Research Article

A Sustainable Manufacturing Strategy from Different Strategic Responses under Uncertainty

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This paper presents a decision framework that highlights the integration of manufacturing strategy (MS) and sustainability along with strategic responses as a significant component. This integration raises complexity and uncertainty in decision-making following the number of subjective components with their inherent relationships that must be brought into context and the huge amount of required information in eliciting judgments. Thus, a proposed hybrid multicriteria decision-making (MCDM) approach in the form of an integrated probabilistic fuzzy analytic network process (PROFUZANP) is adopted in this work. In this method, analytic network process (ANP) serves as the main framework in identifying policy options of manufacturing strategy. Fuzzy set theory (FST) is used to describe vagueness in decision-making which is carried out by eliciting judgments in pairwise comparisons using linguistic variables with corresponding triangular fuzzy numbers (TFNs). Probability theory is used to handle randomness in aggregating judgments of multiple decision-makers. Results show that a stakeholder-oriented approach is considered the most relevant strategic response in developing a sustainable manufacturing strategy. The contribution of this work lies in identifying the policies which constitute a sustainable manufacturing strategy using an integrated MCDM approach under uncertainty.

1. Introduction

The work of Wickham Skinner in 1969 became the focal point of discussion regarding the role of manufacturing strategy in attaining corporate goals and objectives. Skinner [1] developed the hierarchical top-down strategy framework that links corporate strategy, business strategies, and functional strategies which include manufacturing strategy [2]. This framework eventually became the guidelines of later approaches in this research domain [3–5]. Scholars agree that manufacturing strategy could only support business strategy if a sequence of decisions over structural and infrastructural categories is consistent over a considerable amount of time [6]. Structural decision areas include process technology, facilities, capacity, and vertical integration while infrastructural decision areas contain organization, manufacturing planning and control, quality, new product introduction, and human resources. Each of these decision areas involves

a finite number of policy options available to the decision-maker. Certainly, identifying the best policy for each decision area requires careful attention and systems thinking due to the number of decision components that must be taken into consideration which make the decision-making a complex one. Manufacturing strategy has evolved as a diverse field covering theoretical and empirical works across various disciplines; however, the field is criticized over its lack of progress particularly on its integration with current approaches [5] with emphasis on sustainability.

Emerging concerns on sustainability compel manufacturing firms to incorporate in their decision-making processes the interests of the triple-bottom line, that is, economic, environmental, and social issues [7], especially those related to material, energy, and wastes [8, 9] as the primary concerns of manufacturing. Manufacturing industry holds one-third of world energy consumption and CO₂ emissions are increasing at a significant rate [10, 11]. Thus, an approach known as

sustainable manufacturing was eventually coined by the U.S. Department of Commerce which promotes the idea of having products and processes which are not only profitable, but also safe to the environment and to the society [12]. This gains significant attention from both industry and academia following research agenda in developed economies working toward this direction [13].

This work attempts to provide a framework that integrates manufacturing strategy and sustainable manufacturing with emphasis on considering strategic responses of firms toward sustainability. The proposed framework identifies the policies that must be placed in various manufacturing decision areas with the goal of promoting competitiveness and sustainability which were understated in previous literature in this field. The main departure of this work is the integrative decision-making framework that attempts to holistically capture various decision components with their intrinsic interrelationships. The emphasis on strategic responses was highly motivated by several works, for example, Sweeney [14], Miller and Roth [15], and Frohlich and Dixon [16] together with the work of de Ron [17] and Heikkurinen and Bonnedahl [18]. Sweeney [14] made the first attempt to comprehensively group manufacturing strategies into “generic manufacturing strategies” that include caretaker, marketeer, reorganizer, and innovator strategies. The main idea was that manufacturing organizations, as the result of the complex interactions of organizational culture and values with the options taken by business and manufacturing policies, tend to brand themselves into a specific stance on key decisions in developing manufacturing strategy. This claim was further elaborated by Miller and Roth [15] and was eventually supported by Frohlich and Dixon [16] using different empirical samples. However, with slight modifications, Frohlich and Dixon [16] identified three types of manufacturing strategies that include caretakers, marketeers, and innovators.

