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Development of sustainability performance measurement framework for measuring complex sustainability impacts in the manufacturing industry

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Purpose: This research aims to develop a framework of sustainability performance measurement and to propose sustainability impact criteria that can be used to measure complex sustainability impacts in the manufacturing industry.
Methodology: Fuzzy-Analytical Hierarchy Process (Fuzzy-AHP) and the Delphi method were used to calculate the weights of sustainability impact criteria. Then, the impact pathway of a life cycle assessment was constructed to illustrate the interrelationship between each impact criterion. A proposed framework of sustainability performance measurement is presented along with the suggested sustainability impact criteria.
Findings: Based on the Delphi method and Fuzzy-AHP, the environmental aspect is the area that has received the highest concern (49.4%). The important endpoint impact criteria of the environmental aspect consist of Effect on global climate, Ecosystem quality, Animal biodiversity, and Resource management.
Originality: The biggest challenge of sustainable development that is yet to be answered is how to measure sustainability performance. The environmental aspect is the area that has received the most attention while the economic and social aspects are still under-represented. To fill the gap, this research proposes a framework of sustainability performance measurement that considers all interrelationships between each sustainability aspect.

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1 Introduction

Sustainability has become an important topic in our society especially in the recent time of economic globalization and environmental social movement. It was brought into public focus for the first time in 1987. The United Nations described the definition of sustainability as "a development that meets the needs of the present without compromising the ability of future generations to meet their needs" (United Nations 1987). It became the most often quoted and referred to regarding sustainability. In 1998, John Elkington introduced a sustainable development framework called the Triple Bottom Line (TBL) that not only considers traditional monetary factors but also integrates environmental and social aspects into sustainability (Elkington 1998). The increasing awareness of sustainability has driven many organizations and firms to re-evaluate their supply chain management strategies and business models.

In the past, decision-makers often focused and based their decisions solely on the economic aspect. This trend has changed over the past decade. Nowadays, the focus is projected towards the development of a sustainable supply chain that considers the goals of all three sustainability aspects namely, economic, environment, and social. Thus, Sustainable Supply Chain Management (SSCM) became a crucial element in many organizations' strategies, especially the manufacturing sector. To be sustainable, all players in the supply chain must be committed to the principle of sustainability (Amindoust et al. 2012). For this reason, measuring sustainability performance among players in the supply chain remains one of the biggest challenges in order to create a sustainable supply chain.

Life-Cycle based methods are the most popular tools used for evaluating sustainability. In the late '60s, Life Cycle Costing (LCC) was introduced and became well-known among economists. Unlike the traditional cost accounting tools, LCC considers not only certain specific costs such as investment cost or operating cost, but rather overall costs associated throughout the whole life cycle of a product or service (Gluch and Baumann 2004; Woodward 1997). After that, the concern over environmental pollution and environmental movement during the 70s' motivated the development of another life-cycle based tool called "Life Cycle Assessment (LCA)" (Hauschild et al. 2018). It is used to assess and evaluate the environmental impacts that are caused by the life cycle of a product or service. It is a well-constructed tool that integrates environmental international standards such as ISO 14040 or 14044 in the analysis (Ness et al. 2007).

At this point, the focus of sustainability has been mainly on economic benefits and environmental impacts while the social aspect does not appear to be considered as often as the other two perspectives. Social Life Cycle Assessment (SLCA) was the last life cycle assessment tool that was introduced to assess the positive and negative impacts on the social aspect (O'Brien et al. 1996). Even though the topic of SLCA is still fairly new to the area of life cycle assessment but the topic has gained more attention among researchers and scholars during the past decade (Finkbeiner et al. 2010).

However, most of the life cycle assessment tools are often applied to each sustainability aspect separately (Klöpffer 2003). Due to this reason, many researchers have proposed a hybrid approach that combines two or more approaches together such as a combination between LCC and SLCA, or LCC and LCA. It is also suggested that each aspect of sustainability should be equally evaluated to avoid the complication in the process of result interpretation (Neugebauer et al. 2016; Kloepffer 2008). The combination of the life cycle assessment tools is believed to be a better approach that can represent the overall sustainability in the life cycle.

