THE EVALUATING MACHINE SAFETY AND SUSTAINABILITY BY CIRCULAR DESIGN: A COMPOSITE INDICATOR

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ABSTRACT

Circular design offers significant potential for creating more environmentally friendly and sustainable machines. However, its implementation also presents a number of challenges, particularly related to operational safety and sustainability evaluation. A comprehensive evaluation approach and clear technical standards are needed to ensure that circularly designed machines remain efficient, safe, and suitable for long-term use. This research method uses a literature review to develop indicators. The results of this article identify 16 indicators that can be used to develop sustainable machine designs. These indicators are divided into two main categories: 8 indicators related to environmental aspects, including energy savings, recycling, reuse, toxic and hazardous materials, number of components, product durability, and environmentally friendly components; and 9 indicators related to technical aspects, including assembly and disassembly, product dimensions, product weight, maintenance, safety of use, ease of operation, ease of cleaning, ease of production, and product adaptability. Furthermore, indicator validation is crucial to ensure that the indicators used are relevant, accurate, and reliable in the context of developing sustainable machine designs.

KEYWORDS Machine, Safety, Sustainability, Design, Indicator

INTRODUCTION

Sustainability can be defined as a system that integrates three main pillars: environmental, economic, and social aspects, in a balanced and holistic manner. These three aspects are interrelated and must be considered together to achieve sustainable development goals. Currently, sustainability has become a crucial and strategic topic in various fields, such as politics, industry, society, research, and product design development (Agusti, Buwono, Dwyanton, & Wahyono, 2025). Along with the changing times and increasing awareness of the importance of environmental protection and socio-economic balance, the concept of sustainability continues to be developed and adopted in almost all scientific fields, using various approaches and methods.

One form of applying the concept of sustainability in design is known as sustainable design or circular design. Circular design is an approach to product development that considers environmental impact, economic efficiency, and social responsibility throughout the product's life cycle. Similar to the general concept of sustainability, sustainable design also refers to three main aspects: environmental, economic, and social. The goal of green design is to create products that not only meet the functional needs of users but also maintain and reuse resources from previous products, thereby reducing negative impacts on the environment and promoting efficiency in resource use. Thus, sustainability in product design is the ability to maintain the existence of a product in a sustainable manner, through an environmentally friendly, economical and socially responsible approach.

Circular design is an approach to product design that emphasizes efficient resource use and sustainability principles. The primary goal of this approach is to minimize waste, maximize product lifespan, and reduce environmental impacts from the production process through to the end of the product's useful life. Circular design is part of the circular economy concept, which offers an alternative to the traditional linear economic model (take → make → dispose). In a circular economy, the approaches used include: Reuse, Repair, Recycle, and Remanufacture. Thus, circular design encourages longer, more efficient, and more environmentally friendly product life cycles.

There are five main principles of circular design: recyclability, use of environmentally friendly materials, extending product life, reducing waste, and reusability of components for future production (Falsafi, Togiani, Colley, & Varis, 2025). The explanation of each principle of circular design is as follows: (1) Design for recycling and repair: products are designed to be easily disassembled, repaired, or upgraded. This aims to prevent immediate disposal of products when damaged or functionally impaired. (2) The use of environmentally friendly materials prioritizes materials that are recyclable, biodegradable, or sourced from renewable sources, in order to reduce the environmental footprint. (3) Extending the life of products: products are designed to have a long useful life, so that they do not quickly become damaged or obsolete, and continue to meet user needs for a long time. (4) Reducing waste and emissions: production processes and material selection are focused on efficiency and waste reduction, including efforts to reduce carbon emissions and environmental pollution. (5) Closed loop: components or product materials that have been used can be returned to the production cycle to be reused or processed into new products.

Circular design can be applied in various fields. It is widely used in electronic products, such as replacing damaged components without replacing the entire device. It is also used in the use of clothing made from recycled materials, which can be returned to manufacturers for reprocessing into new products (Dreier, et al., 2025). Furthermore, it is applied in machine tools designed so that their components can be upgraded or repaired, eliminating the need to replace the entire unit when one part fails.

Circular design offers great potential for creating more environmentally friendly and sustainable machines. However, its application also presents a number of challenges, particularly related to operational safety and sustainability evaluation. These include: Design Complexity, Uncertainty of Recycled Material Quality, Lack of Sustainability Evaluation Standards, Cost and Limitations of Safety Validation Technology, Incompatibility with Conventional Production Systems, and Challenges in Component Remanufacturing. The application of circular design in machine design faces significant challenges in balancing sustainability and safety. A comprehensive evaluation approach and clear technical standards are required to ensure machines resulting from circular design remain efficient, safe, and suitable for long-term use jam (Agusti, Wisudawati, Risqi, & Kumaratunggadewi, 2022). Therefore, this study aims to evaluate machine safety and sustainability using circular design.

