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AHP as a strategic decision-making tool to justify machine tool selection

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Abstract

Machine tool selection has strategic implications that contribute to the manufacturing strategy of a manufacturing organization. In such a case, it is important to identify and model the links between machine tool alternatives and manufacturing strategy. This study presents such a strategic justification tool for machine tools. With the new strategic justification tool, the evaluation of investment in machine tools can model and quantify strategic considerations. AHP and ANP are applied in calculation of the contributions of machine tool alternatives to the manufacturing strategy of a manufacturing organization. Hierarchical decision structures are formed in the application of the AHP and ANP approaches. Ranking scores which are used to rank the alternatives are obtained as outcomes of the applications. Application of the ANP approach also enabled the incorporation of interdependencies among the components of decision structures. An illustrative example is provided. The company management found the application and results satisfactory and implementable in their machine tool selection decisions.

Keywords: Machine selection; Strategic consideration; Analytic network process; Analytic hierarchy process; Manufacturing strategy; Machine characteristics

1. Introduction

For manufacturing companies, one of the starting points to achieving high competitiveness in the market is the selection of machine tools. Generally, return on investment (ROI) method is applied in justification of machine tools [10,11,24]. Investments in machine tools are often accepted as stand-alone replacement projects, which do not improve the performance of a company enough to affect its strategic positioning against its competitors in the market [18,21].

However, the newest machine tools, namely machining centers, work independent of human operators, combine multiple machining operations performed by several conventional machine tools previously, and handle tool exchange, part exchange, and many activities automatically. They combine cost and time reducing efficiency features of specialized machines with the flexibility of conventional non-dedicated machine tools. The capability of accepting any one of a range of parts in random order provides advantages that have major implications for a firm in the market against its competitors, such that a strategic justification is necessary to incorporate the strategic benefits into the selection process of machine tools.

In the literature, there are papers proposing models for machine tool selection problems. For example, Atmani and Lashkari [3], Tabucanon et al. [26], and Wang et al. [28] studied the machine selection problem for flexible manufacturing systems (FMS). However, a thorough study of the strategic implications of the machine tool selection decision is not available in the literature to the best knowledge of the author. This paper is along the lines of justifying stand-alone machine tools, and it focuses on the strategic implications of the machine tool selection decision and develops a model in which the strategic benefits of the machine tool selection decision are identified and quantified.

In a strategic approach, it is necessary to build a bridge between manufacturing strategy and individual machine tool options [2]. A multi-level decision hierarchy and intermediate decision levels are required to link machine tool properties with the company's manufacturing strategy. Furthermore, different types of evaluation criteria will exist in the decision hierarchy. Among the available multi-attribute approaches, only the analytic hierarchy process (AHP) approach has the capabilities to combine different types of criteria in a multi-level decision structure to obtain a single score for each alternative to rank the alternatives.

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In the literature, Arslan et al. [1], Lin and Yang [14] and Oeltjenbruns et al. [19] proposed AHP for machine selection problem. However, the proposed AHP models are limited in terms of strategic implications of their selection decisions. Another important observation related with the proposed AHP models is that none of them has the ability to handle interdependencies, or interrelationships, among the evaluation criteria. The justification criteria are assumed to be independent of each other, and their weights in the achievement of the company's goals are calculated ignoring contributions to each other. However, to calculate real weight of a criterion, interdependencies among the criteria must be identified, quantified, and included into the calculation of weight of criteria in the machine tool justification problem. AHP cannot incorporate interdependent relationships among and within the levels of criteria. In such a situation, the general form of AHP, ANP (analytic network process), need to be applied along with AHP (see [4,16,17]).

2. Application of the AHP and ANP in strategic justification of machine tools

Structuring decision hierarchies for machine tool selection problem, pairwise comparison and determining the weights (contributions) of the components of the hierarchies, and synthesis to reach overall ranking scores for machine tool alternatives are the three functions performed step by step in the application of the AHP approach.

2.1. Development of decision hierarchies

As a first step of the application of the AHP approach, decision hierarchies are developed. The first hierarchy has a two-level structure and links the competitiveness goal of the company to the manufacturing priorities and is used to measure the weight of manufacturing priorities (Fig. 1).

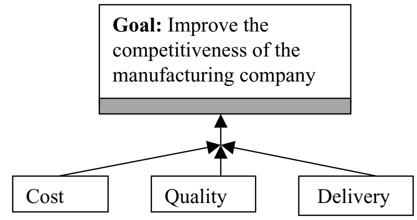

Fig. 1. The decision hierarchy of manufacturing strategy.

The other three hierarchies link manufacturing priorities with alternative machine tools which are represented in terms of the machine tool characteristics (Figs. 2–4). At the lowest levels of the three hierarchies, alternative machine tools in terms of their characteristics are placed. The hierarchical structures link the alternative machine tools to the manufacturing strategy placed at the third level through an intermediate level of manufacturing benefits. The first four machine tool characteristics (i.e. process quality, actual machining time of a typical part, set-up time of an activity, and number of operations/parts that can be performed at the machine tool) are benefit-related and ultimately contribute to all three manufacturing priorities in terms of savings in cost and time and improvements in efficiency. They are causes of the manufacturing benefits, and the differences in the characteristics of different machine tool alternatives lead to different levels of achievements in manufacturing benefits [15,20]. On the other hand, the last two characteristics (i.e. initial and running costs) are the expenses that are necessary to purchase or operate the alternative machine tools. In the hierarchies developed for cost and delivery priorities, it should be noted that the manufacturing benefits are interrelated. As an example, the relationships among manufacturing lead time, lot size and inventory level can be presented. In a manufacturing plant, any reduction in manufacturing lead time will lower inventory levels and lot sizes. In return, lower inventory levels and lot sizes further reduce manufacturing lead time. At the same time, lower lot sizes reduce inventory levels. Therefore, in the calculation of the weight of a benefit with respect to a manufacturing priority, its contributions on other benefits should be added to its independent weight.