This research aims to develop sustainability impact criteria and to propose a sustainability performance measurement framework for measuring the complex sustainability impacts in the manufacturing industry.

2 Exploring frameworks of sustainability assessment

To assess sustainability performance, we need to understand the basic characteristic of activities that might affect each sustainability aspect. Figure 1 displays four fundamental flows as inputs and outputs of a corporation (Hutchins and Sutherland 2008). A common goal of every organization is to convert these fundamental flows into a product or service. In general, the focus on financial resource flow is one of the most important aspect in conducting business. However, it is inevitable that emissions or any other negative substances would also be a part of the output. This requires the corporations to balance the focus to all three sustainability aspects equally. As mentioned in the first section, LCA is commonly used to evaluate the environmental effects that are related to all stages of the product life cycle. In 1997, the International Organization for Standardization (ISO) released a set of standards (ISO 14040) to support the principle and framework of LCA. It is separated into 4 phrases which are Goalsand scope definition, Inventory analysis, Impact assessment, and Interpretation (Hauschild et al. 2018). The principle of LCA is to assess the change of physical substances chemically and evaluate the effect of the activities on two impact categories namely midpoint impact criteria, and endpoint impact criteria. For example, Human Health is categorized as one of the endpoint impact criteria. The impact pathway of Human Health is affected by several midpoint impact criteria such as ozone depletion, acidification, or eutrophication. Inventory data such as emissions of carbon dioxide, sulfur dioxide, or methane is required to analyze the impact on both midpoint and endpoint impact criteria. Thus, the input flows can be linked to the assessment as a cause of the impact pathway. To support the interpretation of the result, using both midpoint and endpoint impact criteria when conducting LCA is recommended. It is proved that the endpoint categories are more relevant to decision-makers (Bare et al. 2000). The result from LCA represents mainly the aspect of the environment. Hence, the result of LCA cannot be interpreted as an overall sustainability performance. To achieve that, LCC and SLCA must be performed as well.

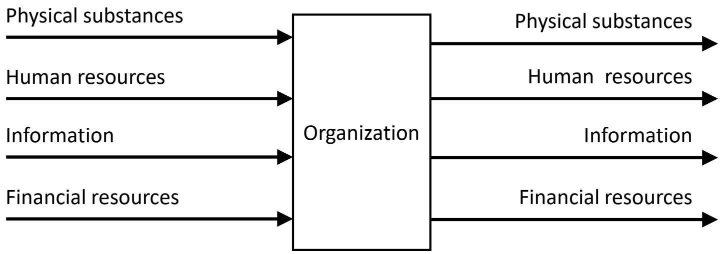

Figure 1: Primary flow of a corporation adopted from (Hutchins and Sutherland, 2008)

Classical LCC is often conducted only for economical gain for the company. In some cases, environmental and social aspects are integrated into the evaluation of LCC (Gluch and Baumann 2004). In 2016, Economic Life Cycle Assessment (EcLCA) was introduced. The framework of EcLCA suggests that midpoint impact categories and endpoint impact categories should be constructed to evaluate economic sustainability. It is believed to be a better reflection of the economic aspect. (Neugebauer et al. 2016).

