

Fuzzy Axiomatic Design for Product Design Selection for Dishwashing Machine

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Abstract

Sustainable modular product design requires effective decision support for end-of-life (EOL) strategies, where early stage evaluations are often affected by uncertainty and imprecise data. This study proposes a Fuzzy Axiomatic Design (FAD) framework to support the selection of EOL alternatives for components in a modular dishwasher component. Functional requirements (FRs) are established across economic, environmental, and social dimensions. Furthermore, the uncertainty in performance assessment is addressed using linguistic variables represented by triangular fuzzy numbers (TFNs). Evaluation data are classified into qualitative levels and converted into fuzzy values, which are then aggregated to estimate system performance for multiple EOL options, including reuse, remanufacturing, recycling, incineration, and landfill. The Information Axiom is extended using fuzzy set theory to calculate fuzzy information content based on the overlap between system performance and a predefined design range. The alternative with the minimum information content is selected as the most suitable option. The case study demonstrates the applicability of the proposed framework and enables systematic ranking of EOL strategies for a dishwasher, with results indicating that the approach effectively incorporates uncertainty into sustainability decision-making in modular product design.

Keywords

Fuzzy Axiomatic Design, Sustainability, Decision Making, Uncertainty

1. Introduction

In today's highly competitive business environment, the modern trend calls for developing products that will not only satisfy the customers' expectations but also effectively use their resources and be environmentally friendly. The process of product design and selection is particularly important, as decisions made during this process influence aspects such as manufacturing costs, product quality, performance, and customer satisfaction (Tauhid & Okudan 2007). The current trend toward sustainable design has led to particular interest in developing EOL methods for modular products (Suh, 1990; Zadeh, 1965). An appropriate decision-making process is needed to determine the optimal strategy for handling the EOL of modular product components, such as dishwashers (Kulkarni & Desai, 2017). On the other hand, the early stages of evaluating potential solutions can be affected by imprecision and uncertainty, which makes it difficult to make appropriate decisions (Klir & Yuan, 1995). Modern research emphasizes the need for reliable decision-making approaches based on sustainability that incorporate multi-criteria analysis in conditions of uncertainty (Aly et al., 2022; Greenland et al., 2023; Gou et al., 2024).

By moving towards circular economies, product designers' factor in EOL strategies concerns as early as possible in the design process (Ellen MacArthur Foundation, 2023; Ghosh & D'Amato, 2022). Modular designs, commonly adopted in home appliance products to enhance repairability and upgradeability, present numerous complexities in deciding EOL strategies (Go et al., 2015; Vongbunyong et al., 2016). The selection criteria encompass economic viability, reduced environmental impact, and adherence to social and legislative constraints. Meanwhile, EOL analyses at early design stages inherently entail uncertainties due to factors such as fluctuating material yields, unknown labor-disassembly costs, and modeled environmental impacts throughout the product's life cycle (Wang & Chen, 2021; Zampou et al., 2014).

Traditional Multi-Criteria Decision Making (MCDM) methodologies, such as Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), or Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), tend to rely on clear-cut inputs and deterministic preferences, which cannot effectively account for the vagueness and incomplete data in the conceptual design phase (Behzadian et al., 2010; Mardani et al., 2015). Axiomatic Design (AD), built upon the Independence and Information Axioms, offers a systematic framework that explicitly connects FRs and Design Parameters (DPs) and calculates the probability of success (Suh, 1990, 2001). Yet, the classic application of AD requires exact numerical inputs, thereby limiting its use in sustainability assessments that involve fuzzy variables and subjective measures (Gao et al., 2020; Park & Seo, 2019). To overcome these restrictions, fuzzy set theory is commonly used in MCDM frameworks to represent linguistic variables and vague data. In recent years, much attention has been drawn to fuzzy MCDM approaches that offer flexible and powerful models for solving problems with inherent uncertainties common for complex engineering tasks (Xue & Lin, 2025; İskefiyeli et al., 2025; Lin et al., 2025). Nevertheless, some fuzzy MCDM approaches rely on scoring functions based on aggregation that do not allow probabilistic interpretation of design feasibility or the estimation of the probability of satisfying FRs.