The manufacturing priorities are parts of the manufacturing strategy. Quality priority is important in achieving tighter specifications in terms of surface quality and tolerances and better conformance with defined specifications.

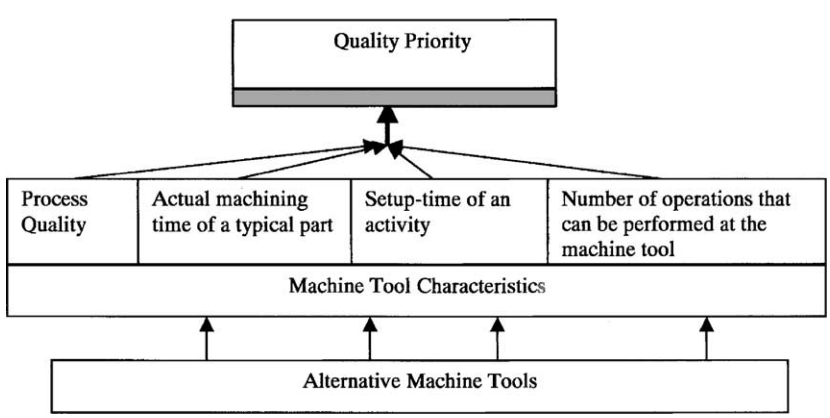

Fig. 2. The decision hierarchy of quality priority.

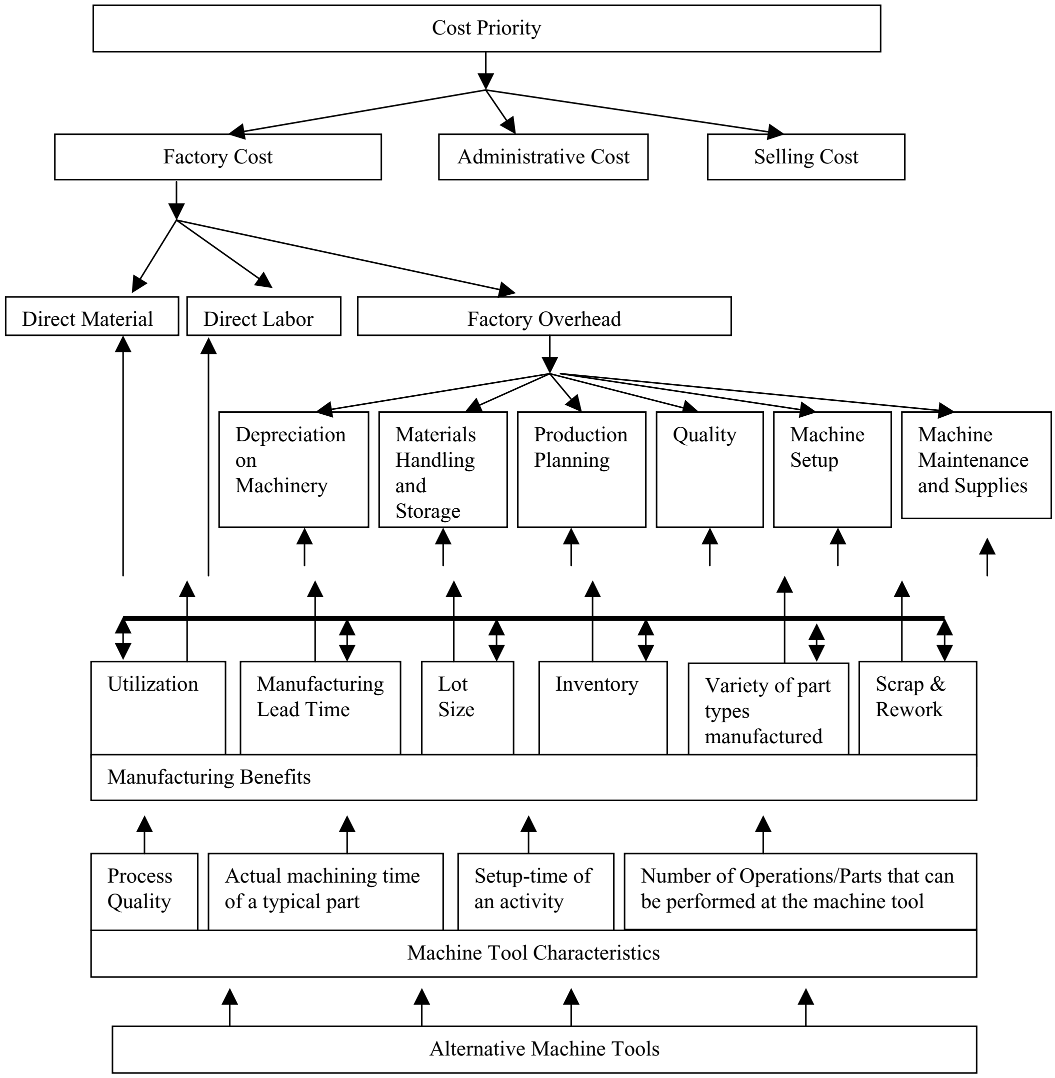

Fig. 3. The decision hierarchy of the cost priority.