In the context of sustainability, the social context is still underrepresented. In general, social assessment is performed only to report and evaluate the progress regarding the social context of the organization such as working hours, or average wages. In 2006, the first methodological framework of social life cycle assessment was proposed. It is suggested that an area of protection such as human well-being should be used in the evaluation. The impact category should consist of stakeholders who are affected by the business such as workers, supply chain players, or society (Dreyer et al. 2006). In 2008, an analysis of existing approaches of SLCA was conducted. It can be concluded that people's perception regarding social impacts is varied, subjective, and can be difficult to measure (Jørgensen et al. 2008). Since most of the social criteria evaluate the degree of human satisfaction and social value, they are not easy to quantify. (Santiteerakul and Sekhari 2011). In 2009, the United Nations Environment Programme (UNEP) published the first international social life cycle assessment guideline called "Guidelines for Social Life Cycle Assessment of Products" (Benoît and Mazijn 2009). The framework of SLCA suggested by UNEP can be combined with LCA since they share a common framework. There are available sets of social indicators that are published by several international organizations such as Global Report Initiative (GRI) or United Nations-indicators of Sustainable Development (UN-CSD) (Joung et al. 2013).

From this literature, the decision makers' perspective on sustainability has not been fully integrated into the framework of life cycle assessment tools. The method of Multiple Criteria Decision Making can be combined with the methodological structure of the life cycle assessment to deal with a complex problem with contradictory goals (Verones et al. 2017). Each decision-maker often has different perceptions and perspectives regarding sustainability. One of the advantages of using MCDM is that the decision-makers have control over the sustainability aspects in which they are interested in. This approach was first mentioned in 1997, it is suggested that the step of goal definition and scope in LCA is subjective and should be guided by decision-makers. Thus, it is necessary to use the Analytical Hierarchy Process (AHP) to evaluate and select the impact categories (Miettinen and Hämälänien 1997). In recent research, a combination approach between MCDM and LCA was used to evaluate renewable energy technologies. It shows that the hybrid approach, especially the combination of LCA and AHP, is a better option to evaluate comprehensive sustainability (Campos-Guzmán et al. 2019; Santoyo-Castelazo and Azapagic 2014; Ong et al. 2020).

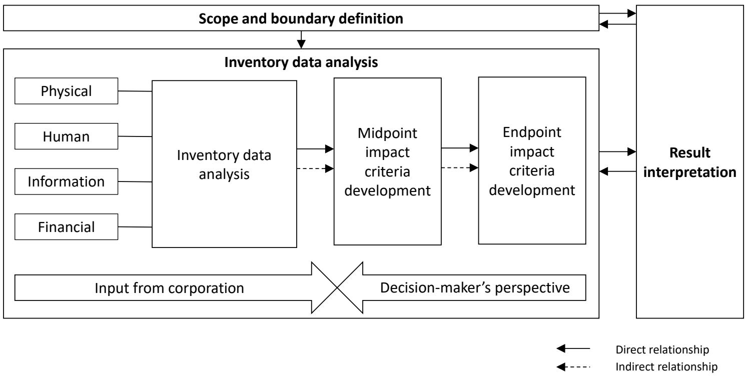

Figure 2: A proposed framework of sustainability performance measurement

Base on this literature, we developed a proposed framework of a sustainability performance measurement (Figure 2). It was constructed base on the integration of LCA, SLCA, and EcLCA. During the stage of inventory analysis and impact assessment, the impact pathway must be constructed to display the relationship between the corporation flows and the concept of life cycle assessment. The diagram is influenced by both sides, the left side of the diagram is affected by the corporation flows. The right side of the diagram consists of midpoint and endpoint impact criteria that are influenced by the decision-maker's perspective regarding sustainability.

3 Development of the endpoint impact criteria using a combination of Fuzzy-AHP and the Delphi method

This section focuses on the development of the endpoint impact criteria by using the combination of the Delphi method and Fuzzy-AHP.

3.1 Delphi method

The Delphi method is one of the most popular tools for evaluating expert opinions. It method can be applied and integrated with many decision-making tools due to the broad coverage of its principle (Vidal et al. 2011). The Delphi method is commonly used to deal with the qualitative data such as opinions or judgments in order to obtain a consensus perspective from a group of experts (Rahimianzarif and Moradi 2018). In this research, we used the Delphi method to qualify results from the experts and reach a consensus of experts' opinions.

