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A COMPREHENSIVE EVALUATION OF SUSTAINABLE MANUFACTURING PROGRAMS USING ANALYTIC NETWORK PROCESS (ANP)

Abstract

Evaluation of programs initiated by manufacturing firms that are geared toward sustainability is worthy of attention in research due to the current global demands of addressing not just economic growth but environmental and social burdens. This paper attempts to provide a comprehensive evaluation framework using the hierarchical structure of sustainable manufacturing (SM) indicators set developed by the US National Institute of Standards and Technology (US NIST) and a multi-criteria decision-making (MCDM) approach, the analytic network process (ANP). ANP is deemed appropriate, aside from the multi-criteria nature of the problem, because of the presence of subjective components that are interrelating in complex relationships. A real case study is carried out in a semiconductor manufacturing firm in the Philippines in the evaluation of its programs toward sustainability. The results show that the creation and implementation of cleaner production technologies are considered the most relevant programs. Developing energy-efficient products and adopting lean six sigma programs are considered second on the list. This paper proposes that sustainability is achieved by formulating strategies that enhance customer and community well-being via addressing environmental concerns especially on toxic substance, greenhouse gas (GHG) and air emissions. The contribution of this paper consists in providing an evaluation framework which is comprehensive enough to capture real-life complex decision-making processes. Limitations and possibilities for future research are also presented in this paper.

Keywords: Multi-criteria decision-making, sustainable manufacturing, sustainability, analytic network process.

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1. Introduction

Due to several emerging concerns about sustainable development, manufacturing firms are compelled by various stakeholders that require firms to align their manufacturing processes and manufactured products along with the context of sustainability. This issue raises various questions that force researchers and practitioners to discuss matters in different areas of the sustainability domain. Towards this end, a widely-accepted approach is to use the concept of the triple-bottom line (TBL) (Elkington, 1997). TBL expanded traditional, purely profit-based strategies into initiatives that address environmental, economic and social issues. A parallel and recently-organized focus under the sustainability umbrella is the sustainable manufacturing (SM) approach which is defined by the US Department of Commerce as the "creation of manufactured products that use processes that minimize negative environmental impact, conserve energy and natural resources, are safe for employees, communities and consumers, and are economically sound" (International Trade Administration, 2007; Joung et al., 2013). Studies in the literature converged on the idea which suggests that firms that promote sustainability as their focus are more likely to be successful in their respective industries (Azapagic, 2003; Jayal et al., 2010).

While the motivation of SM is clear, the approaches that would link these elusive concepts to manufacturing decisions remain vague. Discussion of the current literature focuses on how to refine these concepts of SM to a plausible level of being concrete and operational (Labuschagne et al., 2005). Ocampo and Clark (2014a) found out that current strategies of manufacturing firms are fragmented in the sustainability focus which may result in unorganized and ill-directed utilization of company resources. With several approaches and initiatives published in the literature, leaning toward addressing sustainability issues, such as cleaner production, corporate social responsibility (CSR), eco-efficiency (Lozano, 2012), life-cycle assessment (Ageron et al., 2012), ISO certifications (Lozano, 2012; Ageron et al., 2012), manufacturing firms are left with a challenge of determining the priorities attached to each initiative in relation to SM. Such evaluation of these approaches is deemed necessary to elucidate their significance on sustainability and thus providing firms with relevant information for decision-making. Due to the complexity of such evaluation involving tangible and highly intangible aspects with assessment structure that comprises value judgments, assumptions and scenarios (Heijungs et al., 2010), a multi-criteria decision-making (MCDM) approach is deemed appropriate (Cho, 2003; Herva and Roca, 2013). For instance, the evaluation of CSR activities such as company involvement in community-enhancement projects would require measurement framework that is hardly quantifiable because of the presence of factors with no available measurement system.

Previous studies have embarked on MCDM methods in environmental or sustainability assessment. These methods include analytic hierarchy process (AHP) (de Brucker et al., 2013), analytic network process (ANP) (Tseng et al., 2009a), fuzzy set theory (Tseng et al., 2009b), preference ranking organization method for enrichment evaluation (PROMETHEE) (Vinodh and Girubha, 2012), grey system theory (Baskaran et al., 2012) and decision-making trial and evaluation laboratory (DEMATEL) (Tseng et al., 2012). Aside from being a multi-criteria problem, evaluation of SM programs must reflect interdependencies and interrelationships of decision components which are inherent in the sustainability framework (Ocampo and Clark, 2014a). Considering such an argument, ANP is used in this study because of the following reasons: (1) sustainability program evaluation is a complex and multi-dimensional problem which characterizes the ANP framework; and (2) ANP overcomes hierarchical limitation, as most of MCDM methods have, and supports interrelationships of decision components (Saaty, 2001). Although various works have been published on sustainability assessment, a comprehensive evaluation of the most relevant SM program at firm level is missing in the literature. This area is significant as it provides valuable insights for managers and decision-makers in manufacturing firms especially on selecting programs in the presence of tangible and intangible criteria in addition to the inherent interrelationships among decision components. Thus, the objective of this paper is to present an evaluation method for selecting the most relevant SM program in the context of comprehensive consideration of the TBL. An evaluation system based on the US National Institute of Standards and Technology (US NIST) is presented in this paper and a case study of a semiconductor manufacturing firm is used to convey the methodology.

