APEM journal

Advances in Production Engineering & Management
Volume 10 | Number 1 | March 2015 | pp 40–50
http://dx.doi.org/10.14743/apem2015.1.191

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

A hierarchical framework for index computation in sustainable manufacturing

Ocampo, Lanndon A.[a,*]

[a]University of San Carlos, Department of Mechanical Engineering, Cebu City, Cebu, Philippines

A B S T R A C T

Environmental regulations, the desire for market leadership and social stewardship along with pressing environmental crises have shifted manufacturing industries from focusing on traditional, purely profit-based strategies into pursuing the sustainability of manufactured products and manufacturing processes. However, assessing the sustainability levels of manufacturing industries poses a challenge due to the lack of holistic methods when in performing such assessments. In this area, current literature has embarked on computing an aggregate index for assessing sustainability performance. Nevertheless, approaches in computing sustainable manufacturing index are scarce in the literature. This paper presents a preliminary framework for computing a sustainable manufacturing index using the analytic hierarchy process. In this context, sustainability is interpreted from a triple-bottom line approach and the set of elements that comprise the index obtained from the US National Institute of Standards and Technology sustainable manufacturing repository. The use of this repository highlights a holistic approach in aggregate index computation as it offers a comprehensive list of elements of the triple-bottom line within the context of the manufacturing industry. Preliminary results have provided valuable insights into measuring sustainable manufacturing levels and could serve as a basic framework for index computation. The contribution of this work is on presenting a simple yet holistic approach towards computing a sustainable manufacturing index.

A R T I C L E I N F O

Keywords:
Manufacturing
Sustainability
Index computation
Analytic hierarchy process

**Corresponding author:*
don_leafriser@yahoo.com
(Ocampo, Lanndon A.)

Article history:
Received 5 February 2015
Revised 12 February 2015
Accepted 1 March 2015

1. Introduction

In this period when human activities pose environmental and social issues, solely profit or cost-based initiatives are insufficient to sustain manufacturing and its development through time. Stakeholders, which include customers, employees, investors, suppliers, communities, and governments [1], highlight manufacturing industry to focus on the performance of its manufactured products and manufacturing processes and to position them within the context of ongoing concerns on resource depletion, environmental impact, socio-economic issues and health problems. These stimulate manufacturing firms in broadening their perspectives beyond economic gains and to consider environmental and social benefits [2]. Firms seek to reconfigure physical, human, information and financial resources so that financial resources exiting the system are lower than those that enter it [1]. However, with these pressing concerns, other dimensions must be placed into the equation. This has prompted manufacturing firms to adopt approaches such as cleaner production, life cycle assessments, design for environment, environmental conscious manufacturing, and green technologies into more systemic approaches such as greening supply chains and industrial symbiosis. Synergy of these available tools may not adequately assist industry decision-makers at firm level who are required to assess and evaluate their operations in terms of internal and external impacts. These concepts, strategies and approaches constitute a much wider approach of sustainable manufacturing.

The US Department of Commerce defined sustainable manufacturing as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [3]. This definition implies the existence of the three significant dimensions of sustainability, i.e. economic growth, environmental stewardship and social well-being. Manufacturing industries as key players in sustainable development initiatives, must at the macro level, deliver manufactured products with minimal impacts to the environment throughout product life cycles while maintaining social equity and reasonable economic growth. Thus, at the micro level, firms must ensure that their performance across and beyond the boundaries of the supply chain must be sustainable by (1) designing and producing products with processes that pose minimal environmental impacts, (2) taking on corporate initiatives that reduce cost, increase profit and provide higher returns on investments and (3) providing programs which enhance well-being of employees, customers and communities. These courses of actions must be organized in such a way that the total impact on the triple-bottom line is maximized. Current arguments suggest that manufacturing firms that promote sustainability focus in their business decision-making activities are more likely successful in their respective industry [4].

To address this challenge, manufacturing firms must adopt an approach that measures aggregate firm level sustainability performance. This enables firms to assess its sustainability level and to identify specific challenges and opportunities that firms must resolve and undertake in order to promote performance. This also brings insights on how initiatives must be specifically developed after learning firm's sustainability level. This may extend towards project selection, supplier selection, product development, process engineering, employee training programs and other decision-making areas that must be holistically integrated in order to promote firm-wide sustainability. Current literature offers potential approaches in terms of measuring sustainability level through the use of indicators and indices [1]. There are increasing interests on establishing sustainability indicators which enable firms in measuring sustainability initiatives and in establishing concrete, long term plans for sustainable manufacturing. Nevertheless, the fundamental guideline on developing such indicators and indices is that they must be operational and comprehensive enough to account for the complexity of the requirements of sustainability. Thus, this paper attempts to present a methodology in computing sustainable manufacturing index as a measurement for an aggregate sustainability level. This work adopts the comprehensive sustainability indicators set developed by Joung et al. [2] from a careful integration of 11 established indicators sets. Following the hierarchical nature and the multi-dimensional and multi-level sustainability indicators set of Joung et al. [2], the use of analytic hierarchy process (AHP) becomes highly appropriate and helpful. Analytic hierarchy process provides a multi-criteria decision-making platform that allows decision-makers to allocate weights for each element in a decision model which is necessary in index computation. The contribution of this work lies in presenting a holistic framework of index computation that attempts to measure sustainability at firm level.