3.2 Triangular fuzzy set theory

The fuzzy set theory was introduced to objectify human judgment that is often uncertain and subjective. It helps decision-makers to evaluate the decisions that involve uncertainty in the assessment process (Govindan et al. 2013). Triangular fuzzy numbers are commonly used as a fuzzy extension of the multiplicative pairwise comparison method (Krejčí 2018). Thus, triangular fuzzy numbers were selected to use in this research. According to the triangular fuzzy set theory, a fuzzy set is a class of objects where memberships can vary on a scale of 0 to 1. A membership function can be defined as equation 1.

$$M_W(x) = \begin{cases} 0, & x < a, x > c \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \end{cases} \quad (1)$$

Where a is the lower boundary value, c is the upper boundary value, and b is the middle value of the triangular fuzzy number. Let's consider two triangular fuzzy numbers W_1 and W_2 where $W_1 = (a_1, b_1, c_1)$ and $W_2 = (a_2, b_2, c_2)$. The main operational laws for two triangular fuzzy numbers are as follows:

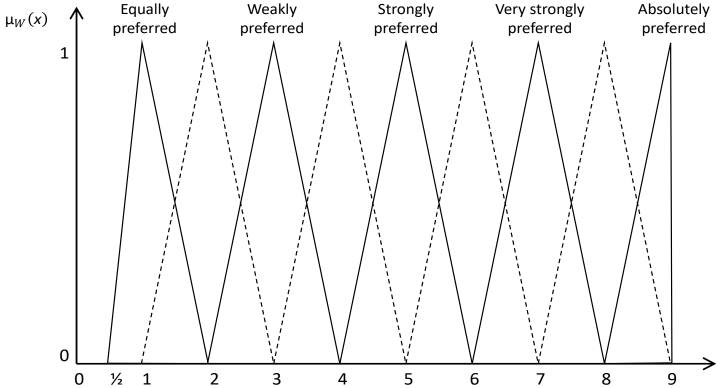

Figure 3: 9-point scale membership functions adapted from (Saaty, 1977)

$$\begin{aligned} &W_1 + W_2 = (a_1+a_2, b_1+b_2, c_1+c_2), \\ &W_1 \otimes W_2 \approx (a_1a_2, b_1b_2, c_1c_2), \\ &\lambda \otimes W_1 = (\lambda a_1, \lambda b_1, \lambda c_1), \lambda > 0, \lambda \in R, \\ &W_1^{-1} \approx (1/c_1, 1/b_1, 1/a_1) \end{aligned} \quad (2)$$

In this research, we used a 9-point fuzzy scale of membership function which was customized from Saaty's scale (Saaty 1977; Krejčí and Talasová 2013). The output of the fuzzy sets in terms of linguistic are "equally preferred", "equally and weakly preferred", "weakly preferred", "weakly and strongly preferred", "strongly preferred", "strongly and vary strongly preferred", "vary strongly preferred", "vary strongly and absolutely preferred", and "absolutely preferred". These linguistic terms represent the fuzzy numbers scale in numerical scores vary between 0.5 to 9 as seen in Figure 3.
For example, if the criteria i is strongly preferred than criteria j, according to the linguistic terms, the fuzzy number of this comparison will be $a_{ij} = (4,5,6)$.

3.3 Multicriteria decision-making approach

As mentioned in the previous section, the combination of Fuzzy-AHP and the Delphi method was used to calculate, rank, and analyzed criteria. There are two main groups of criteria, main criteria, and sub-criteria. Main criteria consist of three sustainability as aspects namely economic, social, and environment while sub-criteria refer to a group of endpoint impact criteria.

