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Proposed Framework for Assessing the Sustainability of Membrane Life Cycle

Salwa Mahmood[a,]*, Muhamad Zameri Mat Saman[a], Noordin Mohd Yusof[a]

[a]*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai Johor, Malaysia*

* Corresponding author. Tel.: +6-013-7041541; fax: +6-07-5534881.*E-mail address:*salwamahmood@gmail.com

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Abstract

Developments in sustainability assessment tools are leading to an increased interest in sustainability assessment for products and services. Several sustainability measurement tools and frameworks have been developed. However, most of these tools only focus on environmental considerations while some of the frameworks only focus on governmental progress. In this paper, a comprehensive framework for assessing sustainability is presented. During framework development, the Life Cycle Assessment (LCA) and fuzzy logic approach was applied. LCA determined the sustainability parameters and estimated the potential environmental impact from the membrane product. Next, the fuzzy logic approach was applied to deal with the qualitative and quantitative data. The proposed framework focuses on the evaluation of membrane products. However, the proposed framework can be adopted for other related products.

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*Keywords:*Sustainability assessment; framework; fuzzy logic approach; membrane; product life cycle.

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1. Introduction

Sustainability assessment has become evolution of quality and efficiency indicator for product life cycle. This theory is generally viewed as a tool of impact assessment processes which needs to be integrated with several criteria. Over the years, local, regional, national, and international efforts to identify an appropriate sustainability indicator have been consistent [1]. However, these efforts depend on the sustainability context and coverage. An evaluation according to resource use and environmental impact along the production chain of the product life cycle is preferred for product-related assessment tools.

The main objective of assessing the sustainability of a membrane life cycle is to indicate the sustainability performance level of a membrane product. Several membrane types exist, such as hollow fiber membrane, flat sheet membrane, and tubular membrane. Membrane product is an important factor in filtration processes and should be monitored in terms of sustainability. The performance level can be identified at every membrane life cycle phase. Weak areas can be detected to improve a product, such as the material used, process, design, and ergonomic factors. When the product sustainability level is improved, users become more satisfied with the quality product and sustainability label. Sustainability refers to the balance in the triple bottom line (TBL), which includes environmental, economical, and social aspects. Sustainability should minimize negative environmental impact, conserve energy and natural resources, and be economically sound and safe for the community [2].

For the sustainability assessment, the goals of each sustainability element need to be arranged. This step reflects the desire to achieve TBL objectives. Several goals are prepared for the development of a sustainability assessment framework that involves all the sustainability aspects. For the environmental aspect, potential negative environmental impact, such as global warming potential, acidification potential, eutrophication potential, and waste potential should be reduced. For the economical aspect, the involved costs should be optimized. For the social aspect, potential fatalities should be eliminated and ergonomic factors improved.

Chapter 2 describes the existing sustainability assessment framework. Most of this framework focused on one sustainability criterion. For the aspect of environmental support, Life Cycle Assessment (LCA) was applied to

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estimate the environmental burdens of the membrane system described in Chapter 3. In addition, few frameworks could integrate the uncertainties of qualitative and quantitative data. Thus, fuzzy logic approach was applied in the development of the framework methodology to overcome the data uncertainties on the proposed framework.

2. Existing sustainability assessment framework

Several tools for sustainability evaluation have been developed, such as LCA, Eco-Indicator 95, Eco-Indicator 99, Life Cycle Index (LinX), Green Pro, and Ten Golden Rules. However, most of these tools do not integrate a nature-economic-society aspect because they mainly focus on the environmental aspects. Other frameworks include those developed by the United Nations Commission on Sustainable Development (CSD), the Global Report Initiative (GRI) of The Institution of Chemical Engineers (IChemE), and the Lowell Centre for Sustainable Production (LWSP) and Wuppertal Sustainable frameworks of the United Nation CSD. These frameworks are focused on the governmental progress of countries that belong to the United Nations. Table 1 shows the details of existing sustainability assessment methods.