The concept of AD offers a consistent approach to product evaluation grounded in two basic axioms: the Independence Axiom postulates the independence of FRs, and the Information Axiom concerns designs of minimal information content (Lee & Omar, 2014). Nonetheless, conventional AD faces challenges when dealing with qualitative judgments, which are often used at early stages of evaluation. The fuzzy set theory, initially developed by Zadeh, represents linguistic terms such as "poor," "fair," or "very good" using TFNs (Liu & Pedrycz, 2009). AD implies a design methodology that offers a rational approach to design decisions (Suh, 1990). The AD process involves defining FRs, determining DPs that satisfy them, and evaluating design alternatives based on FRs and DPs (Suh, 1990). Nevertheless, traditional AD proves inefficient when applied to uncertain and vague data (Zadeh, 1965).

Fuzzy set theory has been widely used to address uncertainties and vague data in design decision-making (Zadeh, 1965; Klir & Yuan, 1995). Thus, the combination of fuzzy set theory with AD has led to the development of the notion of FAD aimed at solving design selection problems under uncertainties (Kulkarni & Desai, 2017).

FAD bridges this gap by embedding fuzzy set theory into the information axiom, enabling designers to model linguistic uncertainty, compute fuzzy information content, and rank EOL alternatives under imprecise conditions (Kulak & Kahraman, 2005; Babic & Veza, 2002). This paper develops a comprehensive FAD framework for selecting EOL strategies for modular dishwasher components.

To address this gap, this study proposes a comprehensive FAD framework for evaluating and selecting optimal EOL strategies for modular product components under uncertainty. The proposed approach integrates fuzzy set theory with the Information Axiom to model linguistic evaluations, compute fuzzy information content, and rank alternatives based on their probability of satisfying sustainability-oriented FRs. The framework is applied to a modular dishwasher case study, and its effectiveness is validated through comparative analysis with fuzzy MCDM methods and sensitivity analysis.

The following research objectives are established to address the problem outlined above. At the end of this paper, each objective is fulfilled and articulated in the conclusion. The main objective of this research is to develop an FAD framework for selecting the most suitable EOL strategy for modular dishwasher components under uncertain decision conditions.

The specific objectives of the study are as follows: (i) to convert linguistic assessments into TFNs and aggregate them into fuzzy system ranges, (ii) to calculate fuzzy information content for five EOL alternatives (reuse, remanufacturing,

recycling, incineration, landfill) and rank them, and (iii) to validate the proposed framework through a case study of a modular dishwasher and propose improvements for industrial applications.

The following sections are organized as follows. Section 2 provides an overview of existing research on EOL strategies for modular components, fuzzy decision-making approaches, and sustainability assessment methods. Section 3 describes the overall structure and architecture of the proposed FAD framework, including its components and relationships, and outlines the steps for developing and implementing the framework. The results of the case study are presented and discussed in Section 4, highlighting the advantages and limitations of the proposed FAD framework. Section 5 concludes the paper.

2. Literature review

Increased emphasis on sustainable product development has made the EOL strategy selection problem one of the most significant decision-making issues in engineering design, especially in modular product architecture. By definition, the modular approach entails splitting the entire system into smaller components whose functions are interrelated but can be developed separately, thereby enabling greater sustainability through higher reusability and upgradability ([Baldwin & Clark, 2000](#); [Bocken et al., 2016](#)). When applied to household items like dishwashers, the modular structure enables more flexible approaches regarding different EOL strategies, each depending on the module's material, lifespan, and value ([Li et al., 2008](#); [Ma et al., 2016](#)).

The classical choice among EOL strategies includes reuse, remanufacture, recycling, incineration, and landfilling, each with varying implications for economic, environmental, and social parameters ([Ghisellini et al., 2016](#); [Potting et al., 2017](#)). Reuse and remanufacturing are classified as high-value strategies, while recycling focuses mainly on recovering materials and represents a less sustainable disposal method than other options ([Rashid et al., 2013](#); [Sabaghi et al., 2016](#)). Research conducted over recent years shows that when making decisions in accordance with sustainability principles, one must apply approaches associated with circular economy models and uncertainty management ([Aly et al., 2022](#); [Greenland et al., 2023](#); [Gou et al., 2024](#)).