Aside from classifying manufacturing strategy types, Sweeney [14] highlighted the notion of transition paths or routes for firms to achieve the most positive form of strategy. These transition paths served as guide for firms on manufacturing policies and competitive advantages they must place to support a particular route. This research domain became prominent following several published works which show consistency of the types of strategic responses. With the onset of growing interests in sustainability, former taxonomies were paralleled by the responses or stances of firms toward sustainability issues as described by the works of de Ron [17] and Heikkurinen and Bonnedahl [18]. Their works highlighted the three strategic responses that firms engage in embracing sustainability issues: stakeholder-oriented, market-oriented, and sustainability-oriented.

This paper attempts to extend previous works on strategic responses by integrating manufacturing taxonomies of Sweeney [14], Miller and Roth [15], and Frohlich and Dixon [16] with the sustainability responses described by de Ron [17] and Heikkurinen and Bonnedahl [18]. This work highlights the framework which introduces two transition routes: first is the stakeholder-oriented $\rightarrow$ market-oriented $\rightarrow$ sustainability-oriented route and second is the stakeholder-oriented $\rightarrow$ sustainability-oriented route. These

responses and transition routes are brought into the context of developing a sustainable manufacturing strategy. The goal is to identify the content strategy that addresses both competitiveness and sustainability as the result of these transition routes. Due to the complexity in decision-making, the use of multicriteria decision-making methods (MCDM) particularly analytic hierarchy process/analytic network process (AHP/ANP) becomes appropriate and fundamental. AHP/ANP is a theory of relative measurement that allows decision-makers to structure their decision problems into a hierarchy or a network with subjective components [19, 20]. A number of AHP/ANP applications include computing product sustainability index [21], computing sustainability index with time as an element [22], developing sustainability index for a manufacturing enterprise [23], developing multiactor multicriteria approach in complex sustainability project evaluation [24], evaluating industrial competitiveness [25], evaluating energy sources [26], and developing an AHP-based impact matrix and sustainability-cost benefit analysis [27]. A number of reviews of AHP/ANP application in operations management [28], its methodological development [29], dominant applications [30], and its integration with other operations research tools [31] were conducted.

Following various arguments on the uncertainty of decision-making in the context of AHP/ANP ([32]; Tseng and Chiu [33]), this work adopted the proposed method of Ocampo and Clark [34] coined as PROFUZANP which is based on fuzzy set theory, probability theory, and ANP. In this approach, ANP is used to handle decision-making complexity, FST is used to address vagueness individual decision-maker's judgment, and probability theory is used to handle randomness of aggregating judgments. The contribution of this work lies in identifying policy options of manufacturing strategy resulting from the strategic responses carried out by manufacturing organizations. This paper is organized as follows: Section 2 provides an introduction of ANP, fuzzy set theory, and the PROFUZANP approach, Section 3 describes the problem structure, Section 4 presents the results of this study, and finally Section 5 highlights a discussion and conclusion of this work.

2. Methodology

2.1. Analytic Network Process (ANP). ANP is the general framework of analyzing complex decisions with qualitative and quantitative components and elements [19, 20]. ANP structures the decision problem as a network of decision components and elements with dependence relationships. Saaty [35] explained that pairwise comparison is central to the measurement of subjective or of intangible elements. Pairwise comparisons are done by comparing elements with respect to a parent element from the same or another component. These comparisons form a positive reciprocal square matrix. Saaty [19] proposed an eigenvalue problem which determines the local eigenvector (w) of the matrix:

$$Aw = \lambda_{\max} w, \quad (1)$$

where A is the positive reciprocal of the pairwise comparison matrix, $\lambda_{\max}$ is the largest eigenvalue of matrix A , and w is

the principal eigenvector associated with $\lambda_{\max}$. For consistent judgment, $\lambda_{\max} = n$; otherwise, $\lambda_{\max} > n$. Consistency of judgment 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

$$CI = \frac{\lambda_{\max} - n}{n - 1}. \quad (2)$$

The consistency ratio (CR) is computed as

$$CR = \frac{CI}{RI}, \quad (3)$$

where RI is the mean random consistency index. $CR \leq 0.10$ is an acceptable degree of inconsistency [19]. Decision-makers would be asked to reconsider paired comparisons in case of $CR > 0.10$.

Local eigenvectors are plugged into the supermatrix. The numerical approach of computing the global priority vector is done by normalizing columns and then raising the supermatrix to large powers. This approach enables the supermatrix convergence to a limit value. Each column of the limit supermatrix is a unique positive column eigenvector associated with the principal eigenvalue $\lambda_{\max}$ [36]. This principal column eigenvector resembles the stable priorities of the limit supermatrix and can be used to measure the overall relative dominance of one element over another element in a network structure [37].

