in machining centers and flexible transfer machines, and may vary over a wide range in conventional machine tools.

Repeatability, on the other hand, varies highly according to the production technology; in particular, the lower the number of part placements, the greater the repeatability. In addition, the thermal stability of the machine must also be considered. For these reasons, conventional transfer machines have an advantage due to the single positioning and, since they often work 24 h/d, thermal transients are irrelevant. Machining centers have generally good but lower level of repeatability, as the spindle is in continuous movement, and conventional machines are disadvantaged due to the numerous re–placing of parts.

4.4 Impact on the operations

By impact on operations, we mean the impact on the production system caused by the integration of the new machines. The following aspects have to be considered.

- *Impact on layout*: this parameter is very favourable in the case of rotary transfer machines, because they allow high productivity in very compact space, while machining centers or conventional machines installed in large numbers, on the other hand, occupy much more space.
- *Compatibility*: this must take into account the ease of interfacing the machine with the company's production system in terms of type of numerical control, type of tool attachments, type of coolant used, etc.
- *Customisation*: this can be a fundamental parameter for those companies that require special features on their machines, such as specific tool attachments, tool magazine or customised CNC interface. These solutions are easy to implement on transfer machines, as each machine is designed according to the customer's needs, while it is more complex and expensive for machining centers.
- *Ease of installation and use*: this parameter regards both the machine and the automation systems. The transfer machine is advantageous since automation is relegated only to the loading/unloading of the piece and for a lower number of machines than when using machining centers. With reference to the ease of use, this means the level of training needed by the operators.

4.5 Reliability and maintenance

Although it is possible to assess machine reliability quantitatively, this option was considered impractical, both for the complexity and for the lack of data available a priori. This criterion is therefore evaluated qualitatively, taking into account the following considerations.

- Special machines, such as transfer machines designed for a high productivity, are generally designed for providing a very high reliability; machining centers and conventional machines, especially in the case of production with large batches, often have a slightly lower reliability. This is confirmed by the fact that the useful life of transfer machines can reach more than twenty years without the need for major extraordinary maintenance; on the other hand, the useful life of machining centers hardly reaches 15 years.
- In the event of plant downtime, a flexible production system, based for example on a battery of machining centers, can provide alternative routes to compensate for the unavailability of one of its units. This is not possible in the case of transfer machines.

4.5 Safety and Environment

Machine safety and environmental impact are increasingly important parameters for any production system.

With reference to the health and safety of workers, considering that machine safety is regulated in all developed countries, it may happen that comparing different machines does not allow a definite priority to be expressed.

From an environmental performance point of view, the elements considered most relevant are the electrical energy consumption of the machines and the production of special waste, both hazardous and non–hazardous.

5. Case study

The case study analysed concerns the production of brake calipers for the automotive industry by a supplier of an automotive manufacturer located in Northern Italy. In this sector, most companies produce by means of machining centers that have been adapted to mass production. In recent years, however, with the introduction of flexible transfer machines, some companies have turned to this technology. It is therefore a context in which the developed decision–making support model could provide a relevant contribution.

An increase in production capacity is required to satisfy the demand of a customer that plans to put a new model into production in 1,000 cars per day, resulting in a requirement for 2,000 brake calipers for the front axle of the vehicle and 2,000 for the rear. The order has a duration of 18 months with an option to extend it up to 5 years.

The front and rear brake calipers are made of cast iron and differ in terms of geometry but not in terms of machining operations and cycle times. The company rejects a priori the option of using conventional machines because of the high number of repositionings that would be necessary and the low productivity.

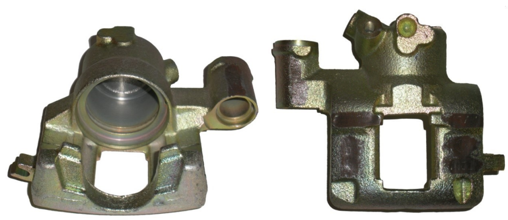

Figure 1: Cast iron front brake caliper.

5.1 Alternatives

Machining centers

The machining center selected is a 4–axis horizontal type, with a 500×500×500 mm working area, cone 40, and 400 mm double pallet system with 1 indexing degree and integrated pallet rack with 454 kg of load capacity. The single is vector–driven with a power of 15 kW at 8,000 rpm, with lubrication through the tool at 20 bar. The tool magazine has a capacity of 70 units. The chip evacuation is belt driven; the working area is shower washed. The space occupied by the machine is about 20 m^2.