These complex decision-making processes have often involved the use of MCDM techniques, specifically AHP, TOPSIS, and PROMETHEE, among others ([Behzadian et al., 2010](#); [Mardani et al., 2015](#)). Recently, fuzzy MCDM has become a popular methodology because of its ability to handle imprecision and linguistic terms ([Xue & Lin, 2025](#); [İskefiyeli et al., 2025](#); [Lin et al., 2025](#)). Advanced fuzzy MCDM models, such as fuzzy AHP–MARCOS and fuzzy full consistency approaches, have demonstrated superior performance in sustainable design evaluation by accounting for uncertainties in weighting criteria and in evaluating alternatives ([Wang et al., 2024](#); [Ocampo, 2022](#); [Badi et al., 2022](#)). Nevertheless, most MCDM models employ weighted average methods or distance metrics, which cannot effectively reflect the probability of fulfilling FRs.

On the other hand, AD, developed by Suh ([1990, 2001](#)), is another theoretical framework for evaluating design concepts in terms of how well they fulfill their FRs. In particular, the Independence Axiom helps ensure independence among FRs, whereas the Information Axiom selects the design concept with the least information, namely a logarithmic function of the probability of success. In this regard, one advantage of using AD for design decisions is the incorporation of the probability of satisfying the FRs, something that conventional MCDM does not consider. However, classical AD assumes exact design ranges, hence making it unsuitable for dealing with situations with uncertain and linguistic DPs.

As already mentioned above, fuzzy set theory, proposed by Zadeh ([1965](#)), can help in modeling imprecision. TFNs have been widely used owing to their simplicity and ease of understanding as bounded intervals ([Klir & Yuan, 1995](#); [Chang, 1996](#)). More recent research shows that fuzzy decision-making approaches perform well at handling sustainable design challenges, particularly when faced with data imprecision and linguistic terms ([Zhang & Gao, 2022](#); [Hameed et al., 2022](#)).

The integration of fuzzy set theory with AD has led to the development of FAD, which extends the Information Axiom to uncertain environments by representing system and design ranges as fuzzy sets ([Kulak & Kahraman, 2005](#); [Kulkarni & Desai, 2017](#)). In this framework, information content is calculated from the overlap between fuzzy system performance and fuzzy design requirements, enabling the evaluation of alternatives under uncertainty. Recent applications of FAD have demonstrated its effectiveness in sustainable process selection and supplier evaluation, particularly when combined with other decision-making methods ([Sezer & Durna Pişkin, 2025](#); [Ardali et al., 2025](#)).

These studies confirm that FAD provides a robust and interpretable framework for engineering decision-making by preserving the probabilistic structure of design evaluation.

In the context of EOL strategy selection, several gaps remain in the literature. First, many studies treat economic, environmental, and social criteria as weighted aggregates, without preserving the functional independence required by the AD framework, which may lead to biased or non-robust decision outcomes ([Suh, 2001](#); [Ghosh & D'Amato, 2022](#)). Second, the application of FAD at the component level within modular product architectures is limited, despite the fact that EOL strategies are inherently component-specific and influenced by localized design characteristics ([Vongbunyong et al., 2016](#); [Ma et al., 2016](#)). Third, the computational procedures for translating linguistic evaluations into probabilistic measures of requirement satisfaction are often insufficiently detailed, reducing the transparency and reproducibility of proposed methods ([Wang & Chen, 2021](#)).

Accordingly, there is a clear need for a structured and transparent decision-making framework that integrates fuzzy evaluation with the probabilistic foundation of AD, while explicitly addressing component-level EOL strategy selection within modular systems. This study responds to this gap by developing a comprehensive FAD-based methodology that systematically converts linguistic assessments into fuzzy system ranges, computes information content based on fuzzy overlap, and ranks EOL alternatives according to their probability of satisfying sustainability-oriented FRs. By embedding triple-bottom-line criteria into the FR–DP mapping structure and operationalizing fuzzy information aggregation, the proposed framework advances the theoretical and practical applications of FAD in sustainable product design.

