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A robust evaluation of sustainability initiatives with analytic network process (ANP)

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Abstract: This paper presents a methodology on evaluating sustainable manufacturing initiatives using analytic network process (ANP) as its base. The evaluation method is anchored on the comprehensive sustainable manufacturing framework proposed recently in literature. A numerical example that involves an evaluation of five sustainable manufacturing initiatives is shown in this work. Results show that sustainable manufacturing implies enhancing customer and community well-being by means of addressing environmental issues related to pollution due to toxic substances, greenhouse gas emissions and air emissions. To test the robustness of the results, two approaches are introduced in this work: (1) using Monte Carlo simulation and (2) introducing structural changes on the evaluation model. It suggests that the results are robust to random variations and to marginal changes of the network structure. The contribution of this work lies on presenting a sustainable manufacturing evaluation approach that addresses complexity and robustness in decision-making.

Key words: Analytic Network Process, Evaluation, Manufacturing, Robustness, Sustainability.

1. Introduction

In sustaining manufacturing industry, purely profit-based strategies became insufficient brought about by various issues that concern environmental degradation, resource depletion, carbon emissions, and social responsibility. These issues are associated with the interests of various stakeholders who are capable of influencing salient decisions of manufacturing firms (Pham and Thomas, 2012). These stakeholders, which include customers, employees, investors, suppliers, communities and governments (Theyel and Hofmann, 2012) directly or indirectly compel manufacturing firms to manage the performance of their products and processes in order to satisfy persistent issues on resource depletion, socio-economic concerns and human health problems. When these demands from stakeholders are integrated in mainstream decision-making, manufacturing firms could establish long term relations with these stakeholders (Harrison *et al.*, 2010). This is believed to be beneficial from the perspective of the manufacturing industry as stakeholders play a crucial role in the sustainability of manufacturing firms (Kassinis and Vafeas, 2006; Paloviita and Luoma-aho, 2010).

Ocampo and Clark (2014a) implied that these demands from stakeholders are pushing firms to gear up towards a more holistic concept of the triple-bottom-line – a term first coined by Elkington (1997) – which interprets sustainability into three main dimensions: environmental stewardship, economic growth and social well-being. Labuschagne *et al.* (2005) claimed that optimal approaches of manufacturing firms towards sustainability are only possible when these three dimensions are taken into consideration. From the perspective of sustainability of manufacturing firm emerges specialized framework popularly known as ‘sustainable manufacturing’ and is defined 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). Operationally, manufacturing firms must:

(1) design and manufacture eco-efficient products with processes that possess minimal environmental footprint using a life cyclce assessment (LCA) approach, (2) develop initiatives on cost reduction and return on investment maximization across organizational levels, and (3) maintain programs that enhance well-being of stakeholders (Ocampo, 2015). Recent studies claim that firms that promote sustainability in their decision-making are more likely to be successful in their respective industries (Jayal *et al.*, 2010).

Among various research domains in this area, evaluation of manufacturing initiatives that promote sustainability is popularly taken (Joung *et al.*, 2013; Ocampo and Clark, 2015). The basis of evaluation is usually anchored on some established indicator sets (Jayal *et al.*, 2010; Ocampo and Clark, 2014b; Ocampo and Clark, 2015). These indicator sets provide verifiable standards in evaluating products, processes, firm, economic sectors or even countries and regions in the context of sustainable manufacturing (Joung *et al.*, 2013). A review of these indicator sets were discussed in Mayer (2008), Joung *et al.* (2013), Ocampo and Clark (2014b), Ocampo and Clark (2015), Ocampo (2015) and will not be repeated here. The challenge of these indicators sets is twofold: (1) being comprehensive, and (2) being operational. A plausible integration of these indicators sets that attempts to cover sustainability areas in great detail was proposed by Joung *et al.* (2013) and this framework was used by Ocampo and Clark (2014b), Ocampo and Clark (2015) and Ocampo (2015).

Ocampo (2015) utilized the framework of Joung *et al.* (2013) in index computation to assess sustainability of manufacturing at firm level. Ocampo and Clark (2015) used the same structure to evaluate sustainable manufacturing of a case firm using analytic hierarchy process (AHP). Ocampo and Clark (2014b) extended the former evaluation to include causal relationships between criteria and across the decision model using the general analytic network process (ANP). Despite of these recent works, the specific problem that is advanced in this paper is an evaluation framework that captures complexity and robustness of decision-making in the framework of sustainable manufacturing.