Quality priority can be directly connected with machine tool characteristics without the use of any manufacturing benefit (Fig. 2). On the other hand, the alternative machine tools increase factory cost through initial and running costs and at the same time generate savings in various cost items for the cost priority (Fig. 3). Initial and running costs primarily affect depreciation on machinery and maintenance and supplies costs respectively [9]. The impact of initial and running costs need to be weighted against the sum of cost savings generated by a new machine tool. The weight of the increase in expenses against cost savings need to be estimated by the company to incorporate the complete affect of an alternative machine tool on cost priority. Finally, the delivery priority essentially measures the success of a company in meeting the customers' requirements and needs in delivery of the products [12]. Delivery priority is defined in terms of three dimensions: time between order and delivery, on-time shipments, and shipment accuracy and its decision structure is presented in Fig. 4.

2.2. Calculation of the weights

AHP approach is employed in the determination of the weights of independent components of the decision hierarchies. In the hierarchies, manufacturing priorities, machine tool characteristics, and alternative machine tools are independent components, so that AHP is enough to calculate their weights with respect to their parent components. In the application of the AHP approach, a pairwise comparison matrix is formed. In the pairwise comparison matrix, rows and columns of the pairwise comparison matrix are allocated to the components belonging to the same parent component in the decision hierarchy. The weight of component i compared to component j with regard to the parent component is determined using Saaty's scale (Table 1) and assigned to the (i, j)th position of the pairwise comparison matrix [22]. Automatically, the reciprocal of the assigned number is assigned to the (j, i)th position. Once the pairwise comparison matrix is formed, weights of components are calculated

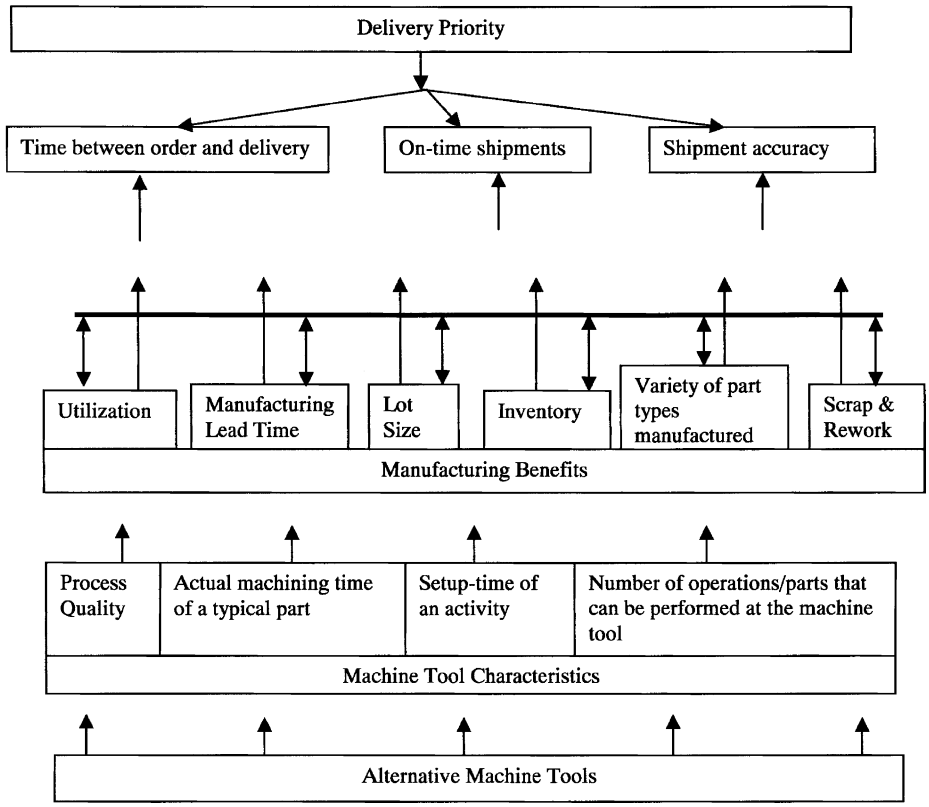

Fig. 4. The decision hierarchy of the delivery priority.

by solving for the eigenvector of the pairwise comparison matrix.

