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Evaluating the Effectiveness of Strategic Decisions at Various Levels of Manufacturing Strategy: A Quantitative Method

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Abstract: Many structured formulations for manufacturing strategy have been developed to now, but the evaluation methods for the strategic decisions are specifically considered in few of them. Some of the evaluation methods propose the use of Importance-Performance matrix to prioritize the strategic decisions concerned, but these do not represent quantitative measures for effective comparison between those priorities. In this study, considering the use of I-P matrix in formulating manufacturing strategy, a quantitative method has been proposed to evaluate the effectiveness of the strategic decisions at various levels of manufacturing strategy. In order to quantify the measure of the matrix, a multiple-input-single-output fuzzy model has been developed which uses experts' judgments to determine membership functions and the corresponding rules. To demonstrate the application of the model it has been programmed using MATLAB fuzzy toolbox. The study further describes the use of the method through a numerical example.

Key words: Manufacturing strategy · Decision making · Importance-performance matrix · Fuzzy modeling

INTRODUCTION

Skinner [1] in his study set out the importance of explicit linkage between manufacturing choices and the firm's success in the marketplace. Since then considerable attention was given to various aspects of manufacturing strategy including its formulation process, from which we may refer to some publications such as [2], [3] and [4]. Also some of the authors have considered the implementation process as well as decision making methods at various levels of the strategy development [5-8].

Dangayach and Deshmokh [9] reviewing a vast amount of the literature in manufacturing strategy identified two major groups of content and process related issues. They also stressed on the need for further research regarding decision making functions required in the manufacturing strategy development.

While manufacturing strategy development is mainly a qualitative process in nature, as supported by the literature, quantitative methods are needed to support some of the decision making functions in this process. Therefore, based on this finding a research work was conducted aiming to develop quantitative methods to help some decision making activities within the manufacturing strategy.

This study, while briefly describes the manufacturing strategy process considered in this work, more specifically, discusses two of the methods developed to quantify some decision making activities concerned in this process.

The first method is concerned with quantifying the Importance-Performance (I-P) matrix which is a well-known qualitative method for prioritizing improvement activities regarding identified critical success factors for any firm [10]. In this respect a Multiple-Input-Single-Output (MISO) fuzzy model has been developed which uses experts' judgments to determine membership functions and corresponding inference rules.

While the above mentioned method has been detailed in a next section, a second method which is developed to evaluate the potential effectiveness of decision areas and to assess critical success factors Performance and Improvement Priority in holistic way is discussed in short in this study.

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CONCEPTUAL FRAMEWORK

As described by Wheelwright [11] and many other authors, there are 3 main levels of strategy: corporate strategy, business strategy and functional strategy. Manufacturing strategy as a functional strategy and in conjunction with the two other levels of the strategy, reconciles market requirements with the operations resources within the manufacturing system [12].

Between existing manufacturing strategy frameworks and processes published in the literature [2-6, 12, 13] we considered in this study, the framework proposed by Platts and Gregory [4], consists of three following main stages:

Stage 1: Understanding business marketplace,

Stage 2: Assessing manufacturing performance,

Stage 3: Developing Manufacturing Strategy.

Stage 1, through the analysis of the business market place, involves managers listing the competitive criteria/ CSFs for the product, or family of products, under consideration and assigning "relative importance" scores to each.

Having interpreted CSFs at the manufacturing system level, stage 2 mainly concerns with the assessment of the manufacturing system performance with regard to these criteria and against managers general view of competitor's performance.

Stage 3 audits the current practice of the operation in various areas of activity and asks managers to estimate the degree of influence each activity area has over the achievement of required performance for each CSF. Finally, all these analyses are considered together in order to identify any mismatches between the relative importance of each CSF and the achieved performance for each. Action plans are developed based on these mismatches.

One of the more significant activities in the operations strategy formulation process is the derivation of a list of CSFs which is prioritized. The list of ranked CSFs can be used to help determine strategic improvement priorities among CSFs. This approach typically involves comparing the importance rating of each CSF with some concept of its required performance [10].

In this study we focus on the stages 2 and 3 of the Platts and Gregory formulation. So, in the process of manufacturing strategy formulation, we consider that all SBUs of the company and its CSFs had been identified and for a given SBU, managers had encountered to assess manufacturing system performance and select strategic action plans.