3. Methodology

This study adopts FAD as the decision-support methodology to evaluate EOL strategies for modular dishwasher components under uncertainty. FAD integrates the principles of AD with fuzzy set theory, enabling the quantification of design performance in the presence of imprecise and linguistic data ([Suh, 2001](#); [Zadeh, 1965](#)). The approach is particularly suitable for early-stage sustainability assessment, where data availability is limited and expert judgment dominates ([Kulak & Kahraman, 2005](#)).

The proposed framework, demonstrated in Figure 1, follows a five-step sequential procedure: (i) criteria definition and linguistic evaluation, (ii) fuzzification of linguistic variables, (iii) aggregation into sustainability dimensions, (iv) computation of fuzzy information content, and (v) ranking of EOL alternatives.

This study considers a modular dishwasher system with multiple functional components, which are evaluated for EOL strategy selection. The system includes eleven key components: a pump motor, a tub, a door, a control unit, a dispenser, a drain valve, a heating element, an inlet valve, a float switch, dish racks, and a circulation pipe. These components represent the primary structural and functional elements influencing sustainability performance across economic, environmental, and social dimensions. A schematic representation of the dishwasher components is provided in Figure 2.

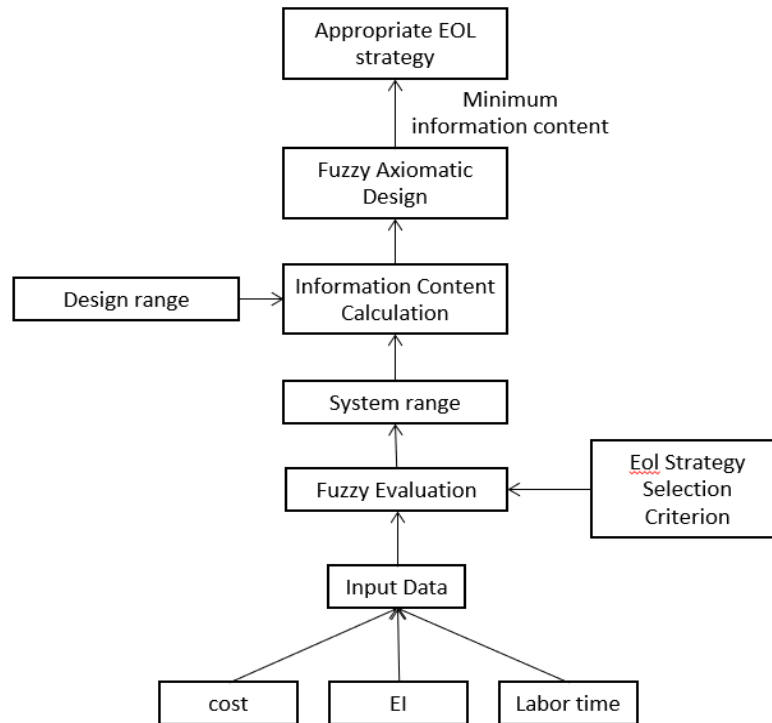


Figure 1. Framework of the proposed FAD methodology.