On the other hand, in the calculations of weights of manufacturing benefits with respect to manufacturing priorities, the general form of AHP (ANP) is used to incorporate the interdependencies that exist among them by using the following three-step ANP algorithm:

- *Step 1*. The relative priority of one benefit with respect to another benefit, while disregarding the effects on all other benefits is considered. A pairwise comparison matrix is constructed in this step and solved for its principal eigenvector, denoted as x, as an outcome of this step.
- *Step 2*. The relative effect of one benefit with respect to another, on the contribution of a third benefit towards the improvement in selected cost or delivery item is considered. For each manufacturing benefit, a pairwise comparison matrix is constructed and a principal eigenvector of each individual matrix is obtained. These principal eigenvectors represent the dependencies among criteria and are denoted by c. The contribution of benefit i to benefit j is represented by $c_{i \to j}$.
- *Step 3*. To obtain the weight of a manufacturing benefit, its independent weight and its contributions to other benefits are added and normalized. Eq. (1) is developed to calculate individual weight, denoted by z, of each benefit i, where n is the total number of benefits. To simplify the calculations, the contribution vectors (c's) of pairwise comparison matrices are collected in a matrix called "contribution matrix" and denoted as "C". In this case, weights

Table 1
Saaty's 1–9 scale for pairwise comparison

Intensity of weight	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one over another
5	Strong importance	Experience and judgment strongly favor one over another
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The importance of one over another affirmed on the highest possible order
2, 4, 6, 8	Intermediate values	Used to represent compromise between the priorities listed above
Reciprocals of above non-zero numbers	If activity i has one of the above non-zero numbers assigned to it when compared to activity j, then j has the reciprocal value when compared with i	

of benefits in a cost or delivery item can be calculated using Eq. (2):

$$z_i = x_i + \sum_{j=1;\, j\neq i}^{n} c_{i\to j} x_j \tag{1}$$

$$z = Cx \tag{2}$$

2.3. Synthesis of the weights to obtain the ranking scores

Once the weights of components of the decision hierarchies are calculated, they are synthesized to obtain the ranking scores of alternative machine tools. Weights are synthesized from the highest level down by multiplying weights by the weight of their corresponding parent component in the level above and adding them for each component in a level according to the component it affects [7].

3. An illustrative example

The AHP approach is tested in Dizayn Machinery Manufacturing and Engineering Inc., which is located in Ankara, Turkey, and works as a subcontract manufacturer to other large-size assembly and manufacturing companies. The company receives short-to-medium-run orders and in some cases prototype orders.

The company wants to purchase new machine tools to reduce lead times without compromising quality and cost of its products. The delivery of orders as early as possible even before their promised due-dates is critical in the company's customers' preference. After going through a fairly extensive search within the manufacturing plant, the management decided to purchase a vertical machining center for their immediate need. The company considered three different models of Mazak vertical machining centers, namely VTC-200B (3 Axis), FJV-250 (3 Axis), and VARIAXIS 500 (5 Axis) along with a conventional milling machine. Initial and running costs are provided in Table 2.

Table 2
Proposed alternatives for the vertical machining center

	Initial cost (US$)	Annual running cost (US$)
VTC-200B (3 Axis)	120,000	1000
FJV-250 (3 Axis)	240,000	2000
VARIAXIS 500 (5 Axis)	500,000	3500
Conventional	23,000	300

The company's accounting data was used in assigning the weight of cost items (Table 3). Also, to combine cost savings with investment expenses, it is required to compare total annual cost savings in cost priority generated by manufacturing benefits to the increases in total annual cost caused by the initial and running costs. The 0.20 is assigned as the weight for cost savings, whereas 0.72 and 0.08 are assigned as weights for initial cost and running cost, respectively.

Table 3
Weights of cost items of factory cost

Cost items (factory cost)	Weight
Direct material	0.20
Direct labor	0.15
Factory overhead	0.65
Depreciation on machinery	0.45
Materials handling and storage	0.15
Production planning	0.07
Quality	0.15
Machine set-up	0.08
Machine maintenance and supplies	0.10

3.1. Calculation of the weights of the components in the decision hierarchies

The contributions of machine tool alternatives in manufacturing priorities are calculated separately by using the decision hierarchies of the manufacturing priorities. To illustrate the application of AHP, the calculation of weights of manufacturing priorities is presented in detail in the following section. Similarly, quantification of interdependencies among manufacturing benefits is provided to illustrate the ANP approach.

3.1.1. Calculation of the weights of the independent components

As a first step in the application of the AHP approach, the manufacturing priorities are compared pairwise using Saaty's 1–9 scale and compiled in a pairwise comparison matrix (Table 4). As an example for relative comparison among the priorities, "delivery" and "quality" priorities are pairwise compared. As "delivery" is considered moderately more important over the "quality" a whole number "2" is

Table 4
Calculation of weights of manufacturing priorities

Manufacturing priorities	Cost	Quality	Delivery	Normalized cost	Normalized quality	Normalized delivery	Row sum	Weight
Cost	1.00	2.00	0.50	0.29	0.40	0.25	0.94	0.31
Quality	0.50	1.00	0.50	0.14	0.20	0.25	0.59	0.20
Delivery	2.00	2.00	1.00	0.57	0.40	0.50	1.47	0.49
Column sum	3.50	5.00	2.00				3.00	

Table 5
Weights of machine tool characteristics in manufacturing benefits

Machine tool characteristics	Manufacturing benefits					
	Utilization	Lead time	Lot size	Inventory	Variety of parts	Scrap and rework
Process quality	0.121	0.094	0.076	0.072	0.256	0.598
Actual machining time	0.067	0.456	0.283	0.553	0.060	0.080
Set-up time	0.579	0.303	0.489	0.229	0.093	0.076
Number of operations/parts	0.233	0.146	0.152	0.147	0.591	0.245

entered to the position corresponding to “delivery” row and “quality” column. The reciprocal of the assigned number (i.e. $1/2 = 0.50$) is entered to the position corresponding to “quality” row and “delivery” column. In this study, to get the weight vector the computational procedure described in [8,27] is used. In the procedure, first, the elements of each column of the matrix are divided by the sum of that column (“column sum”) to normalize the pairwise comparisons. The normalized elements are provided in the columns titled “normalized cost”, “normalized quality”, and “normalized delivery” of Table 4. Then, the elements in each resulting row are added (to obtain “a row sum”), and the row sums are divided by 3 (the number of manufacturing priorities being compared) to obtain the weight vector (last column in Table 4).