Table 1: Main criteria and sub-criteria

Economic	Social	Environment
Cost reduction and saving	Workers well being	Green image
Financial risk	Consumer well being	Resource management
Variety of products and services	Cultural diversity	Animal biodiversity
Market share	Society responsibility	Ecosystem quality
Financial growth	landscape aesthetics	Global climate
Promotion of innovation	Regional economy	Waste management

3.3.1 Expert survey and initial criteria development

Before conducting an interview, the initial main criteria and sub-criteria must be identified. As mentioned above that the main criteria are represented using three main sustainability aspects. On the other hand, a of the endpoint impact criteria were investigated using a literature review and expert interview (Bai and Sarkis 2010; Begić and Afgan 2007; Domingues et al. 2015; Evans et al. 2009; Haddad et al. 2017; Liu 2014; Liu et al. 2013; Hirschberg et al. 2008). There were 6 experts in the areas of sustainability and manufacturing participated in the interview. The experts were asked to review and give their opinions regarding the list of literature criteria. Apart from the literature criteria, two additional criteria were suggested by the experts which are "Variety of products and services", and "Green image". The summary or the main criteria and sub-criteria is presented in table 1.

3.3.2 Pairwise comparison and the Delphi method

Based on the literature criteria, a pairwise comparison was constructed. Questionnaires in the form of pairwise comparisons were sent out to the experts. Using the 9-point fuzzy scale, the experts had to compare and decide for each pairwise comparison a 1 - 9 scale.

After the first round of pairwise comparison, the results were sent to each expert in which they could see other's evaluations anonymously and reconsider their results. The analysis of the second round revealed that only three participants had varied their pairwise comparison answers. The result from the second round was sent to the expert one more time. At this round, the experts did not change their answers in their pairwise comparisons. Thus, the result from the experts had reached global consensus in the second round. The result of the second round was later used for the final evaluation.

3.3.3 Consistency test

Verifying consistency was used to evaluate results from pairwise comparisons whether the preference information provided by the experts is inconsistent. Based on the Saaty's AHP methodology, consistency index is used to evaluate the consistency of the judgment in each comparison matrix

(Saaty 1977). It is suggested that the consistency analysis should be performed based on the typical AHP approach (Liu et al. 2017).

Table 2: The value of RI (Deng 2017)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Thus, comparison matrices must be checked for consistency before fuzzifying. The consistency index (CI) and the consistency ratio (CR) can be calculated using equations as follows:

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

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

Where λ_{max} is the largest eigenvalue of the comparison matrix, n is the dimension of the matrix, and RI is a random consistency index. The dimension of the matrix determines the RI value (table 2). According to Saaty, the comparison matrix is acceptable if CR is less than 10% (Saaty 1977).

After the process of pairwise comparison, the results from each expert were checked individually to determine whether they are consistent using the method mentioned above. If the result fails the consistency test, the expert must revise the pairwise comparisons. The result will be further processed in the next step when they are all consistent and reach consensus.

3.3.4 Fuzzy pairwise comparison matrix

After the pairwise comparisons and consistency check, the given scales from each expert were converted into fuzzy numbers. The result is shown in table 3. Using the method mentioned in section 3.3.2, an example of a fuzzy matrix of the pairwise comparison for three main criteria (economic, social, and environment) can be calculated as follows:

Table 3: Pairwise comparison of the main criteria

	Economic (Ec)	Social (S)	Environment (En)
Economic (Ec)	(1, 1, 1)	(4, 5, 6) (1/4, 1/3, 1/2) (1/4, 1/3, 1/2) (1/4, 1/3, 1/2) (1/4, 1/3, 1/2) (2, 3, 4)	(2, 3, 4) (1, 2, 3) (1/4, 1/3, 1/2) (1/4, 1/3, 1/2) (1/4, 1/3, 1/2) (1/4, 1/3, 1/2)
Social (S)	(1/6, 1/5, 1/4) (2, 3, 4) (2, 3, 4) (2, 3, 4) (2, 3, 4) (1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2) (1/4, 1/3, 1/2) (1/3, 1/2, 1) (1/2, 1, 2) (1/2, 1, 2) (1/4, 1/3, 1/2)
Environment (En)	(1/4, 1/3, 1/2) (1/3, 1/2, 1) (2, 3, 4) (2, 3, 4) (2, 3, 4) (2, 3, 4)	(2, 3, 4) (2, 3, 4) (1, 2, 3) (1/2, 1, 2) (1/2, 1, 2) (2, 3, 4)	(1, 1, 1)