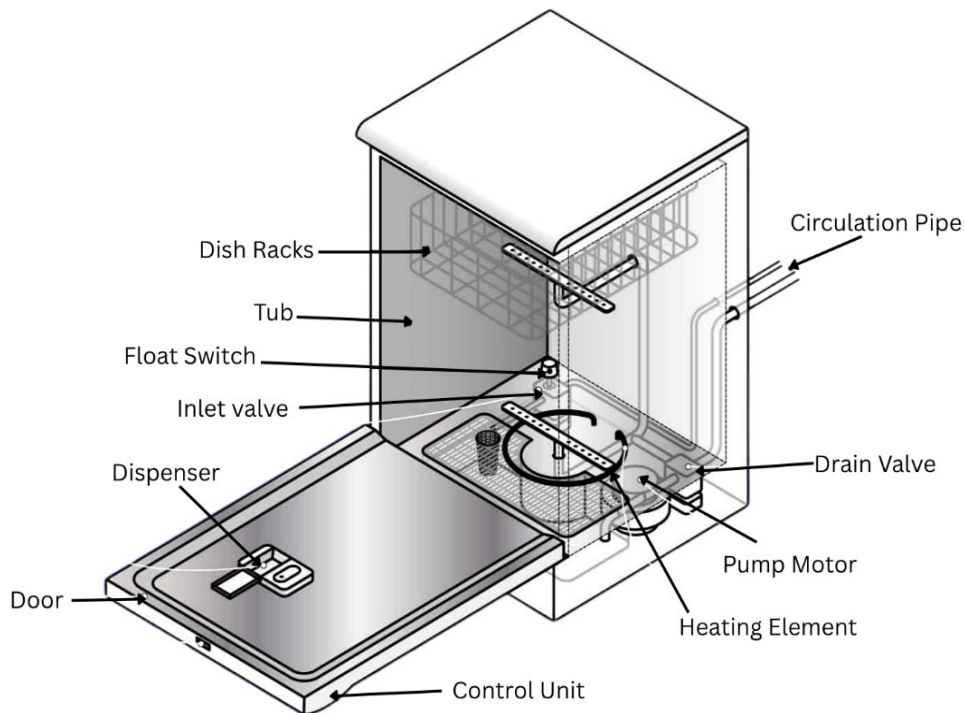


Figure 2. Dishwasher Component

The dishwasher system consist of a set of components, $C=\{C_1, C_2, \dots, C_{11}\}$ in which C_1 : pump motor, C_2 : tub, C_3 : door, C_4 : control, C_5 : dispenser, C_6 : drain valve, C_7 : heating element, C_8 : inlet valve, C_9 : float switch, C_{10} : dish racks, C_{11} : circulation pipe (Table 1).

The system also consists of a set of evaluation criteria: $N=\{N_1, N_2, \dots, N_{14}\}$ in which N_1 : durability, N_2 : EOL condition, N_3 : quantity of high value, N_4 : calorific capacity, N_5 : difficulty with the component's disassembly, N_6 : level of integration, N_7 : quantity of parts, N_8 : difficulty of dismantling part attachment, N_9 : amount of different materials, N_{10} : amount of hazardous materials, N_{11} : component weight, N_{12} : regulation support, N_{13} : customer preference, N_{14} : succedaneum price.

There is a set of EOL alternatives, $A=\{A_1, A_2, A_3, A_4, A_5, A_6\}$, which correspond to reuse, remanufacturing, primary recycling, secondary recycling, incineration, and landfill, respectively.

Each component is evaluated against the criteria using linguistic variables, which are widely employed in decision-making problems involving uncertainty and qualitative assessments ([Zadeh, 1965](#); [Klir & Yuan, 1995](#)). The criteria are defined to capture economic, environmental, and social aspects of sustainability, consistent with the triple-bottom-line perspective ([Ghosh & D'Amato, 2022](#)).

Linguistic evaluations are converted into TFNs to enable mathematical processing while preserving uncertainty ([Chang, 1996](#)). A TFN is defined as Eq. (1).

$$\tilde{x} = (a, b, c), \quad a \leq b \leq c \quad (1)$$

where a , b , and c represent the lower, modal, and upper bounds of the fuzzy number, respectively. The membership function is defined as Eq (2).

Table 1. Dishwasher Concept Fuzzy Evaluation

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
N1	P	VP	F	F	VP	VG	G	VP	F	VP	F
N2	VP	VG	P	VP	P	F	VG	P	F	VG	VG
N3	VG	F	F	VP	F	VP	G	VP	VG	VG	VG
N4	VP	G	F	VG	F	VG	P	G	F	P	G
N5	G	P	P	VP	F	VG	VG	VG	VG	F	VG
N6	P	G	VP	G	F	VP	G	VG	P	VG	VG
N7	F	VG	P	VG	VG	F	F	G	VG	G	P
N8	P	P	G	P	VG	F	G	P	P	F	VP
N9	VP	VP	VP	P	VP	P	VG	G	F	VG	G
N10	VG	P	F	G	VP	VG	VG	P	VP	G	P
N11	F	G	VP	F	VP	P	VP	VG	P	VG	VG
N12	G	G	VG	G	P	VG	P	VP	P	P	F
N13	P	VG	VP	G	P	VG	G	VG	VG	VP	G
N14	P	F	G	G	VG	F	G	F	P	F	P

$$\mu_{\tilde{x}}(t) = \begin{cases} 0 & t < a \\ \frac{t-a}{b-a} & a \leq t \leq b \\ \frac{c-t}{c-b} & b \leq t \leq c \\ 0 & t > c \end{cases} \quad (2)$$