Let us consider a hierarchical way -like as Quezada *et al*. [13] - which a SBU with its CSFs and manufacturing Decision Areas (DAs) are identified at the first stage. We consider manufacturing DAs as proposed by many researches [7, 11], to include: facilities, capacity, process and technology, vertical integration, quality management, human resource management, control systems, management of suppliers and product design. Further, to link the manufacturing strategy process in depth with the operations, a second level of manufacturing (for instance assembly shop, machine shop, etc) can also be considered in this process (Fig. 1).

In the first step of the proposed method, we start by determining importance of eachCSF using a 7-point scale with the range of [-3 3].

I_i: Importance of i_{th} CSF.

To assess performance of each CSF, in step 2, we define a measure to compute the effectiveness of DAs. In this step the relative contribution of each DA to each CSF is defined which represents the support given by each DA to each CSF. In section 4 a method has been developed to evaluate potential effectiveness of decision areas and assess the performance of CSFs.

Based on comparing the importance rating of each CSF (I_i) with its current performance (P_i), step 3 prioritizes CSFs to help determine the improvement priorities among CSFs.

Ip_i: Improvement Priority of i_{th} CSF.

For this purpose, there is a well-known Importance–Performance Matrix, but as the general form of I-P matrix is a qualitative method, in section 3 a method has been developed which quantifies the I-P matrix using fuzzy system modeling.

Also, in this step, current situation of the total improvement priority of SBU has been measured using an index.

$$\mathrm{TIP}_0 = \sum_i \mathrm{IP}_i$$

TIP_0=Total Improvement Priority index for the current situation.

In step 4, an analysis is undertaken for the SBU not only based on the improvement priorities of CSFs but also on the potential effectiveness of DAs determined in previous steps and managers propose appropriate action plans to implement. To determine a range of more effective action plans, also Tan and Platt's method [14] could be a comprehensive method which uses AHP technique in the process of generation of alternative plans.

As if a given action plan is implemented, some performances of DAs related to CSFs would be changed and so on the total improvement priority of SBU.

The change in this index has a measure to rank action plans. In this regard, the more improvement in the performance using the appropriate action plan, the more reduction in improvement priority of CSFs.

Like as the Quezada *et al*. method [7] to establishment of action plans, this is done using the following procedure:

1. Take one action plan.
2. Investigate how the performance of the DAs is changed if this action plan is implemented (managers were asked to consider the new performances).
3. Calculate a new total improvement priority Index.

Let TIP_m= Total Improvement Priority index if action plan m is implemented.

ΔTIP_m=Change in TIP due to implementation m_{th} action plan (n: number of action plans).

A weight for m_{th} action plan is defined as

$$R_m = \frac{\Delta \mathrm{TIP}_m}{\sum_n \Delta \mathrm{TIP}_m}$$

which is used to rank action plans.

DEVELOPMENT OF A QUANTIFIED IMPORTANCE-PERFORMANCE (I-P) MATRIX

In this section we first review the general form of the I-P matrix and then we describe the proposed quantified I-P matrix.

The General Form of the I-P Matrix: Prioritization of the required improvements in relation to given CSFs is an important activity in the manufacturing strategy formulation processes. The use of I-P matrix has been suggested for this purpose by many authors including Hill [2] and Platts and Gregory [4]. Using this matrix, the improvement priority regarding each critical success factor is obtained based on corresponding importance and performance measures (Fig. 2). In this method, for any given CSF, both importance and performance values are judged, for instance using simple 9-point scales, while the matrix is divided into zones of improvement priorities [10, 12]. Four resulted zones which imply distinctive priorities are briefly described below.

Performance with regard to any CSF, when located in the 'Appropriate' zone is considered to be satisfactory at least in a short-to-medium term. This performance however, in a long term will be wished to edge towards the upper boundary of the zone. Any factor which falls in the 'Improve' zone has achieved poor performance, but it doesn't mean that it has the first priority for improvement. Certainly, in medium term it would need to be improved up to the lower bound of the appropriate zone.