Table 1. Existing evaluation tools/frameworks for measuring sustainability

Tools/frameworks	Details
LCA	LCA methodology is a generalized tool that can be applied to evaluate any type of product and service. LCA focuses on the environmental aspect to estimate the environmental burden during a product life cycle. This tool does not consider economical aspects, such as cost. However, LCA is an advantageous tool when supporting the environmental aspect from beginning to end.
Eco Indicator 95	The Eco Indicator 95 is a generalized tool that can be used to evaluate any product type. A designer can easily apply this tool because the environmental terms are easy to understand. The tool also considers both environmental and social aspects. However, it does not consider economical aspects, such as cost, resource depletion, and technology.
Eco Indicator 99	This tool is a modification of Eco Indicator 95, which is based on the damage-oriented method for LCA. The Eco Indicator 99 was developed based on three main categories: human health, ecosystem, and mineral resources. Similar to the Eco Indicator 95, Eco Indicator 99 is a generalized tool that can be used to evaluate any product type. This tool is also well documented and accepted as an international standard. However, Eco Indicator 99 still does not include an analysis of cost and technology.
LInX	This tool is an indexing system for the evaluation of process design. The environmental, economical, and social aspects are considered. This tool is a generalized tool that can be used to screen and evaluate any product type and process design. However, the boundary analysis is limited from cradle to gate, which does not cover all the life cycle stages or does not reach the end of a product life.
Green Pro	Green Pro is a systematic methodology for process design that considers the assessment and minimization of environmental impact. This analysis includes environmental, technological, and economical factors at the design stage to determine a cost-effective solution. The main element of this tool is the application of multi-criteria decision making, which is a guide for making decisions. The boundary analysis is limited from cradle to gate, which does not cover the usage and life end of products. In addition, this tool does not consider social aspects.
Ten Golden Rules	Ten Golden Rules is a qualitative analysis method that provides the common foundation used as a basis and guide for the development of a specific product design. The rules can be customized based on the specific product requirements. However, this tool only considers environmental aspects. Furthermore, a user must already have background knowledge to properly use these rules. The analysis results may also differ depending on user knowledge and experience.
United Nation CSD	This framework was developed to monitor the various sustainability indicators for assessing the performance of governmental progress. It has an additional element called institutional aspects. This framework focuses on the governmental progress of the United Nations Development. However, other case studies or applications can adopt this framework.
GRI	The IChemE introduced a set of sustainability indicators to measure the operation sustainability within a process industry. This framework is less complex, impact-oriented, and strongly favors environmental aspects. It focuses more on the development of social indicators than on balancing each sustainability element of the framework.
LWSP	This framework has seven sustainability fronts, namely, waste elimination, benign emission, renewable energy, loop closing, resource-efficient transportation, sensitivity hook-up, and commerce redesign. It consists of five levels toward sustainable system. LWSP framework focuses on increasing the comprehensive measurement of environmental impact.
Wuppertal sustainable framework	This framework is an innovation of the United Nations CSD framework, and its indicators are applicable for national focus. The framework focuses on the governmental progress of the United Nations Development. However, other case studies or applications can adopt this framework.

As seen from the examples of generalized tools and frameworks, some tools do not consider all three main elements of sustainability while some tools utilize the qualitative method in the assessments. In addition, there are no tools developed can deal with data uncertainties. This study introduces an assessment sustainability framework that considers TBL aspects. The proposed framework can deal with data uncertainties using the fuzzy logic approach, which focuses on the membrane product. However, the frameworks can be adopted for other applications or case studies [3,4,5].

3. Methodology

3.1. Life Cycle Assessment

In this study, LCA was applied to support the sustainability assessment framework, which can estimate the environmental burdens of membrane products at every phase of the life cycle. The environmental burdens includes all types of impact to the environment, including depletion of natural resources, energy consumption, and land, water, and air emissions. Using LCA can ensure that all types of environmental impact are assessed within a consistent LCA framework to minimize the possibility of *problem shifting* [6]. For the past 35 years, LCA has been used in varied forms to evaluate the environmental impact of a product or service throughout an entire life cycle [7, 8, 9]. It has also been successfully used in various applications, such as the membrane filtration process [8].

The structure is divided into four phases based on the ISO standard. These phases are goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. The goal of the applied LCA is to estimate the environmental burdens of a membrane product. The scope of the LCA focuses on the membrane product and includes the consumption of materials and energy, such as electricity. Parameters can be determined by identifying the elementary input and output that cross the system boundary, as shown in Figure 1.

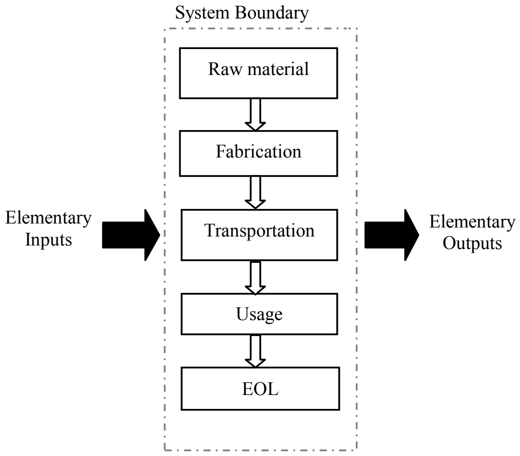

Fig. 1. System boundary from cradle-to-grave

Mass and energy balance are performed to quantify all elementary input and output flows, wastes, and emissions involved in a membrane life cycle. The LCA software, GaBi 6.0, is used to estimate air, water, and soil wastes and emissions according to the model developed in the software [10].The impact assessment phase is created to evaluate the significance of potential environmental impacts using the LCI results. Based on the results, the environmental impact associated with the membrane life cycle can be identified and selected as input parameters for the framework development.