The linguistic scale is mapped into TFNs as in Table 2. This representation ensures computational simplicity while maintaining interpretability (Chang, 1996; Wang & Chen, 2021). Basic fuzzy arithmetic operations are applied component-wise to TFNs, allowing aggregation and transformation without loss of uncertainty information (Klir & Yuan, 1995).

Table 2. Linguistic variable level fuzzy set

EOL characteristic fuzzy score (0~10)	
Linguistic variable level	Fuzzy set
Very Poor	(0, 0, 2.5)
Poor	(0, 2.5, 5)
Fair	(2.5, 5, 7.5)
Good	(5, 7.5, 10)
Very Good	(7.5, 10, 10)

The evaluation criteria are grouped into three sustainability dimensions. For each component-EOL strategy pair, sustainability performance values are calculated across three dimensions (Economic (D_1), Environmental(D_2), Social (D_3)) using the transfer equations from Ma & Kremer (2016). The equations in Table 3 transform the 14 fuzzy-evaluated criteria into composite performance scores.

Basic arithmetic operations on TFNs are performed using extension principle-based approximations, which allow mathematical manipulation of fuzzy quantities without defuzzification (Zadeh, 1965; Dubois & Prade, 1980). To represent uncertainty in linguistic evaluations, this study employs TFNs, which are defined as a unified set that includes their membership functions and arithmetic operations (Zadeh, 1965; Klir & Yuan, 1995; Dubois & Prade, 1980).

Table 1. Transfer equations

Sustainability dimensions	Reuse (A ₁)	Remanufacturing (A ₂)	Primary recycle (A ₃)	Secondary recycle (A ₄)	Incineration (A ₅)	Landfill (A ₆)
Economic performance	$\frac{N_{13} \times VG \sqrt{(N_2 - VP)(N_1 - VG)}}{N_{14} \times (VG - VP)}$	G	N_3	$N_3 \times \frac{F}{VG}$	N_4	VP
Environmental performance	VG	G	$N_{12} \times F$	$N_{12} \times P$	$\frac{N_{10}^{-1}}{P} \times \frac{N_{11}^{-1}}{VG^2}$	$\frac{N_{10}^{-1}}{VP} \times \frac{N_{11}^{-1}}{VG^2}$
Social performance	N_7	$\frac{N_5 + N_6 + N_7 + N_8}{4 \times N_2^2}$	$\frac{N_5 + N_6 + N_7 + N_8}{4}$	N_9	VP	VP

The notation N^{-1} means that the higher assessment of the parameter, the lower its performance. If $N_n = VG$, then $N_n^{-1} = VP$; if $N_n = G$, then $N_n^{-1} = P$; if $N_n = F$, then $N_n^{-1} = F$

Let two TFNs be defined as: $\tilde{A} = (a_1, b_1, c_1)$, $\tilde{B} = (a_2, b_2, c_2)$. The basic fuzzy arithmetic operations are defined as Eq. (3) – Eq. (6).

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (3)$$

$$\tilde{A} \ominus \tilde{B} = (a_1 - b_3, a_2 + b_2, a_3 + b_1) \quad (4)$$

$$\tilde{A} \otimes \tilde{B} \approx (a_1 b_1, a_2 b_2, a_3 b_3), a_i, b_i \geq 0 \quad (5)$$

$$\tilde{A} \oslash \tilde{B} \approx \left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1} \right), b_i \geq 0 \quad (6)$$

These operations are derived from the extension principle and are widely adopted in fuzzy decision-making due to their computational efficiency and ability to preserve uncertainty throughout the analysis (Zadeh, 1965; Klir & Yuan, 1995; Chen et al., 2018). In this study, the unified TFN framework is used to transform linguistic variables into quantitative representations, aggregate multi-criteria evaluations, and support the computation of fuzzy system ranges and information content. The use of TFNs and associated operations ensures that uncertainty is explicitly preserved throughout the decision-making process, which is critical in early-stage sustainability assessment (Zhang & Gao, 2022; Hameed et al., 2022).

