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# An integrated sustainable manufacturing strategy framework using fuzzy analytic network process

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**A B S T R A C T**

This paper adopts a fuzzy analytic network process approach for developing a sustainable manufacturing strategy under the influence of stakeholders' interests. Frameworks developed in literature tend to structure manufacturing strategy in such a way that addresses market needs and expectations. As the move towards sustainability becomes highly pronounced, literature in domain manufacturing is developing approaches and initiatives that explore different facets of sustainability. However as this impetus becomes increasingly famous, manufacturing firms are faced with the challenge of integrating sustainability with the classical function of manufacturing, which is to support firms' competitive advantages. Thus, an inclusive approach would constitute a manufacturing strategy that would support not only sustainability but enhance the competitive strategy of a firm. In order to integrate these two objectives it is necessary to take into consideration the different stakeholders' interests as significant drivers towards sustainability. This work explores the significance of these interests when developing a manufacturing strategy using the proposed approach. In the proposed method, an analytic network process handles the complexity of the decision framework, and judgment elicitation during pairwise comparisons is described using linguistic variables with equivalent triangular fuzzy numbers. The proposed approach is useful when handling complexity and uncertainty especially in group decision-making. The content of the sustainable manufacturing strategy using a fuzzy analytic process is presented in this paper.



**A R T I C L E  I N F O**

*Keywords:*
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## 1. Introduction

The classical model of Skinner [1] and Wheelwright [2] on manufacturing strategy was highly motivated by market behavior and market requirements. Resulting from buying experiences, dynamic needs, etc., the market creates a priority set of the four widely accepted competitive priorities which are cost, quality, dependability and flexibility [2-4]. This prioritization process of the market motivates the priority set of competitive priorities of a business unit which eventually influences the manufacturing function. When manufacturing decisions are consistent over nine decision categories, manufacturing creates capabilities which must be positioned in line with the competitive priorities set up by the business unit. This network of influences seems to function only when the market is solely the focal point of interest. However, this network fails to address the conditions that demand simultaneous considerations of several stakeholders. The best example of these conditions is sustainability-related issues. Thus, an update of this network becomes necessary to address the complex interests of various stakeholders.

An emerging body of literature claims that the role of stakeholders in the sustainability efforts of firms is arguably significant [5-7]. Aside from exerting pressures on manufacturing firms which is the general claim [8], stakeholders could assist firms in deciding which environmental and social initiatives to adopt because stakeholders have already established some forms of perspectives, experiences and resources vital in addressing sustainability issues. Creating initiatives that enhance close relations with employees and suppliers advances the capability of firms in integrating environmental aspects into key organizational processes. With the emerging issues on sustainability encountered by manufacturing firms, manufacturing organizations must proactively create value through investment in customers, suppliers, employees, processes, technology and innovation [9]. Models developed by previous literature lack quantitative integration of manufacturing strategy and sustainable manufacturing into a framework that addresses both sustainability and competitiveness.

This paper aims to develop the content of a sustainable manufacturing strategy with the influence of different stakeholders' interests. This is significant as it provides possible direction for manufacturing industry on the policy options that must be made in order to address both competitiveness and sustainability of manufacturing. Due to the multi-criteria nature of the decision problem under vague decisions which are brought about by the subjective nature of most of the criteria, a fuzzy analytic network process is thus used. This approach was also used in identifying the structural decisions of sustainable manufacturing strategy under the relevance of firm sizes [10] and of the strategic responses of firms [11]. Fuzzy set theory handles the uncertainty of decision-making [12] while analytic network process is a multi-criteria decision making tool which is used to handle complex decision-making [13]. The use of analytic network process and its special case, the analytic hierarchy process, in strategy and sustainability research is rich in literature, e.g. Ocampo and Clark [14], Ocampo [15], Pan et al. [16]. The contribution of this work lies in developing a comprehensive framework in identifying specific decisions that comprise a sustainable manufacturing strategy with the influence of stakeholders' interests.

## 2. Literature review

### 2.1 Manufacturing strategy

Definitions of manufacturing strategy presented by previous studies can be summarized into few unifying concepts. First, manufacturing strategy represents a pattern of coordinated and consistent decisions over a relatively narrow area [17]. Second, manufacturing strategy determines the capabilities of the manufacturing function and provides its competitive advantage [18]. Lastly, manufacturing strategy is consistent with the objectives of the business strategy [17-19]. Inspired largely by the work of Skinner [1], subsequent works agreed that manufacturing function involves a number of decision categories which are shown in Table 1.

Depending on the decisions made within these categories, manufacturing strategy develops a set of capabilities [21]. Four competitive priorities were widely known in literature: cost, quality, dependability and flexibility [2, 3].