The cost of the machine is approximately € 190,000, including the automatic pallet magazine. To this cost the purchase of a robot with vision system costing about 100,000 € for each machine must be added.

The piece cannot be made with a single placement, given the presence of two holes that cannot be machined on a 4–axis machining center. These holes, for the oil inlet and outlet, must be drilled twice each and tapped (6 machining operations). The other machining operations are 16 in total and can be carried out with a single clamping.

It is therefore necessary to draw up two different cycle times for the two placements, thus estimating the overall production capacity and the number of machines to be purchased to meet the demand.

Table 1: Cycle times for machining 8 brake calipers.

Operation	Time (s)	I center	II center
Machining	6	16	6
Tool changes	3	16	6
Table rotation	1.2	16	6
Rapid movements	0.2	256	80
Pallet change time	6	1	1
Total cycle time (min)	–	16	6

Assuming to machine a pallet with 8 pieces fixed, the cycle time on the first machining center for the single piece is 119 s, while on the second, where the number of machinings are lower, it is 45 s.

With this cycle times, to satisfy the overall demand of 4,000 pieces per day (both front and rear brake calipers), 6 machines are required for the first cycle and 3 for the second cycle, for a total of 9 machines.

In this case, machining saturation is very high (95%), since the tool replacement time is hidden, given the large number of tools in the warehouse.

The machine equipment is rather expensive, being composed of the clamping cube for the pieces with three clamping cylinders for each piece, the 4 jigs to be mounted on each cube and the respective pallet. The total cost is about 20,000 €, to be doubled, as there are two pallets for each machine.

Flexible transfer machine

In the flexible transfer machine chosen for this case, all units are CNC controlled and move on carriages with 200 mm strokes. The spindle nose is equipped with revolver heads carrying 4 tools or with twin–spindle units to increase productivity and decrease tool change times.

The machine is a vertical axis one. It has 8 stations, 8 units and 21 tools. The vices are all rotating and indexable to ensure higher flexibility. All tools are equipped with quick change and with internal lubrication. The machine can be easily retooled for the production of other brake calipers or other similar parts by changing the turret head arrangement and replacing the tools. Even the non–orthogonal units can be offset and have a degree of freedom to be reoriented as required.

The duration of the cycle time is calculated at 34 s, the saturation is rather low (80%), given the need to replace the tools (carbide plates) every 500 pieces, which involves 4 hours of downtime per day. To meet demand, therefore, 2 machines are needed, each producing 2032 pieces per day.

The cost of this machine is 1,200,000 €. The automation system requires the installation of two robots with vision system at a cost of 100,000 € each.

The space occupied is about 20 m^2, including the automation system. The installed power is about 100 kW for an effective absorption of 30 kW.

The equipment is quite expensive, as a normal self–centering vice is not sufficient, but a 3–point clamping with hydraulic pistons is required: the cost of each vice is 2,500 €. The tooling includes tools with carbide inserts costing 500 € each plus 7 € for each plate.

Conventional transfer machine

The machining cycle, in the case of a conventional transfer machine, is the same as that of the flexible transfer machine, with the only difference that the machining operations are distributed over 12 stations, to further reduce cycle times, which stand at 22 seconds. In this case it is possible to satisfy the entire demand with two machines working on two shifts per day.

The purchase cost of the machine is 900,000 €. Flexibility in this case is very limited, since the machine can only produce the two brake calipers in question and nothing else. The loading system consists of a 70,000 € manipulator and a 25,000 € tipper.

Equipment and tooling cost the same as for the flexible transfer machine and the space occupied is 20 m^2.

5.2 AHP analysis

The necessary judgments and evaluations for the AHP analysis were made by the head of the technical office and by the head of operations of the company. The calculations were carried out using the software Super Decision 3.2.0 and the inconsistency index resulted in 0.0387.