Factors located in the 'Urgent Action' zone are the most critical factors to be improved, due to their being high in importance; but their achieved performance being far below that it ought to be. So in the short term those performances need to be improved up to the lower bound of the improve zone. Finally if the achieved performance for any factor is above its required level, it lies in the 'Excess?' zone.

This general form of the I-P matrix as described in many references, [10] and [12], indicates that it can only classify factors into the defined zones of the matrix and no measurable index is assigned to those priorities. Consequently, all factors falling in the same zones are given the same degrees of improvement priority. Thus, it would be too difficult to imply a ranked list of factors.

Proposed Quantified I-P Matrix: Compared to traditional mathematical modeling methods, fuzzy system modeling possesses some distinctive advantages such as the mechanism of reasoning in human understandable terms and the ability of taking linguistic information from human experts and combining it with numerical data [15].

Since the importance and the performance are the two linguistic input variables of the I-P matrix and the Action Preference (Improvement Priority (IP)) is the only output from this matrix, a rule format can be used to represent the relationship between those inputs and the output. It is assumed that input variables are determined using a 7-point scale with the range of the inputs being [-3 3] and the output variable IP is determined using a 9-point scale with the range of [-4 4]. Having identified relevant input and output variables of the system together with ranges of their values, selection of meaningful linguistic states for each variable is the next step. These states need to be expressed as an appropriate fuzzy set format. Linguistic

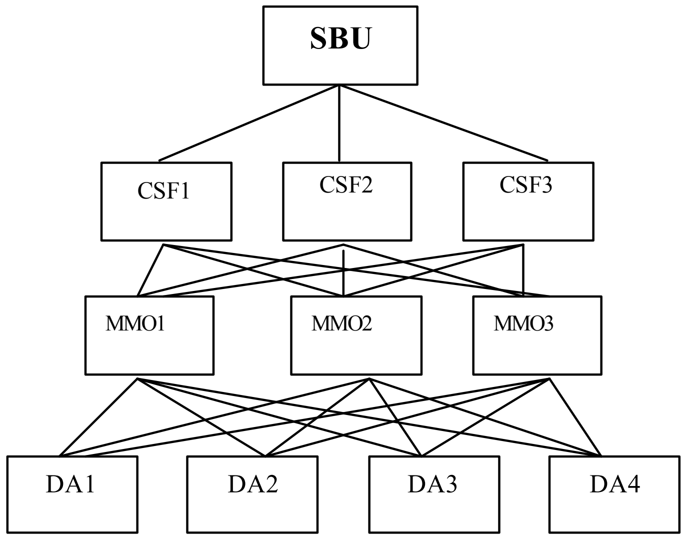

Fig. 1: Proposed Hierarchical Structure of Decision Making

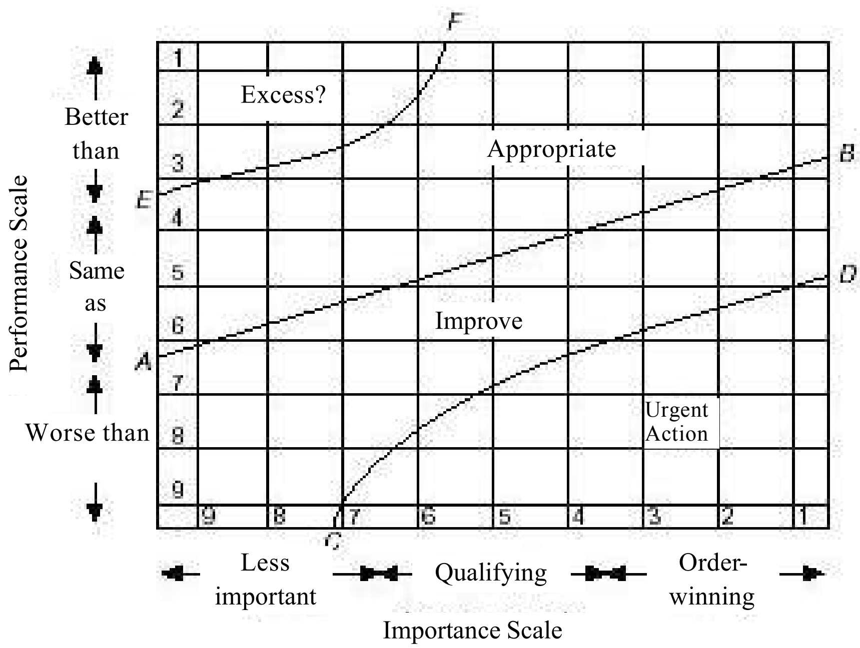

Fig. 2: Importance-Performance Matrix

states for these input/output variables are described in Table 1.