2.2. Fuzzy Set Theory (FST). Zadeh [38] introduced the fuzzy set theory (FST) as a mathematical way in handling imprecision and vagueness in decision-making. In particular, fuzzy numbers provide a way of expressing vagueness in FST. A fuzzy number can be represented by a fuzzy set $F = \{(x, u_F(x)), x \in R\}$, where x takes on any value on the real number line $R : -\infty < x < +\infty$ and $u_F(x)$ is a continuous mapping on the closed interval $(0, 1)$. Various forms of a fuzzy number are available but the widely used one is the triangular fuzzy number (TFN) [36, 39]. TFN can be defined as a triplet $A = (l, m, u)$ with a membership function. An introductory discussion of fuzzy numbers and their arithmetic operations can be found in Kaufmann and Gupta [40].

FST is shown to enhance MCDM methods in handling complex and imprecise judgments. Since most evaluators find it hard to elicit numerical judgments, more realistic evaluations use linguistic variables to represent judgment [41]. Linguistic variables have the form of phrases or sentences in a natural language [42]. Tseng [39] argues that linguistic variables can be appropriately associated with corresponding TFNs.

2.3. PROFUZANP Approach. PROFUZANP approach was detailed in the work of Ocampo and Clark [34]; important points are discussed in this section. This approach shares similarity with the works of Tseng [32] which transform TFNs into crisp values before raising the pairwise comparisons matrices to large powers. Since any fuzzy aggregation method requires defuzzification [39], the defuzzification process used by Tseng et al. [43] is derived from the algorithm proposed

by Opricovic and Tzeng [44]. The linguistic variables are presented in Table 1 with equivalent TFNs adopted from Tseng et al. [45].

The notations used in this paper were lifted from the notations used by works of Tseng [32]. Suppose a set of k decision-makers with $\tilde{w}_{ij}^k = (a_{1ij}^k, a_{2ij}^k, a_{3ij}^k)$ as the influence of i th criteria on j th criteria assessed by the k th evaluators.

Normalization:

$$xa_{1ij}^k = \frac{a_{1ij}^k - \min a_{1ij}^k}{\Delta_{\min}^{\max}}, \quad (4)$$

$$xa_{2ij}^k = \frac{a_{2ij}^k - \min a_{1ij}^k}{\Delta_{\min}^{\max}}, \quad (5)$$

$$xa_{3ij}^k = \frac{a_{3ij}^k - \min a_{1ij}^k}{\Delta_{\min}^{\max}}, \quad (6)$$

where

$$\Delta_{\min}^{\max} = \max a_{3ij}^k - \min a_{1ij}^k. \quad (7)$$

Compute left ls and right rs normalized values:

$$xls_{ij}^k = \frac{xa_{2ij}^k}{1 + xa_{2ij}^k - xa_{1ij}^k}, \quad (8)$$

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

Compute total normalized crisp value:

$$x_{ij}^k = \frac{xls_{ij}^k (1 - xls_{ij}^k) + xrs_{ij}^k xrs_{ij}^k}{1 - xls_{ij}^k + xrs_{ij}^k}. \quad (9)$$

Compute crisp values:

$$w_{ij}^k = \min a_{1ij}^k + x_{ij}^k \Delta_{\min}^{\max}. \quad (10)$$

In integrating judgments of decision-makers, however, Ocampo and Clark [34] introduced a probabilistic approach defined as

$$\tilde{w}_{ij} = \bar{w}_{ij} \pm (1 - \alpha) p, \quad (11)$$

where $\tilde{w}_{ij}$ is an integrated judgment of decision-makers from a normal distribution that represents the influence of row element on column element, $\bar{w}_{ij}$ is the geometric mean of all judgment of decision-makers of i on j and is defined as

$$\bar{w}_{ij} = \sqrt[k]{w_{ij}^1 w_{ij}^2 w_{ij}^3 \dots w_{ij}^k}. \quad (12)$$

$(1 - \alpha)$ is the confidence level of the distribution, and $p \in [0, 1]$ is proportion of perturbation about the geometric mean. The value of p denotes a range of judgmental uncertainties that usually range from 2% to 20% [46].

TABLE 1: Linguistic variables adopted from Tseng et al. [45].