The AHP approach is also applied to calculate weights of machine tool characteristics at manufacturing benefits (Table 5), weights of machine tool characteristics in quality priority (Table 6), and weights of machine tool alternatives at machine tool characteristics (Table 7).

3.1.2. Calculation of the weights of the interdependent components (benefits)

The three-step ANP algorithm presented in Section 2.2 is applied to calculate the weights of the benefits:

- *Step 1*. Pairwise comparison matrices and corresponding x-vectors are calculated for every cost item and delivery dimension (Appendix A).
- *Step 2*. The contributions of benefits on other benefits are calculated (Appendix B). Each matrix in Appendix B corresponds to a manufacturing benefit and contains the relative contribution of other benefits with respect to each other on the left-out benefit. The eigenvectors of pairwise comparison matrices are calculated and provided under “contribution” heading, and represent $c_{i\to j}$’s given in Eq. (1).
- *Step 3*. The contributions of benefits on other benefits are collected in the contribution matrix (C):

$$
C = \begin{array}{l} \\ \text{Utilization} \\ \text{Lead Time} \\ \text{Lot Size} \\ \text{Inventory} \\ \text{Variety of Parts} \\ \text{Scrap \& Rework} \end{array}
\begin{array}{cccccc} \text{Utilization} & \text{Lead Time} & \text{Lot Size} & \text{Inventory} & \text{Variety of Parts} & \text{Scrap \& Rework} \\
\left|\begin{array}{cccccc}
1.000 & 0.053 & 0.059 & 0.054 & 0.124 & 0.113 \\
0.083 & 1.000 & 0.519 & 0.429 & 0.302 & 0.282 \\
0.108 & 0.481 & 1.000 & 0.317 & 0.453 & 0.043 \\
0.057 & 0.217 & 0.117 & 1.000 & 0.071 & 0.064 \\
0.451 & 0.162 & 0.241 & 0.144 & 1.000 & 0.498 \\
0.302 & 0.087 & 0.065 & 0.056 & 0.050 & 1.000
\end{array}\right| \end{array}
$$

Table 6
Weights of machine tool characteristics in quality priority

Machine tool characteristics	Weight
Process quality	0.54
Actual machining time	0.12
Set-up time	0.07
Number of operations/parts	0.27

Application of Eq. (2) provides the weights of the benefits (z-vector). To illustrate the application, weights of the benefits in direct material cost item are calculated and provided below

$$
z = \begin{vmatrix}
1.000 & 0.053 & 0.059 & 0.054 & 0.124 & 0.113 \\
0.083 & 1.000 & 0.519 & 0.429 & 0.302 & 0.282 \\
0.108 & 0.481 & 1.000 & 0.317 & 0.453 & 0.043 \\
0.057 & 0.217 & 0.117 & 1.000 & 0.071 & 0.064 \\
0.451 & 0.162 & 0.241 & 0.144 & 1.000 & 0.498 \\
0.302 & 0.087 & 0.065 & 0.056 & 0.050 & 1.000
\end{vmatrix}
\times \begin{vmatrix} 0.041 \\ 0.063 \\ 0.166 \\ 0.102 \\ 0.102 \\ 0.526 \end{vmatrix}
= \begin{vmatrix} 0.066 \\ 0.188 \\ 0.151 \\ 0.089 \\ 0.224 \\ 0.283 \end{vmatrix}
$$

Similar calculations are repeated for other cost items and delivery dimensions and their respective z-vectors are obtained (Table 8). Along with z-vectors, weights of cost items and delivery dimensions are also presented in the first row of Table 8.

3.2. Synthesis of the weights to obtain the ranking scores

To calculate weights of manufacturing benefits with respect to delivery and cost priorities Eq. (3) is applied. In

Table 7
Weights of machine tool alternatives in machine tool characteristics

Alternatives	Machine tool characteristics					
	Process quality	Actual machining time	Set-up time	Number of operations/parts	Initial cost	Running cost
Conventional	0.053	0.051	0.060	0.143	0.585	0.600
VTC-200B	0.112	0.153	0.151	0.143	0.259	0.242
FJV-250	0.253	0.240	0.151	0.143	0.108	0.108
VARIAXIS 500	0.582	0.555	0.638	0.571	0.048	0.050

Table 8
Weights of manufacturing benefits in cost items and delivery dimensions

Manufacturing benefits	Cost priority								Delivery priority		
	Direct material	Direct labor	Depreciation on machinery	Mat handling and storage	Production planning	Quality	Machine set-up	Maintenance and supplies	Time from order to delivery	On-time shipments	Shipment accuracy
Weight	**0.040**	**0.030**	**0.059**	**0.020**	**0.009**	**0.020**	**0.010**	**0.013**	**0.548**	**0.241**	**0.211**
Utilization	0.066	0.284	0.239	0.056	0.054	0.070	0.159	0.128	0.070	0.053	0.061
Lead time	0.188	0.160	0.141	0.246	0.328	0.216	0.160	0.158	0.333	0.327	0.238
Lot size	0.151	0.129	0.130	0.221	0.239	0.121	0.196	0.151	0.258	0.253	0.168
Inventory	0.089	0.065	0.058	0.270	0.119	0.098	0.058	0.062	0.139	0.138	0.083
Variety of parts	0.224	0.218	0.248	0.127	0.147	0.200	0.307	0.294	0.133	0.155	0.205
Scrap and rework	0.283	0.143	0.184	0.079	0.112	0.294	0.120	0.117	0.068	0.074	0.246