**Table 1** Manufacturing decision categories

| Manufacturing decision categories | Source | Policy areas [2, 20] |
|---|---|---|
| Process technology | [2, 3, 20] | Process choice, technology, integration |
| Facilities | [1-3, 20] | Size, location, focus |
| Capacity | [2, 3, 20] | Amount, timing, type |
| Vertical integration | [2, 3, 20] | Direction, extent, balance |
| Organization | [1, 3, 20] | Structure, reporting levels, support groups |
| Manufacturing planning and control | [1, 2, 20] | System design, decision support, systems integration |
| Quality | [2, 3, 20] | Defect prevention, monitoring, intervention |
| New product introduction | [1, 3, 20] | Rate of innovation, product design, industrialization |
| Human resources | [1-3] | Skill level, pay, security |

Competing on cost requires a manufacturing strategy that minimizes the inefficiencies of manufacturing operations so that products are offered at low costs. This is addressed by labor, materials, capital returns, inventory turnover and unit costs [3]. Manufacturing strategy that emphasizes quality as the dominant capability requires higher quality in standard product or one that offers broader features or performance characteristics compared to other competitors with similar products. Measurement could be percent defectives, frequency field failure, cost of quality and mean time between failures [3]. Dependability involves a manufacturing system that is able to do work as specified, delivered on time and the firm makes sure that its resources are ready so that any failures are corrected immediately. It could be achieved by dealing on product mix flexibility, volume flexibility and lead time for new products [3]. Measurement indicators could be percentage of on-time shipments, average delay and expediting response time [3]. A comprehensive discussion of these four capabilities was outlined by Ward et al. [22].

Note that the competitive strategy reinforced by the manufacturing strategy must support the competitive advantage defined by the business strategy as depicted by Skinner's [1] hierarchical framework. Moreover, aside from maintaining this competitive advantage, the strategy adopted must create and maintain the manufacturing competitive position in the market. Different manufacturing firms emphasize each of the four competitive capabilities in varying degrees [2]. To summarize, manufacturing strategy is derived from business and corporate strategies [1] which are largely driven by the market. Market establishes the requirements of the business unit and consequently identifies the set of competitive priorities. Manufacturing strategy provides the necessary policy to support the strategy of the business while at the same time creates capabilities in the long run. This framework generally addresses competitiveness of the business unit with limited information on how this works when sustainability is eventually placed into the context. One challenging issue that needs to be resolved in the framework is the presence of stakeholders' interests that must be considered when confronting sustainability agenda.

### 2.2 Sustainable manufacturing

While other economic sectors share responsibilities in addressing sustainability, manufacturing sector is undoubtedly an important piece of the puzzle [23]. With expected five-fold increase in GDP per capita over the next fifty years, a corresponding ten-fold increase in total impact in energy consumption, material usage and wastes generation is expected [24]. Hassine et al. [25] pointed out that the energy consumption of manufacturing industries account for 30 % of the global energy demand and 36 % of the global carbon dioxide emissions. This consumption implies adverse environmental impact and degradation of natural resources [25]. Being the leading employment sector and main contributor to the GDP, the manufacturing sector serves as the "backbone" to the well-being of nations and societies [24]. With this, sustainable manufacturing, as an approach, has emerged and is defined by the U.S. Department of Commerce as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound" [26]. Sustainable manufacturing gained overwhelming interests both in industry and academia and inspired leading developed economies to design responsive policy platforms [27]. Nevertheless, this approach gained global momentum [28].

A concise framework on sustainability in general and on sustainable manufacturing in particular is the triple-bottom line approach [29, 30] which was introduced by Elkington [31]. This approach maintains that sustainable manufacturing is achieved by simultaneously considering environmental stewardship, economic growth, and social well-being [26]. This framework has been adopted by various operations management researches [32-35]. While this sounds impressive, it does not provide clear direction on the competitive function of manufacturing as described by Skinner's [1] framework. Conceptual frameworks are on sustainable manufacturing based on the TBL approach. These could be summarized as follows: (1) sustainability is further achieved through collaboration in the supply chain [36, 37], (2) a comprehensive approach to sustainability is through the life-cycle approach [38, 39], and (3) different stakeholders have significant roles in sustainability transformation [40, 41].

#### 2.3 Stakeholders' interests

Recent studies have placed high regard on the role of stakeholders in forging sustainability of manufacturing organizations, e.g. [42-44]. Stakeholders comprise those who are influenced, either directly or indirectly, by the actions carried out by the firm [9]. These include employees, suppliers, customers, industry associations, universities, consultants, governments, community organizations, and the media [44]. Pham and Thomas [9] argue that traditional organizations tend to focus only on a handful, limited number of stakeholders with special attention to shareholders such as board of directors and investors. Griffiths and Petrick [42] contend that such approach fails to develop stakeholder integration for firms. A widely accepted notion is that when stakeholders are managed well, they are capable in offering invaluable assistance and resources beyond simply exerting pressures on firms [45, 46]. For instance, customers can possibly exert pressure on suppliers to establish environmental programs as a precondition to supply [7]. On the other hand, employees can provide recommendations for advancing firm's responsibility to the community by pointing out inputs related to the current socio-economic conditions of the local community. Suppliers play a critical role in providing insights which are associated to technology, materials and processes that could be helpful in strengthening firm's environmental efforts [47, 48]. Harrison et al. [49] claim that manufacturing firms are likely to build trusting relations across several stakeholders when firms integrate them in their key decision-making processes. Having stronger relations with stakeholders, necessary insights for deciding how to allocate limited resources in order to satisfy stakeholders are certainly gained.