2. Literature review

2.1 Sustainable manufacturing

Sustainable manufacturing is oftentimes attached to some other terms such as business sustainability and corporate sustainability. In one representative definition, business sustainability is defined as "adopting business strategies and activities that meet the need of the enterprise and its stakeholders today while protecting, sustaining and enhancing the human and natural resources that will be needed in the future"[5]. On the other hand, corporate sustainability is defined also as "meeting the needs of the firm's direct and indirect stakeholders without compromising its ability to meet future stakeholder needs as well" [6] and "demonstrating the inclusion of social and environmental concerns in business operations and in interactions with stakeholders" [7]. These two terms are similar and interchangeable to some extent. They pose the need of addressing the triple-bottom line through corporate policies, strategies and directives. While such definitions are conceptual, they do not provide options into how firms must manage its efforts and resources quantitatively in promoting sustainability at the corporate level. While corporate sustainability holds at the business level, sustainable manufacturing encompasses this concept by focusing on manufactured products and manufacturing processes and their impacts to various stakeholders.

Since sustainable manufacturing focuses on the impacts of products and processes, improving environmental stewardship and sustainability while maintaining profitability, is increasingly viewed by manufacturing firms as a strategic approach [1]. This view holds that environmental regulations of products and process must not be considered as constraints but part of the overall strategic goal of sustenance and business leadership. Furthermore, promoting employee and community development programs are not merely developed for improving business image but part of the long-term sustainability roadmap.

2.2 Sustainability indicator sets

The notion of sustainability is widely pronounced in literature; nevertheless expressing it in concrete, operational terms remains difficult [8]. A significant approach of measuring and assessing sustainability is through the use of sustainability indicators. Indicators help identify the status of sustainability, the progress made towards this objective, the challenges and problems in moving towards this objective as well as the measures that must be adopted to address these challenges and problems [1]. Roshen and Kishawy [1] argue that an integrated, multidimensional sustainability indicators set that highlights the triple bottom line is necessary to achieve sustainability. Standard indicators will provide a reliable and repeatable means for manufacturing firms when they evaluate and allow comparisons between products, processes, firms, sectors, or countries in view of sustainable manufacturing [2]. However, little research has been conducted on the indicators used to convey quantitative information in sustainability reports [9].

In this line, a number of sustainability indicator sets were proposed by international committees, individual firms and private institutions. These are the Global Report Initiative [10], the Dow Jones Sustainability Indexes [11], the Institution of Chemical Engineers Sustainability Metrics [12], United Nations-Indicators of Sustainable Development [13], the Wuppertal Sustainability Indicators [14], the 2005 Environmental Sustainability Indicators [15], the European Environmental Agency Core Set of Indicators [16], the Environmental Performance Index [17], the Organization for Economic Cooperation and Development Core Environmental Indicators [18], the Japan National Institute of Science and Technology Policy [19], the Ford Product Sustainability Index [20], the Environmental Pressure Indicators for European Union [21], the General Motors Metrics for Sustainable Manufacturing [22, 23], the Wal-Mart Sustainability Product Index [24] and the International Organization for Standardization Environment Performance Evaluation Standard [25]. All of these indicator sets comprise indicators that measure a specific area in sustainability. They are categorized into groups that form the dimensions of sustainability. Most of these indicator sets belong to environmental dimensions [8] while others are country or regional-based specific. Frequently, most economic indicators are net sales, costs of purchased goods, materials, services, total payroll and benefits. Most environmental indicators are energy and water consumption, carbon dioxide emissions, internal initiatives to improve energy efficiency. Most social dimension indicators are workplace health and safety policies and measures, employee education and skill management, and the benefits that employees receive from the organization beyond those that are legally mandated [9].

With these various and complex sets, identifying which set(s) of indicators or a mix of sets applicable in sustainable manufacturing poses difficulty. Thus, a need to select and prioritize indicators is required [26]. A number of characteristics of sustainable manufacturing indicators are the following: (1) relevance, revealing necessary information about a system or process (2) understandability, straightforward and readily understood by experts and non-experts and (3) reliability, providing information that is trustworthy and (4) assessable, based on available and accessible data [1]. The most comprehensive evaluation and investigation of sustainable manufacturing indicators is provided by Joung et al. [2] which eventually became a standard held by the U.S. National Institute for Standards and Technology (NIST). Joung et al. [2] combined indicators from 11 known indicator sets [10, 11, 13, 15-21, 25]. They processed them logically and categorized them into criteria and sub-criteria that form a hierarchy. This builds up 212 indicators from five dimensions of which 77 indicators are from environmental stewardship, 23 for economic growth, and 70 for social well-being dimension, 30 for performance management and 12 for technological advancement management [2]. The repository of these indicators is found in NIST's Sustainable Manufacturing Indicator Repository (SMIR) website [27].