This paper extends previous works by embedding robustness in sustainable manufacturing evaluation in the context of the ANP. Following the argument of Ocampo and Clark (2014b) on the use of ANP, this work imposes such use due to the complexity and multi-dimensionality of the evaluation problem associated with the issues that concern sustainability. Developed by Thomas Saaty, ANP generalizes any decision-making problem by overcoming the hierarchic assumption mostly characterized by other decision-making tools (Saaty, 2001). The use of ANP in sustainable manufacturing evaluation allows comprehensiveness of addressing the complexity inherent in the decision-making process. Chen *et al.* (2012) agreed that AHP and ANP are appropriate analytical tools for addressing location, program or strategy selection problems. Among various applications that highlight the use of ANP include developing sustainability index for a manufacturing enterprise (Garbie, 2011), developing multi-actor multi-criteria approach in complex sustainability project evaluation (de Brucker *et al.*, 2013), evaluating industrial competitiveness (Sirikrai and Tang, 2006), evaluating energy sources (Chatzimouratidis and Pilavachi, 2009), developing an impact matrix and sustainability-cost benefit analysis (Chiacchio, 2011), etc. The departure of this work include: (1) evaluating robustness of the results of the evaluation problem and, (2) determining the impact of structural changes of the evaluation problem on the results of the ANP. The contribution of this work is on presenting a sustainable manufacturing evaluation approach that addresses complexity and robustness in decision-making.

This paper is organized as follows: Section 2 presents the methodology of the study. Section 3 highlights the evaluation model along with the results of the ANP and robustness tests. Section 4 provides the discussion and ends with concluding remarks in Section 5.

2. Methodology

The proposed evaluation approach can be generally described in the following procedure:

1. Incorporate feedback and dependence relationships on the hierarchical sustainable manufacturing evaluation framework proposed by Ocampo and Clark (2015). This is presented in the parallel work of Ocampo and Clark (2014b). The ten sustainable manufacturing initiatives under evaluation were described in the concept paper of Ocampo and Clark (2014a). Although, they attempt to develop an evaluation method following the demands of stakeholders and the triple-bottom line, the approach was not generalizable (Ocampo and Clark, 2014a). By convention, an arrow that emanates from one component to another component implies

that the latter influences the former. Introducing these dependence relationships is based from theory and practice of sustainability as discussed by Ocampo and Clark (2014a).

2. Based from the resulting network of step 1, corresponding pairwise comparisons matrices are constructed. A detailed discussion on this topic was provided by Saaty (2001). In eliciting pairwise comparisons, generally we ask this question: "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?" (Promentilla, *et al.*, 2006). Saaty's Fundamental Scale (Saaty, 1980), as shown in Table 1, is used to compare elements pairwise. Note that a pairwise comparisons matrix possesses a reciprocal characteristic, i.e. $a_{ji}=\frac{1}{a_{ij}}$.

Table 1. Saaty fundamental scale (adopted from Saaty, 1980).

	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	The evidence favoring one element over another is one of the highest possible order or affirmation

Determining the priority vector of a pairwise comparisons matrix involves solving an eigenvalue problem in the form

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

where A is the positive reciprocal of the pairwise comparisons matrix and w is the principal eigenvector associated with the maximum eigenvalue λ_{max}. Saaty (1980) claimed that w is the best estimate of the priority vector of the pairwise comparisons matrix.

For consistent judgment, $\lambda_{max}=n$; otherwise, $\lambda_{max}>n$ where n is the number of elements being compared. Consistency of judgment is measured using consistency index (CI) and consistency ratio (CR). CI is a measure of the degree of consistency of judgment and is denoted by

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

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 consistency (Saaty, 1980). Otherwise, decision-makers will be asked to reconsider their judgments.

3. Form the initial supermatrix based from the network developed in step 1. See Saaty (1980) on the discussion of supermatrix. Populate this initial supermatrix with the local priority vectors obtained in step 2. Then, transform the initial supermatrix to column stochastic supermatrix by normalizing column values such that column sum is unity. Finally, raise the stochastic supermatrix to sufficiently large powers until row values become identical. Each column of this limiting supermatrix is likewise identical and is known as the global eigenvector of the supermatrix. This is used to describe the overall dominance of the elements in the decision network.