## 3. Methodology

#### 3.1 Fuzzy set theory

Fuzzy set theory was developed by Zadeh [50] as a mathematical approach of handling imprecision and vagueness in decision-making. A fuzzy number can be represented by a fuzzy set $F = \{(x, u_F(x)), x \in \mathbb{R}\}$ where $x \in \mathbb{R}$ and $u_F(x) \rightarrow [0,1]$. The binary set [0, 1] is a crisp set and any value that is represented between 0 and 1 indicates partial acceptance. Various types of fuzzy numbers emerge in literature but the widely used one is the triangular fuzzy number (TFN) [51, 52]. TFN can be defined as a triplet $A = (l, m, u)$ and the membership function $\mu_{\tilde{M}}(x)$ can be defined as

$$\mu_A(x) = \begin{Bmatrix} 0 & x < l \\ (x-l)/(m-l) & l \le x \le m \\ (u-l)/(u-m) & m \le x \le u \\ 0 & x > u \end{Bmatrix} \quad (1)$$

and the representation of a TFN is

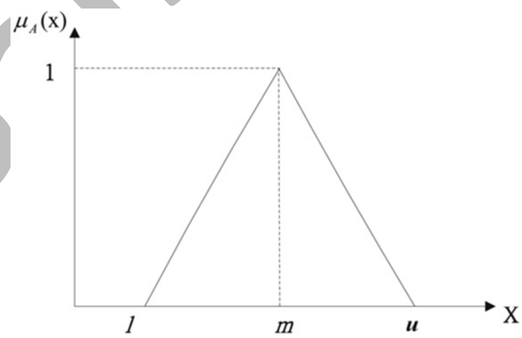


**Fig. 1** A TFN A = $(l, m, u)$ [10]

Suppose two TFNs $\tilde{A}$ and $\tilde{B}$ are defined by the triplet $(a_1, a_2, a_3)$ and $(b_1, b_2, b_3)$, respectively. The basic operations of these two TFNs are as follows:

$$\tilde{A} + \tilde{B} = (a_1, a_2, a_3) + (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (2)$$

$$\tilde{A} - \tilde{B} = (a_1, a_2, a_3) - (b_1, b_2, b_3) = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \quad (3)$$

$$\tilde{A} \otimes \tilde{B} = (a_1, a_2, a_3) \times (b_1, b_2, b_3) = (a_1 b_1, a_2 b_2, a_3 b_3) \quad (4)$$

$$\tilde{A} \div \tilde{B} = (a_1, a_2, a_3) \div (b_1, b_2, b_3) = (a_1 / b_3, a_2 / b_2, a_3 / b_1) \quad (5)$$

FST enhances the capability of MCDM methods in handling complex and imprecise judgments [10]. Most evaluators could hardly elicit exact numerical values to represent opinions based on human judgment [52]. More realistic evaluations use linguistic variables to represent judgment rather than numerical values [53]. Linguistic variable represents linguistic values with form of phrases or sentences in a natural language [54]. Expressing judgment in linguistic variables is a useful method in dealing with situations that are described in quantitative expressions [53]. The integration of fuzzy set theory in the context of AHP/ANP draws several techniques. Refer to the work of Promentilla et al. [51], Wang et al. [55], Ocampo and Clark [56] for a review on these techniques. The approach adopted in this study shares similarity with the works of Tseng [12, 52] which transform TFNs into crisp values before raising the pairwise comparisons matrices to large powers. This method has been used because of the simplicity of the approach and the validity of previous works that embarked on it. Tseng [52] argued that any fuzzy aggregation method must contain defuzzification method. An algorithm in determining the crisp values was proposed by Opricovic and Tzeng [57]. The linguistic variables are presented in Table 2 with equivalent TFNs adopted from Tseng et al. [58].