The following are the priorities attributed to the assessment criteria, which represent the weights of the criteria with respect to the decision goal:

- Flexibility: 0.457
- Quality: 0.206
- Impact on the operations: 0.065
- Reliability and maintenance: 0.236

- Safety and environment: 0.036

Below are the priorities attributed to the alternatives, which represent the ability of the alternatives to achieve the decision goal:

- Machining center: 0.447
- Conventional rotary transfer machine: 0.343
- Flexible transfer machine: 0.210

From the ranking, it can be seen that, in terms of non–financial evaluation criteria, the machining center is the preferred alternative, followed by the flexible transfer machine and the conventional transfer machine. The need for high flexibility prevailed over the reliability and quality characteristics of the transfer machines. The overall consistency of the method is also verified.

5.3 Cost analysis

The results of the cost analysis for the various cost items considered are presented below. Consider that all values are related to cash outflows. In this case, therefore, the lowest NPV is preferred.

Table 2: Cost items.

	Machining center	Conventional transfer machine	Flexible transfer machine
Machines (#)	9	2	2
Machine unit cost (€)	190,000	900,000	1,200,000
Automation system unit cost (€)	100,000	95,000	100,000
Equipment cost (€)	418,000	76,400	61,400
Tools costs (€/y)	153,000	103,000	131,000
Workers per shift (#)	3	1	1
Shift per day (#)	3	2	3
Direct labor cost (€/y)	317,000	74,000	106,000
Effective power absorption per machine (kW)	8	27	36
Energy cost (€/y)	38,000	25,000	50,000
Maintenance cost (€/y)	1,8000	8,000	8,000
NPV (5 years, 4% discount rate)	5,369,659	3,001,283	3,974,688

The other cost items, in particular indirect costs, storage costs, waste and rework costs and machine downtime costs were not calculated, as it was considered that the differential contribution between the three alternatives was negligible.

The NPV was calculated with a time horizon of 5 years and a discount rate of 4%. The results reward the conventional rotary transfer machine due to the low operating costs, followed by the flexible transfer machine and by the machining center, which is the least preferable alternative.

5.4 Final ranking

The final indicator obtained from the normalised sum of the AHP scores and the normalised NPVs is shown below. In practice, for each of the three scores, the values of the three alternatives are divided by their sum, so that the scores all fall between 0 and 1.

Table 3: Final scores of indicators.

	Machining center	Conventional transfer machine	Flexible transfer machine
AHP normalised score	0.45	0.21	0.34
Cost normalised score	0.28	0.38	0.34
Global score	0.37	0.29	0.34

From the ranking, it can be seen that the machining center is the preferred alternative, followed by the flexible transfer machine and the conventional transfer machine.

Although machining centers are markedly penalized from the perspective of overall financial performance, their particular flexibility characteristics, combined with the high priority given to the flexibility criterion in the AHP analysis, led to them prevailing in the global score.

In contrast, conventional transfer machines, while having the best cost performance, are penalized by their lack of flexibility, making this alternative the least preferable.

6. Conclusions

The MADM model presented in this paper for the choice of machine tools has been developed taking into account the specific reference context for which its application is designed, namely that of small or medium–sized subcontracting companies in the machining sector. In particular, the model includes some evaluation criteria that are rarely present in other models described in the literature, such as the impact on operations. Moreover, its structure allows for an emphasis on the financial performance of the investment, which is an aspect commonly considered of primary importance. On the other hand, its application helps firms to give due consideration to the impact of their choice from an operational performance perspective. In fact, while these firms recognize the importance of this impact, they struggle to take it into account in a sufficiently structured and thorough way when making investment decisions.

References

Ayağ, Z., and Özdemir, R.G. (2006). A fuzzy AHP approach to evaluating machine tool alternatives. *Journal of Intelligent Manufacturing*, 17(2), 179-190.

Ayağ, Z., and Özdemir, R.G. (2011). An intelligent approach to machine tool selection through fuzzy analytic network process. *Journal of Intelligent Manufacturing*, 22(2), 163-177.

Babic, Z., and Plazibat, N. (1998). Ranking of enterprises based on multicriterial analysis. *International Journal of Production Economics*, 56-57, 29-35.

Brauers, W.K.M., Zavadskas, E.K., Turskis, Z., and Vilutiene, T. (2008). Multi–objective contractor's ranking by applying the Moora method. *Journal of Business Economics and Management*, 9(4), 245-255.