2.3 Sustainable manufacturing index

Indices are significant pieces that can be aggregated by weight-based mathematical methods into a single score [2]. With this single score, a sustainability level can be set and used as a metric for performance [2]. There are practical significant gains a manufacturing firm can have out of a sustainable manufacturing index. This enables manufacturing decision-makers for trade-off analysis in sustainability decisions given diverse interests of stakeholders [1]. It means that a firm can control which category or sub-category must be given relevant attention so that long term objectives are met and issues on sustainability are addressed. Sustainable manufacturing index also provides manufacturing firm a view on its strengths and weaknesses. Furthermore, sustainable manufacturing index can be used as a risk-mitigating criterion for upstream manufacturers in the supply chain by identifying and ranking potential business partners based on their sustainability performance [28]. Despite of this importance of developing methodology for measuring sustainable manufacturing performance level, this is scarcely provided in literature. There is no consensus yet on measuring sustainability performance [8, 26, 28] and little has been reported on the quantitative modelling on overall sustainable manufacturing level [2, 29].

There were attempts made by previous works. De Silva, et al. [29] proposed a new scoring method for product sustainability index (PSI) through 6 sustainability elements defined in 44 influencing factors described in 24 sub elements. The influencing factors (or indicators) are equally weighted and PSI is computed as the weighted average of sub elements. Ghadimi, et al. [30] developed a product sustainability assessment methodology using fuzzy analytic hierarchy process (AHP). They proposed an algorithm termed as weighted fuzzy assessment method (WFAM) to achieve improved product sustainability index by addressing the current sustainability index. Jaafar et al. [31] presented a comprehensive procedure for computing PSI by calculating the weighted sum of different sub elements within the triple-bottom line for each life cycle stages (pre-manufacturing, manufacturing, use and post-use). Gupta et al. [26] developed a procedure for specifying and streamlining sustainability assessment without compromising significantly on comprehensiveness of product sustainability involving the use of AHP to prioritize sustainability elements based on the unique needs for a particular design scenario. However, these methodologies are focused only on product sustainability. Other works involving measuring or enhancing sustainability performance were the use of close-loop 6R methodology in the product life-cycle [4], introducing linear programming extended Data Envelopment Analysis [28], using systems approach by involving technology, energy and material for environmentally sustainable manufacturing through LCA methodology [32] and providing strategic sustainability decision-making approach by recommending additional analytical support systems [33]. Despeisse et al. [34] highlight a down-scaling of the concept of industrial symbiosis at a factory level. They presented a focus on overall performance of manufacturing systems using a model of MEW (Material, Energy, Wastes) in three components of manufacturing system – manufacturing operations, supporting facilities and surrounding buildings.

2.4 Summary of the review

Based from the preceding review, there is a gap in literature on the development of methodology of measuring sustainable manufacturing index. This index is vital for manufacturing firms at it provides an overview on their sustainability level and may be used as risk-mitigating criterion for long term coordination in the supply chain. This paper provides a methodology of computing sustainable manufacturing index from a repository of indicators in US National Institute for Standards and Technology [27] as a comprehensive set of indicators drawn from established and known indicator sets. US NIST [27] indicator repository is structured as a hierarchy of categories and subcategories. In order to complement with the hierarchical structure of the sustainable manufacturing framework of Joung et al. [2], this paper adopts the use of analytic hierarchy process (AHP) in computing weights of categories and sub-categories. AHP is a powerful tool in multi-criteria decision analysis especially in hierarchal decision-making. AHP, developed by Saaty [35], requires decision-makers to provide pairwise comparisons of elements. By solving an eigenvalue problem proposed by Saaty [35], weights can be computed in the hierarchy [35]. Due to the difficulty of transforming the triple-bottom line into purely quantitative scales [2], AHP can capture the subjective judgments of decision-makers and then transform them into numerical values. A review of the application of AHP in operations management reports 21 published papers in measuring and improving activities on products, process and systems [37]. A review of modelling approaches in sustainable supply chain management which is multi-criteria in nature reveals AHP as one of the effective methodologies in decision-making [38]. These reviews show that AHP is widely used in decision-making.

3. Methodology

3.1 Research framework

The framework for this paper is described in Fig 1. The indicators set adopted in this paper is the one provided by Joung, et al. [2] which is now maintained by the US National Institute for Standards and Technology [27]. This is chosen for a number of reasons: (1) it is a combination of 11 established indicator sets [10-11, 13, 15-21, 25] published by recognized international bodies, manufacturing leaders, research and private institutions, (2) the selection of the indicators to be included in the US NIST standards undergoes a systematic and rigid process, (3) sustainable manufacturing framework developed by Joung, et al. [2] is hierarchal which provides groupings of indicators into sub categories, sub categories into categories, and categories into sustainable manufacturing dimensions and (4) it is the most comprehensive indicator set recently developed. The choice of the indicator set does not affect the methodology of computing sustainable manufacturing index. However, it has implications regarding the structure of sustainable manufacturing and its components which may alter the value of the index. Improvement in the contents of the indicator set does not affect the process of obtaining the sustainable manufacturing index.