For example, the fuzzy pairwise comparison between Ec and S can be calculated into fuzzy numbers as follows:

$(4 \times 1/4 \times 1/4 \times 1/4 \times 1/4 \times 2)^{1/6} = 0.561$

$(5 \times 1/3 \times 1/3 \times 1/3 \times 1/3 \times 3)^{1/6} = 0.755$

$(6 \times 1/2 \times 1/2 \times 1/2 \times 1/2 \times 4)^{1/6} = 1.070$

Therefore, the fuzzy matrix of the main criteria are as follows:

$$\text{Fuzzy Matrix} = \begin{array}{c} \\ Ec \\ S \\ En \end{array} \begin{array}{c} \begin{array}{ccc} Ec & S & En \end{array} \\ \begin{bmatrix} (1,1,1) & (0.561, 0.755, 1.070) & (0.445, 0.648, 0.953) \\ (0.935, 1.325, 1.782) & (1,1,1) & (0.330, 0.514, 0.891) \\ (1.049, 1.543, 2.245) & (1.122, 1.944, 3.026) & (1,1,1) \end{bmatrix} \end{array}$$

Using the same method, the fuzzy matrixes of all criteria were calculated.

3.3.5 Calculation of weight vectors

To obtain the weight vector, the extent analysis method was applied (Chang 1996). The method can be described as follows:

Assume that X and U are an object set and a goal set respectively where $X = \{x_1, x_2, \ldots, x_3\}$ and $U = \{u_1, u_2, \ldots, u_3\}$. Then we take each object and conduct extent analysis for each goal, respectively. Thus, we can obtain m extent analysis values for each object as follows:

$$W_{g_i}^1, W_{g_i}^2, \ldots, W_{g_i}^m \qquad i = 1,2,\ldots,n$$

Where $W_{g_I}^j$ $(j = 1, 2, \ldots, m)$ represent triangular fuzzy numbers. Then we calculate the fuzzy synthetic degree value with respect to ith object as follows:

$$S_i = \sum_{j=1}^{m} W_{gi}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} W_{gi}^j \right]^{-1} \tag{4}$$

According to the fuzzy comparison pairwise matrix in section 3.3.4, the fuzzy synthetic degree value of the main criteria (economic) can be calculated using equation 4.

$$\sum_{i=1}^{3}\sum_{j=1}^{3} W_{gi}^{j} = (1, 1, 1)+(0.561, 0.755, 1.070)+\ldots+(1, 1, 1)$$
$$= (7.443, 9,729, 12,967)$$
$$\sum_{j=1}^{3} W_{gi}^{j} = (1, 1, 1)+(0.561, 0.755, 1.070)+(0.445, 0.648, 0.953)$$
$$= (2.007, 2.403, 3.023)$$

Thus, the fuzzy synthetic degree value of the main criteria (economic) is equal to

$$S_{Ec} = (2.007, 2.403, 3.023) \otimes \left(\frac{1}{12.967}, \frac{1}{9.729}, \frac{1}{7.443}\right)$$
$$= (0.155, 0.247, 0.406)$$

Applying the same calculation, the fuzzy synthetic degree value of the main criteria (social, and environment) can be calculated as follows:

$$S_{S} = (2.265, 2.839, 3.673) \otimes \left(\frac{1}{12.967}, \frac{1}{9.729}, \frac{1}{7.443}\right)$$
$$= (0.175, 0.292, 0.493)$$
$$S_{Ec} = (3.172, 4.487, 6.271) \otimes \left(\frac{1}{12.967}, \frac{1}{9.729}, \frac{1}{7.443}\right)$$
$$= (0.245, 0.461, 0.843)$$