**Table 2** Linguistic variables adopted from Tseng et al. [58]

| Linguistic scale | Code | Triangular fuzzy scale | Triangular fuzzy reciprocal scale |
|---|---|---|---|
| Just equal | | (1,1,1) | (1,1,1) |
| Equal importance | EQ | (1/2,1,3/2) | (2/3,1,2) |
| Moderate importance | MO | (5/2,3,7/2) | (2/7,1/3,2/5) |
| Strong importance | ST | (9/2,5,11/2) | (2/11,1/5,2/9) |
| Demonstrated importance | DE | (13/2,7,15/2) | (2/15,1/7,2/13) |
| Extreme importance | EX | (17/2,9,9) | (1/9,1/9,2/17) |

Let $\widetilde{w}_{ij}^k = \left(a_{1ij}^k, a_{2ij}^k, a_{3ij}^k\right)$ be the influence of ith criteria on jth criteria assessed by the kth evaluator. The defuzzification process proposed by Opricovic and Tzeng [57] is as follows:

*Step 1:* Normalization

$$xa_{1ij}^k = \frac{a_{1ij}^k - min\, a_{1ij}^k}{\Delta_{min}^{max}} \quad (6)$$

$$xa_{2ij}^k = \frac{a_{2ij}^k - min\, a_{1ij}^k}{\Delta_{min}^{max}} \quad (7)$$

$$xa_{3ij}^k = \frac{a_{3ij}^k - min\, a_{1ij}^k}{\Delta_{min}^{max}} \quad (8)$$

where

$$\Delta_{min}^{max} = max\, a_{3ij}^k - min\, a_{1ij}^k.$$

*Step 2:* Computation of left $ls$ and right $rs$ normalized values

$$xls_{ij}^k = \frac{xa_{2ij}^k}{1 + xa_{2ij}^k - xa_{1ij}^k} \quad (9)$$

$$xrs_{ij}^{k} = \frac{xa_{3ij}^{k}}{1 + xa_{3ij}^{k} - xa_{2ij}^{k}} \tag{10}$$

*Step 3:* Computation of total normalized crisp value

$$x_{ij}^{k} = \frac{xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) + xrs_{ij}^{k}xrs_{ij}^{k}}{1 - xls_{ij}^{k} + xrs_{ij}^{k}} \tag{11}$$

*Step 4:* Computation of crisp values

$$w_{ij}^{k} = min\, a_{1ij}^{k} + x_{ij}^{k}\Delta_{min}^{max} \tag{12}$$

### 3.2 Analytic network process

ANP is the general theory of analysing complex decision problems where analytic hierarchy process (AHP) is a special case. Local priorities in ANP are obtained similar to how local priorities in AHP are computed; that is, by performing paired comparisons. In ANP, the decision problem is structured as a network of constructs that describes dependence relations of one component on another component. The advantage of using ANP in a wide array of decision problems is in capturing both qualitative and quantitative criteria in a model that attempts to resemble reality. The input of local priorities depends on the presence and type of dependence relations described in the network. The eigenvector method, as described in the theory of Oskar Perron which was discussed by Saaty [59], is referred to as the exact way of computing relative local priorities of these elements. Saaty [60] proposed an eigenvalue problem to obtain the desired ratio-scale priority vector (or weights) $w$ of $n$ elements:

$$Aw = \lambda_{max}w \tag{13}$$

where $A$ is the positive reciprocal pairwise comparisons matrix, $\lambda_{max}$ is the maximum (or principal) eigenvalue of matrix $A$. For consistent judgment, $\lambda_{max} = n$, otherwise, $\lambda_{max} > n$. The measure of judgment consistency is measured using the Consistency Index ($CI$) and Consistency Ratio ($CR$). The Consistency Index ($CI$) is a measure of the degree of consistency and is represented by

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{14}$$

The consistency ratio ($CR$) is computed as

$$CR = \frac{CI}{RI} \tag{15}$$

where $RI$ is the mean random consistency index. $CR \leq 0.10$ is an acceptable degree of inconsistency. Decision-makers would be asked to reconsider the paired comparisons in case of $CR > 0.10$.

Global priority ratio scales or priorities can be computed based on the synthesizing principle of the supermatrix [51]. By raising the matrix to large powers, the transmission of influence along all possible paths in the network is captured in the process [13]. The convergence of initial priorities (stochastic matrix) to an equilibrium value in the limit supermatrix provides a set of meaningful synthesized priorities from the underlying decision network [51]. Saaty [13] assured that as long as the supermatrix representation is a primitive irreducible matrix in a strongly connected digraph, the initial supermatrix will eventually converge to a limit supermatrix. The numerical approach of solving the limit supermatrix denoted by $L$ is by normalizing columns and then raising the supermatrix to $p = 2k + 1$ power where $k$ is an arbitrary large number.

$$\lim_{p\to\infty}\left(\frac{S}{\lambda_{max}}\right)^{p} = \lim_{p\to\infty}(\bar{S})^{p} = L \tag{16}$$

Each column of the limit supermatrix is a unique positive column eigenvector associated with the principal eigenvalue $\lambda_{max}$ [51]. This resembles the priorities of the limit supermatrix and can be used to measure the overall relative dominance of one element over another element in a network [51].