4. To test the robustness of the results, this paper adopted two approaches. First, Monte Carlo simulation was performed to determine the effect of repeated decisions on the final ranking of results. Second, structural changes of the decision network were introduced to evaluate their impact on the final ranking. Comparison of the results with the findings of Ocampo and Clark (2014b) and Ocampo and Clark (2015) were reported.

3. Results

The evaluation problem proposed by Ocampo and Clark (2015) was based from the hierarchical sustainability indicators set proposed by Joung *et al.* (2013) along with the sustainable manufacturing initiatives discussed by Ocampo and Clark (2014b). This problem is composed of the goal, the triple-bottom line (environmental stewardship, economic growth and social well-being), 10 sub-criteria, 33 attributes and 5 sustainability initiatives. Using analytic hierarchy process (AHP), the work was able to assign priority ranking of sustainability initiatives that the case firm must adopt to further promote sustainability.

Although the dependence relationships were shown in Ocampo and Clark (2014b), the motivations behind these relationships are discussed in this paper. In this work, the hierarchical structure of Joung *et al.* (2013) was still used while feedback and dependence relations in the criteria and sub-criteria components were introduced. This approach of introducing feedback and dependence relationships in the criteria and sub-criteria components, excluding the attribute component, was done to provide interrelationships at an intermediate level while maintaining hierarchical dependence at lower level. This allows control from upper level decision components to the lower level components. Figure 1 shows the evaluation problem and Table 2 presents the decision components and elements along with their corresponding codes. The details of this coding system were discussed by Ocampo and Clark (2014b).

As shown in Figure 1, attribute component contains no dependence relationships as they only become redundant due to the existing relationships in higher level components. The hierarchical dependence relationships from goal – criteria – sub-criteria – attributes were based from the work of Ocampo and Clark (2015). Note that all decision components have feedback control loop towards the goal component. This is a structural issue as it guarantees that the the goal component takes control over all other components in the evaluation problem.

In this paper, pairwise comparisons matrices of the hierarchical dependence relationships from goal – criteria – sub-criteria – attributes were obtained from Ocampo and Clark (2015). Generally, there are three sets or levels of pairwise comparisons matrices performed in this work. First is the dependence relationships among elements in the criteria component and Table 3 shows a sample of these

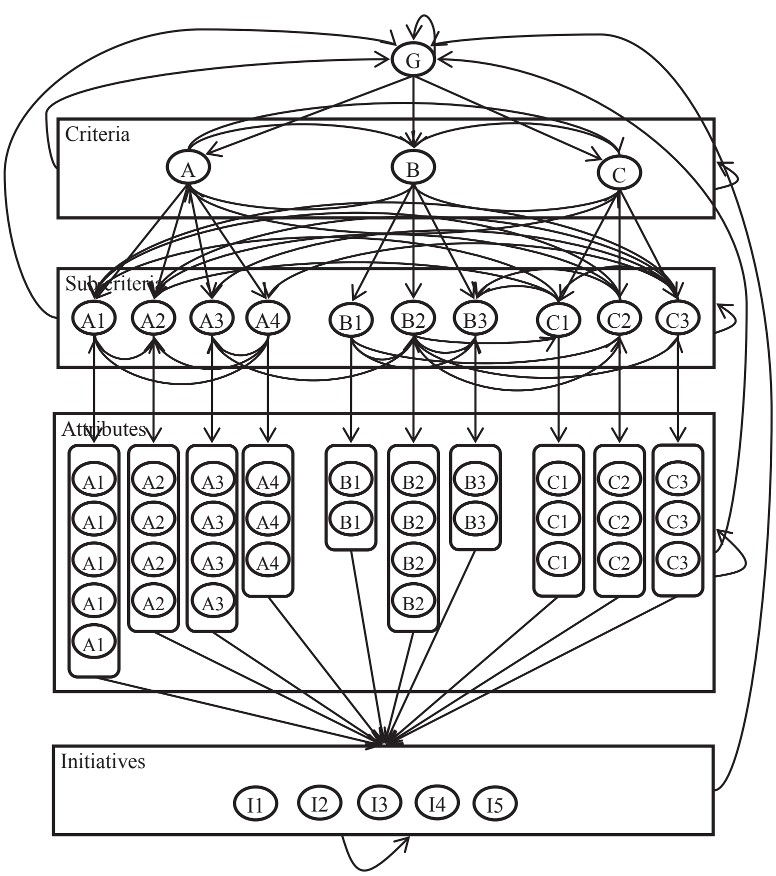

Figure 1. Decision network of the evaluation of sustainable manufacturing initiatives.