This paper is organized as follows. Section 2 provides a review of the literature in sustainability evaluation framework and a review of the ANP. Section 3 presents the general methodology of the evaluation problem. Section 4 presents a case study in a semiconductor manufacturing firm. Section 5 shows the results of such evaluation using ANP. Section 6 provides a discussion of the relevance of the results to sustainability assessments. Section 7 concludes the study with a short discussion of future research.

2. Literature review

2.1. Approaches to sustainability evaluation

Current approaches in this area are focused on developing sustainability indicators. Indicators provide standards in evaluating products, processes, companies, economic sectors or even countries in view of SM (Joung et al., 2013). A number of indicator sets are known in the literature from various sources such as the government, private sector, research and academic institutions. Among these indicator sets are the Global Report Initiative (GRI, 2006), the Dow Jones Sustainability Indexes (SAM Index, 2007), the Institution of Chemical Engineers Sustainability Metrics (IChemE, 2002), United Nations-Indicators of Sustainable Development (UN CSD, 2007), the Wuppertal Sustainability Indicators (Spangenberg and Bonniot, 2007), the 2005 Environmental Sustainability Indicators (ESI, 2005), the European Environmental Agency Core Set of Indicators (EEA CSI, 2005), the Environmental Performance Index (EpfI, 2010), the Organization for Economic Cooperation and Development Core Environmental Indicators (OECD CEI, 2003), the Japan National Institute of Science and Technology Policy (JSTA, 1995), the Ford Product Sustainability Index (Schmidt and Taylor, 2006), the Environmental Pressure Indicators for European Union (EprI, 1999), the General Motors Metrics for Sustainable Manufacturing (Feng et al., 2010; Dreher et al., 2009), the Wal-Mart Sustainability Product Index (Walmart Sustainability Product Index, 2009) and the International Organization for Standardization Environment Performance Evaluation Standard (ISO, 1999). The challenge of these indicators lies both in comprehensiveness and in being operational. Joung et al. (2013) developed a systematic integration of 11 indicator sets (see Joung et al., 2013). The resulting integration was formed into a hierarchical structure of an SM indicator set. This interesting work outlined a more comprehensive and operational SM because the integrated indicator set came from a number of established indicator sets. Furthermore, due to its hierarchical structure, the details of remembering decision components are more defined as one goes down the hierarchy.

Another stream of current research in this domain supports measuring sustainability performance of a product or manufacturing facility. De Silva et al. (2009) developed a scoring method for product sustainability index from a TBL approach. Ghadimi et al. (2012) proposed a sustainability product assessment methodology. Jaafar et al. (2007) presented a comprehensive procedure for computing PSI by calculating the weighted sum of different subelements within the triple-bottom line for each life-cycle stage (pre-manufacturing, manufacturing, use and post-use). A hierarchical approach using AHP with time element in evaluating the sustainable development index of firms was proposed by Krajnc and Glavic (2005). However, none of these studies deals with the selection of an SM program in a comprehensive TBL-based evaluation framework.

2.2. Analytic network process (ANP)

Analytic Hierarchy Process (AHP)/Analytic Network Process (ANP), developed by Saaty (1980; 2001) is a general theory of relative measurement. It is used to derive priority scales from paired comparisons of elements with respect to a higher element in the hierarchy or network. Comparisons are taken from actual measurements using Saaty's fundamental scale of absolute numbers. Elements are organized into homogeneous clusters or components in the decision problem. AHP/ANP is used in almost all applications related to decision-making such as planning, selection of the best alternative, conflict resolution, resource allocation and even optimization (Cho, 2003; Chen et al., 2012; Ocampo and Clark, 2014b). ANP, which is a generalization of AHP, organizes decision models represented in networks of decision components of alternatives, criteria, objectives and other factors that influence each other's priorities (Cho, 2003). This allows for flexibility in decision-making, taking all consideration of interdependencies and interrelationships among decision components and elements which are often representative of actual real-life scenarios. A special case where decision components are organized in a multi-level hierarchy is an AHP.

Local priorities in ANP are computed in a way similar to how local priorities in AHP are established, based on pairwise comparisons and judgments. The advantage of using ANP in a wide array of decision problems lies in capturing both qualitative and quantitative criteria in an analytical decision model and then allowing interrelationships with each decision component, which is one of the shortcomings of current unilateral decision-making schemes. Figure 1 represents an example of the form of the network structure used in a particular decision-making process. A comprehensive theoretical discussion of networks, interdependencies, pairwise comparisons processes along with the framework of AHP/ANP can be found in Saaty (1980; 2001).

The input to the supermatrix of a hierarchical network depends on the presence and type of dependence relations described in the digraph as shown in Figure 1.