The core of the methodology is based on the Information Axiom, which states that the best design minimizes information content (Suh, 2001). The design range is defined as a fuzzy set $D = (5, 7.5, 10)$, representing the desired performance level (“Good”). The design range is defined at the “Good” performance level to establish a balanced acceptance threshold that is neither overly restrictive nor overly permissive. This selection ensures meaningful discrimination among alternatives by enabling partial overlap between system and design ranges, thereby producing informative probability values within the Information Axiom framework.

For two TFNs $\tilde{A} = (a_1, b_1, c_1)$, $\tilde{B} = (a_2, b_2, c_2)$, their intersection is defined as in Eq. (7). If there is no overlap, the intersection is null.

$$\tilde{A} \cap \tilde{B} = (\min(a_1, a_2), \min(b_1, b_2), \min(c_1, c_2)) \quad (7)$$

The area of a TFN is calculated as in Eq. (8).

$$A(\tilde{A}) = \frac{1}{2}(c - a) \quad (8)$$

The information content is computed as in Eq. (9).

$$I = \log_2 \left(\frac{1}{P} \right) \quad (9)$$

When $P = 0$, the information content approaches infinity, indicating that the design completely fails to meet the specified requirement. Information content for pump motor is given as an example in Table 4.

Table 4. Information Content of Pump Motor

	Reuse	Remfg	PriRec	SecRec	Incinerate	Landfill
Economic	0	0	1	1.285	Inf	Inf
Environmental	1	0	Inf	3.981	Inf	Inf
Social Performance	2	Inf	3.806	Inf	Inf	Inf

The total information content for each component and alternative is calculated as in Eq. (10), and the optimal EOL strategy is determined by Eq. (11).

$$I_{jk} = \sum_{m=1}^3 I_{jkm} \quad (10)$$

$$A_k^* = \arg \min I_{jk} \quad (11)$$

Hence, the alternative with the minimum total information content is selected as the most suitable option, as shown in Table 5 for the pump motor example.

Table 5. Total Information Content of Pump Motor

	Reuse	Remfg	PriRec	SecRec	Incinerate	Landfill
Pump Motor	3	Inf	Inf	Inf	Inf	Inf

All fuzzy operations were implemented programmatically to ensure reproducibility and computational accuracy. The implementation includes fuzzy arithmetic operations, intersection calculations, and evaluation of information content. Special attention was given to handling non-overlapping fuzzy sets and numerical stability in logarithmic computations.

4. Results and Discussion

The application of the FAD framework yielded optimal EOL strategies for each of the eleven dishwasher components by minimizing total information content. The results are summarized in Table 6. The optimal alternatives correspond to the minimum values of total information content I_{jk} , reflecting the highest probability of satisfying sustainability-oriented FRs under uncertainty (Suh, 2001). Notably, no component selected incineration or landfill as the optimal strategy, indicating their consistently poor alignment with the defined design range.

Table 6. EOL ranking result

Component	Optimal EOL Strategy	Total Information Content
Pump Motor	Reuse	3.000
Tub	Reuse	5.052
Door	Remanufacturing	0.000
Control	Reuse	4.099
Dispenser	Remanufacturing	0.000
Drain Valve	Reuse	7.165
Heating Element	Primary Recycling	3.262
Inlet Valve	Remanufacturing	0.000
Float Switch	Primary Recycling	4.693

Component	Optimal EOL Strategy	Total Information Content
Dish Racks	Reuse	3.322
Circulation Pipe	Secondary Recycling	4.455