After calculating the fuzzy synthetic degree value of each criterion, the degree of possibility must be calculated by comparing between two triangular fuzzy numbers. The degree of possibility between two triangular fuzzy numbers, $W_1 = (a_1, b_1, c_1) \geq W_2 = (a_2, b_2, c_2)$, can be defined as $V(W_1 \geq W_2) = \sup_{y \geq x}[\min(\mu_{W_1}(x), \mu_{W_1}(y))]$ which is equivalent to $V(W_1 \geq W_2) = hgt(W_1 \cap W_2)$. Then

$$\mu(d) = \begin{cases} 1, & \text{if } b_1 \geq b_2 \\ \frac{a_1 - c_1}{(b_1 - c_1) - (b_2 - a_2)}, & \text{if } a_2 \geq c_1 \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

Where d is the maximum intersection value between W_1 and W_2

Equation 6 defines the degree of possibility for a fuzzy number that is greater than k fuzzy numbers W_i (i = 1, 2, …, k).

$$V(W \geq W_1, W_2, \ldots, W_k) = \min V(W \geq W_i),\ i = 1, 2, \ldots, k \quad (6)$$

Assume that $d'(A_i) = \min V(S_i \geq S_k)$, for k = 1, 2, …, n; k ≠ i. We can obtain the weight vector by

$$M' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T \quad (7)$$

Where A_i ($i = 1, 2, \ldots, n$) are n elements. After that, the normalized weight vectors must be calculated. Finally, final a non-fuzzy number (M) can be defined by

$$M = (d(A_1), d(A_2), \ldots, d(A_n))^T \quad (8)$$

Using the same example from previously, the weight vector of the main criteria can be calculated using equation 5 to 8, as follows:

$$V(S_1 \geq S_2) = \frac{0.175\text{-}0.406}{(0.247\text{-}0.406)\text{-}(0.292\text{-}0.175)} = 0.838$$

$$V(S_1 \geq S_3) = \frac{0.245\text{-}0.406}{(0.247\text{-}0.406)\text{-}(0.461\text{-}0.245)} = 0.430$$

$$V(S_2 \geq S_1) = 1$$

$$V(S_2 \geq S_3) = \frac{0.245\text{-}0.493}{(0.292\text{-}0.493)\text{-}(0.461\text{-}0.245)} = 0.595$$

$$V(S_3 \geq S_1) = 1$$

$$V(S_3 \geq S_2) = 1$$

Finally, the weight vector of the main criteria before normalization is

$$d'(A_1) = \min V(S_1 \geq S_2, S_3) = \min\{0.838, 0.430\} = 0.430$$

$$d'(A_2) = \min V(S_2 \geq S_1, S_3) = \min\{1, 0.595\} = 0.595$$

$$d'(A_3) = \min V(S_3 \geq S_1, S_2) = \min\{1, 1\} = 1$$
$$M' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T = (0.430, 0.595, 1)$$

Thus, the non-fuzzy weight vectors of the three main criteria after normalizing are as shown below.

$$M = (0.212, 0.294, 0.494)$$

Using the same calculation, the non-fuzzy weight vectors of all sub-criteria were calculated. Overall, the environmental aspect is the most important main criterion (0.494), followed by the social (0.294) and economic (0.212) aspects respectively. The result shows that the criteria 'Effect on global climate" is the most concerned criterion (0.215) in the environmental category. For the social aspect, "Worker well-being" receives the highest weight (0.161), while the most important midpoint criterion in economic aspects is "Promotion of innovation" (0.058). The null weight problem occurred to two criteria from each category. Therefore, the final selected endpoint impact criteria are highlighted in Figure 4.