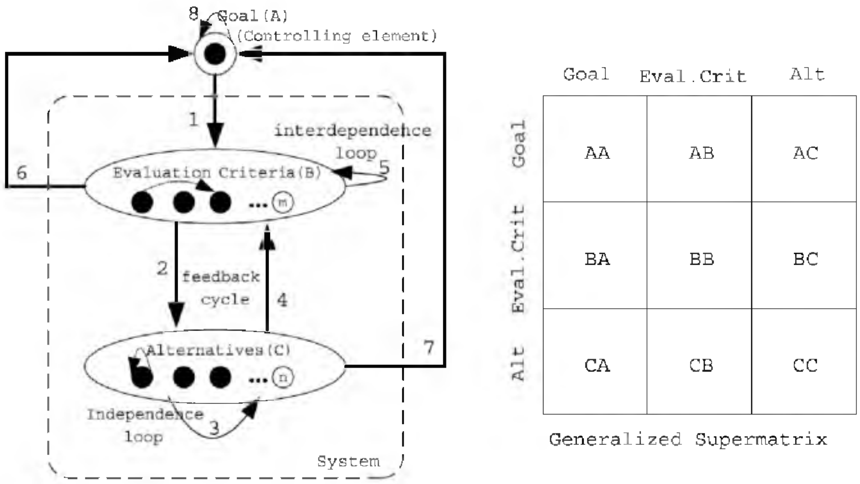

Figure 1. A sample network structure and its corresponding supermatrix

Source: Adapted from: Promentilla et al. (2006a).

The values of the block matrices, for instance AB, in the initial supermatrix are the estimated priorities that provide the relative strength of dominance of an element over another element in the component with respect to a common element from which the arc emanates. The eigenvector method is one of the popular methods used to quantify the relative dominance of the elements from pairwise comparison matrices. Saaty (1980) proposed the following eigenvalue formulation to obtain the desired ratio-scale priority vector (or weights) **w** of n elements:

$$\mathbf{Aw} = \lambda_{max}\mathbf{w} \tag{1}$$

where **A** is the positive reciprocal pairwise comparisons matrix, λ_{max} is the maximum (or principal) eigenvalue of the matrix **A**.

The measure of consistency of judgment is based on using the Consistency Index (CI) and Consistency Ratio (CR). The Consistency Index (CI), as a measure of degree of consistency, was calculated using the formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

The consistency ratio (CR) is computed as:

$$CR = \frac{CI}{RI} \tag{3}$$

where RI is the mean random consistency index [see Alonso and Lamata (2006) for Tables of RI]. Acceptable CR values must be less than 0.1. Decision-makers were asked to repeat the pairwise comparisons for CR values greater than 0.1.

Global priority ratio scales or priorities can be obtained based on the synthesizing concept of the supermatrix. By raising the matrix to large powers, the transmission of influence along all possible paths defined in the decision structure is captured in the process (Saaty, 2001). 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 structure (Promentilla et al., 2008). Saaty (2001) assured that as long as the supermatrix representation is a primitive irreducible matrix in a strongly connected digraph, the initial supermatrix must converge to a limit supermatrix. Promentilla et al. (2008) discussed that the limit supermatrix denoted by **L** exists when the initial supermatrix is standardized by its principal eigenvalue as shown by the equation:

$$\lim_{p\to\infty}\left(\frac{\mathbf{S}}{\lambda_{max}}\right)^p = \lim_{p\to\infty}\left(\overline{\mathbf{S}}\right)^p = \mathbf{L} \tag{4}$$

Each column of the limit supermatrix is a unique positive column eigenvector associated with the principal eigenvalue λ_{max} (Promentilla et al., 2008). This principal column eigenvector corresponds to the stable priorities from the limit supermatrix and can be used to measure the overall relative dominance of one element over another in a hierarchical network structure (Promentilla et al., 2006a).

3. Methodology

In general, the proposed procedure in evaluating SM programs is as follows:

1. Incorporate feedback and dependence on the hierarchical SM structure which was organized by Joung et al. (2013) and is published on the US NIST website (SMIR, 2011). The details of each component can be accessed through the website. Introducing interdependencies is done by gradually introducing feedback and dependence loops to the hierarchical SM structure. A group of experts must establish these loops based on theoretical and practical perspectives of sustainability. The general evaluation network is shown in Figure 2. Note that if an arrow emanates from $\mathbf{C}_1$ to $\mathbf{C}_2$ in the decision network, it means that $\mathbf{C}_1$ is influenced by $\mathbf{C}_2$. An arrow emanating from and to the same element or component means an existence of inner dependence of an element or elements within a component.
2. Elicit pairwise comparisons based on the network developed in 1. In eliciting paired comparisons, in general we ask the question: "Given a control element, a component (element) of a given network, and given a pair of components (or elements), how much more does a given member of the pair dominate the other member of the pair with respect to a control element?" (Promentilla et al., 2006a). Saaty's Fundamental Scale (1980) is used to compare elements pairwise as shown in Table 1. A pairwise comparison matrix has a reciprocal characteristic. For instance, comparing a_1 with a_2 will have a 3 ratio scale, then comparing a_2 with a_1 should have a ratio scale of 1/3 as the reciprocal of 3. Local priority vectors are obtained using equation (1). Consistency ratios are checked using equations (2) and (3).