Table 2. Decision elements and their codes (adopted from Ocampo and Clark, 2015).

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 from 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	Health and wellness program	I1
Investment	B3	Habitat management	A43	Employee compensation and career development	I2
Employee	C1	Revenue	B11	Occupational health and safety	I3
Customer	C2	Profit	B12	Elimination of lead in plating process	I4
Community	C3	Materials acquisition	B21	Lean six sigma initiatives	I5
Toxic substance	A11	Production	B22		
Greenhouse gas emissions	A12	Product transfer to customer	B23		
Ozone depletion gas emissions	A13	End-of-service-life product handling	B24		
Noise	A14	Research and development	B31		
Acidification substance	A15	Community development	B32		

pairwise comparisons matrices. The question being asked in Table 3 is: "Comparing environmental dimension (A) and economic dimension (B), which one more dominates environmental dimension (A) and by how much?" The resulting priority vector is reported using equation (1). Second is the dependence relationships among elements in the sub-criteria component and Table 4 shows a sample of these pairwise comparisons matrices. The question being asked in Table 4 is: "Comparing pollution (A1) and emission (A2), which one more influences the community (C3) and by how much?" The resulting priority vector is again reported. Lastly, pairwise comparisons were performed on the hierarchical dependence relationships of sub-criteria to sustainable manufacturing initiatives. Table 5 shows a sample of these pairwise comparisons matrices. The question being asked in Table 5 is: "Comparing health and wellness program (I1) and employee compensation and benefits (I2), which one more characterizes toxic substance (A11) and by how much?" The resulting priority vector is reported.

The supermatrix in Table 6 is populated by the priority vectors provided by Ocampo and Clark (2015) on hierarchical dependence relationships of the network model and the resulting vectors obtained in this work. To facilitate discussion, let A, B, C, D and E be the goal, criteria, sub criteria, attributes and initiatives decision components. Generally, based from the network presented in Fig. 1, the supermatrix can be structured as in Table 6.

Table 3. Pairwise comparisons of the dominance of criteria with respect to environmental criterion (A).

A	A	B	C	Priority vector
A	1	3	2	0.5396
B	1/3	1	1/2	0.1634
C	1/2	2	1	0.2970

λ_{max}=3.009, CR=0.009

Table 4. Pairwise comparisons of the dominance of sub-criteria with respect to community (C3).

C3	A1	A2	A3	A4	Priority vector
A1	1	2	4	3	0.4673
A2	1/2	1	3	2	0.2772
A3	1/4	1/3	1	1/2	0.0954
A4	1/3	1/2	2	1	0.1601

λ_{max}=4.031, CR=0.012

Table 5. Pairwise comparisons of the dominance of sustainable manufacturing initiatives with respect toxic substance (A11).

A11	I2	I3	I4	I5	I9	Priority vector
I2	1	4	2	1/2	4	0.2697
I3	1/4	1	1/3	1/5	1	0.0682
I4	1/2	3	1	1/3	3	0.1688
I5	2	5	3	1	5	0.4252
I9	1/4	1	1/3	1/5	1	0.0682

λ_{max}=5.062, *CR*=0.014

The supermatrix in Table 6 is populated by the priority vectors provided by Ocampo and Clark (2015) on hierarchical dependence relationships of the network model and the resulting vectors obtained from this work.