Representing linguistic states of input variables by triangular-shape fuzzy numbers, equally spread over each range, the fuzzy quantization is obtained. This is exemplified for the importance and performance variables in Fig. 3 and 4 respectively. Further, triangular-shape fuzzy numbers for the IP variable are showed in Fig. 5.

According to some experts [16, 17] the triangular shapes are chosen as preliminary candidates, so, it is possible for future work to modify them by appropriate learning methods, often implemented by neural networks.

In the next step, the knowledge pertaining to the matrix is formulated in terms of a set of fuzzy inference rules. In this model inference rules have the canonical form:

If Importance=A and Performance=B then IP=C.

Where A, B and C are fuzzy numbers chosen from the set of fuzzy numbers that represent their relative states. Since each input variable has seven linguistic states, the total number of possible non conflicting fuzzy inference rules is $7_*7=49$. To establish relations between input and output variables of the matrix for a set of fuzzy rules, we asked some experts to identify a reasonable output for each possible rule. Then a generalized fuzzy mean function is applied to experts' judgments about the output of each rule.

In the next step, in order to combine measurements of input variables properly with relevant fuzzy information rules to build inferences regarding the output variable, Mamdani type of inference [18] is used as an individual-rule base inference system. In the last step, defuzzification method needs to be applied. This is to convert each conclusion obtained by the inference engine, which is expressed in terms of a fuzzy set to a single real number indicating measure of Improvement Priority for a given factor. From those methods which are proposed in the literature [16], gravity method was selected.

To demonstrate the application of the model, it is programmed using MATLAB fuzzy toolbox. Figure 6 shows the results for a specific example. In this example, we assume that there are three CSFs namely: quality, flexibility and cost identified for the given company. To determine the importance and performance of each CSF, some managers and experts in the company were asked each to record an importance value for each CSF using a 7-point scale with the range -3 to +3. They were also asked to record performance measure values with regard to each CSF on the benchmarking basis using the same 7-point scale. Results after using a geometric mean on the given values are:

Quality-Importance= 2.55
Quality-Performance= -1.51
Flexibility-Importance= 2.76
Flexibility-Performance= -2.35
Cost-Importance= 1.74
Cost-Performance= -1.14

Using a general form of the I-P matrix for these results, the matrix indicates 'urgent action priority' required for both quality and flexibility while the category of 'improve priority' is specified for the cost factor.

To compare the two methods, we entered the above importance and performance values for the flexibility factor in the proposed model and the result indicated 'Improvement Priority value' equal to 2.77 (assuming a range of -4 to +4).

Results from the proposed model are illustrated in Fig. 6. First and second columns represent the two input variables, while the importance and performance values are shown by the two vertical lines in the column for each variable. The third column shows the output result. So each row represents a specific rule in the model. Based on these input values four rules are fired in the model and finally, using the defuzzification method, the output of the model for flexibility is obtained as 2.77 for this example.

Repeating this process for quality and cost factors, their Improvement Priority values were obtained equal to 2.04 and 1.19 respectively.

Thus, the example illustrated the capability of the proposed model to quantitatively rank CSFs for improvement based on their Improvement Priorities.

With regard to the proposed model, we can also conclude that whilst it is possible to change used fuzzy sets of inputs and output as well as the consequence of each rule as regard to experts' opinions, the model possesses some level of flexibility to adopt expectations of various companies based on their requirements.