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)

2.4. Procedure. The procedure implemented in this paper can be described as follows.

- (1) The decision model was established from a rigorous literature review that integrates classical manufacturing strategy and sustainability into a single model. Figure 1 shows the problem structure developed in this work.
- (2) Respondents were selected to provide expert judgments of the problem structure.
- (3) Following the AHP/ANP context, pairwise comparisons were performed based on the problem structure. Comparisons were elicited using the linguistic variables in Table 1. Using (4) through (10), corresponding crisp values of the TFNs were computed.
- (4) Local priority vectors and CI and CR values of pairwise comparisons matrices were computed using (1) through (3).
- (5) Using (11) through (12) by assigning $\alpha = 0.05$ and with assigned $p = 0.25$ which shows the upper limit perturbation of judgments [47], judgments of individual decision-makers were aggregated. Local aggregated priority vectors of these matrices were obtained using (1).
- (6) An initial supermatrix from the decision model was constructed and then was populated with local eigenvectors obtained in step (4) for each value of p . Normalizing columns and raising the supermatrix to large powers solve the global priority vector.

3. Problem Structure

In reference to the discussion in Section 1, the problem structure is described into two parts. The first part presents the hierarchical structure of corporate strategy, business strategy, and functional strategies. Each component is composed of a number of elements defined in the literature. The second part highlights the influence of strategic responses in developing a manufacturing strategy. This part is supported by the hierarchical structure of decision categories, policy areas, and policy options as described by Wheelwright [48]. A number of policy options comprise a particular policy area and each policy area is composed of a number of finite policy options. This part elucidates the departure of this work from the current literature. Figure 1 presents the problem structure developed in this work.

FIGURE 1: Problem structure.

The problem structure in Figure 1 is composed of eight components which are the goal, corporate strategy, business strategy, manufacturing strategy, strategic responses, manufacturing strategy decision categories, policy areas, and policy options. The model is largely motivated by the hierarchical framework of Skinner [1] with the inclusion of strategic responses as a mediating component that prescribes the content of the manufacturing strategy. Each component comprises a set of decision elements. The goal component contains a single element which is to develop a sustainable manufacturing strategy. Corporate strategy component has two elements: sustainable businesses and commitment to sustainability. Business strategy has likewise two elements: market-oriented and technology-oriented. Manufacturing strategy is a single-element component which is a sustainable manufacturing strategy. Strategic responses component has three elements: 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 proposed by Wheelwright [48] and Hallgren and Olhager [4]. Likewise, each policy contains policy options available to the manufacturing firm. The objective of this problem structure is to provide the content of a sustainable manufacturing strategy as the result of the

TABLE 2: Coding system of the elements of the problem structure.

Decision components	Decision elements	Code
Goal	Develop sustainable manufacturing strategy	A
Corporate strategy	Sustainable businesses	D1
	Commitment to sustainability	D2
Business strategy	Market-oriented	E1
	Technology-oriented	E2
Manufacturing strategy	Sustainable manufacturing strategy	F
Strategic responses	Stakeholder-oriented	G1
	Market-oriented	G2
	Sustainability-oriented	G3
Manufacturing decision categories	Process technology	C1
	Facilities	C2
	Capacity	C3
	Vertical integration	C4
	Organization	C5
	Manufacturing planning and control	C6
	Quality	C7
	New product introduction	C8
	Human resources	C9
	Process choice	C11
Policy areas	Technology	C12
	Process integration	C13
	Facility size	C21
	Facility location	C22
	Facility focus	C23
	Capacity amount	C31
	Capacity timing	C32
	Capacity type	C33
	Direction	C41
	Extent	C42
	Balance	C43
	Structure	C51
	Reporting levels	C52
	Support groups	C53
	System design	C61
	Decision support	C62
	Systems integration	C63
	Defect prevention	C71
	Monitoring	C72
	Intervention	C73
	Rate of innovation	C81
	Product design	C82
	Industrialization	C83
	Skill level	C91
	Pay	C92
	Security	C93
	Job shop	C111
	Batch	C112
	Continuous	C113
	Project	C114
	Robotics	C121

TABLE 2: Continued.