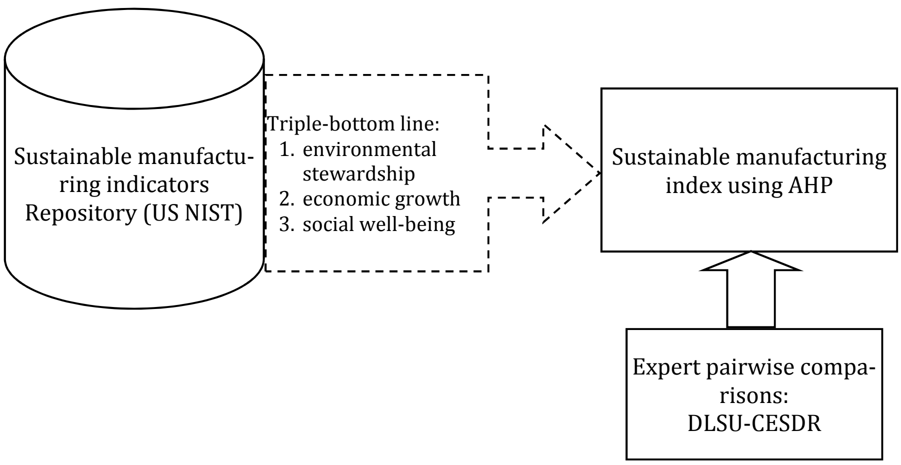

Fig. 1 Methodological approach of the study

Indicators set provided by US NIST [27] defines sustainable manufacturing in five dimensions namely, environmental stewardship, economic growth, social well-being, performance management, and technology advancement management. The last two dimensions appeared because of the presence of indicators in these two aspects [2] from the established 11 indicator sets being analysed. However, Joung et al. [2] maintained that these two aspects are inherent in the triple-bottom line and can be merged until further revisions of the indicator set are done. In this paper, the triple-bottom line approach is maintained with particular emphasis on the first three dimensions with all its categories, sub-categories and indicators. This choice is cognizant with various works in literature which promote the triple-bottom line [4, 8, 9, 26]. The hierarchical structure of sustainable manufacturing as depicted in US NIST [27] is presented in Fig. 2. There are 4 levels in the structure denoted as level 0, level 1, level 2 and level 3 for sustainable manufacturing index, sustainable manufacturing dimensions, criteria and sub-criteria, respectively. Each sub-criterion in level 3 has distinct number of indicators as indicated in Fig 2. The number of indicators varies with the sub-criterion with 1 as the least number of indicators. Note that environmental stewardship has 77 indicators, economic growth has 23 indicators and social well-being has 70 indicators with a total of 170 indicators were used in this paper.

3.2 Computation

Components in each level of Fig. 2 have specific weights which correspond to the degree of importance in sustainable manufacturing. We find it necessary to have an outside expert in sustainable manufacturing researches to assess and provide pairwise comparisons on the elements in Fig. 2 as defined in the AHP methodology.

To achieve expert-based results, we invite De La Salle University Centre for Engineering and Sustainable Development Research (DLSU-CESDR) to provide us with pairwise comparisons on each level in Fig 2. De La Salle University has been one of leading academic institutions that is active in sustainable development research since a decade ago. Results are expected to be valid as far as their expert knowledge and experience in the field are concerned. Individual weights for level 1, 2 and 3 are then computed using Saaty's [35] method. Consistency ratio (C.R.) is also computed for each pairwise comparisons matrix which explains the degree of consistency in decision-maker's judgment. Acceptable C.R. value is 10 % (0.10) as suggested by Saaty [39]. Sample pairwise comparisons matrix with the computed weights and consistency ratio is provided in Table 1.

Table 1 shows an actual pairwise comparison matrix elicited by DLSU-CESDR. The sample matrix is derived from comparing the relevance of the three sustainable manufacturing dimensions. There are a total of 14 pairwise comparison matrices in this paper. For instance a score of 2 in row 2 column 1 suggests that experience and judgment slightly favoured economic growth over environmental stewardship (see Saaty [39] for a detailed discussion on Pairwise Comparison Scale). The column weights are the relative weights computed using the eigenvector approach of Saaty [39]. A C.R. value of 0.0 means perfect consistency on the decision-maker's judgment [39].

As soon as each of the elements in Fig 2 has computed priority weights, then a weight distribution in the hierarchical structure is obtained. The sustainable manufacturing index of any manufacturing firm can be computed through a case study. A questionnaire that contains a list of all 170 indicators which the firm's representative must rate from 0-10 with 10 as the highest and 0 as the lowest is sent to a firm. To provide a discussion with regard to the computation of the weights, Table 2 provides a sample detail. Table 2 is derived from environmental sustainability dimension under the pollution category and under Toxic Substance sub-category. This sub-category has 11 indicators as shown in Fig. 2. Actual score column lists scores provided by the firm on the level of their performance on an indicator. For instance, lead used indicator has a score of 1. It means that the company has relatively fewer amount of lead used in their products and processes. Next, we used an absolute method of translating the actual score to a normalized score. The indicators provided in the subcategory denote a negative performance in the category. Values from 0 to 10 mean that the performance in this sub-category is deteriorating. By providing a rating of 1 on these indicators means a -1 to the performance. To come up with a positive value, we add algebraically the actual rating which is -1 to 10 to obtain the normalized score which is 9 in this case. A value of 9 in our rating means that the company has relatively higher environmental performance. This is referred to as the absolute method. This value is then multiplied with the weight obtained in the AHP method (in this case, toxic substance has a weight of 0.348 to get the computed index. These indicator indices are then averaged to get the Toxic Substance Index. A value of 2.025 means that on the rate from 0-10 the company has less performance in toxic substance. This value is brought up in the hierarchy by multiplying with the respective category weight and the weights of the sustainable manufacturing dimensions. Performing this process to all sub-categories, the sustainable manufacturing index can be computed.