Table 6. Blocks of the 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 is composed of blocks AA, AB, AC, AD, and AE is a unity vector. This is the representation of the feedback control loop from components to the goal element. Block BA, i.e. B dominates A, is a hierarchical dependence relation from goal to criteria component. Blocks CB and DC are diagonal matrices resulting from dominance relationships of lower level elements to their parent criteria. CB denotes dominance relations of sub-criteria component to their parent criteria element while DC is the dominance of attributes to their parent sub-criteria. Blocks BB and CC denote interdependencies in the criteria and sub-criteria component, respectively. Block DC is a hierarchical dependence relation of attribute component to sustainable manufacturing initiatives. Identity matrices represented by blocks DD and EE show inner dependence relationships of the elements in the attributes and initiatives components, respectively. Null matrices for the rest of the blocks in the supermatrix represent non-existent feedback and dependence relationships on the elements of decision components. The initial supermatrix is presented in Appendix 1. A stochastic matrix is formed by dividing column values of the initial supermatrix with their corresponding column sums. Then, the stochastic matrix is raised to large powers until it converges to its Cesaro sum. Convergence exists if row values are identical. Each column is the global priority vector and is used to measure the overall dominance of each element in the supermatrix. Priority ranking of elements was performed per decision component. This was obtained by normalizing values per component. Table 7 shows the ranking of the elements per component.

Table 7. Priority ranking of decision elements.

Elements	Raw vector	Distributive ranking	Ideal ranking	Rank
G	0.39578	1	1	1
A	0.06823	0.22986	0.59151	3
B	0.11535	0.38861	1	1
C	0.11325	0.38153	0.98180	2
A1	0.01920	0.10449	0.59689	5
A2	0.02279	0.12408	0.70875	3
A3	0.01337	0.07278	0.41571	8
A4	0.00428	0.02330	0.13308	10
B1	0.01758	0.09568	0.54653	6
B2	0.02279	0.12406	0.70864	4
B3	0.02454	0.13358	0.76305	2
C1	0.01447	0.07875	0.44986	7
C2	0.03216	0.17506	1	1
C3	0.01253	0.06822	0.38967	9
A11	0.00334	0.04495	0.40775	6
A12	0.00334	0.04495	0.40775	6
A13	0.00115	0.01554	0.14097	22
A14	0.00062	0.00837	0.07592	31
A15	0.00115	0.01554	0.14097	22
A21	0.00263	0.03544	0.32152	10
A22	0.00526	0.07089	0.64305	2
A23	0.00263	0.03544	0.32152	10
A24	0.00088	0.01181	0.10717	27
A31	0.00201	0.02702	0.24516	15
A32	0.00067	0.00901	0.08172	30
A33	0.00201	0.02702	0.24516	15
A34	0.00201	0.02702	0.24516	15
A41	0.00107	0.01442	0.13080	26
A42	0.00053	0.00721	0.06540	32
A43	0.00053	0.00721	0.06540	32
B11	0.00330	0.04441	0.40289	8
B12	0.00330	0.04441	0.40289	8
B21	0.00228	0.03071	0.27861	13
B22	0.00228	0.03071	0.27861	14
B23	0.00114	0.01536	0.13930	24
B24	0.00114	0.01536	0.13930	24
B31	0.00409	0.05512	0.50000	3
B32	0.00818	0.11023	1	1
C11	0.00260	0.03509	0.3184	12
C12	0.00087	0.01170	0.1061	28
C13	0.00087	0.01170	0.1061	28
C21	0.00193	0.02600	0.2359	18
C22	0.00386	0.05201	0.4718	5
C23	0.00386	0.05201	0.4718	4
C31	0.00157	0.02111	0.1915	19
C32	0.00157	0.02111	0.1915	21
C33	0.00157	0.02111	0.1915	19
I1	0.00876	0.17697	0.5898	3
I2	0.00701	0.14160	0.4719	5
I3	0.00837	0.16919	0.5639	4
I4	0.01484	0.30004	1	1
I5	0.01050	0.21220	0.70726	2

In order to test the robustness of these results, two approaches were performed. First, a Monte Carlo simulation of 500 runs is used to show the impact of randomness on the final results. This is done in a POM for Windows application software which is available in public domain. Second, structural revisions of the decision network were introduced to assess the impact of dependence relationships on the ANP results. In this approach, interdepence relationships of the sub-criteria component were eliminated and then results were subsequently reported. Furthermore, all interdependence relationships of criteria and sub-criteria components were removed and results were reported.

Table 8 summarizes the Monte Carlo simulation results. It shows that the ANP order ranking of I4-I5-I1-I3-I2 in decreasing priority is fairly robust after 500 random simulation runs which yield the order ranking of I4-I5-I1-I2-I3 in decreasing priority with rank reversal in the last two initiatives.