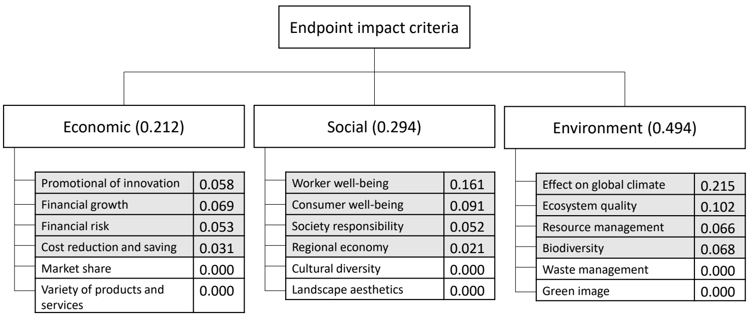

Figure 4: Final weights of main criteria and sub-criteria

4 Impact pathway development

Based on the finding of the endpoint impact criteria from section 3, the impact pathway of sustainability assessment was developed. As we were able to identify the endpoint impact criteria using an integration of the Delphi method and Fuzzy AHP, the next step is to address the midpoint impact criteria. Literature review and international guidelines such as GRI or UNEP were used to identify related midpoint impact criteria and their relationships to the endpoint impact criteria. Relationships between midpoint and endpoint impact criteria are displayed using arrows. Direct and common relationships are illustrated with solid lines, while indirect relationships are shown in dash lines. Figure 5 illustrates the impact pathway of the midpoint and endpoint impact criteria and a summary of the proposed framework of sustainability performance measurement for the manufacturing industry.

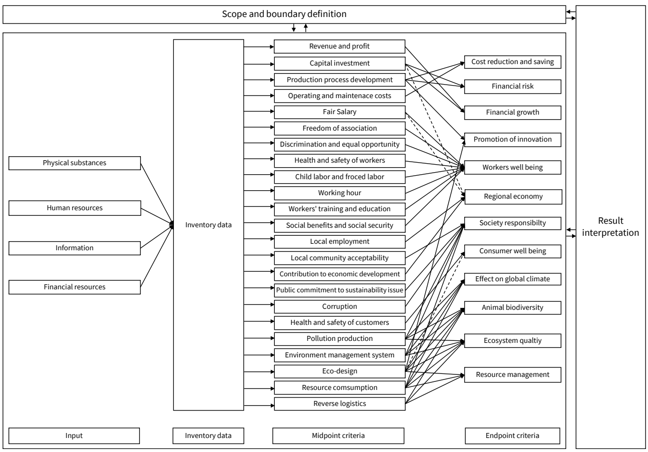

Figure 5: Impact pathway of midpoint and endpoint impact criteria

5 Summary and conclusion

This research has presented a proposed framework of a sustainability performance measurement which aims to measure the complex sustainability impacts in the manufacturing industry. We integrated the principle of LCA and MCDM to cover both of the sustainability thinking and the perspectives of decision-makers. In this research, Fuzzy AHP and the Delphi method were used to identify the endpoint impact criteria. During this phase, six experts from the area of sustainability and manufacturing were participating. The result shows that the most concerning aspect of sustainability is the environment. By applying the principle of Pareto, 4 endpoint impact criteria from each sustainability aspect were selected. An impact pathway was developed base on the selected endpoint impact criteria to illustrate the interrelationship between endpoint impact criteria, midpoint impact criteria, inventory data, and corporate flows.

This framework adds to the topic that is widely discussed on how to incorporate the opinions of decision-makers into the life cycle assessment approach. By constructing an impact pathway, we can clearly see the complex relationships of midpoint and endpoint criteria. The framework is still under development, even though the development of midpoint and endpoint criteria was implemented in this research, several issues must be further discussed. Firstly, the step of scope and boundary definition was not considered in this research because there were several experts that came from different manufacturing fields. Secondly, the analysis of inventory data and how it affects midpoint and endpoint impact criteria has not yet been accomplished. As for the environmental and economic aspects, the existed methods might be suitable to map out the effects of inventory data on certain midpoint and endpoint impact criteria. However, for the social aspect, it is still challenging to analyze the inventory data and its impacts because it consists of both quantitative and qualitative midpoint and endpoint impact criteria which could be a subject for future research.

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