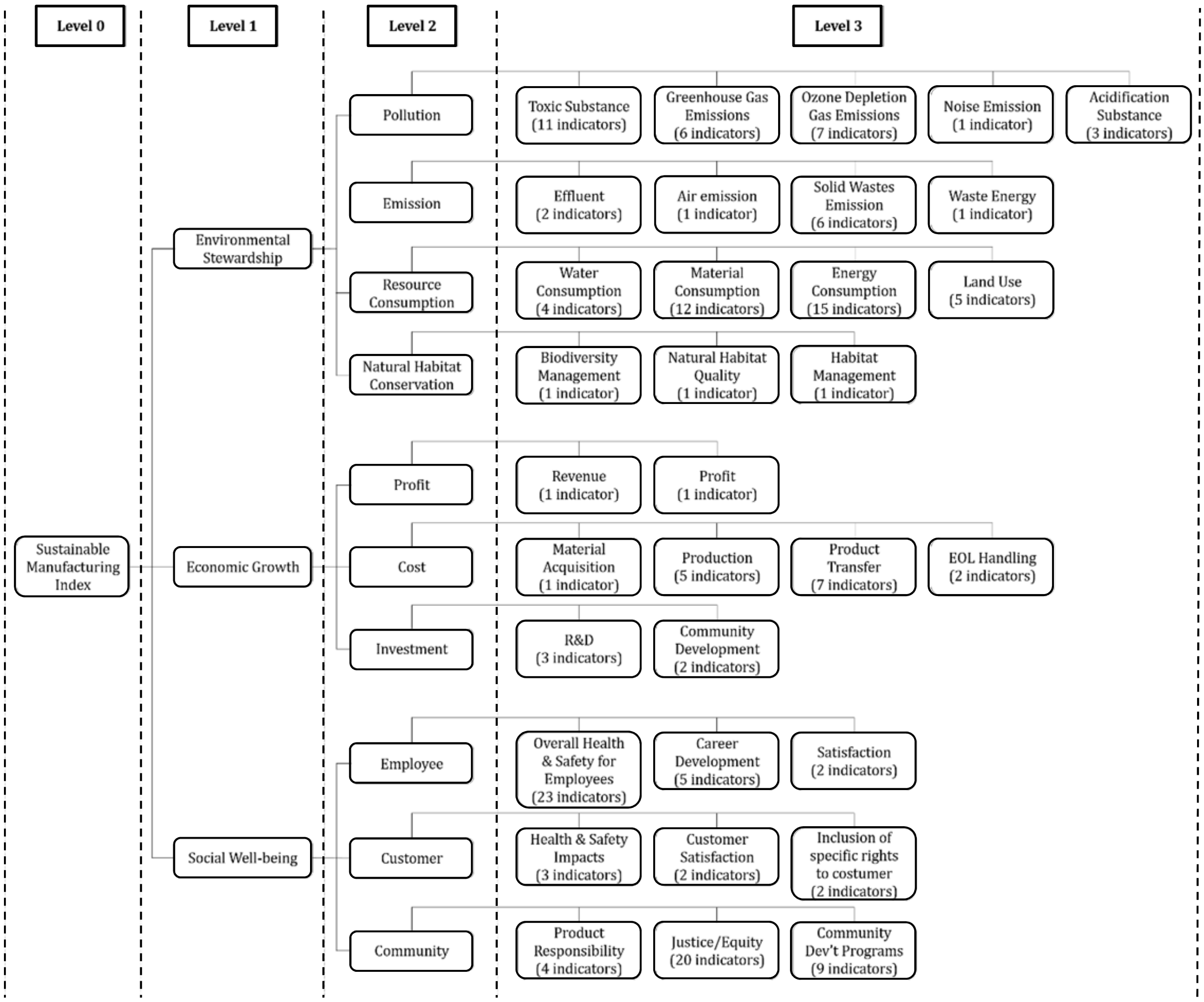

Fig. 2 Sustainable manufacturing hierarchal structure

Table 1 Actual sample of pairwise comparisons matrix with computed weights and consistency ratio

	Environmental stewardship	Economic growth	Social well-being	Weight	Consistency ratio (CR)
Environmental stewardship	1	1/2	1/2	**0.2**	**0.0**
Economic growth	2	1	1	**0.4**	
Social well-being	2	1	1	**0.4**	

Table 2 Sample detail of case study computation

Dimension: Environmental Stewardship Category: Pollution				
Sub-category: Toxic Substance	Actual score	Normalized score	Weight	Computed index
Lead (Pb) used	1	9	0.348	3.132
Mercury (Hg) used	1	9	0.348	3.132
Hexavalent chromium (Cr6+) used	1	9	0.348	3.132
Cadmium (Cd) used	1	9	0.348	3.132
Polybrominated biphenyl flame retardants (PBB) used	7	3	0.348	1.044
Polybrominated diphenyl ether flame retardants (PBDE) used	7	3	0.348	1.044
Eco-toxic substance effluent	6	4	0.348	1.392
Eco-toxic waste produced	6	4	0.348	1.392
Number of WEEE-related registrations	5	5	0.348	1.740
Chemical spills	6	4	0.348	1.392
Eco-toxic substances emissions	5	5	0.348	1.740
				2.025

4. Results and discussion

Using Saaty's Fundamental 9-point scale [39], pairwise comparisons were performed on sustainable manufacturing dimensions, criteria and sub-criteria. There were 34 pairwise comparison matrices elicited by DLSU-CESDR. Using the eigenvector method proposed by Saaty [39], respective weights for each of the elements can be computed. Complete weight distribution using the AHP is illustrated in Table 3.