Table 8. Comparison with Monte Carlo simulation results.

Sustainable manufacturing initiatives	ANP results		Monte Carlo simulation	
	Priority	Rank	Priority	Rank
I1	0.18	3	0.16	3
I2	0.14	5	0.15	4
I3	0.17	4	0.12	5
I4	0.30	1	0.29	1
I5	0.21	2	0.28	2

Table 9 presents a comparison of ANP results with the results from structural changes. It shows that the absence of interdependencies in the sub-criteria component changes the ranking of I1 and I3. On the other hand, the complete absence of interdependencies in the decision network changes the top priority, i.e. I5 instead of I4.

Table 9. Impact of structural changes in the decision network.

	ANP results		Absence of sub-criteria interdepencies		Complete absence of interdependencies	
	Priority	Rank	Priority	Rank	Priority	Rank
I1	0.18	3	0.17	4	0.17	4
I2	0.14	5	0.14	5	0.15	5
I3	0.17	4	0.18	3	0.18	3
I4	0.30	1	0.26	1	0.25	2
I5	0.21	2	0.25	2	0.26	1

Finally, the results of this paper were compared with the results of Ocampo and Clark (2014b) and Ocampo and Clark (2015). Table 10 highlights the comparison.

Table 10. Comparison of the results.

	Current results with Monte Carlo simulation	Ocampo and Clark (2015) with AHP	Ocampo and Clark (2014b) with ANP
	Rank	Rank	Rank
I1	3	4	3
I2	4	5	5
I3	5	3	4
I4	1	2	1
I5	2	1	2

Table 10 shows that the results of the methodology are not consistent with the results of Ocampo and Clark (2015) but are fairly consistent with Ocampo and Clark (2014b).

4. Discussion

Valuable insights could be gained from the results of this paper. ANP provides insightful approach in better understanding the evaluation of sustainable manufacturing initiatives. In the criteria component, economic dimension (B) is preferred over social dimension (C) which ranks second and environmental dimension (A) which ranks third. This ranking supports the results of Ocampo and Clark (2015) with minor differences on the priority weights. Economic and social dimensions have almost equal weights which means that manufacturing firms must focus on economic gains and their corresponding social impacts, i.e. welfare of stakeholders which may include employees, customers and community. Addressing social issues as results of economic decisions could be achieved via environmental impact on manufactured products and manufacturing processes. This claim is supported by the ranking in the sub-criteria component. Customer (C2), investment (B3), emissions (A2), cost (B2), and pollution (A1) are sub-criteria on top priority. The details of this ranking could be examined by taking a look at the priority attributes in the lower level decision component. Community development (B32), air emissions (A22), investment to research and development (B31), inclusion of customer rights (C23), customer satisfaction (C22), toxic substance (A11), and GHG emissions (A12) are on top priority in the attribute component. Thus, manufacturing decision-making must focus on maximizing revenue and profit by maximizing investment on research and development in technology and investment that contributes community development. Investments on community development implies developing and implementing initiatives that minimize environmental impact of toxic substance, GHG and air emissions. Revenue and profit are maximized by reinforcing customer satisfaction strategies and by inclusion of customer rights on manufactured products. Developing initiatives that simultaneously enhance customer satisfaction and community development by addressing environmental concerns on toxic substance, GHG emissions and air emissions is fundamentally important to increase revenue and profit. This ranking influences the priority ranking of sustainable manufacturing initiatives. The rank is as follows: elimination of lead in plating process (I4), lean six sigma initiatives (I5), health and wellness program (I1), occupational health and safety (I3) and employee compensation and career development (I2). The first initiative, which is a cleaner production technology, is developed to satisfy customer requirements and at the same time promotes community development through embedding decreased risks associated with occupational sarety and health. Cleaner production in a wider scale could promote greater social welfare as the society becomes a direct stakeholder on the environmental issues related to manufactured products and manufacturing process.

These results differ marginally with the results of Ocampo and Clark (2015) using AHP of the same research problem. Their results provide less emphasis on environmental impact and greater emphasis on minimizing costs due to the pure independence assumption in the criteria component. When feedback and dependence are taken into account, environmental issues must be addressed to enhance social impact which is vital for sustainability. Future research must direct how to develop strategies in designing products and processes that will provide long term benefits to the customer and to the community as well.