Decision components	Decision elements	Code
Policy options	Flexible manufacturing system	C122
	Computer-aided manufacturing	C123
	Cellular	C131
	Process	C132
	Product	C133
	One big plant	C211
	Several smaller ones	C212
	Close to market	C221
	Close to supplier	C222
	Close to technology	C223
	Close to competitor	C224
	Close to source of raw materials	C225
	Product groups	C231
	Process types	C232
	Life cycle stages	C233
	Fixed units per period	C311
	Based on inputs	C312
	Based on outputs	C313
	Leading	C321
	Chasing	C322
	Following	C323
	Potential	C331
	Immediate	C332
	Effective	C333
	Forward	C411
	Backward	C412
	Horizontal	C413
	Sources of raw materials	C421
	Distribution to final customers	C422
	Low degree	C431
	Medium degree	C432
	High degree	C433
	Functional	C511
	Product groups	C512
	Geographical	C513
	Top	C521
	Middle	C522
	First line	C523
	Large groups	C531
	Small groups	C532
	Make-to-order	C611
	Make-to-stock	C612
	Close support	C621
	Loose support	C622
	High degree	C631
	Low degree	C632
	High quality	C711
	Low degree	C712
	High frequency	C721
	Low frequency	C722
	High frequency	C731
	Low frequency	C732

TABLE 2: Continued.

Decision components	Decision elements	Code
	Slow	C811
	Fast	C812
	Standard	C821
	Customized	C822
	New processes	C831
	Follow-the-leader policy	C832
	Specialized	C911
	Not specialized	C912
	Based on hours worked	C921
	Quantity/quality of output	C922
	Seniority	C923
	Training	C931
	Recognition for achievement	C932
	Promotion	C933

overarching problem structure in Figure 1. Using the proposed PROFUZANP approach developed by Ocampo and Clark [34], the proposed model will be able to determine the policy options for each policy area. These options constitute the sustainable manufacturing strategy of the manufacturing firm. In order to facilitate easy recall, a comprehensive coding system is shown in Table 2 to represent each element in the decision model.

In the coding system shown in Table 2, the goal component is assigned as A and corporate strategy as D. Business strategy is denoted as E, manufacturing strategy is represented as F and strategic responses as G, and decision category, policy areas, and policy options components are designated with appropriate alpha-numeric codes of C#, C##, and C###, respectively, with # representing an integer. The coding system in Table 2 is so structured to facilitate remembering of elements associated with their parent element. For instance, C111 represents job shop process and is listed down as the first policy option under C11 policy area which is process choice. C11, on the other hand, also defines the first policy option under C1 manufacturing decision category, process technology.

Respondents were carefully selected with the goal of providing well-informed and expert judgments of the problem structure. Preselection of these respondents was based on their expertise in the manufacturing industry. All domain experts are located in the Philippines who worked for multinational manufacturing firms and were exposed to international practices. In this work, ten experts were selected to provide valid results. Background checks were done for each respondent based on available public data. A threshold criterion is set at least 10-year managerial experience in manufacturing industries to ensure that they have the capability and previous knowledge in carrying out vital manufacturing decisions. This choice of these respondents is consistent with the MCDM studies published by Lin et al. [49], Tseng [32], and Tseng and Chiu [33].

The following steps were undertaken for data gathering required for this work. Questionnaires containing pairwise

comparisons matrices were distributed to ten respondents. They were arranged for a supervised survey according to their preferred schedule. However, in a case of a respondent with no available time for a supervised survey or being out of the country, an email containing the survey questionnaire was sent. Respondents were given a maximum of two to four weeks to answer the questionnaire. Within this time period, regular follow-ups were made to ensure timeliness of their output. Upon receipt of their answers, judgment consistency for each pairwise comparisons matrix was checked. When inconsistency was observed, specific matrices were emailed back to the respondent with a note why the matrix is inconsistent. This means that the respondent was informed that his or her judgment on elements a to b and b to c is inconsistent with his or her judgment on a to c. Respondents were given another one or two weeks to reconsider their judgment on specific inconsistent matrices. At this period, regular follow-ups were undertaken.

4. Results

For brevity, the computations carried out in this work are not presented in this paper. All computations were performed using Microsoft Excel spreadsheet and a VBA add-on. A sample pairwise comparisons matrix in linguistic variables from a single decision-maker is shown in Table 3.

Note that only the upper triangle of the matrix is filled out as the lower triangle represents the straightforward reciprocal of the upper triangular matrix. This matrix compares the influence of strategic responses in addressing the goal of developing a sustainable manufacturing strategy. From Table 3, corresponding TFNs and their respective reciprocals are shown in Table 4.

From the TFNs shown in Table 4, the defuzzification process proposed by Opricovic and Tzeng [44] is used to obtain appropriate crisp values of the TFNs. Crisp values were computed using (4) through (10). Table 5 shows the corresponding crisp values of the sample pairwise comparisons matrix under consideration.