The total weight of all sub-criteria in particular criterions as well as the total weight of criteria in a particular sustainable manufacturing dimension are equal to 1.0. In a particular sub-criterion there are a number of indicators ranging from 1 up to 23. The complete discussion of indicators and relevant explanation of criteria and sub-criteria as to their meanings, methods of measurement are discussed in the NIST SMIR website [27]. Weight allocation of all the elements in the sustainable manufacturing hierarchy is completed. We apply these weight allocations to a case firm in coming up with a sustainable manufacturing index using the methodology described in the previous section. C.R. < 0.10 for all pairwise comparisons performed in this work. Thus, all judgments of the pairwise comparison matrices are consistent.

Table 4 shows a summary of case firm's sustainable manufacturing index with comparison to the ideal index shown in Table 3. It is shown that the case firm's performance is just halfway of the ideal sustainability score. It is apparent that the case firm's performance can be treated as fair with several rooms for improvement. Identifying specific areas with rich potential for improvement can be identified using the proposed sustainable manufacturing index approach. The proposed methodology is beneficial for firms as (1) it provides a comprehensive approach in assessing firm wide sustainability level, (2) it offers a platform in determining specific areas which are potential for improvement, (3) it is simple and comprehensible for non-technical decision-makers, and (4) it provides inputs to policy making and long term strategic actions. In general, firms can apply the proposed method in assessing sustainability level. However, these conditions must exist: (1) decision-makers must be cross functional who could provide inputs from various perspectives, (2) decision-makers must be highly knowledgeable of firm's core products and processes, (3) decision-makers must make assessment based on hard data available from the firm.

Table 3 Sustainable manufacturing weight allocation using analytic hierarchy process

Elements			Priority weight		
Environmental stewardship					0.200
	Pollution			0.351	
		Toxic substance	0.348		
		Greenhouse gas emissions	0.348		
		Ozone depletion gas emissions	0.120		
		Noise	0.065		
		Acidification substance	0.120		
	Emissions			0.351	
		Effluent	0.231		
		Air emissions	0.462		
		Solid waste emissions	0.231		
		Waste energy emissions	0.077		
	Resource consumption			0.161	
		Water consumption	0.300		
		Material consumption	0.100		
		Energy/electrical consumption	0.300		
		Land use	0.300		
	Natural habitat conservation			0.137	
		Biodiversity management	0.500		
		Natural habitat quality	0.250		
		Habitat management	0.250		
Economic growth					0.400
	Profit			0.400	
		Revenue	0.500		
		Profit	0.500		
	Cost			0.400	
		Materials acquisition	0.333		
		Production	0.333		
		Product transfer to customer	0.167		
		End-of-service-life product handling	0.167		
	Investment			0.200	
		Research and development	0.333		
		Community development	0.667		
Social well-being					0.400
	Employee			0.250	
		Employees health and safety	0.600		
		Employees career development	0.200		
		Employee satisfaction	0.200		
	Customer			0.500	
		Health and safety impacts from manufacturing and product use	0.200		
		Customer satisfaction from operations and products	0.400		
		Inclusion of specific rights to customer	0.400		
	Community			0.250	
		Product responsibility	0.333		
		Justice/equity	0.333		
		Community development programs	0.333		

Table 4 Summary of case firm's index

Sustainability dimension	Ideal index	Case firm index
Environmental stewardship	2	0.923
Economic growth	4	2.131
Social well-being	4	2.041
Sustainable manufacturing index	10	4.173

5. Conclusion and future work

Using analytic hierarchy process, weights for the sub-criteria, criteria and sustainable manufacturing dimensions in a hierarchically designed sustainable manufacturing were obtained. These elements, including respective indicators, can be found from the US National Institute of Standards and Technology (US NIST) Sustainable Manufacturing Indicators Repository (SMIR) [27]. The weights are normalized from 0 to 1. The weights in the hierarchy assume the portion of contribution of that particular element (sub-criteria, criteria or dimensions) to the sustainable manufacturing score. By way of viewing them as contribution, these values can be considered as upper limit or ideal value of the element. The method integrates both objective and subjective judgments of decision-makers in assessing firm's sustainability performance. Managers can easily access the method due to its simple analytical procedure. Thus, this paper provides a preliminary framework in computing firm-wide sustainable manufacturing index.

Further works on this paper are significant. First, one can list down all the sub-criteria in decreasing order of their contribution to sustainable manufacturing index. From here, managers can prioritize which indicators impact sustainability. Second, optimization methods can be used to determine strategies of a particular manufacturing firm that will optimize sustainability using the weights obtained from AHP. Lastly, one could investigate the interrelationships of the criteria and sub-criteria using analytic network process (ANP). The existence of interrelationships in criteria and sub-criteria will provide significant information to manufacturing firms as they address complexity in decision-making.

Acknowledgement

Dr. L. Ocampo is grateful for the Ph.D. scholarship grant of the Engineering Research and Development for Technology of the Department of Science and Technology, Republic of the Philippines.