### 3.3 Procedure

To summarize, the research procedure implemented in this paper is as follows:

1. Perform pairwise comparisons based from the decision network motivated from literature. The generic question that is asked in doing pairwise comparison is "Given a control element, a component (element) of a given network, and given a pair of component (or element), how much more does a given member of the pair dominate other member of the pair with respect to a control element?" [51]. Instead of using the Saaty's fundamental scale, comparisons are made using linguistic scales as shown in Table 2.
2. Transform linguistic variables into corresponding TFNs in Table 2. Using Eq. 6 through Eq. 12, compute corresponding crisp values of the TFNs.
3. Compute local priority vectors, $CI$ and $CR$ values of pairwise comparisons matrices using Eq. 13 through Eq. 15. If $CR > 0.10$, decision-makers should be asked to reconsider judgments in paired comparisons.
4. Aggregate the pairwise comparisons matrices of decision-makers using Eq. 17. After constructing aggregated pairwise comparisons matrices, compute local priority vectors of these matrices using Eq. 13.

$$\bar{w}_{ij} = \left(\prod_{k} w_{ij}^{k}\right)^{1/k} \tag{17}$$

5. Construct an initial supermatrix from the decision network developed in step 1. Then, populate this initial supermatrix with the local priority vectors obtained in step 4. Normalize the columns of the initial supermatrix in order to attain a stochastic matrix. Then raise the stochastic matrix to large powers Eq. 16 to compute for the final priority vector.

## 4. Decision model

Following the literature review in Section 2, the decision model can be described into two parts. The first part presents the hierarchical structure of decision categories, policy areas and policy options. This shows that each decision category is composed of policy areas and each policy area has policy options or choices. This part is largely influenced by the second part of the model. The second part illustrates the relationships of stakeholders' interests, competitive priorities and strategic responses. Stakeholders' interests dominate competitive priorities which is vital in sustainability. Instead of the market exclusively setting up the competitive priorities consistent with the former arguments of Wheelwright [2], the model holistically considers the interests of different stakeholders in determining competitive priorities. These priorities influence the strategic responses of firms toward sustainability. In effect, these responses influence the decisions which would eventually comprise the sustainable manufacturing strategy. Fig. 2 shows the decision model developed in this work.

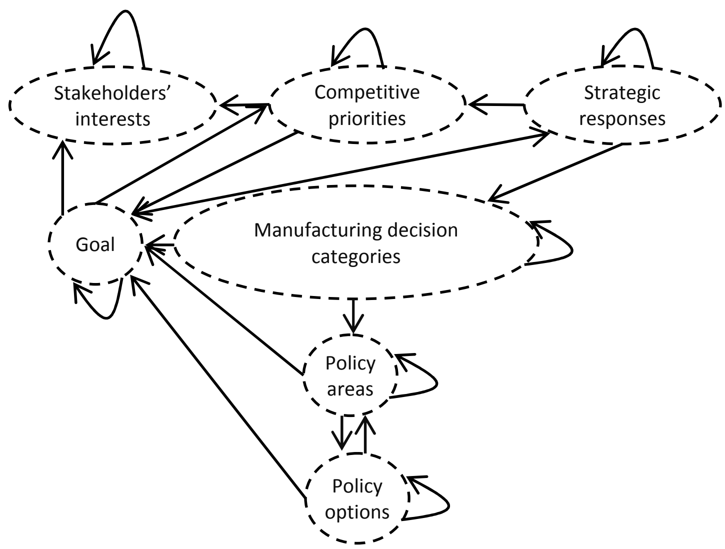


**Fig. 1** Proposed decision model

The decision model in Fig. 2 has six components which are composed of the goal, stakeholders' interests, competitive priorities, strategic responses, manufacturing strategy decision categories, policy areas and policy options. These components are linked together in a network of dependence relations. Each component of the model comprises respective decision elements. The goal component contains a single element which is to develop SMS. Stakeholders' interests have two sub-components: stakeholders' component which has eight decision elements and stakeholders' interests' component with 28 children elements. Competitive priorities have four elements as discussed in the previous section. Strategic responses have three elements which are stakeholder-oriented, market-oriented and sustainability-oriented. Manufacturing decision categories component has nine elements and each element has its own set of policy areas as described in Table 1. Furthermore, each policy contains policy options which a manufacturing firm could deliberately choose from. The objective of this work is to analytically choose a particular set of options that comprise SMS which best addresses the goal resulting from the interrelationships of the components and elements described in Fig. 2. In order to facilitate easier computations, a comprehensive coding system is shown in Table 3 to represent each element in the decision model. The coding system is so structured to facilitate remembering of elements associated with their parent element.