Table 9
Weights of manufacturing benefits in cost and delivery priorities

	Manufacturing benefits					
	Utilization	Lead time	Lot size	Inventory	Variety of parts	Scrap and rework
Cost priority	0.0314	0.0363	0.0304	0.0186	0.0447	0.0374
Delivery priority	0.0640	0.3115	0.2378	0.1269	0.1535	0.1070

Eq. (3), weight of the jth cost item or delivery dimension given in the first row (in bold) of Table 8 is denoted as X_{1j}, and weight of the ith manufacturing benefit corresponding to the jth cost item or delivery dimension is donated as X_{ij}. U_{ki} represents the weight of the ith manufacturing benefit corresponding to the chosen manufacturing priority (k). The calculated weights of manufacturing benefits in cost and delivery priorities are provided in Table 9:

$$U_{ki} = \sum_{j} X_{ij} X_{1j} \tag{3}$$

The next step is to calculate the weights of machine tool characteristics in manufacturing priorities using Eq. (4). Since weights of machine tool characteristics in quality priority are already calculated and provided in Table 6, calculations are necessary for only delivery and cost priorities. In Eq. (4), K_{mi} represents the weight of the mth machine tool characteristic corresponding to manufacturing benefit i (Table 5). The outcome of Eq. (4), weight of the mth manufacturing benefit corresponding to the kth cost item or delivery dimension, is denoted as L_{mk}:

$$L_{mk} = \sum_{i} K_{mi} U_{ki} \tag{4}$$

The calculated weights of machine tool characteristics in manufacturing priorities are shown in Table 10. To incorporate the expenses the weight of initial and running costs are also included in Table 10.

Finally, the ranking scores of alternatives are calculated by combining the weights of alternatives in machine

Table 10
Weights of machine tool characteristics in manufacturing priorities

Machine tool characteristics	Manufacturing priorities		
	Cost	Delivery	Quality
Process quality	0.0447	0.1675	0.5400
Actual machining time	0.0432	0.3016	0.1220
Set-up time	0.0553	0.2992	0.0710
Number of operations/parts	0.0556	0.2321	0.2670
Initial cost	0.7200		
Running cost	0.0800		

Table 11
Ranking scores of machine tool alternatives

	Manufacturing priorities[a]			Ranking scores
	Cost (0.31)	Quality (0.20)	Delivery (0.49)	
Conventional	0.49	0.08	0.08	0.20
VTC-200B	0.23	0.13	0.14	0.17
FJV-250	0.12	0.21	0.19	0.18
VARIAXIS 500	0.16	0.58	0.59	0.45

[a] Values in parenthesis refer to weight.

tool characteristics (Table 7) with the weights of machine tool characteristics in manufacturing priorities (Table 10). Table 11 presents the ranking scores of the machine tool alternatives. The greater the ranking score of an alternative, the greater the preference for that alternative. The alternative with the highest ranking score is selected for recommendation to the company management.

3.3. Discussion of the results

For this illustrative case study, VARIAXIS 500 is recommended for the manufacturing company. The ranking scores of other alternatives are very low indicating their low contribution to the manufacturing strategy of the company. VARIAXIS 500 dominates other alternatives in spite of its high initial and running costs. The ranking scores of the other three alternatives are very close to each other. Conventional machine tool is the second best choice because of the impact of its low initial and running costs on the cost priority. The company management found the results of the AHP application consistent with their findings. It is noted that when the company considers the quality or delivery priorities more critical than the cost priority, VARIAXIS 500 will always be preferred over others. The only situation where another alternative, namely conventional machine tool, is preferred over VARIAXIS 500 is that cost priority dominates other priorities in its contribution to the competitiveness of the company. Such a case is quite possible when similar types of products are produced over the years and price is critical in the preference of the company's customers.

During the implementation of the proposed approach, the company management had difficulties in making pairwise comparisons. For the management to answer pairwise comparison questions the quantities of the components being compared must be presented. The company management saw the proposed AHP/ANP approach as a systematic decision-making tool to determine the strategic implications of machine tool selection decision and an improvement over individually-developed ways that are currently used in the company. The management also found the strategic justification tool more suitable as a group decision-making tool and the input from various departments especially necessary to perform pairwise comparisons correctly.

4. Concluding remarks

The ranking scores are the outcomes of the approach, and by definition a ranking score show the contribution of an alternative to the manufacturing strategy of a manufacturing firm. The user can obtain not only a ranking of the alternatives but also the degree of dominance among the alternatives using the scores. As the difference between two scores gets larger, the attractiveness of the higher-scored alternative, and consequently its dominance, increases compared to the lower-scored alternative.