Table 1: Linguistic states for input and output variables

Importance	Very Low(VL)	Low(L)	Slightly Low(SL)	Medium (M)	Slightly High(SH)	High(H)	Very High(VH)		
	-3	-2	-1	0	1	2	3		
Performance	Very Bad(VB)	Bad(B)	Slightly Bad(SB)	Medium (M)	Slightly Good(SG)	Good (G)	Very Good(VG)		
	-3	-2	-1	0	1	2	3		
IP	Ninth IP	Eighth IP	Seventh IP	Sixth IP	Fifth IP	Forth IP	Third IP	Second IP	First IP
	-4	-3	-2	-1	0	+1	+2	+3	+4

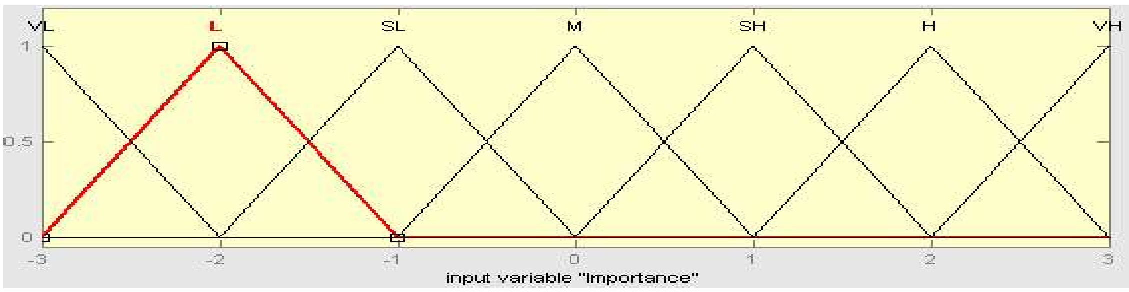

Fig. 3: Triangular fuzzy membership functions of Importance Variable

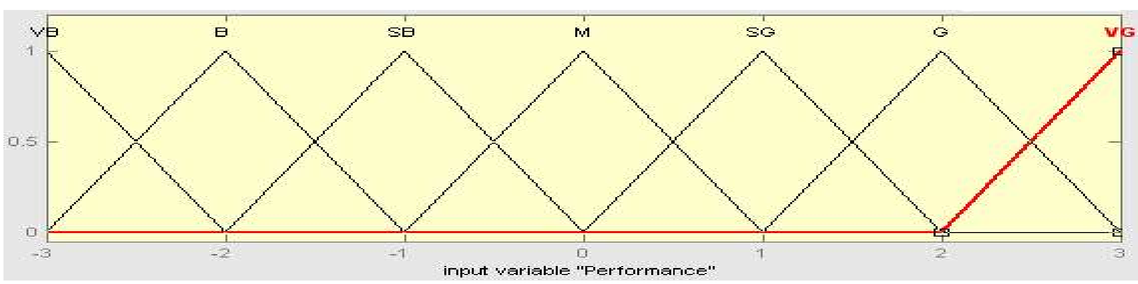

Fig. 4: Triangular fuzzy membership functions of Performance Variable

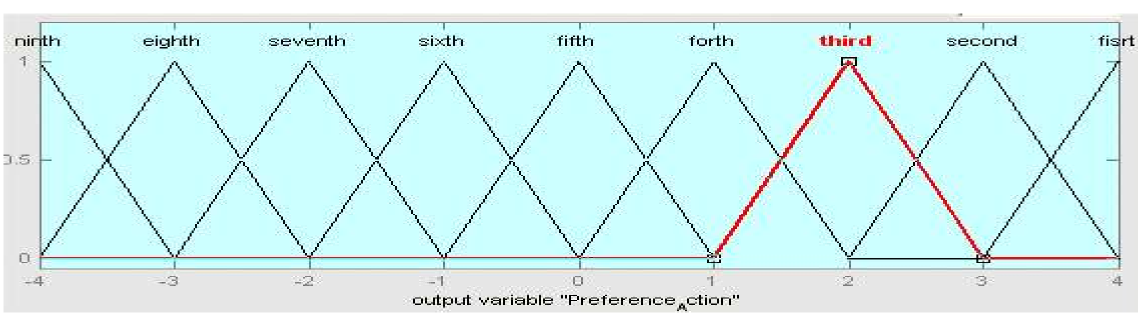

Fig. 5: Triangular fuzzy membership functions of Improvement Priority Variable

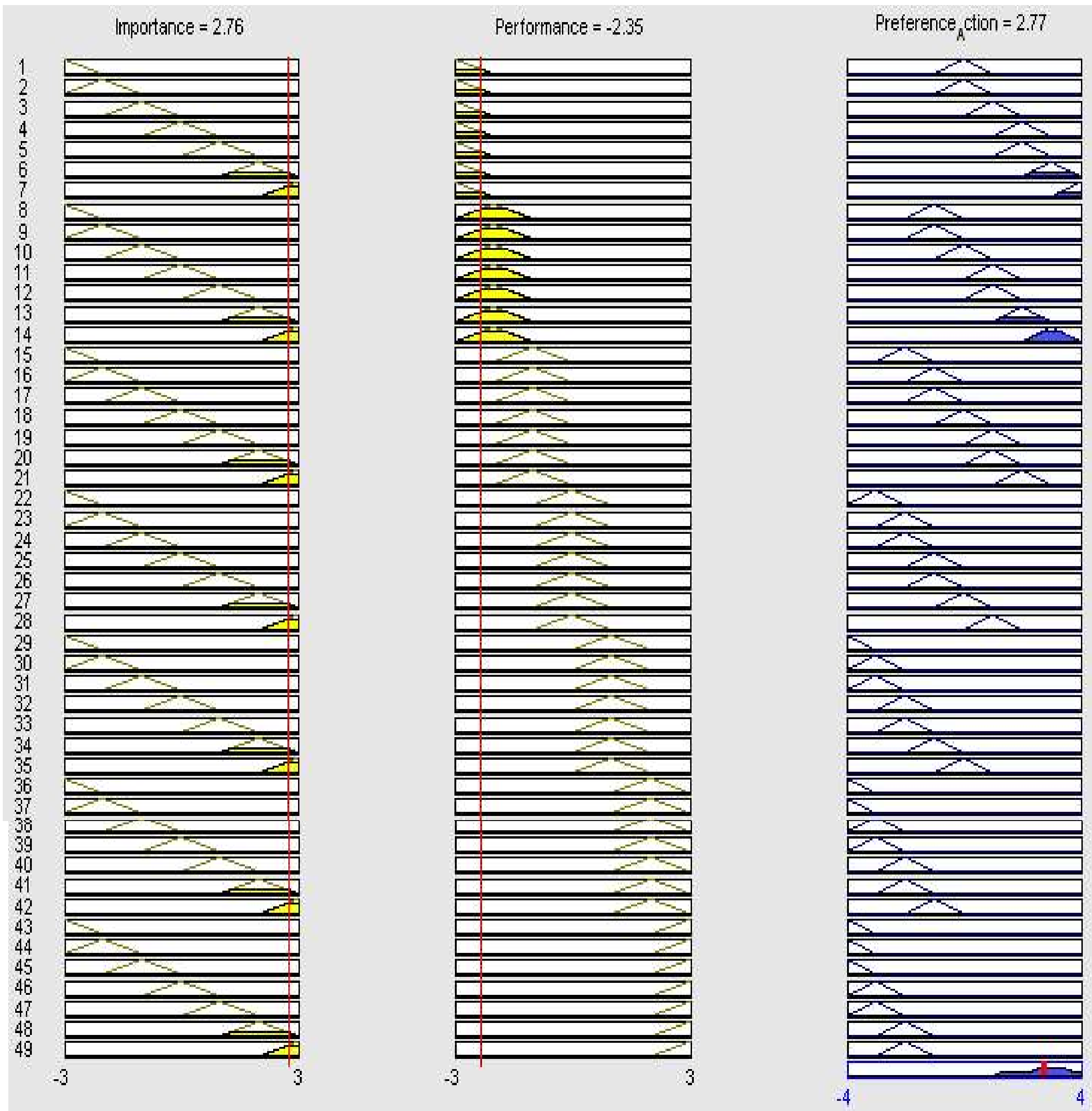

Fig. 6: Sample Result of the Model

EVALUATION OF THE POTENTIAL EFFECTIVENESS OF DECISION AREAS FOR IMPROVEMENT

As mentioned in section 2, we consider the overall manufacturing system consisting of a number of Manufacturing Major Operations (MMOs). These include for instance: assembly shop, machine shop, sub assembly, painting and so on (or in general plant1, plant2, etc). Having defined this level of major operations, decision areas are also to be considered for each of these MMOs within the manufacturing system. Figure 1 depicts this concept in a hierarchical structure, where for instance for a given SBU, 3 CSFs related to 3 manufacturing major operations and 4 manufacturing decision areas (for each manufacturing major operation) have been considered as a case.