**Table 3** Coding system of the stakeholder-motivated competitive priority decision model

| Decision components | Decision elements | Code | Decision components | Decision elements | Code |
|---|---|---|---|---|---|
| Goal | develop sustainable manufacturing strategy | A | Policy options | job shop | C111 |
| Stakeholders | government | H1 | | batch | C112 |
| | suppliers | H2 | | continuous | C113 |
| | shareholders | H3 | | project | C114 |
| | business customers | H4 | | robotics | C121 |
| | consumers | H5 | | flexible manufacturing system | C122 |
| | community | H6 | | computer-aided manufacturing | C123 |
| | employees | H7 | | cellular | C131 |
| | competitors | H8 | | process | C132 |
| Stakeholders' sustainability interests | government's increased taxes | H11 | | product | C133 |
| | government's environmental protection | H12 | | one big plant | C211 |
| | government's health & safety | H13 | | several smaller ones | C212 |
| | suppliers' compliance with international standards | H21 | | close to market | C221 |
| | suppliers' quality | H22 | | close to supplier | C222 |
| | suppliers' cost | H23 | | close to technology | C223 |
| | suppliers' delivery | H24 | | close to competitor | C224 |

**Table 3** Coding system of the stakeholder-motivated competitive priority decision model (continuation)

| | | | | |
|---|---|---|---|---|
| | shareholders' profitability | H31 | close to source of raw materials | C225 |
| | shareholders' environmental equity | H32 | product groups | C231 |
| | shareholders' social equity | H33 | process types | C232 |
| | business customers' quality | H41 | life cycle stages | C233 |
| | business customers' cost | H42 | fixed units per period | C311 |
| | business customers' delivery | H43 | based on inputs | C312 |
| | business customers' international certifications | H44 | based on outputs | C313 |
| | consumers' quality | H51 | leading | C321 |
| | consumers' cost | H52 | chasing | C322 |
| | consumers' delivery | H53 | following | C323 |
| | community's environmental effect | H61 | potential | C331 |
| | community's employment | H62 | immediate | C332 |
| | community's health & safety | H63 | effective | C333 |
| | employees' health & safety | H71 | forward | C411 |
| | employees' benefits | H72 | backward | C412 |
| | employees' salaries & wages | H73 | horizontal | C413 |
| | employees' career development | H74 | sources of raw materials | C421 |
| | competitors' complying international standards | H81 | distribution to final customers | C422 |
| | competitors' quality | H82 | low degree | C431 |
| | competitors' cost | H83 | medium degree | C432 |
| | competitors' delivery | H84 | high degree | C433 |
| Competitive priorities | cost | I1 | functional | C511 |
| | quality | I2 | product groups | C512 |
| | dependability | I3 | geographical | C513 |
| | flexibility | I4 | top | C521 |
| Strategic responses | stakeholder-oriented | G1 | middle | C522 |
| | market-oriented | G2 | first line | C523 |
| | sustainability-oriented | G3 | large groups | C531 |
| Manufacturing decision categories | process technology | C1 | small groups | C532 |
| | facilities | C2 | make-to-order | C611 |
| | capacity | C3 | make-to-stock | C612 |
| | vertical integration | C4 | close support | C621 |
| | organization | C5 | loose support | C622 |
| | manufacturing planning & control | C6 | high degree | C631 |
| | quality | C7 | low degree | C632 |
| | new product introduction | C8 | high quality | C711 |
| | human resources | C9 | low degree | C712 |
| Policy areas | process choice | C11 | high frequency | C721 |
| | technology | C12 | low frequency | C722 |
| | process integration | C13 | high frequency | C731 |
| | facility size | C21 | low frequency | C732 |
| | facility location | C22 | slow | C811 |
| | facility focus | C23 | fast | C812 |
| | capacity amount | C31 | standard | C821 |
| | capacity timing | C32 | customized | C822 |
| | capacity type | C33 | new processes | C831 |
| | direction | C41 | follow-the-leader- policy | C832 |
| | extent | C42 | specialized | C911 |
| | balance | C43 | not specialized | C912 |
| | structure | C51 | based on hours worked | C921 |
| | reporting levels | C52 | quantity/quality of output | C922 |
| | support groups | C53 | seniority | C923 |
| | system design | C61 | training | C931 |
| | decision support | C62 | recognition for achievement | C932 |
| | systems integration | C63 | promotion | C933 |
| | defect prevention | C71 | | |
| | monitoring | C72 | | |
| | intervention | C73 | | |
| | rate of innovation | C81 | | |
| | product design | C82 | | |
| | industrialization | C83 | | |
| | skill level | C91 | | |
| | pay | C92 | | |
| | security | C93 | | |

Respondents were carefully selected to provide expert judgment of the decision problem raised from this work. Initially, respondents were selected in advance and selection was based on their expertise in the manufacturing industry. This choice of respondents is consistent with the MCDM studies published by Tseng and Chiu [12]. All experts are located in the Philippines who worked for multinational manufacturing firms and were exposed to international practices. In this work, ten expert respondents were selected to provide meaningful results.

## 5. Results and discussion

For brevity, a sample pairwise comparisons matrix in linguistic variables from a single decision-maker is shown in Table 4.