Table 1

Saaty's Fundamental Scale

	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
2	Weak	between equal and moderate
3	Moderate importance	Experience and judgment slightly favor one element over another
4	Moderate plus	between moderate and strong
5	Strong importance	Experience and judgment strongly favor one element over another
6	Strong plus	between strong and very strong
7	Very strong or demonstrated importance	An element is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	between very strong and extreme
9	Extreme importance	Evidence favoring one element over another is either of the highest possible order or affirmation

3. Populate the initial supermatrix with the local priority vectors obtained in step 2. Then transform the initial supermatrix to a column stochastic matrix by normalizing column values so that sum of each column is equal to 1. This is done by dividing each value in a column by the sum of that column. Finally, using equation 4, raise the stochastic supermatrix to sufficiently large powers until each column becomes identical. The resulting values are the principal vector of dominance of the elements in the supermatrix.

4. Case study

To illustrate the methodology, a real case study is carried out in a semiconductor manufacturing firm in the Philippines. The profile of the firm and the SM programs undertaken have been published elsewhere (Ocampo and Clark, 2014a). FC semiconductor, being a multinational firm, has manufacturing sites strategically located in Asia with a test and assembly site in Cebu, Philippines (Ocampo and Clark, 2014a). The firm, is committed to incorporate sustainability in their decision-making especially in their products and processes. The firm has promoted ten programs in their approach toward sustainability. These are: reforestation program (PI), health and wellness program (P2), competitive employee compensation and career development (P3), sound occupational health and safety (P4), elimination of lead in plating process (P5), adoption of "green" molding compound (P6), elimination of PVC in plastic packaging (P7), energy efficient products (P8), lean six sigma projects (P9) and energy management program (P10). The firm is faced with the problem: to which programs they must attach higher priorities in their effort and resources to characterize sustainability effectively.

Derived from the work of Joung et al. (2013) on the comprehensive sustainability indicator set and the case information of SM programs, Table 2 shows identified clusters or decision components with their corresponding codes. Figures 3-5 elucidate the decision network based on the general framework in Figure 2. Environmental, economic and social criteria are coded with A, B, and C, respectively. The subcriteria, in the level-2 cluster, are coded in a way that shows reference from their parent criterion. For instance, the subcriteria under environmental criteria are coded as A_i, i = 1,2,3,…,n . The attributes, in the level-3 cluster, are likewise coded in a form that references their parent subcriteria. Attributes under A_1 subcriteria for instance, are coded as A_{1j}, j = 1,2,3,…,k. SM programs are coded as P_l, 1 = 1,2,3,…,m.

Table 2

Decision components and their codes

Decision components and elements	Code	Decision components and elements	Code	Decision components and elements	Code
Evaluation of sustainable manufacturing	G	Effluent	A21	Employees health and safety	C11
Environmental stewardship	A	Air emissions	A22	Employees career development	C12
Economic growth	B	Solid waste emissions	A23	Employee satisfaction	C13
Social well-being	C	Waste energy emissions	A24	Health and safety impacts from manufacturing and product use	C21
Pollution	A1	Water consumption	A31	Customer satisfaction with operations and products	C22
Emissions	A2	Material consumption	A32	Inclusion of specific rights to customer	C23
Resource consumption	A3	Energy/electrical consumption	A33	Product responsibility	C31
Natural habitat conservation	A4	Land use	A34	Justice/equity	C32
Profit	B1	Biodiversity management	A41	Community development programs	C33
Cost	B2	Natural habitat quality	A42	Reforestation program	P1
Investment	B3	Habitat management	A43	Health and wellness program	P2
Employee	C1	Revenue	B11	Competitive employee compensation and career development	P3
Customer	C2	Profit	B12	Sound occupational health and safety	P4
Community	C3	Materials acquisition	B21	Elimination of lead in plating process	P5
Toxic substance	A11	Production	B22	Adoption of "green" molding compound	P6
Greenhouse gas emissions	A12	Product transfer to customer	B23	Elimination of PVC in plastic packaging	P7
Ozone depletion gas emissions	A13	End-of-service-life product handling	B24	Energy efficient products	P8
Noise	A14	Research and development	B31	Lean six sigma programs	P9
Acidification substance	A15	Community development	B32	Energy management program	P10