RESEARCH METHOD

This research consists of four main stages that form a systematic flow in developing product sustainability indicators. These four stages include: (1) collecting articles, (2) sorting articles, (3) selecting indicators, and (4) developing indicators. Figure 1 depicts a flowchart of the overall research process from the initial to the final stage, while Table 1 presents a list of previous studies used as references. Based on the initial research concept, several research sources were obtained from the opinions of experts and previous researchers. Table 1 is a list of previous research.

Table 1. List of Previous Research

No	Method	Variabel	Author
1	Axiometic Design	Energy saving, Recycle, Reuse, Toxic & hazardous materials, Number of components	(Arkouli, Michalos, Kokotinis, & Markis, 2024)
2	Axiometic Design	Assembly-Dissassembly, Product dimensions	(Liu, et al., 2023)
3	Fuzzy Axiometic Design	Ease of operation, Adaptive products	(Feng & Chen, 2025)
4	AHP, QFD, TRIZ	Ease of operation, Ease of cleaning	(Sarpong, Akowuah, Amoah, & Darko, 2024)
5	Axiometic Design	Number of components, Product weight	(Kittichotsatsawat, Auch, & Tippayawong, 2024)
6	AHP QFD	Energy saving, Recycle, Reuse	(Li & Li, 2024)
7	Fuzzy QFD	Assembly-Dissassembly, Maintenance	(Khalid & Mola, 2025)
8	Axiometic Design, Triz	Recycle, Product durability, Product weight, Safety of use	(Renjith, Kreme, & Park, 2018)
9	Axiometic Design	Recycle, Reuse, Product durability, Ease of operation, Number of components	(Verma, Maiti, & Boustras, 2020)
10	Axiometic Design, HOQ	Energy saving, Number of components, Environmentally friendly components, Assembly-Dissassembly	(Andriani, Choiri, & Desrianto, 2018)

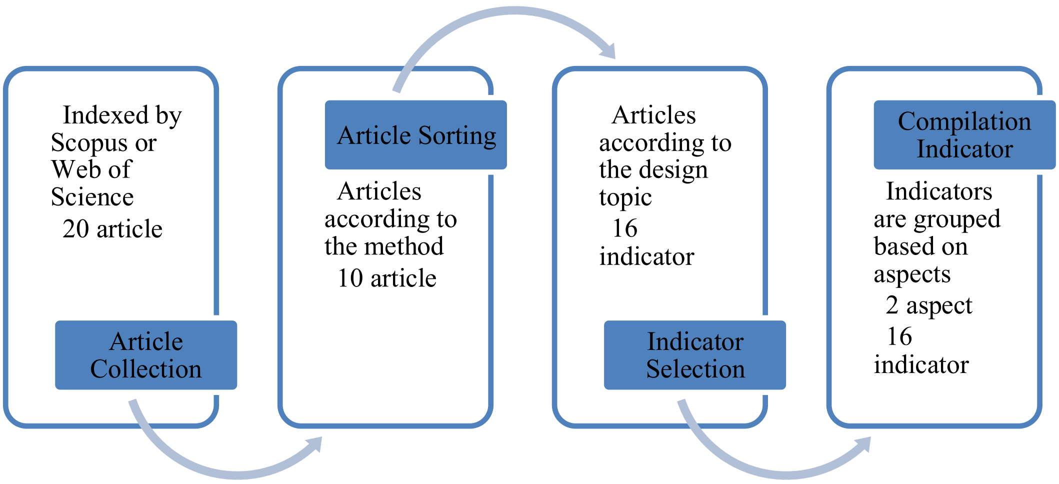

Figure 1. Research Flowchart

Stage 1: Article Collection

The first stage aims to gather relevant literature as a basis for indicator development. This collection was conducted by searching articles from various academic sources, using three main criteria:

a. Articles must come from reputable international journals (e.g., journals indexed by Scopus or Web of Science),
b. Proceedings of credible international conferences, and
c. National journals accredited by authorized institutions.

This search was conducted using keywords relevant to the topic of product sustainability, such as "sustainable product design," "sustainability indicators," and "environmental product assessment." The result of this stage was the collection of 20 scientific articles deemed to meet these three criteria and be relevant to the research topic.

Stage 2: Article Selection

In the second stage, a further selection process was conducted on the 20 articles collected. The selection was based on two additional criteria:

a. Topic relevance, meaning the article must directly address sustainability in the context of product design or sustainability indicators,
b. Research method suitability, meaning the method used in the article must be appropriate or applicable within the research methodology framework (e.g., a relevant qualitative, quantitative, or mixed methods approach).