However, LCA is not a complete sustainability assessment because only the environmental aspect is covered [11]. Thus, LCA is applied as a strategic tool to determine the sustainability parameters and estimate the environmental burdens that occur in the framework development.

3.2. Application of fuzzy logic approach

Fuzzy logic is a suitable tool for uncertainties, which can be regarded as useful and practical functions from the mathematical perspective [12]. Fuzzy logic, which uses common sense codification, is a suitable approach for mapping inputs to an output. The fuzzy inference system (FIS) was adopted because framework inputs come in the form of qualitative and quantitative data. FIS is a method that interprets the values in the input vector and assigns them to output vectors based on the same set of rules [13]. Fuzzy logic analysis and control methods are shown in Figure 2.

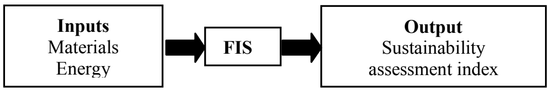

Fig. 2. The fuzzy logic control-analysis method

The fuzzy operation starts after the elementary input and output that cross the system boundary are selected, which determine the parameters [14]. The next sub-topic discusses the fuzzy operation and consists of fuzzy membership function (mf), fuzzy rules, fuzzification, FIS, and defuzzification:

- Mf allows the smooth assessment of input variables toward the output. Triangular mf is adopted in various assessments because it is the simplest and most commonly used [15, 16]. Triangular mf is adopted in the present study because of these characteristics.
- Fuzzy rules present the linguistic of the if-then proposition of the situation. The if part consists of one or more facts while the then part includes only one part, which is the output [13]. The number of fuzzy rules exponentially increases according to the number of elements considered.
- Fuzzification is a process that determines the membership degree of the input variables. After considering the input value, the input degree should be determined with the use of the mf. During the fuzzification process, the numerical input values will convert into linguistic variables.
- FIS is an approach for integrating quantitative and qualitative data [15]. FIS can formulate the mapping from the obtained input to the output value. It consists of an implication process and an aggregation process. The implication process defines the fuzzy conclusion while the aggregation process combines fuzzy conclusions into a single fuzzy set. Output value is the overall sustainability performance of a membrane life cycle in terms of indices. A membrane life cycle can be categorized as sustainable or not-very-sustainable with the use of the indices.
- Defuzzification is the process of transforming the output fuzzy result into a single numerical value, such as an index or a percentage from zero to one. Defuzzification does the opposite of fuzzification. The most common technique for defuzzification is the center of gravity method, which calculates the center of the area under the curve [17].

With the use of the fuzzy logic approach, the developed sustainability assessment framework can manage data uncertainties while considering three main sustainability aspects. Moreover, the framework can be the intermediate between a sustainable and non-sustainable membrane product.

4. Proposed Framework

Figure 3 shows the proposed framework for assessing the sustainability performance of a membrane life cycle. The assessment first selects a membrane product and reviews the product specifications or bill of material (BOM), which includes the materials and processes for obtaining the sustainability parameters or input data with the use of LCA. After parameters are collected, the parameters are classified into the corresponding categories or the environmental, economical, and social aspects as discussed below.

4.1. Environmental aspect

The intensive use of materials, energy, and the potential for environmental pollution from the intensive processes within a life cycle characterizes a membrane life cycle. Furthermore, chemical use in post treatment may result in toxicity. The backwashing process also involves chemical use and may result in the discharge of heavy toxic metals and chlorinated residues.

4.2. Economical aspect

The costs considered in this aspect are material cost, fabrication cost, transportation cost, usage cost, and life end cost. In terms of sustainability, cost optimization is important and involves the reduction of chemical use, energy and resources, transportation, labor, treatment cost, operating cost, and management cost. Less energy and material consumption indicates a higher sustainability level [18].

4.3. Social aspect

For the social aspect, the developed framework considers the control of the hazardous material used, ergonomics factors, as well as the safety and control of the emissions that may potentially harm human health. Several components are considered in the human health factor, such as the heavy metal and carcinogen produced in all membrane life cycle phases. Other factors such as dust and toxic gas can also cause health impairment.