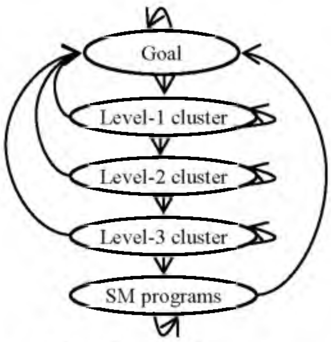

Figure 2. General evaluation framework based on ANP

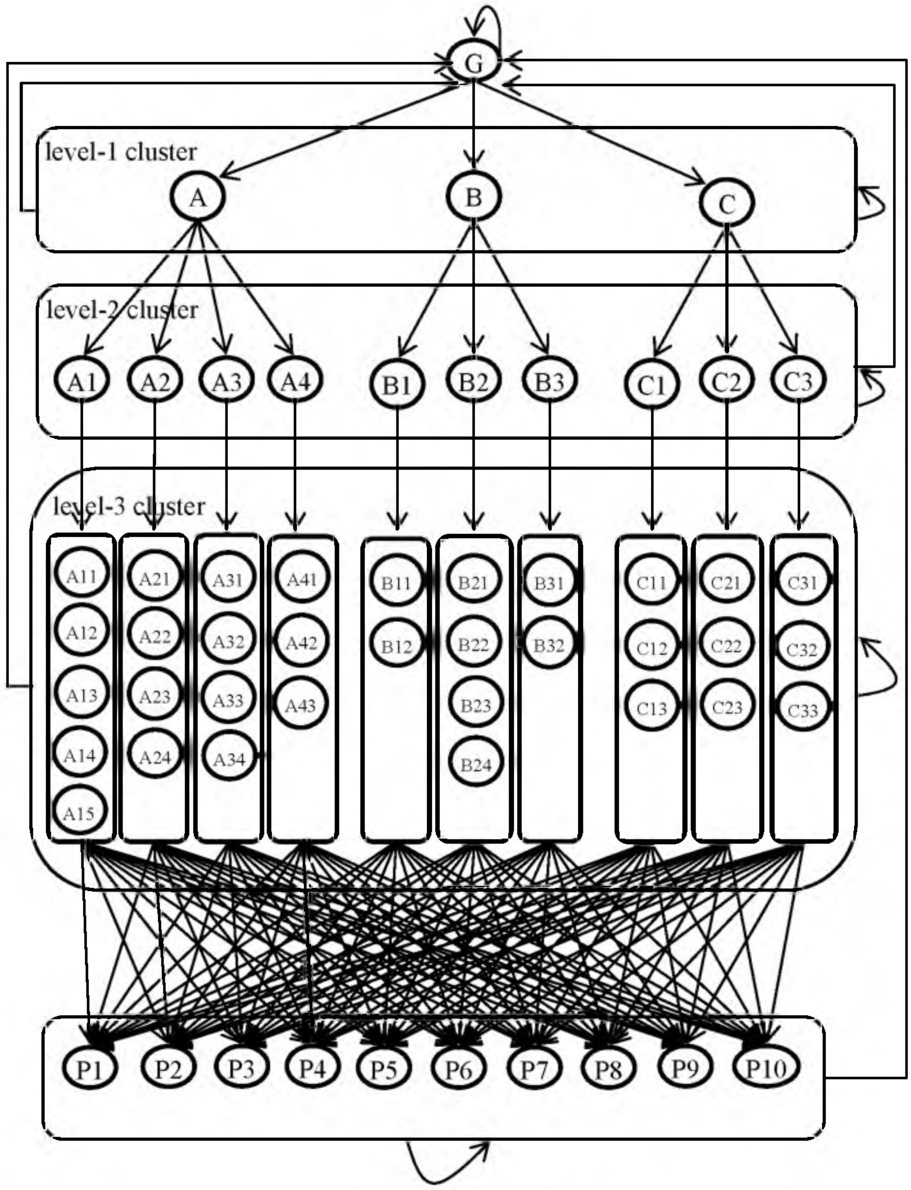

Figure 3. Decision problem of the evaluation of sustainable manufacturing programs