Through this selection process, the number of articles deemed worthy of further analysis was narrowed down to 10. These articles were then used as the basis for the next stage.

Stage 3: Indicator Selection

The third stage focused on identifying the sustainability indicators used in the selected articles. Each emerging indicator was analyzed in terms of:

a. Its relevance to product design,
b. Its relationship to sustainability principles (environmental, social, and economic), and
c. Its frequency of occurrence in the literature.

The goal was to identify key indicators that have been tested or suggested by previous researchers in the context of sustainable product design. This stage resulted in a diverse initial list of indicators, covering various aspects of sustainability.

Stage 4: Penyusunan Indikator
The final stage is the process of grouping and compiling the previously selected indicators. This grouping is based on three main aspects of sustainability:
a. Environmental aspects (e.g., energy use, carbon emissions, material recycling),
b. Social aspects (e.g., worker welfare, impact on society), and
c. Economic aspects (e.g., cost efficiency, product added value).

Through this process, a comprehensive product sustainability indicator framework is developed that can be used in the development of future sustainable product designs.

RESULT AND DISCUSSION

One of the well-known methods for product development is the QFD (Quality Function Deployment) method. According to Otto and Wood, Quality Function Deployment (QFD) was created to incorporate customer demands into the design process by defining and prioritizing their relationship to product specifications (Lapinskiene & Motuziene, 2021) (Otto & Wood, 2001) The redesign is also based on green design which aims to minimize production costs, duplication, waste that can utilize one shared component, not using hazardous materials, and recyclable (Fazeli & Peng, 2022). The Quality Function Deployment method uses the House of Quality (HOQ). The process of the House of Quality (HOQ) in the study is as follows:
a. Identifying consumers, including consumers, production, regulators, marketing, sales, and distribution, and determining customer needs (WHAT). Customer requirements are the objectives to be achieved in the House of Quality (HOQ).
b. Transforming consumer needs into customer requirements.
c. Determining the importance or priority of customer needs (scale 1-5 or 1-10).
d. Determining the direction of improvement for each technical parameter.
e. Determining the relationship between technical parameters or ways of meeting customer needs (HOW) and customer needs (WHAT).
f. Conducting competitive comparisons, namely shallot slicing machines and almond slicing machines, aimed at determining competitors' ability to meet customer needs based on expert opinion from workshops.
g. Conducting competitive comparisons, namely shallot slicing machines and almond slicing machines, aims to determine the ability of competitors to meet customer needs based on expert opinions, (scale 1-5, with 1 indicating unsatisfactory and 5 indicating most satisfactory).
h. Connecting engineering parameters to determine design relationships.

Axiomatic design was developed by Professor Nam Pyo Suh of MIT (Massachusetts Institute of Technology) as an effort to create logic in the design process. Terms used in Axiomatic Design:

Customer Attribute (CA)	:	the domain that accommodates user needs
Functional Requirement (FR)	:	the domain that accommodates all the functions to be achieved from a design
Design Parameter (DP)	:	the domain of how the functions of the FR domain are realized
Process Variable (PV)	:	the domain that discusses how the design or product is produced

The design procedure is determined based on the relationship between the two domains at each level of the design process hierarchy as shown in Figure 1.

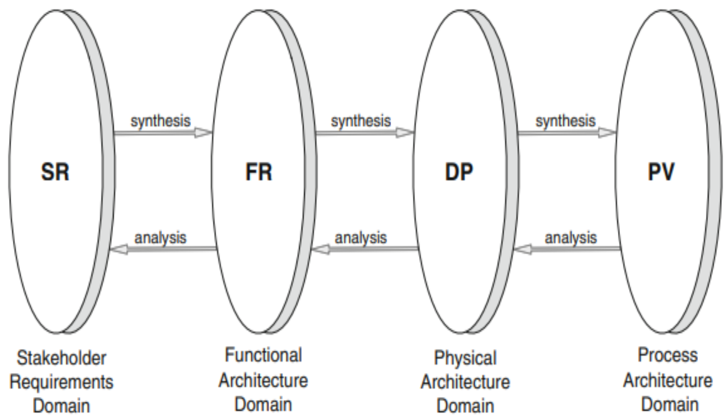

Figure 1. Process Domain Design
Sumber: (Farid & Suh, 2016)