Note that only the upper triangle of the matrix is filled out as the lower triangle represents straightforward reciprocal value of the upper triangular. This matrix describes the comparisons of stakeholders with their significance in addressing the goal of developing a sustainable manufacturing strategy. From Table 4, corresponding TFNs are shown in Table 5.

**Table 4** A sample pairwise comparisons matrix in linguistic variables

| | Government | Suppliers | Shareholder | Business customers | Consumers | Community | Employees | Competitors |
|---|---|---|---|---|---|---|---|---|
| Government | | 1/MO | 1/MO | 1/MO | 1/MO | 1/MO | 1/MO | 1/MO |
| Suppliers | | | 1/MO | 1/MO | 1/MO | 1/MO | MO | MO |
| Shareholders | | | | 1/MO | 1/MO | MO | MO | MO |
| Business customers | | | | | 1/MO | MO | MO | MO |
| Consumers | | | | | | MO | MO | MO |
| Community | | | | | | | MO | MO |
| Employees | | | | | | | | MO |
| Competitors | | | | | | | | |

**Table 5** A sample pairwise comparisons matrix in TFNs

| | Government | Suppliers | Shareholder | Business custo-mers | Consumers | Community | Employees | Competitors |
|---|---|---|---|---|---|---|---|---|
| Government | (1,1,1) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) |
| Suppliers | (5/2,3,7/2) | (1,1,1) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (5/2,3,7/2) | (5/2,3,7/2) |
| Shareholders | (5/2,3,7/2) | (5/2,3,7/2) | (1,1,1) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Business customers | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (1,1,1) | (2/7,1/3,2/5) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Consumers | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (1,1,1) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Community | (5/2,3,7/2) | (5/2,3,7/2) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) | (5/2,3,7/2) | (5/2,3,7/2) |
| Employees | (5/2,3,7/2) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) | (5/2,3,7/2) |
| Competitors | (5/2,3,7/2) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) |

Table 6 shows the corresponding crisp values of the sample pairwise comparisons matrix obtained from a single decision-maker.

From the aggregated matrix, local priority vectors, the principal eigenvalue and *CR* value were then computed. *CR* values of all pairwise comparisons matrix are below the 0.10 threshold value. The local priority vectors of all aggregated pairwise comparisons matrices are populated in the supermatrix. The general supermatrix of the decision model presented in Fig. 2 is shown in Table 7.

**Table 6** A sample pairwise comparisons matrix in crisp values

| | Government | Suppliers | Shareholder | Business customers | Consumers | Community | Employees | Competitors | Eigenvector |
|---|---|---|---|---|---|---|---|---|---|
| Government | 1 | 0.3349 | 0.3349 | 0.3349 | 0.3349 | 0.3349 | 0.3349 | 0.3349 | 0.0398 |
| Suppliers | 2.9863 | 1 | 0.3349 | 0.3349 | 0.3349 | 0.3349 | 2.9646 | 2.9646 | 0.0902 |
| Shareholders | 2.9863 | 2.9863 | 1 | 0.3349 | 0.3349 | 2.9646 | 2.9646 | 2.9646 | 0.1557 |
| Business customers | 2.9863 | 2.9863 | 2.9863 | 1 | 0.3349 | 2.9646 | 2.9646 | 2.9646 | 0.2048 |
| Consumers | 2.9863 | 2.9863 | 2.9863 | 2.9863 | 1 | 2.9646 | 2.9646 | 2.9646 | 0.2692 |
| Community | 2.9863 | 2.9863 | 0.3373 | 0.3373 | 0.3373 | 1 | 2.9646 | 2.9646 | 0.1188 |
| Employees | 2.9863 | 0.3373 | 0.3373 | 0.3373 | 0.3373 | 0.3373 | 1 | 2.9646 | 0.0689 |
| Competitors | 2.9863 | 0.3373 | 0.3373 | 0.3373 | 0.3373 | 0.3373 | 0.3373 | 1 | 0.0525 |

$\lambda_{\max} = 9.086, \mathrm{C.R.} = 0.1$

**Table 7** The generalized supermatrix

| | **A** | **H#** | **H##** | **I** | **G** | **C#** | **C##** | **C###** |
|---|---|---|---|---|---|---|---|---|
| **A** | I | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **H#** | H#A | I | 0 | H#I | 0 | 0 | 0 | 0 |
| **H##** | 0 | H##H# | I | 0 | 0 | 0 | 0 | 0 |
| **I** | IA | 0 | 0 | I | IG | 0 | 0 | 0 |
| **G** | GA | 0 | 0 | 0 | GG | 0 | 0 | 0 |
| **C#** | 0 | 0 | 0 | 0 | C#G | C#C# | 0 | 0 |
| **C##** | 0 | 0 | 0 | 0 | 0 | C##C# | I | 1 |
| **C###** | 0 | 0 | 0 | 0 | 0 | 0 | C###C## | I |

Because the numerical supermatrix runs in the order 151×151, it is highly difficult to present it here as it requires large amount of space. For brevity, the generalized supermatrix and the resulting global priority vector are only shown to elucidate the process of the ANP. Shown in Table 8 are the decision elements with corresponding codes, the global priority vector and ranking of each element per decision component.