Applying the same process to the rest of the decision-makers' judgments and pairwise comparisons matrices, pairwise comparisons matrices in crisp values are obtained. Aggregation of all judgments across decision-makers is then processed at the pairwise comparisons matrix level. The goal of the aggregation process is to come up with a single matrix that fairly represents the judgments of all decision-makers for a specific pairwise comparisons matrix. Using the proposed PROFUZANP approach of Ocampo and Clark [34] which is also presented in Section 2.3, aggregating judgment of decision makers involves the application of (11) and (12). With α set at 0.05, which is widely used in statistical analysis, and the value of p set at 0.25 following the argument of Hauser and Tadikamalla [47], a sample aggregated matrix of the same set of comparisons is shown in Table 6.

From the aggregated matrix, local priority vectors, the principal eigenvalue, and CR value were then computed using (1), (2), and (3), respectively. Table 7 shows a sample of a local eigenvector of an aggregated pairwise comparisons matrix.

TABLE 3: A sample pairwise comparisons matrix in linguistic variables.

	Stakeholder-oriented	Market-oriented	Sustainability-oriented
Stakeholder-oriented		1/MO	1/MO
Market-oriented			MO
Sustainability-oriented			

TABLE 4: A sample pairwise comparisons matrix in TFNs.

	Stakeholder-oriented	Market-oriented	Sustainability-oriented
Stakeholder-oriented	(1, 1, 1)	(2/7, 1/3, 2/5)	(2/7, 1/3, 2/5)
Market-oriented	(5/2, 3, 7/2)	(1, 1, 1)	(5/2, 3, 7/2)
Sustainability-oriented	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)	(1, 1, 1)

TABLE 5: A sample pairwise comparisons matrix in crisp values.

	Stakeholder-oriented	Market-oriented	Sustainability-oriented
Stakeholder-oriented	1.0000	0.3349	0.3349
Market-oriented	2.9863	1.0000	2.9646
Sustainability-oriented	2.9863	0.3373	1.0000

TABLE 6: A sample aggregated pairwise comparisons matrix with $\alpha = 0.05$, $p = 0.25$.

	Stakeholder-oriented	Market-oriented	Sustainability-oriented
Stakeholder-oriented	1	1.521558	1.062221
Market-oriented	0.657221	1	1.71808
Sustainability-oriented	0.941424	0.582045	1

TABLE 7: A sample local eigenvector of an aggregated pairwise comparisons matrix.

	Local eigenvector
Stakeholder-oriented	0.391017
Market-oriented	0.331778
Sustainability-oriented	0.277206

$\lambda_{\max} = 3.094$; CR = 0.090.

Each column of the limiting pairwise comparisons matrix in Table 8 is the principal eigenvector of the matrix as discussed by Saaty [19]. 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 Figure 1 is shown in Table 8.

The numerical supermatrix runs in the order of 116×116 ; thus it is difficult to present the results here as it consumes 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. In order to determine the priority ranking of each policy choice in relation to the goal, Table 9 ranks policy choice according to decreasing global priority values. This ranking provides insights for firms on the sequence of implementation of policy choices. However, this must be taken into context together with business conditions, individual corporate goals, and the propensity of investment

TABLE 8: Generalized supermatrix.

	A	D	E	F	G	C#	C##	C###
A	I	1	1	1	1	1	1	1
D	DA	I	0	0	0	0	0	0
E	0	ED	I	0	0	0	0	0
F	0	0	FE	I	0	0	0	0
G	GA	0	0	GF	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

decisions of firms. Table 9 provides the ranking of the priority policy choices.

Table 10 provides the policy choice for each manufacturing decision area. These policies constitute a sustainable manufacturing strategy. Special attention is also regarded in the prioritization of strategic responses. This sets the type of manufacturing strategy the business would engage. Priority rankings of corporate strategy, business strategy, and strategic responses are presented in Table 11.

Priority rankings of corporate strategy, business strategy, and strategic responses are presented in Table 11. The rankings show that sustainable businesses have the highest priority in corporate strategy and a market-oriented business strategy is highly prioritized. Inconsistent with previous

TABLE 9: Global priority vector and ranking.