Using pair wise comparisons at the manufacturing major operations level, relative weight for each MMO to support a given CSF is determined through an evaluation process by a group of managers. Repeating the process for each CSF, relative weights for MMOs are then obtained:

W_{ij}: relative weight of j_{th} manufacturing major operation to support i_{th} CSF

$$\text{For } \forall i \ \sum_{j} W_{ij} = 1$$

Then at a lower level, the previous process is repeated for the Decision Areas (DAs) related to each MMO considering any CSF identified for the given MMO. Through this process those DAs related to a given MMO are compared to determine their relative supporting weight with respect to any given CSF.

W_{ijk}: relative weight of k_{th} DA of j_{th} manufacturing major operation to support i_{th} CSF

$$\text{For } \forall i, j \sum_{k} W_{ijk} = 1$$

Finally, effectiveness measure of each DA with respect to each MMO on each CSF is defined as:

$$E_{ijk} = W_{ijk*} W_{ij}$$

E_{ijk}: Effectiveness of k_{th} DA of j_{th} manufacturing major operation on i_{th} CSF

To assess the current performance of each CSF, managers are asked to score the current performance of each DA of manufacturing major operations with respect to the given CSF.

P_{ijk}: current performance of k_{th} DA of j_{th} manufacturing major operation with respect to i_{th} CSF

And so:

$$P_i = \sum_{j} \sum_{k} \left(P_{ijk} \times E_{ijk} \right)$$

P_i = Current performance of i_{th} CSF.

Entering the I_i and P_i of each i_{th} CSF to the proposed quantified I-P matrix, the Improvement Priority of i_{th} CSF (IP_i) is achieved by the model.

NUMERICAL EXAMPLE

To demonstrate the usability of the methods, in this section we introduce a numerical example. Let us propose that a company has decided to release a manufacturing strategy for its exporting products as an important SBU and it has 2 CSFs (Delivery Speed and Price).

Step 1: Some managers of the company have defined the importance of delivery speed and price using a 7-point scale with the range -3 to +3. Using a geometric mean on the results shows:

$$I_1 = 2.55 \text{ and } I_2 = 2.76$$

Step 2: Consider 2 plants of the company as the MMOs and Facilities, Capacity and Process as 3 main DAs.

Using pair wise comparisons respect to the Delivery Speed at the MMOs level, relative weight for plant1 and plant2 to support Delivery Speed is determined through an evaluation process by a group of managers. Repeating the process for Price, relative weights (W_{ij}) are then obtained and described in Table 2.

The previous process is repeated for the DAs related to each MMO considering any CSF identified for the given MMO. Through this process those DAs related to a given MMO are compared to determine their relative supporting weight with respect to any given CSF. Relative weights (W_{ijk}) are then obtained and described in Table 3.

The effectiveness measure of each DA with respect to each MMO on each CSF is calculated by multiplying two previous measures (Table 4). Table 5 shows the current performance of DAs of each MMO with respect to each CSF defined by managers (P_{ijk}). The current performances of Delivery Speed and Price are calculated as:

$$P_1 = -0.21, P_2 = -0.128$$

Table 2: Relative weights of manufacturing major operations to support CSFs

W_{ij}	Plant1	Plant 2	Total
Delivery Speed	0.6	0.4	1
Price	0.3	0.7	1

Table 3: Relative weight of DAs of manufacturing major operations to support CSFs

W_{1jk} (Delivery Speed)	Facilities	Capacity	Process	Total
Plant1	0.2	0.3	0.5	1
Plant2	0.3	0.3	0.4	1
W_{2jk} (Price)	Facilities	Capacity	Process	Total
Plant1	0.7	0.1	0.2	1
Plant2	0.4	0.2	0.4	1