Tabel 2. Indicator sustainability of design product

No	Aspects	Variabel	Author
1.	Environmental Aspects	Energy saving, Recycle, Reuse, Toxic & hazardous materials, Number of components, Product durability	(Arkouli, Michalos, Kokotinis, & Markis, 2024) (Feng & Chen, 2025) (Sarpong, Akowuah, Amoah, & Darko, 2024)
	Technical Aspects	Assembly-Dissassembly, Product dimensions	
2.	Environmental Aspects	Number of components	(Feng & Chen, 2025) (Kittichotsatsawat, Auch, & Tippayawong, 2024)
	Technical Aspects	Product weight	
3.	Environmental Aspects	Energy saving, Recycle, Reuse	(Feng & Chen, 2025) (Li & Li, 2024) (Liu, et al., 2023)
	Technical Aspects	Maintenance, Safety of use	
4.	Environmental Aspects	Recycle, Product durability	(Feng & Chen, 2025) (Li & Li, 2024) (Liu, et al., 2023)
	Technical Aspects	Safety of use, Ease of operation, Ease of cleaning	
5.	Environmental Aspects	Recycle, Reuse, Number of components, Product durability, Ease of production	(Li & Li, 2024) (Liu, et al., 2023)
	Technical Aspects	Safety of use, Product weight	
6.	Environmental Aspects	Product durability	(Khalid & Mola, 2025) (Verma, Maiti, & Boustras, 2020)
	Technical Aspects	Ease of operation, Adaptive products	
7.	Environmental Aspects	Energy saving, Number of components, Environmentally friendly components	(Andriani, Choiri, & Desrianto, 2018) (Renjith, Kreme, & Park, 2018)

Technical Aspects	Assembly-Dissassembly

Based on Table 1, it can be seen that designing or redesigning a product requires several variables based on technical and environmental aspects. A summary of the variables based on these aspects can be seen in Table 1. In future research, in addition to focusing on customer needs, environmental aspects should also be included. Figure 2 is an intersection that shows the location of the research or innovation.

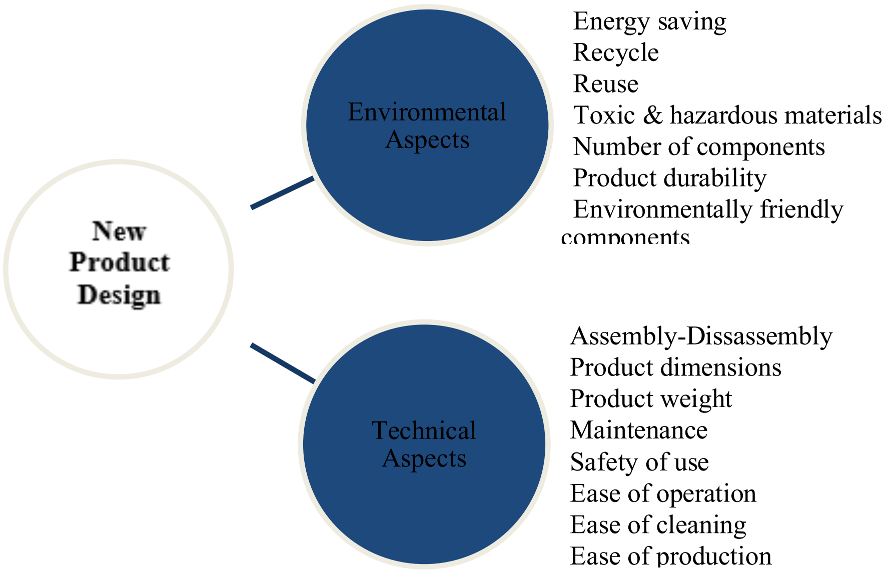

Figure 2. State of The Art

CONCLUSION

This article suggests a model framework and the development of indicators that can be used in developing sustainable machine design. Sustainable design is based on three main pillars of sustainability: economic, social, and environmental. However, for the purposes of application to machine design, these three pillars are summarized into two main aspects: technical and environmental.

Furthermore, this article identifies 16 indicators that can be used to develop sustainable machine design. These indicators are divided into two main categories: 8 indicators related to environmental aspects, including energy saving, recycling, reuse, toxic and hazardous materials, number of components, product durability, and environmentally friendly components; and 9 indicators related to technical aspects, including assembly-disassembly, product dimensions, product weight, maintenance, safety of use, ease of operation, ease of cleaning, ease of production, and adaptive products.

These indicators can be applied in further research, such as to assess, rank, or position products, tourism, or companies. Indicator validation is essential. This validation aims to ensure that the indicators used are relevant, accurate, and reliable in the context of developing sustainable machine design. Several methods can be used to validate indicators, including the Delphi method, expert opinion, surveys, Dynamic Composite

Indicator (DCI), and Structural Equation Modeling (SEM). With the right validation methods, these indicators will be ready to be used to develop more sustainable machine designs.

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