These results were subjected to test of robustness using Monte Carlo simulation that attempts to repeat the results over several simulation runs, i.e. 500 runs in this study. Results show that these ANP results are fairly robust with the exception in the bottom two initiatives. It implies that this priority ranking is dependable and the case firm could use this as an input in prioritizatizing investments, for instance. The absence of interdependence relationships among sub-criteria could also change the ranking except for the first two initiatives. This indicates that the first two decisions are robust enough such that minor changes in the decision model could hardly change their priority ranking. Lastly, it is interesting to note that the ranking with complete absence of interdependencies are consistent with the results of Ocampo and Clark (2015) using AHP. This is due to the inherent structure of the decision network. When interdependencies are removed, the decision network approaches the structure of a hierarchy such that the appropriate methodology becomes the AHP.

5. Conclusion

This paper demonstrates the use of analytic network process (ANP) in evaluating sustainable manufacturing initiatives. The decision problem is structured as a hierarchical network which is built upon the model of Ocampo and Clark (2014b) and Ocampo and Clark (2015). Results show that cleaner production technologies, i.e. elimination of lead in the plating process, are considered on topmost priority. This work suggests that sustainable manufacturing is achieved by formulating strategies that address issues on customer and community well-being by means of focusing on environmental concerns, e.g. toxic substance, GHG emissions and air emissions. To test the robustness of these results, this work adopts two approaches: (1) using Monte Carlo simulation, (2) introducing structural changes on the evaluation model. Results show that the first two topmost sustainable manufacturing initiatives are robust enough for the case firm to subscribe in these results. Future work must focus on formulating specific policies regarding the design of products and processes that could enhance customer and community welfare.

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	G	A	B	C	A1	A2	A3	A4	B1	B2	B3	C1	C2	C3	A11	A12	A13	A14	A15	A21	A22	A23	A24	A31
G	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
A	0.2000	0.5396	0.2297	0.2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B	0.4000	0.1634	0.6483	0.2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
C	0.4000	0.2970	0.1220	0.6000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A1	0	0.3511	0	0	0.667	0	0	0.1601	0	0	0	0.3333	0.6667	0.4673	0	0	0	0	0	0	0	0	0	
A2	0	0.3511	0	0	0.333	1	0	0.095	0	0	0	0.6667	0.3333	0.277	0	0	0	0	0	0	0	0	0	
A3	0	0.1609	0	0	0	0	1	0.277	0	1	0	0	0	0.095	0	0	0	0	0	0	0	0	0	
A4	0	0.1368	0	0	0	0	0	0.467	0	0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	
B1	0	0	0.4000	0	0	0	0	0	0.5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B2	0	0	0.4000	0	0	0	0	0	0.2500	0.7500	0	1	0	0	0	0	0	0	0	0	0	0	0	
B3	0	0	0.2000	0	0	0	0	0	0.2500	0.2500	1	0	1	0	0	0	0	0	0	0	0	0	0	
C1	0	0	0	0.2500	0	0	0	0	0	0.297	0	1	0	0.2500	0	0	0	0	0	0	0	0	0	
C2	0	0	0	0.5000	0	0	0	0	1	0.54	0	0	1	0	0	0	0	0	0	0	0	0	0	
C3	0	0	0	0.2500	0	0	0	0	0	0.163	0	0	0	0.7500	0	0	0	0	0	0	0	0	0	
A11	0	0	0	0	0.3475	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
A12	0	0	0	0	0.3475	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	
A13	0	0	0	0	0.1201	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	
A14	0	0	0	0	0.0647	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
A15	0	0	0	0	0.1201	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	
A21	0	0	0	0	0	0.2308	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	
A22	0	0	0	0	0	0.4615	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
A23	0	0	0	0	0	0.2308	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	
A24	0	0	0	0	0	0.0769	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
A31	0	0	0	0	0	0	0.3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A32	0	0	0	0	0	0	0.1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A33	0	0	0	0	0	0	0.3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A34	0	0	0	0	0	0	0.3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A41	0	0	0	0	0	0	0	0.5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A42	0	0	0	0	0	0	0	0.2500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A43	0	0	0	0	0	0	0	0.2500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B11	0	0	0	0	0	0	0	0	0.5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B12	0	0	0	0	0	0	0	0	0.5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B21	0	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0	0	0	0	0	0	0	0	
B22	0	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0	0	0	0	0	0	0	0	
B23	0	0	0	0	0	0	0	0	0	0.1667	0	0	0	0	0	0	0	0	0	0	0	0	0	
B24	0	0	0	0	0	0	0	0	0	0.1667	0	0	0	0	0	0	0	0	0	0	0	0	0	
B31	0	0	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0	0	0	0	0	0	0	
B32	0	0	0	0	0	0	0	0	0	0	0.6667	0	0	0	0	0	0	0	0	0	0	0	0	
C11	0	0	0	0	0	0	0	0	0	0	0	0.6000	0	0	0	0	0	0	0	0	0	0	0	
C12	0	0	0	0	0	0	0	0	0	0	0	0.2000	0	0	0	0	0	0	0	0	0	0	0	
C13	0	0	0	0	0	0	0	0	0	0	0	0.2000	0	0	0	0	0	0	0	0	0	0	0	
C21	0	0	0	0	0	0	0	0	0	0	0	0	0.2000	0	0	0	0	0	0	0	0	0	0	
C22	0	0	0	0	0	0	0	0	0	0	0	0	0.4000	0	0	0	0	0	0	0	0	0	0	
C23	0	0	0	0	0	0	0	0	0	0	0	0	0.4000	0	0	0	0	0	0	0	0	0	0	
C31	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0	0	0	0	
C32	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0	0	0	0	
C33	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3333	0	0	0	0	0	0	0	0	0	
I1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2697	0.2000	0.2156	0.2264	0.2889	0.1869	0.1750	0.1250	0.1237	0.1[illegible]
I2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0682	0.0780	0.0801	0.0558	0.0727	0.0534	0.0636	0.1250	0.1237	0.1[illegible]
I3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1688	0.1255	0.1293	0.4904	0.1228	0.1213	0.1077	0.1250	0.1237	0.1[illegible]
I4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4252	0.5459	0.5231	0.0867	0.4429	0.5871	0.5900	0.5000	0.2343	0.4[illegible]
I5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0682	0.0507	0.0518	0.1407	0.0727	0.0513	0.0636	0.1250	0.3945	0.2[illegible]