Chakraborty, S. (2011). Applications of the MOORA method for decision making in manufacturing environment. *International Journal of Advanced Manufacturing Technology*, 54, 1155-1166.

Chatterjee, P., Athawale, V.M., and Chakraborty, S. (2010). Selection of industrial robots using compromise ranking and outranking methods. *Robotics and Computer–Integrated Manufacturing*, 26(5), 483-489.

Çimren, E., Çatay, B., and Budak, E. (2007). Development of a machine tool selection system using AHP. *International Journal of Advanced Manufacturing Technology*, 35, 363-376.

Dağdeviren, M. (2008). Decision making in equipment selection: An integrated approach with AHP and PROMETHEE. *Journal of Intelligent Manufacturing*, 19(4), 397-406.

Durán, O., and Aguilo, J. (2008). Computer–aided machine–tool selection based on a Fuzzy–AHP approach. *Expert Systems with Applications*, 34(3), 1787-1794.

Ilangkumaran, M., Sasirekha, V., Anojkumar, L., Boopathi Raja, M. (2012). Machine tool selection using AHP and VIKOR methodologies under fuzzy environment. *International Journal of Modelling in Operations Management*, 2(4), 409-436.

Ju–Long, D. (1982). Control problems of grey systems. *Systems and Control Letters*, 1(5), 288-294.

Kuo, Y., Yang, T., and Huang, G.–W. (2008). The use of grey relational analysis in solving multiple attribute decision–making problems. *Computers and Industrial Engineering*, 55(1), 80-93.

Lashgari, A., Yazdani–Chamzini, A., Fouladgar, M.M., Zavadskas, E.K., Shafiee, S., Abbate, N. (2012). Equipment Selection Using Fuzzy Multi Criteria Decision Making Model: Key Study of Gole Gohar Iron Mine. *Engineering Economics*, 23(2), 125-136.

Lin, Z.–C., and Yang, C.–B. (1996). Evaluation of machine selection by the AHP method. *Journal of Materials Processing Technology*, 57(3-4), 253-258.

Marciano, F., Cocca, P., Stefana, E., and Alberti, M. (2016). Selection of occupational health and safety management software using Analytic Hierarchy Process. *Proceedings of the Summer School Francesco Turco*, 13-15 September 2016, 252-256.

Morán, J., Granada, E., Míguez, J.L., Porteiro, J. (2006). Use of grey relational analysis to assess and optimize small biomass boilers. *Fuel Processing Technology*, 87(2), 123-127.

Önüt, S., Kara, S.S. and Efendigil, T. (2008). A hybrid fuzzy MCDM approach to machine tool selection. *Journal of Intelligent Manufacturing*, 19(4), 443-453.

Paramasivam, V., Senthil, V., and Rajam Ramasamy, N. (2011). Decision making in equipment selection: An integrated approach with digraph and matrix approach, AHP and ANP. *International Journal of Advanced Manufacturing Technology*, 54, 1233-1244.

Rossi, D., Bertoloni, E., Fenaroli, M., Marciano, F., and Alberti, M. (2013). A multi–criteria ergonomic and performance methodology for evaluating alternatives in manuable material handling. *International Journal of Industrial Ergonomics*, 43(4), 314-327.

Saaty, T.L. (1980). *The Analytic Hierarchy Process*. McGraw–Hill, New York

Samvedi, A., Jain, V., and Chan, F.T.S. (2012). An integrated approach for machine tool selection using fuzzy analytical hierarchy process and grey relational analysis. *International Journal of Production Research*, 50(12), 3211-3221.

Sen, P., and Yang, J.–B. (1998). *Multiple Criteria Decision Support in Engineering Design*. Springer–Verlag, London.

Tabucanon, M. T. (1988) *Multiple Criteria Decision Making in Industry*. Elsevier: Amsterdam.

Taha, Z., and Rostam, S. (2012). A hybrid fuzzy AHP–PROMETHEE decision support system for machine tool selection in flexible manufacturing cell. *Journal of Intelligent Manufacturing*, 23(6), 2137-2149.

UCIMU – Italian machine tools, robots and automation manufacturers' association (2020). *2019 Sector Report*. UCIMU, Milan.

Yurdakul, M. (2004). AHP as a strategic decision–making tool to justify machine tool selection. *Journal of Materials Processing Technology*, 146(3), 365-376.