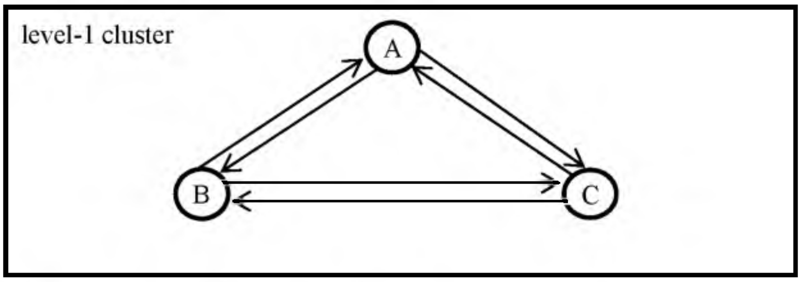

Figure 4. Interdependencies of the level-1 cluster

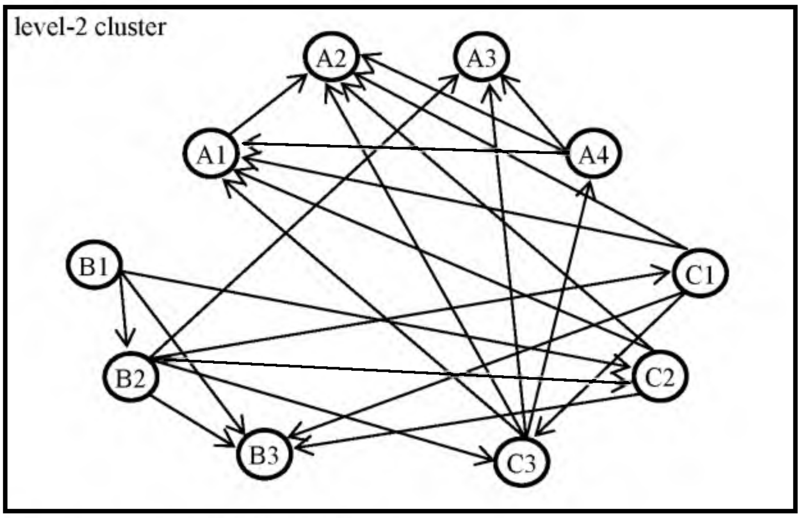

Figure 5. Interdependencies of the level-2 cluster

Note that the level-1 to level-3 clusters, as well as the SM programs cluster, have outer dependence loop to the goal. Thus, the goal serves as a controlling element of the decision network shown in Figure 3. This is consistent with the emphasis of Saaty on the existence of a control hierarchy on ANP (Saaty, 2001). In practice, this loop guarantees that the elements in the lower level clusters conform to the goal. This ensures a strong irreducible digraph which is a requisite to achieve a limit supermatrix (Promentilla 2006a; 2006b). A group of experts in sustainability and manufacturing research and practice has been invited to a focus group discussion (FGD) to provide inputs on the interdependencies of the hierarchical framework of Joung et al. (2013) and to conduct paired comparisons based from these interdependencies. The expert group is composed of four researchers and five manufacturing managers and consultants who have sufficient background in manufacturing and sustainability research. This method of gathering experts' judgments is consistent with several applications of ANP in various domains, e.g. Promentilla et al (2006b); Tseng et al. (2009a). The group was already familiar with the purpose of the discussion and the hierarchical structure of the evaluation framework before the FGD was conducted. Based from the group's unified judgment, interdependencies of cluster-1 and cluster-2 are identified as shown in Figures 4 and 5. The results of paired comparisons are shown in the next section.

5. Results

In general, there are six types of paired comparisons in this paper. The first four sets are the results of the hierarchical dependence from the goal down to cluster-1, from cluster-1 to cluster-2, from cluster-2 to cluster-3 and from cluster-3 to the SM programs cluster, while the last two sets are drawn from the interdependencies described in Figures 4 and 5. First, paired comparisons are done on the dependence of cluster-1 elements with respect to the goal. Second, paired comparisons are done on the dependence of cluster-2 elements with respect to their parent element in the first cluster. Third, paired comparisons are done on the dependence of cluster-3 elements with respect to their parent element in the second cluster. Fourth, paired comparisons are done based on the efficiency of elements in the SM programs cluster, with respect on each element in the third cluster. Fifth, paired comparisons are done on the influence of elements on other elements in cluster-1. Lastly, paired comparisons are done on the influence of elements on other elements in cluster-2.

For the purpose of brevity, we show here only samples of paired comparisons and the general structure of the supermatrix. Due to the large space needed for a 56x56 supermatrix, we could not present here the initial, column stochastic and limiting supermatrices. Readers are advised to contact the corresponding author through email if they wish to have a Microsoft Excel file of these supermatrices. Table 3 shows a sample of the paired comparisons of the first type. The question being asked in Table 3 is: "Comparing environmental stewardship (A) and economic growth (B), which one dominates the goal (G) more and by how much?" The resulting eigenvector (priority vector) is shown in Table 3. Table 4 shows a sample of the paired comparisons of the second type. The question being asked in Table 4 is: "Comparing pollution (A1) and emission (A2), which one dominates environmental stewardship (A) more, and by how much?". Table 5 shows a sample of the paired comparisons of the third type. The question being asked in Table 5 is: "Comparing toxic substances (A11) and greenhouse gas emissions (A12), which one dominates pollution (A1) more, and by how much?". Table 6 shows a sample of pairwise comparisons matrix of the performance of SM programs with respect to each element in cluster-3. The question being asked in Table 6 is this: "Comparing reforestation program (P1) and health and wellness program (P2), which one characterizes toxic substance (A11) better and by how much?". The resulting priority vector is reported in Table 6. Table 7 shows the dominance of other elements over a specific element in cluster-1. The question in Table 7 is: "Comparing environmental stewardship (A) and economic growth (B), which one dominates environmental stewardship (A) more and by how much?". The resulting priority vector is reported in Table 7. Lastly, Table 8 also shows a sample of pairwise comparisons matrix of the interdependencies of elements on cluster-2. The question being asked in Table 8 is: "Comparing pollution (A1) and emission (A2), which one influences the community (C3) more and by how much?". The resulting priority vector is again reported.