The application of the model also provides the weights for the components of the decision hierarchies. The firm can follow through the calculations and see the contributions of any component in the ranking scores. The components whose weights are high (above a certain threshold value determined by the firm) can be considered as critical ones; and the alternatives that score low in the critical components can be directly eliminated from further consideration. Such a two-level approach can especially be useful when the number of alternatives is higher than seven alternatives. In the literature, it is advised that less than seven alternatives should be pairwise compared to keep track of the pairwise comparisons previously made by the user.

Although the approach can be used alone as shown in the illustrative example, it can easily be integrated with other approaches. For example, the presented strategic justification approach and economic analysis can be integrated in a two-phase machine selection framework. In such a two-phase process for machine selection, an economic analysis can be performed to reduce the number of potential alternatives to a manageable size in the first phase. Phase 2 may involve performing a detailed strategic analysis using the developed AHP/ANP model to select the most suitable one among the remaining alternatives. In a different possible application, the outcomes of the AHP/ANP approach can be input in a multi-objective mathematical programming application as weighting or a preference vector for machine tool alternatives (coefficients of the objective function). Such a combined model can consider resource limitations in the selection process and guarantees a feasible solution [23]. Badri [5,6] Ghodsypour and O'Brien [13], Schniederjans and Garvin [23] and Suresh and Kaparthi [25] illustrate the integration of the AHP approach with multi-objective mathematical programming approaches.

To conclude, once properly introduced and implemented in a manufacturing company, the AHP/ANP approach provides a structure to the inclusion of strategic considerations by linking the machine tool alternatives and the manufacturing strategy. Furthermore, inclusion and quantification of the interdependencies that exist among manufacturing benefits using the ANP approach is an important contribution to the machine tool selection literature. Incorporation of interdependencies resulted in increases in the weights of the manufacturing benefits which contribute to other benefits.

Appendix A

Pairwise comparison matrices and x-vectors of manufacturing benefits for cost items and delivery dimensions

Benefits	Utilization	Lead time	Lot size	Inventory	Variety of parts	Scrap and rework	x-Vector
Direct material							
Utilization	1.00	0.50	0.25	0.33	0.33	0.13	0.04
Lead time	2.00	1.00	0.33	0.50	0.50	0.14	0.06
Lot size	4.00	3.00	1.00	2.00	2.00	0.20	0.17
Inventory	3.00	2.00	0.50	1.00	1.00	0.17	0.10
Variety of parts	3.00	2.00	0.50	1.00	1.00	0.17	0.10
Scrap and rework	8.00	7.00	5.00	6.00	6.00	1.00	0.53
Direct labor							
Utilization	1.00	5.00	7.00	9.00	6.00	6.00	0.53
Lead time	0.20	1.00	3.00	5.00	2.00	2.00	0.17
Lot size	0.14	0.33	1.00	1.00	0.50	0.50	0.05
Inventory	0.11	0.20	1.00	1.00	0.33	0.33	0.04
Variety of parts	0.17	0.50	2.00	3.00	1.00	1.00	0.10
Scrap and rework	0.17	0.50	2.00	3.00	1.00	1.00	0.10
Depreciation on machinery							
Utilization	1.00	5.00	5.00	7.00	3.00	3.00	0.42
Lead time	0.20	1.00	1.00	2.00	0.50	0.33	0.08
Lot size	0.20	1.00	1.00	3.00	0.33	0.33	0.08
Inventory	0.14	0.50	0.33	1.00	0.25	0.20	0.04
Variety of parts	0.33	2.00	3.00	4.00	1.00	0.50	0.16
Scrap and rework	0.33	3.00	3.00	5.00	2.00	1.00	0.22
Material handling and storage							
Utilization	1.00	0.33	0.33	0.13	1.00	0.50	0.05
Lead time	3.00	1.00	0.50	0.25	3.00	3.00	0.15
Lot size	3.00	2.00	1.00	0.33	3.00	3.00	0.19
Inventory	8.00	4.00	3.00	1.00	8.00	6.00	0.47
Variety of parts	1.00	0.33	0.33	0.13	1.00	0.33	0.05
Scrap and rework	2.00	0.33	0.33	0.17	3.00	1.00	0.09
Production planning							
Utilization	1.00	0.13	0.25	0.33	0.50	0.33	0.04
Lead time	8.00	1.00	4.00	5.00	5.00	3.00	0.45
Lot size	4.00	0.25	1.00	2.00	3.00	2.00	0.19
Inventory	3.00	0.20	0.50	1.00	2.00	0.50	0.10
Variety of parts	2.00	0.20	0.33	0.50	1.00	0.33	0.07
Scrap and rework	3.00	0.33	0.50	2.00	3.00	1.00	0.15
Quality							
Utilization	1.00	0.25	0.50	0.33	2.00	0.11	0.05
Lead time	4.00	1.00	3.00	2.00	4.00	0.20	0.18
Lot size	2.00	0.33	1.00	0.50	2.00	0.13	0.07
Inventory	3.00	0.50	2.00	1.00	2.00	0.17	0.11
Variety of parts	0.50	0.25	0.50	0.50	1.00	0.13	0.04
Scrap and rework	9.00	5.00	8.00	6.00	8.00	1.00	0.54
Machine set-up							
Utilization	1.00	5.00	2.00	6.00	0.50	2.00	0.24
Lead time	0.20	1.00	0.25	2.00	0.17	0.33	0.05
Lot size	0.50	4.00	1.00	4.00	0.33	1.00	0.15