Code	Decision elements	Global eigenvector	Rank
A	Develop sustainable manufacturing strategy	0.323232	1
D1	Sustainable businesses	0.113131	1
D2	Commitment to sustainability	0.048485	2
E1	Market-oriented	0.035479	2
E2	Technology-oriented	0.045329	1
F	Sustainable manufacturing strategy	0.040404	1
G1	Stakeholder-oriented	0.085396	1
G2	Market-oriented	0.05754	2
G3	Sustainability-oriented	0.038882	3
C1	Process technology	0.021136	1
C2	Facilities	0.012683	6
C3	Capacity	0.017592	2
C4	Vertical integration	0.009193	8
C5	Organization	0.011126	7
C6	Manufacturing planning and control	0.013316	5
C7	Quality	0.016043	3
C8	New product introduction	0.013573	4
C9	Human resources	0.00655	9
C11	Process choice	0.002177	3
C12	Technology	0.005874	1
C13	Process integration	0.002517	2
C21	Facility size	0.001338	3
C22	Facility location	0.003449	1
C23	Facility focus	0.001554	2
C31	Capacity amount	0.003014	2
C32	Capacity timing	0.004287	1
C33	Capacity type	0.001495	3
C41	Direction	0.002395	1
C42	Extent	0.001002	3
C43	Balance	0.0012	2
C51	Structure	0.0025	1
C52	Reporting levels	0.0017	2
C53	Support groups	0.001363	3
C61	System design	0.003618	1
C62	Decision support	0.000991	3
C63	Systems integration	0.002049	2
C71	Defect prevention	0.005918	1
C72	Monitoring	0.000949	3
C73	Intervention	0.001155	2
C81	Rate of innovation	0.002823	1
C82	Product design	0.002372	2
C83	Industrialization	0.001591	3

TABLE 9: Continued.

Code	Decision elements	Global eigenvector	Rank
C91	Skill level	0.001533	1
C92	Pay	0.000814	3
C93	Security	0.000928	2
C111	Job shop	0.000308	2
C112	Batch	0.000314	1
C113	Continuous	0.000264	3
C114	Project	0.000202	4
C121	Robotics	0.001173	2
C122	Flexible manufacturing system	0.00139	1
C123	Computer-aided manufacturing	0.000374	3
C131	Cellular	0.000479	2
C132	Process	0.000583	1
C133	Product	0.000197	3
C211	One big plant	0.000484	1
C212	Several smaller ones	0.000185	2
C221	Close to market	0.000541	1
C222	Close to supplier	0.000486	2
C223	Close to technology	0.000272	4
C224	Close to competitor	0.000109	5
C225	Close to source of raw materials	0.000316	3
C231	Product groups	0.000315	1
C232	Process types	0.000211	3
C233	Life cycle stages	0.000251	2
C311	Fixed units per period	0.000504	2
C312	Based on inputs	0.000521	1
C313	Based on outputs	0.000482	3
C321	Leading	0.001199	1
C322	Chasing	0.000502	2
C323	Following	0.000443	3
C331	Potential	0.000211	2
C332	Immediate	0.000175	3
C333	Effective	0.000362	1
C411	Forward	0.000524	1
C412	Backward	0.000413	2
C413	Horizontal	0.00026	3
C421	Sources of raw materials	0.000385	1
C422	Distribution to final customers	0.000116	2
C431	Low degree	$8.45E - 05$	3
C432	Medium degree	0.000264	1
C433	High degree	0.000252	2
C511	Functional	0.000708	1
C512	Product groups	0.000372	2
C513	Geographical	0.00017	3
C521	Top	0.000244	3

TABLE 9: Continued.

Code	Decision elements	Global eigenvector	Rank
C522	Middle	0.000331	1
C523	First line	0.000275	2
C531	Large groups	0.000313	2
C532	Small groups	0.000368	1
C611	Make-to-order	0.001068	1
C612	Make-to-stock	0.000741	2
C621	Close support	0.000378	1
C622	Loose support	0.000118	2
C631	High degree	0.00085	1
C632	Low degree	0.000174	2
C711	High quality	0.002623	1
C712	Low degree	0.000336	2
C721	High frequency	0.000417	1
C722	Low frequency	5.75E – 05	2
C731	High frequency	0.000432	1
C732	Low frequency	0.000145	2
C811	Slow	0.000297	2
C812	Fast	0.001115	1
C821	Standard	0.000751	1
C822	Customized	0.000435	2
C831	New processes	0.000665	1
C832	Follow-the-leader policy	0.00013	2
C911	Specialized	0.000625	1
C912	Not specialized	0.000141	2
C921	Based on hours worked	0.000149	2
C922	Quantity/quality of output	0.000194	1
C923	Seniority	6.43E – 05	3
C931	Training	0.000237	1
C932	Recognition for achievement	0.000134	2
C933	Promotion	9.21E – 05	3

works, stakeholder-oriented approach poses most inclination toward developing a sustainable manufacturing strategy.