Table 3

Pairwise comparisons of the dependence of cluster-1 elements on the goal

A	A	B	C	Eigenvector
A	1	1/2	1/2	0.200
B	2	1	1	0.400
C	2	1	1	0.400

Table 4

Pairwise comparisons of the dependence of cluster-2 elements on their parent element in cluster-1

A	A1	A2	A3	A4	Eigenvector
A1	1	1	3	2	0.349
A2	1	1	3	2	0.349
A3	1/3	1/3	1	2	0.147
A4	1/2	1/2	1/2	1	0.155

Table 5

Pairwise comparisons of the dependence of cluster-3 elements on their parent element in cluster-2

A1	A11	A12	A13	A14	A15	Eigenvector
A11	1	1	3	5	3	0.349
A12	1	1	3	5	3	0.349
A13	1/3	1/3	1	2	1	0.118
A14	1/5	1/5	1/2	1	1/2	0.066
A15	1/3	1/3	1	2	1	0.118

Table 6

Pairwise comparisons of the performance of SM programs with respect to an element in cluster-3

A11	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Eigenvector
P1	1	1/5	1	1/4	1/7	1/7	1/7	1/2	1	1/2	0.028
P2	5	1	4	2	1/2	1/2	1/2	3	4	3	0.115
P3	1	1/4	1	1/3	1/5	1/5	1/5	1/2	1	1/2	0.036
P4	4	1/2	3	1	1/3	1/3	1/3	2	3	2	0.074
P5	7	2	5	3	1	1	1	4	5	4	0.205
P6	7	2	5	3	1	1	1	3	5	3	0.199
P7	7	2	5	3	1	1	1	4	5	4	0.205
P8	2	1/3	2	1/2	1/4	1/3	1/4	1	2	1	0.053
P9	1	1/4	1	1/3	1/5	1/5	1/5	1/2	1	1/2	0.036
P10	2	1/3	2	1/2	1/4	1/4	1/4	1	2	1	0.049

Table 7

Pairwise comparisons of the dominance of other elements with respect to an element in cluster-1

A	A	B	C	Eigenvector
A	1	3	2	0.545
B	1/3	1	1/2	0.168
C	1/2	2	1	0.287

Table 8

Pairwise comparisons of the dominance of criteria with respect to an element C3 in cluster-2

C3	A1	A2	A3	A4	Eigenvector
A1	1	2	4	3	0.480
A2	1/2	1	3	2	0.262
A3	1/4	1/3	1	1/2	0.103
A4	1/3	1/2	2	1	0.155

The supermatrix shown in Table 9 is populated by the priority vectors obtained from the six types of paired comparisons. To facilitate discussion, we let A, B, C, D and E denote clusters of the goal, cluster-1, cluster-2, cluster-3 and SM programs cluster, respectively. In general, based on the hiernet presented in Figure 1, the supermatrix can be structured as in Table 9.

Table 9

The general supermatrix

	A	B	C	D	E
A	1	1	1	1	1
B	BA	BB	0	0	0
C	0	diag [CB]	CC	0	0
D	0	0	diag [DC]	I	0
E	0	0	0	DC	I

Note that the first row in the supermatrix which comprises blocks AA, AB, AC, AD, and AE is a unity vector. This represents the feedback control loop from all clusters to the goal element. Block BA (which means that B dominates A) is a hierarchical dependence from goal to cluster-1. Block CB and block DC are diagonal matrices resulting from the dominance of lower level elements to their parent criteria. CB denotes dependence of cluster-2 elements on their parent cluster-1 element while DC is the dependence of cluster-3 elements on their parent cluster-2 elements. Block BB and block CC denote interdependencies of cluster-1 and cluster-2 elements, respectively. Block DC is a hierarchical dependence of SM programs cluster on each element in cluster-3. Identity matrices which are represented by blocks DD and EE, show inner dependence of the elements on the cluster-3 and the SM programs cluster, respectively. Null matrices for the rest of the blocks in the supermatrix describe lack of feedback and dependence on the elements of decision clusters. After populating the supermatrix with the local priority vectors, a stochastic matrix is then obtained by dividing column values by the sum of that column. By applying equation 4, the column stochastic matrix is raised to large powers until it converges to its Cesaro sum. Convergence is observed if each column in the supermatrix is identical. Each column represents the principal right eigenvector of the supermatrix. Priority ranking of elements per cluster is shown in Table 10.

Table 10

Priority ranking of decision components

	Priority Vector		
	Raw	Distributive	Ideal
G	0.3958	1.0000	1.0000
B	0.1156	0.3896	1.0000
C	0.1131	0.3811	0.9782
A	0.0681	0.2293	0.5886
C2	0.0322	0.1752	1.0000
B3	0.0246	0.1338	0.7638
B2	0.0228	0.1242	0.7092
A2	0.0227	0.1234	0.7043
A1	0.0192	0.1045	0.5965
B1	0.0176	0.0959	0.5475
C1	0.0144	0.0784	0.4474
A3	0.0129	0.0704	0.4016
C3	0.0125	0.0683	0.3898
A4	0.0048	0.0260	0.1483