References

[1] Rosen, M.A., Kishawy, H.A. (2012). Sustainable manufacturing and design: Concepts, practices and needs, *Sustainability*, Vol. 4, No. 2,154-174, doi: 10.3390/su4020154.

[2] Joung, C.B., Carrell, J., Sarkar, P., Feng, S.C. (2013). Categorization of indicators for sustainable manufacturing, *Ecological Indicators*, Vol. 24, 148-157, doi: 10.1016/j.ecolind.2012.05.030.

[3] International Trade Administration. How Does Commerce Define Sustainable Manufacturing? U.S. Department of Commerce, from *http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp*, accessed February 12, 2015.

[4] Jayal, A.D., Badurdeen, F., Dillon, O.W. Jr., Jawahir, I.S. (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels, In: D. Tichkiewitch, S., Brissaud, (ed.), *CIRP Journal of Manufacturing Science and Technology*, Vol. 2, No. 3, 144-152, doi: 10.1016/j.cirpj.2010.03.006.

[5] International Institute for Sustainable Development (IISD), Deloitte & Touche, Business Council for Sustainable Development (1992). *Business strategy for sustainable development: Leadership and accountability for the '90s*, International Institute for Sustainable Development, Winnipeg, Canada, doi: 10.1002/bse.3280030307.

[6] Dyllick, T., Hockerts, K. (2002). Beyond the business case for corporate sustainability, *Business Strategy and the Environment*, Vol. 11, No. 2, 130-141, doi: 10.1002/bse.323.

[7] Van Marrewijk, M. (2003). Concepts and definitions of CSR and corporate sustainability: Between agency and communion, *Journal of Business Ethics*, Vol. 44, No. 2-3, 95-105, doi: 10.1023/A:1023331212247.

[8] Labuschagne, C., Brent, A.C., Van Erck, R.P.G. (2005). Assessing the sustainability performances of industries, *Journal of Cleaner Production*, Vol. 13, No. 4, 373-385, doi: 10.1016/j.jclepro.2003.10.007.

[9] Roca, L.C., Searcy, C. (2012). An analysis of indicators disclosed in corporate sustainability reports, *Journal of Cleaner Production*, Vol. 20, No. 1, 103-118, doi: 10.1016/j.jclepro.2011.08.002.

[10] Global reporting initiative (2011). Sustainability Reporting Guidelines, version 3.1, from *https://www. globalreporting.org/resourcelibrary/g3.1-guidelines-incl-technical-protocol.pdf,* accessed February 12, 2015.

[11] SAM Index. The Dow Jones sustainability index, from *http://www.sustainability-indices.com/*, accessed February 12, 2015.

[12] Institution of Chemical Engineers (2012). The sustainability metrics: Sustainable development, progress metrics recommended for use in the process industries, from *http://nbis.org/nbisresources/metrics/triple_bottom_line_indicators_process_industries.pdf,* accessed February 12, 2015.

[13] United Nations (2007). Indicators of sustainable development: Guidelines and methodologies, 3rd edition, United Nations Publication, New York, USA, from *http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf*, accessed February 12, 2015.

[14] Spangenberg, J.H., Bonniot, O. (1998). Sustainability indicators – A compass on the road towards sustainability, Wuppertal paper No. 81, Wuppertal Institute for Climate, Environment, and Energy, Wuppertal, Germany, from *http://www.ulb.ac.be/ceese/STAFF/Tom/spangenberg.pdf*, accessed February 12, 2015.

[15] Environmental Sustainability Indicators. 2005 environmental sustainability index – Benchmarking national environmental stewardship, Yale Center for Environmental Law and Policy, Yale University; Center for International Earth Science Information Network, Columbia University, from *http://www.yale.edu/esi/ESI2005_Main_Report.pdf*, accessed February 12, 2015.

[16] European Environment Agency (2005). EEA core set of indicators – Guide, Technical Report No. 1/2005, from *http://www.eea.europa.eu/publications/technical_report_2005_1*, accessed February 12, 2015.

[17] 2010 Environmental Performance Index. Yale Center for Environmental Law & Policy, Yale University; Center for International Earth Science Information Network (CIESIN), Columbia University; World Economic Forum, Geneva; Joint Research Center of the European Commission, Italy, from *http://www.ciesin.org/documents/EPI_2010_report.pdf*, accessed February 12, 2015.

[18] OECD Environmental Indicators: Development, Measurement and Use. Organisation for Economic, Co-operation and Development, from *http://www.oecd.org/environment/indicators-modelling-outlooks/24993546.pdf*, accessed February 12, 2015.

[19] Science and Technology Indicator Project Team, National Institute of Science and Technology Policy (NISTEP), Science and Technology Agency, Japan (1995). Science and technology indicators: 1994 – A systematic analysis of science and technology activities in Japan, National Institute of Science and Technology, Japan, from *http://www.nistep.go.jp/achiev/ftx/eng/rep037e/pdf/rep037e.pdf*, accessed February 12, 2015.

[20] Schmidt, W.-P., Taylor, A. (2006). Ford of Europe's product sustainability index, In: *Proceedings of 13th CIRP International Conference on Life Cycle Engineering*, Leuven, Belgium, 5-10.