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Appendix 1. Initial supermatrix

	A32	A33	A34	A41	A42	A43	B11	B12	B21	B22	B23	B24	B31	B32	C11	C12	C13	C21	C22	C23	C31	C32	C33	I1	I2	I3	I4	I5
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
084	0.1084	0.1237	0.1667	0.1429	0.1429	0.1429	0.1199	0.0450	0.1237	0.0655	0.1667	0.2000	0.0780	0.3309	0.3325	0.1367	0.1367	0.1429	0.1237	0.1667	0.1237	0.2000	0.2500	1	0	0	0	0
084	0.1084	0.1237	0.1667	0.1429	0.1429	0.1429	0.1199	0.0670	0.1237	0.0655	0.1667	0.2000	0.0780	0.3309	0.0896	0.4030	0.4030	0.1429	0.1237	0.1667	0.1237	0.2000	0.2500	0	1	0	0	0
084	0.1084	0.2343	0.1667	0.1429	0.1429	0.1429	0.2101	0.2191	0.1237	0.2500	0.1667	0.2000	0.1342	0.1985	0.3325	0.1367	0.1367	0.1429	0.1237	0.1667	0.1237	0.2000	0.2500	0	0	1	0	0
737	0.2011	0.1237	0.3333	0.4286	0.4286	0.4286	0.0706	0.1480	0.2343	0.1094	0.1667	0.2000	0.4882	0.0844	0.2012	0.0791	0.0791	0.4286	0.2343	0.1667	0.3945	0.2000	0.1250	0	0	0	1	0
011	0.4737	0.3945	0.1667	0.1429	0.1429	0.1429	0.4795	0.5210	0.3945	0.5096	0.3333	0.2000	0.2215	0.0553	0.0443	0.2444	0.2444	0.1429	0.3945	0.3333	0.2343	0.2000	0.1250	0	0	0	0	1