Table 4: The effectiveness measure of DAs with respect to MMOs on CSFs

E_{1jk}(Delivery Speed)	Facilities	Capacity	Process
Plant1	0.12	0.18	0.3
Plant2	0.12	0.12	0.18
E_{2jk}(Price)	Facilities	Capacity	Process
Plant1	0.21	0.03	0.06
Plant2	0.28	0.14	0.28

Table 5: The current performance of DAs of MMOs with respect to CSFs

P_{1jk}(Delivery Speed)	Facilities	Capacity	Process
Plant1	2.2	-1.5	-0.3
Plant2	1.2	1.6	-2.5
P_{2jk}(Price)	Facilities	Capacity	Process
Plant1	1.5	1.3	0.6
Plant2	-2.3	0.7	0.1

Step 3: The outputs of entering $I_1$and P_1 and I_2 and P_2 to the proposed quantified I-P matrix are the Improvement Priority of Delivery Speed and Price:

$$IP_1=2.11, IP_2=0.46$$

Consequently Priority of Delivery Speed is more than the Price and as a result, the selected action plans should maybe improve performance of DAs of this CSF. Total Improvement Priority index for the current situation (TIP_0) is equal to 2.57.

Step 4: Let us assume that managers based on the external analysis and previous results propose two Action plans to implement and their expectations from the changed performance of DAs after implementing of each action plan are asked.

For action plan1, using the proposed quantified I-P matrix again with new expected Performances and previous Importance of each CSF as input variables, the new Improvement Priority of Delivery Speed and Price are calculated:

$$IP_1=1.3, IP_2= -1.4 \text{ and } TIP_1= -0.1$$

The previous process is repeated for the action plan2:

$$IP_1=-0.3, IP_2= -0.25 \text{ and } TIP_2= -0.55$$

The change in TIP due to implementation of action plan1 is: ΔTIP_1=2.57-(-0.1) =2.67 and change in TIP due to implementation of action plan2 is: ΔTIP_2=2.57-(-0.55) =3.12.

Based on the resulted R_1=0.46 and R_2=0.54, it seems that action plan2 is more appropriate to implement rather than action plan2 because its improving effects on the performance of DAs will decrease Improvement Priorities of CSFs more.

CONCLUSIONS

Manufacturing strategy reconciling operations resources with the market requirements highly affects the success of the firms in the market. The vast amount of the literature in manufacturing strategy suggests the need for further work regarding decision makings approaches required in the manufacturing strategy formulation, more specifically the need to quantitatively support existing qualitative decision making methods.

This study considered a three stage manufacturing strategy process to develop a conceptual method of manufacturing strategy formulation. In this regard, the study, in addition to the overall manufacturing system level, considered a second level of manufacturing (Manufacturing Major Operations-MMOs) to link the manufacturing strategy process in depth with the operations and more specifically discussed two methods to quantify some decision making activities concerned in this process.

The first method is concerned with quantifying the Importance-Performance (I-P) matrix for prioritizing improvement activities regarding identified critical success factors.

As the general form of the I-P matrix can only classify factors into the defined zones of the matrix, if factors fall in the same zones they are given the same degrees of improvement priority and so there is no measurable index for those priorities. Thus, it would be too difficult to imply a ranked list of factors. To solve this problem, a Multiple-Input-Single-Output (MISO) fuzzy model has been developed which uses experts' judgments to determine membership functions and corresponding inference rules. Results of the numerical illustrations of this method shows it could be a useful method to rank CSFs based on their Improvement Priorities. Also the model possesses some level of flexibility to adopt expectations of various companies based on their requirements whilst it is possible to change used fuzzy sets of inputs and output as well as the consequence of each rule as regard to experts' opinions.

The second method was developed to evaluate supportive effectiveness of the manufacturing decision areas with respect to corresponding critical success factors and consequently to use of this measure to assess critical success factors Performance and Improvement Priority in holistic way. This method as discussed in a previous chapter uses pair-wise comparisons to determine the effectiveness measures. A numerical example is used to demonstrate usability and comprehensiveness of the method. Results of the example indicates that although like as most of the manufacturing strategy formulations, implementation of the proposed process and its procedures consumes a lot of time but the outcome of quantification in this process is more practical than qualitative methods in decision making and worthwhile.

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