Appendix A (*Continued*)

Benefits	Utilization	Lead time	Lot size	Inventory	Variety of parts	Scrap and rework	*x*-Vector
Inventory	0.17	0.50	0.25	1.00	0.14	0.25	0.04
Variety of parts	2.00	6.00	3.00	7.00	1.00	4.00	0.39
Scrap and rework	0.50	3.00	1.00	4.00	0.25	1.00	0.13
Machine maintenance and supplies							
Utilization	1.00	4.00	9.00	8.00	1.00	6.00	0.37
Lead time	0.25	1.00	4.00	4.00	0.20	2.00	0.12
Lot size	0.11	0.25	1.00	0.50	0.13	0.33	0.03
Inventory	0.13	0.25	2.00	1.00	0.13	0.33	0.04
Variety of parts	1.00	5.00	8.00	8.00	1.00	3.00	0.34
Scrap and rework	0.17	0.50	3.00	3.00	0.33	1.00	0.09
Time between order and delivery							
Utilization	1.00	0.14	0.25	0.33	2.00	3.00	0.08
Lead time	7.00	1.00	3.00	4.00	6.00	7.00	0.45
Lot size	4.00	0.33	1.00	2.00	3.00	5.00	0.22
Inventory	3.00	0.25	0.50	1.00	2.00	4.00	0.14
Variety of parts	0.50	0.17	0.33	0.50	1.00	1.00	0.06
Scrap and rework	0.33	0.14	0.20	0.25	1.00	1.00	0.05
On-time shipments							
Utilization	1.00	0.13	0.25	0.25	0.33	0.50	0.04
Lead time	8.00	1.00	3.00	3.00	4.00	6.00	0.43
Lot size	4.00	0.33	1.00	2.00	2.00	2.00	0.19
Inventory	4.00	0.33	0.50	1.00	1.00	3.00	0.15
Variety of parts	3.00	0.25	0.50	1.00	1.00	2.00	0.12
Scrap and rework	2.00	0.17	0.50	0.33	0.50	1.00	0.07
Shipment accuracy							
Utilization	1.00	0.17	0.25	0.50	0.33	0.11	0.04
Lead time	6.00	1.00	2.00	3.00	3.00	0.33	0.22
Lot size	4.00	0.50	1.00	3.00	2.00	0.25	0.15
Inventory	2.00	0.33	0.33	1.00	0.50	0.20	0.07
Variety of parts	3.00	0.33	0.50	2.00	1.00	0.20	0.09
Scrap and rework	9.00	3.00	4.00	5.00	5.00	1.00	0.44

Appendix B

Calculation of contributions of manufacturing benefits

Benefits	Lead time	Lot size	Inventory	Variety of parts	Scrap and rework	Contribution
Contributions of other benefits on utilization						
Lead time	1.000	0.500	2.000	0.200	0.250	0.083
Lot size	2.000	1.000	2.000	0.200	0.250	0.108
Inventory	0.500	0.500	1.000	0.167	0.200	0.057
Variety of parts	5.000	5.000	6.000	1.000	2.000	0.451
Scrap and rework	4.000	4.000	5.000	0.500	1.000	0.302
Contributions of other benefits on lead time						
Lead time	1.000	0.167	0.250	0.250	0.500	0.053
Lot size	6.000	1.000	4.000	3.000	5.000	0.481
Inventory	4.000	0.250	1.000	2.000	3.000	0.217

Appendix B (*Continued*)

Benefits	Lead time	Lot size	Inventory	Variety of parts	Scrap and rework	Contribution
Variety of parts	4.000	0.333	0.500	1.000	2.000	0.162
Scrap and rework	2.000	0.200	0.333	0.500	1.000	0.087
Contributions of other benefits on lot size						
Lead time	1.000	0.143	0.333	0.250	1.000	0.059
Lot size	7.000	1.000	6.000	3.000	6.000	0.519
Inventory	3.000	0.167	1.000	0.333	2.000	0.117
Variety of parts	4.000	0.333	3.000	1.000	4.000	0.241
Scrap and rework	1.000	0.167	0.500	0.250	1.000	0.065
Contributions of other benefits on inventory						
Lead time	1.000	0.143	0.167	0.333	1.000	0.054
Lot size	7.000	1.000	2.000	3.000	6.000	0.429
Inventory	6.000	0.500	1.000	3.000	6.000	0.317
Variety of parts	3.000	0.333	0.333	1.000	3.000	0.144
Scrap and rework	1.000	0.167	0.167	0.333	1.000	0.056
Contributions of other benefits on variety of parts						
Lead time	1.000	0.333	0.250	2.000	3.000	0.124
Lot size	3.000	1.000	0.500	5.000	6.000	0.302
Inventory	4.000	2.000	1.000	7.000	6.000	0.453
Variety of parts	0.500	0.200	0.143	1.000	2.000	0.071
Scrap and rework	0.333	0.167	0.167	0.500	1.000	0.050
Contributions of other benefits on scrap and rework						
Lead time	1.000	0.250	3.000	3.000	0.167	0.113
Lot size	4.000	1.000	6.000	6.000	0.333	0.282
Inventory	0.333	0.167	1.000	0.500	0.125	0.043
Variety of parts	0.333	0.167	2.000	1.000	0.167	0.064
Scrap and rework	6.000	3.000	8.000	6.000	1.000	0.498

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