**Table 8** Priority ranking across content of sustainable manufacturing strategy

| Rank | Code | Priority policy choice | Code | Policy area |
|---|---|---|---|---|
| 1 | C711 | high quality | C71 | defect prevention |
| 2 | C122 | flexible manufacturing system | C12 | technology |
| 3 | C321 | leading | C32 | capacity timing |
| 4 | C812 | fast | C81 | rate of innovation |
| 5 | C611 | make-to-order | C61 | system design |
| 6 | C631 | high degree | C63 | systems integration |
| 7 | C821 | standard | C82 | product design |
| 8 | C511 | functional | C51 | structure |
| 9 | C831 | new processes | C83 | industrialization |
| 10 | C911 | specialized | C91 | skill level |
| 11 | C132 | process | C13 | process integration |
| 12 | C221 | close to market | C22 | facility location |
| 13 | C411 | forward | C41 | direction |
| 14 | C312 | based on inputs | C31 | capacity amount |
| 15 | C211 | one big plant | C21 | facility size |
| 16 | C731 | high frequency | C73 | intervention |
| 17 | C721 | high frequency | C72 | monitoring |
| 18 | C421 | sources of raw materials | C42 | extent |
| 19 | C621 | close support | C62 | decision support |
| 20 | C532 | small groups | C53 | support groups |
| 21 | C333 | effective | C33 | capacity type |
| 22 | C522 | middle | C52 | reporting levels |
| 23 | C112 | batch | C11 | process choice |
| 24 | C231 | product groups | C23 | facility focus |
| 25 | C432 | medium degree | C43 | balance |
| 26 | C931 | training | C93 | security |
| 27 | C922 | quantity/quality of output | C92 | pay |

Based on Table 8, high quality defect prevention has the highest priority with respect to the goal. The 'Priority policy choice' column in Table 8 shows the content of the sustainable manufacturing strategy following stakeholders' interests. Process technology decision area is ranked first in the manufacturing strategy decision category and closely followed by capacity. Continuous consideration in material, energy and wastes flows in the production of manufacturing products highlights improvement in developing environmentally-benign technologies [38, 61]. Creation of highly energy-efficient technologies such as new machineries, new processes, new packaging, new material that produce less wastes increase the capability of manufacturing industry in supporting the triple-bottom line [62]. Process technology serves as an interesting focal point in sustainability-related advancements. In each of the manufacturing decision category, priority policy areas are: technology in process technology decision, facility location in facilities decision, capacity timing in capacity decision, direction in vertical integration decision, structure in organization decision, system design in manufacturing planning and control decision, defect prevention in quality decision, rate of innovation in new product introduction, and skill level in human resources decision. Having this prioritization enables practitioners to further focus on more important area within a decision category.

## 6. Conclusion

The main contribution of this work is on the development of a sustainable manufacturing strategy decision model that incorporates the interests of different stakeholders. The proposed model highlights the integration of sustainability consideration with competitive function of manufacturing. Since the model illustrates a complex decision-making under uncertainty, this paper proposed the combination of fuzzy set theory and analytic network process. Analytic network process handles the complex dependence relationships among constructs in the decision problem while fuzzy set theory addresses the uncertainty of individual judgment. Although the proposed methodological approach addresses uncertainty and vagueness in complex decision-making, performing a large number of pairwise comparisons may be cumbersome to decision-makers and may require significant amount of time. Alternatively, further simplification of the proposed decision model such that a decision hierarchy is achieved could be handled by Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) and other multi-criteria decision-making tools. However, such simplification process may oversimplify the decision problem which may lead to counterintuitive results. Statistical tools such as structural decision modelling (SEM) could be possibly used to address the same research question but may require huge amount of data.

Nevertheless, using the proposed approach, the decision model provides the content of the sustainable manufacturing strategy. It shows that the content strategy is inclined toward process centred technology, big, product life cycle stages-focused facilities which are close to suppliers, following capacity strategy, a horizontal integration, first-line reporting with functional or geographical organizational structure, a minimal inventory-focused manufacturing planning and control, high quality prevention, monitoring and intervention policies, fast product introduction with new processes and highly skilled workers with pay based on seniority of quality/quantity of output and security focused on training or promotion. These results could guide practitioners in high level policy-making, resource allocation, strategic goal setting, process and product development, prioritization-related decision-making and in the development of programs and initiatives that address the triple-bottom line, i.e. economic, environmental and social dimensions. The content of the sustainable manufacturing strategy is expected to address both competitiveness and sustainability in manufacturing.

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