The information content values provide a probabilistic interpretation of design feasibility based on the Information Axiom, where $I = \log_2(1/P)$, indicating that lower information content values correspond to higher probabilities that the system range satisfies the design range. In this study, three components: door, dispenser, and inlet valve, achieved zero information content ($I = 0$) under the remanufacturing alternative, implying $P = 1$ and thus complete overlap between system and design ranges; this indicates that these components fully satisfy economic, environmental, and social requirements simultaneously. Such outcomes are typically associated with high structural integrity, favorable disassembly characteristics, and significant residual value, consistent with prior findings on remanufacturing suitability for durable components ([Kulak & Kahraman, 2005](#); [Wang & Chen, 2021](#); [Cai et al., 2024](#)). In contrast, components such as the pump motor, dish racks, control unit, and heating element exhibit moderate information content values ($3 \leq I \leq 5$), corresponding to $0 < P < 1$, indicating partial overlap between the system and design ranges and reflecting uncertainty or performance variability. For example, the pump motor ($I = 3.0$) demonstrates relatively high reuse feasibility due to its durability, though uncertainty arises from operational wear and disassembly complexity. Higher information content values ($I > 5$), as observed for the drain valve ($I = 7.165$), indicate a low probability of satisfying design requirements even under the optimal alternative, which can be attributed to factors such as complex disassembly, low material recovery value, and limited reuse potential, thereby highlighting the need for redesign aligned with design-for-disassembly principles ([Ghosh & D'Amato, 2022](#); [Gou et al., 2024](#)). From a sustainability perspective, the results reveal clear trade-offs across EOL strategies, like remanufacturing, which is preferred when economic and environmental benefits align with feasible recovery processes, reuse is optimal for components requiring minimal processing and stable functional performance, and recycling becomes suitable when direct value retention is not viable. Notably, incineration and landfill are consistently excluded from optimal solutions, as they yield zero overlap with the design range $P = 0 \Rightarrow I \rightarrow \infty$, confirming their inability to meet sustainability thresholds. The incorporation of TFNs enables explicit modeling of uncertainty, where wider fuzzy ranges correspond to increased variability and reduced overlap, resulting in higher information content, while narrower ranges indicate more stable performance and lower information content ([Klir & Yuan, 1995](#); [Zhang & Gao, 2022](#)). This demonstrates that FAD not only ranks alternatives but also provides insight into the robustness of decisions under uncertainty. Compared to conventional multi-criteria decision-making methods such as TOPSIS and AHP, which rely on distance-based or weighted aggregation approaches, FAD evaluates alternatives based on the probability of satisfying FRs, offering a more theoretically grounded interpretation of decision quality ([Suh, 2001](#)), while the integration of fuzzy set theory allows effective handling of linguistic and imprecise data ([Zadeh, 1965](#)).

Recent studies further confirm that fuzzy MCDM frameworks provide robust and consistent decision support under uncertainty, reinforcing the validity of probabilistic evaluation approaches ([Xue & Lin, 2025](#); [Wang et al., 2024](#); [İskefiyeli et al., 2025](#)). Despite its strong discriminative capability, the proposed framework has several limitations, including sensitivity to the definition of the design range, dependence on the quality of input data, and the assumption of independence among criteria, which may not fully capture interdependencies in sustainability assessments; nevertheless, the methodology provides a transparent, systematic, and uncertainty-aware approach for evaluating EOL strategies in early-stage design contexts.

5. Conclusion

In this paper, an innovative FAD technique was proposed to determine the optimal EOL strategy for modular product components under conditions of uncertainty. By using fuzzy sets and AD, this technique enables probabilistic evaluation of sustainable functionality requirements based on vague, imprecise, or even linguistically defined data. The application of FAD to the example of a modular dishwasher demonstrated its ability to perform a comparative probabilistic analysis of EOL scenarios for individual product components. It was found that reuse and remanufacturing were the most appropriate options for durable, high-value modules, whereas recyclable modules could be recycled. Disposal strategies such as incineration and landfilling do not meet sustainability requirements in any scenario. The validation of results obtained using FAD was performed by comparing them with other approaches in the field of MCDM. Sensitivity analysis confirmed the robustness of the proposed approach across variations in criterion importance, design ranges, and levels of uncertainty. This work makes several theoretical contributions: the proposed framework establishes a clear methodology for evaluating sustainability requirements using probabilistic

information content. In practice, the proposed decision support system can prove very useful during early-stage product development, when uncertainty dominates. Further research should address issues such as industrial data, life-cycle assessment metrics, and interdependencies among the sustainable criteria.

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