B32	0.0082	0.1104	1.0000
A22	0.0052	0.0705	0.6383
B31	0.0041	0.0552	0.5000
C23	0.0039	0.0520	0.4713
C22	0.0039	0.0520	0.4713
A11	0.0033	0.0451	0.4085
A12	0.0033	0.0451	0.4085
B11	0.0033	0.0445	0.4032
B12	0.0033	0.0445	0.4032
A21	0.0026	0.0352	0.3192
A23	0.0026	0.0352	0.3192
C11	0.0026	0.0349	0.3163
B21	0.0023	0.0308	0.2785
B22	0.0023	0.0308	0.2785
A33	0.0019	0.0261	0.2366
A34	0.0019	0.0261	0.2366
A31	0.0019	0.0261	0.2366
C21	0.0019	0.0260	0.2357
C31	0.0016	0.0211	0.1914
C33	0.0016	0.0211	0.1914
C32	0.0016	0.0211	0.1914
A41	0.0012	0.0161	0.1456
B23	0.0011	0.0154	0.1393
B24	0.0011	0.0154	0.1393
A13	0.0011	0.0152	0.1379
A15	0.0011	0.0152	0.1379
A24	0.0009	0.0117	0.1064
C12	0.0009	0.0116	0.1054
C13	0.0009	0.0116	0.1054
A32	0.0006	0.0087	0.0789
A14	0.0006	0.0087	0.0785
A42	0.0006	0.0080	0.0728
A43	0.0006	0.0080	0.0728
P7	0.0064	0.1294	1.0000
P6	0.0062	0.1257	0.9718
P5	0.0058	0.1182	0.9137
P8	0.0056	0.1133	0.8755
P9	0.0050	0.1013	0.7827
P1	0.0046	0.0938	0.7253
P10	0.0045	0.0916	0.7080
P2	0.0040	0.0799	0.6178
P4	0.0038	0.0772	0.5969
P3	0.0034	0.0696	0.5383

6. Discussion

Valuable insights could be gained from this comprehensive evaluation of SM programs using ANP. In cluster-1, economic growth (B) is preferred over social well-being (C) which ranks second and environmental stewardship (A) which ranks third. Economic and social dimensions have almost equal priority weight, which means that manufacturing firms must focus on economic gains and the resulting social impact (stakeholders' welfare including those of employees, customers and community) equally, than on the decisions made for maximizing these gains separately. Addressing social concerns as a result of economic decisions could be attained via environmental impact on manufactured products and manufacturing processes. This claim is supported by the ranking of cluster-2 elements. Customer (C2), investment (B3), cost (B2), emissions (A2) and pollution (A1) are top-priority elements. Refining the details of this ranking can be done by taking a look at the top-priority elements in cluster-3. Customer satisfaction (C22), inclusion of customer rights (C23), investment in research and development (B31), community development (B32), revenue (B11), profit (B12), toxic substance (A11), GHG emissions (A12) and air emissions (A22) are top priority in cluster-3. Thus, decision-making in manufacturing must focus on maximizing revenue and profit by strategizing investment on research and development in technology and investment to contribute community development. The way to community development is to develop programs that minimize environmental impact of toxic substance, GHG emissions and air emissions. Revenue and profit are maximized by strengthened customer satisfaction and inclusion of customer rights to manufactured products. Developing programs that simultaneously enhance customer satisfaction and community development by addressing environmental concerns on toxic substance, GHG emissions and air emissions is fundamental to the increase of revenue and profit. Long-term strategy must address customer and community through environmental concerns so that sustainability is attained. This ranking influences the priority ranking of SM programs. The rank is as follows: elimination of PVC in plastic packaging (I7), adoption of "green" molding compound (I6), elimination of lead in the plating process (I5), energy efficient products (I8) and lean six sigma programs. The first three programs, which are cleaner production technologies, are directed at satisfying customer requirements while enhancing community development. Cleaner production on a wider scale can contribute to the greater welfare of society, as a society is the direct stakeholder in environmental concerns, arising from manufacturing processes (Singh et al., 2007). The last two programs focus on increasing profit by enhancing product research and development.

7. Conclusions and future work

This paper presents a comprehensive evaluation of SM programs using ANP. The comprehensiveness of such evaluation lies in the use of a recently concluded study of the US National Institute of Standards and Technology (US NIST) concerning the set of sustainability indicators derived from established and well-known indicator sets. Due to the emergence of a multi-criteria evaluation as a result of this use and due to the complexity of decision components in the evaluation, analytic network process (ANP) is used. ANP is deemed appropriate not only because of the multi-criteria nature of the evaluation process but primarily because of the presence of subjective components that are interrelating in complex relationships. An empirical study is carried out in a semiconductor manufacturing firm in the Philippines in order to evaluate the existing programs toward sustainability using the proposed evaluation framework. The results show that cleaner production technologies, i.e. elimination of PVC in plastic packaging, adoption of green molding compound and elimination of lead in the plating process, are considered top priority programs. Developing energy efficient products and adopting lean six sigma programs are considered second on the list. This paper suggests that sustainability is achieved by formulating strategies that enhance customer and community well-being via addressing environmental concerns especially on toxic substance, GHG emissions and air emissions.

Certain limitations are recognized in this study which are potential challenges for future work. This paper assumes that judgment elicitation is represented by crisp values. Future research could be extended by using fuzzy set theory to address vagueness in decision-making. An industry-wide evaluation could be done using the proposed framework to obtain more general insights regarding appropriate SM programs. Since preferences in evaluation may change over time due to technological, economic and political factors, dynamic judgment could be carried out to explore relevant or hybrid programs which are appropriate at different times in the planning horizon.

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