Next, fuzzy evaluation can determine the indices of every element to obtain an overall sustainability performance index. The elements refer to the potential impact data collected, as shown in Table 2. Currently, 10 elements and the corresponding parameters are considered. In the proposed framework, the weightage process is optional depending on the assessment objective [19, 20]. The present study provides equal weightage because the assessment objective is to balance all aspects.

After the evaluation, the sustainability performance of a membrane life cycle can be obtained in terms of a low, medium, or high index. A low index value indicates a low membrane product sustainability level, whereas a higher index value indicates a high sustainability level. At this stage, the weakness area can be identified. Thus, if the weakness is acceptable, a product sustainability label can be achieved for sustainability satisfaction. Improvements are needed at the weak areas toward membrane product sustainability.

Overall, the integration between all sustainability aspects, namely, environmental, economical, and social, is important in developing the sustainability assessment framework. The proposed framework can be used to assess the sustainability level of a membrane life cycle. Therefore, the sustainability aspects can be balanced.

Table 2. Sustainability aspects, elements and parameters.

Sustainability aspects	Elements	Parameters
Environmental	Global Warming Potential	Carbon dioxide (CO_2) Carbon monoxide (CO) Methane (CH_4)
	Acidification Potential	Sulphur dioxide (SO_2) Nitrogen oxide (NO_x)
	Eutrophication Potential	Biological oxygen demand (BOD) Chemical oxygen demand (COD) Phosphorus (PO_4) Ammonia (NH_3)
	Waste potential	Solid waste Chemical waste
Economical	Material	Renewable material Non-renewable material
	Energy	Renewable energy Non-renewable energy
Social	Human health	Carbon monoxide (CO) Non-methane volatile organic compound (NMVOC) Dust
	Heavy metal	Lead (Pb) Mercury (Hg) Chromium (Cr) Cuprum (Cu)
	Carcinogen	Arsenic Benzene
	Risk	Safety Ergonomic

5. Conclusion

This paper presented a proposed framework for assessing the sustainability of a membrane life cycle. LCA was applied to the framework to determine the involved parameters and to classify as well as assign these parameters to corresponding categories. FIS was applied to determine the indices of the elements involved because these elements were quantitative and qualitative data and could not be integrated with the use of a traditional mathematical approach. Equaling all the element indices could obtain the overall sustainability performance of a membrane life cycle because weightage was optional. The proposed framework could monitor the sustainability performance of a membrane system. Therefore, improvements could be made to achieve membrane product sustainability.

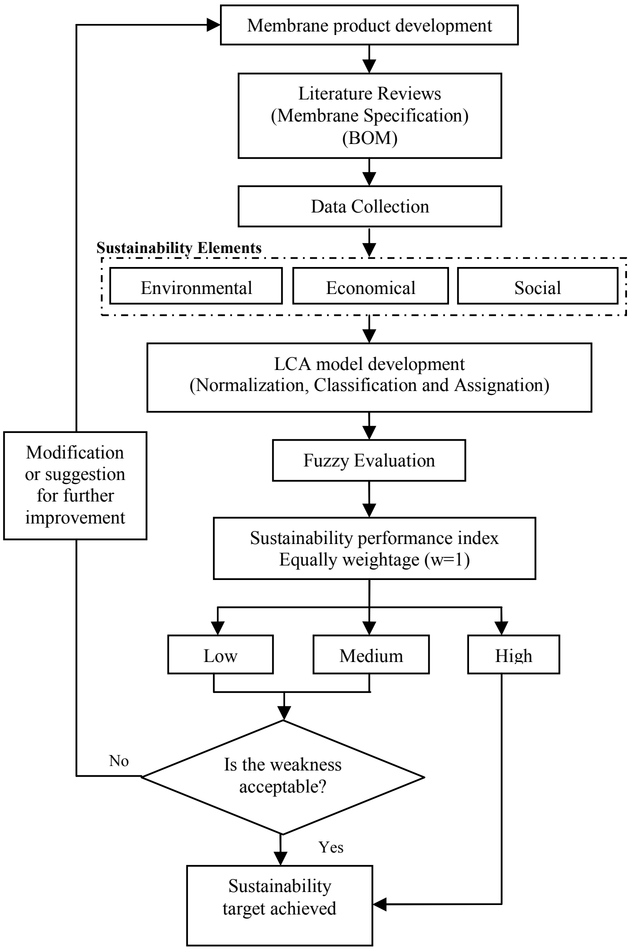

Fig. 3. Proposed framework for assessing sustainability of membrane life cycle.

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