5. Discussion and Conclusion

Sustainable businesses emerge as a more relevant corporate strategy in addressing sustainability and competitiveness. The difference between sustainable businesses and commitment to sustainability is that the former is a proactive approach where sustainability is embedded in corporate values and culture while the latter takes on a more reactive stance where decision-making depends on how a specific issue will appear. In the business strategy component, technology-orientation (E2) is considered a desirable approach compared to market-oriented approach (E1). The reason for this might be that

TABLE 10: Content of a sustainable manufacturing strategy considering strategic responses.

Code	Policy area	Code	Highest priority policy choice
C11	Process choice	C112	Batch
C12	Technology	C122	Flexible manufacturing system
C13	Process integration	C132	Process
C21	Facility size	C211	One big plant
C22	Facility location	C221	Close to market
C23	Facility focus	C231	Product groups
C31	Capacity amount	C312	Based on inputs
C32	Capacity timing	C321	Leading
C33	Capacity type	C333	Effective
C41	Direction	C411	Forward
C42	Extent	C421	Sources of raw materials
C43	Balance	C432	Medium degree
C51	Structure	C511	Functional
C52	Reporting levels	C522	Middle
C53	Support groups	C532	Small groups
C61	System design	C611	Make-to-order
C62	Decision support	C621	Close support
C63	Systems integration	C631	High degree
C71	Defect prevention	C711	High quality
C72	Monitoring	C721	High frequency
C73	Intervention	C731	High frequency
C81	Rate of innovation	C812	Fast
C82	Product design	C821	Standard
C83	Industrialization	C831	New processes
C91	Skill level	C911	Specialized
C92	Pay	C922	Quantity/quality of output
C93	Security	C931	Training

TABLE 11: Ranking of other decision components.

Rank	Strategy
Corporate strategy	
1	Sustainable businesses
2	Commitment to sustainability
Business strategy	
1	Technology-oriented
2	Market-oriented
Strategic responses	
1	Stakeholder-oriented
2	Market-oriented
3	Sustainability-oriented

experts consider technology-orientation as an opportunity to lead an industry into developing environmentally benign technologies with minimum environmental footprint and with less impact on society's health and well-being. A market-oriented approach on the other hand is limited to the interests of market which is a narrow approach toward sustainability. As opposed to the initial contention that the highest form

of manufacturing strategy orientation is a sustainability-orientation [17, 18], results of this work suggest that a stakeholder-orientation in manufacturing serves as a more practical approach in developing a sustainable manufacturing strategy. This result could be viewed from two different perspectives. First, experts likely believe that a better approach in addressing sustainability is hearing the “voice of the stakeholder.” Although it is a reactive stance, this approach ensures that the manufacturing firm addresses each issue of the stakeholders transparently without missing important points along the process. It is particularly similar with the “quality functional deployment” approach in the past; however, a more holistic “voice of the stakeholder” is presented. While a proactive stance in sustainability-orientation is obviously a desirable stance, experts might believe that, in the long run, the manufacturing firms may approach sustainability toward a “strong sustainability” framework where development is very limited. Second, it could be that experts have imprecise knowledge of the contested concepts of sustainability. Since sustainability is still a growing field in the literature with more contestations than a single meaning, experts prefer to give higher priorities to stakeholder-orientation when competitiveness and sustainability are placed into context.

A total of 27 decisions constitute the sustainable manufacturing strategy. Table 10 provides specific policy options corresponding to policy areas. Using the PROFUZANP approach of Ocampo and Clark [34], the decision model provides the content of the sustainable manufacturing strategy. It shows that the content strategy is inclined toward process-centered technology with continuous processes, big, product life cycle stages-focused facilities which are close to suppliers and customers, leading capacity strategy, a backward vertical integration toward sources of raw materials, first-line reporting with functional structure organization, 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. The content of the sustainable manufacturing strategy is expected to address both competitiveness and sustainability in manufacturing.

Disclosure

An earlier version of this work was presented at the 7th IEEE International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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