[21] Towards Environmental Pressure Indicators for the EU, Environment and Energy Paper Theme 8, Luxemborg, European Commission, *http://www.iisd.org/measure/compendium/DisplayInitiative.aspx?id=472*, accessed February 12, 2015.

[22] Feng, S.C., Joung, C.-B., Li, G. (2010). Development overview of sustainable manufacturing metrics, In: *Proceedings of the 17th CIRP International Conference on Life Cycle Engineering 2010*, Hefei, China, 6-12.

[23] Dreher, J., Lawler, M., Stewart, J., Strasorier, G., Thorne, M. (2009). *General Motors – Metrics for sustainable manufacturing*, MIT Sloan School of Management, Cambridge, USA, from *http://mitsloan.mit.edu/actionlearning/media/documents/s-lab-projects/GM-report.pdf*, accessed February 12, 2015.

[24] INSEAD (2011), Wal-Mart's sustainable product index, from *http://centres.insead.edu/social-innovation/what-we-do/documents/5751-WalMart-A-CS-EN-0-07-2011-w.pdf*, accessed February 12, 2015.

[25] International Organization for Standardization (ISO). Environmental management – Environmental performance evaluation – Guidelines, ISO 14031:1999(en), Geneva, Switzerland.

[26] Gupta, A., Vangari, R., Jayal, A.D., Jawahir, I.S. (2011). Priority evaluation of product metrics for sustainable manufacturing, In: Bernard, A. (ed.), *Global Product Development*, Springer-Verlag Berlin Heidelberg, Germany, 631-641, doi: 10.1007/978-3-642-15973-2_63.

[27] National Institute of Standards and Technology, Sustainable Manufacturing Indicator Repository (SMIR), from *http://www.nist.gov/el/msid/smir.cfm*, accessed February 12, 2015.

[28] Lee, K.-H., Saen, R.F. (2012). Measuring corporate sustainability management: A data envelopment analysis approach, *International Journal of Production Economics*, (Sustainable development of manufacturing and services), Vol. 140, No. 1, 219-226, doi: 10.1016/j.ijpe.2011.08.024.

[29] De Silva, N., Jawahir, I.S., Dillon, O. Jr., Russel, M. (2006). A new comprehensive methodology for the evaluation of product sustainability at the design and development stage of consumer electronic products, In: *Proceedings of 13th CIRP International Conference on Life Cycle Engineering*, Leuven, Belgium, 335-340.

[30] Ghadimi, P., Azadnia, A.H., Yusof, N.M., Saman, M.Z.M. (2012). A weighted fuzzy approach for product sustainability assessment: A case study in automotive industry, *Journal of Cleaner Production*, Vol. 33, 10-21, doi: 10.1016/j.jclepro.2012.05.010.

[31] Jaafar, I.H., Venkatachalam, A., Joshi, K., Ungureanu, A.C., De Silva, N., Rouch, K.E., Dillon, O.W. Jr., Jawahir, I.S. (2007). Product design for sustainability: A new assessment methodology and case studies, In: Kutz, M. (ed.), *Environmentally Conscious Mechanical Design*, John Wiley & Soons, Inc., 25-65, Hoboken, New Jersey, USA, doi: 10.1002/9780470168202.ch2.

[32] Yuan, C., Zhai, Q., Dornfeld, D. (2012). A three dimensional system approach for environmentally sustainable manufacturing, *CIRP Annals – Manufacturing Technology*, Vol. 61, No. 1, 39-42, doi: 10.1016/j.cirp.2012.03.105.

[33] Waage, S.A., Geiser, K., Irwin, F., Weissman, A.B., Bertolucci, M.D., Fisk, P., Basile, G., Cowan, S., Cauley, H., McPherson, A. (2005). Fitting together the building blocks for sustainability: A revised model for integrating ecological, social and financial factors into business decision-making, *Journal of Cleaner Production*, Vol. 13, No. 12, 1145-1163, doi: 10.1016/j.jclepro.2004.06.003.

[34] Despeisse, M., Ball, P.D., Evans, S., Levers, A. (2012). Industrial ecology at factory level – a conceptual model, *Journal of Cleaner Production*, Vol. 31, 30-39, doi: 10.1016/j.jclepro.2012.02.027.

[35] Saaty, T.L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation,* McGraw-Hill, New York, USA.

[36] Handfield, R., Walton, S.V., Sroufe, R., Melnyk, S.A. (2002). Applying environmental criteria to supplier assessment: A study in the application of the analytic hierarchy process, *European Journal of Operational Research*, Vol. 141, No. 1, 70-87, doi: 10.1016/S0377-2217(01)00261-2.

[37] Subramanian, N., Ramanathan, R. (2012). A review of applications of Analytic Hierarchy Process in operations management, *International Journal of Production Economics*, Vol. 138, No. 2, 215-241, doi: 10.1016/j.ijpe.2012.03.036.

[38] Seuring, S. (2013). A review of modelling approaches for sustainable supply chain management, *Decision Support System*, Vol. 54, No. 4, 1513-1520, doi: 10.1016/j.dss.2012.05.053.

[39] Saaty, T.L. (2001). *Decision making for leaders: The analytic hierarchy process for decisions in a complex world*, New edition, 3rd edition, RWS Publications, University of Pittsburgh, Pittsburgh, USA.