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Original Research

Optimization of Fuzzy Tsukamoto for Waste Paper Quality Unfitness Weighting

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ABSTRACT

Waste paper has economic value because it can be reused as raw material in the recycling industry. However, the assessment of waste paper quality in purchasing transactions is often still performed manually and may lead to subjective decisions, especially when several variables must be considered simultaneously. This study aims to apply the Fuzzy Tsukamoto method to determine the unfitness weight of waste paper quality as a supporting basis for determining the payable weight in waste paper purchasing transactions. The research was conducted at PT Gusti Putra using an applied research approach with system development. Data were collected through observation, interviews, and literature study. The variables used in the fuzzy calculation consist of vehicle type, gross weight, net weight, and paper quality as input variables, while the output variable is the percentage of waste paper quality unfitness weight. The calculation process includes fuzzification, fuzzy rule formation, inference using the AND operator, and defuzzification using the weighted average method. A case study was conducted using vehicle type K2, gross weight of 1600 kg, net weight of 1150 kg, and paper quality value of 6. The result shows an unfitness weight value of 13.04%, which belongs to the medium category. This result indicates that the Fuzzy Tsukamoto method can provide a more systematic, objective, and measurable assessment of waste paper quality and can support the payable weight calculation process in waste paper purchasing transactions.

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1. INTRODUCTION

Waste paper is a type of waste that still has utility and economic value because it can be reused as raw material in the paper industry. Saputra and Fauzi [1] stated that the utilization of waste paper through recycling can help reduce waste generation while supporting economic activities in the recyclable material trading sector.

Based on data from the National Waste Management Information System in 2025, the composition of paper and cardboard waste in several regions of West Java remains relatively high. These data indicate that paper and cardboard waste have considerable potential to be reused, particularly in recycling activities and waste paper trading. However, quality assessment that relies only on estimation tends to be subjective. Therefore, measurable parameters are required as a basis for decision-making to produce more objective and consistent results [2]. In the trading of used goods, the process of determining value or price is often still carried out manually and based on estimation, which may lead to different perceptions between sellers and buyers [3]. A similar condition occurs in the quality assessment of waste paper, which involves several indicators, such as vehicle type, gross weight, net weight, and paper quality. Assessment involving multiple criteria requires

Table 1: Composition Data of Paper and Cardboard Waste

Year	Province	Regency/City	Paper – Cardboard (%)
2025	West Java	Kab. Bogor	7.66
2025	West Java	Kab. Cianjur	6.94
2025	West Java	Kab. Garut	6.30
2025	West Java	Kab. Ciamis	16.00
2025	West Java	Kab. Kuningan	10.00
2025	West Java	Kab. Cirebon	10.00
2025	West Java	Kab. Sumedang	10.50
2025	West Java	Kab. Indramayu	8.47
2025	West Java	Kab. Bekasi	24.08
2025	West Java	Kota Bogor	20.00

a method capable of processing several variables systematically so that the resulting decision becomes more objective and measurable [4].

One method that can be used to handle uncertainty in the assessment process is the Fuzzy Tsukamoto method. This method applies IF-THEN rules and produces a crisp output through the defuzzification process, making it suitable for generating a clearer and more measurable unfitness weight value [5]. Previous studies have shown that the Fuzzy Tsukamoto method has been applied in various cases, such as determining the price of used smartphones, determining the price of used motorcycles, analyzing the quality of swallow nests, assessing credit eligibility, and providing credit recommendations [6]. However, studies that specifically discuss the assessment of waste paper quality unfitness weight using vehicle type, gross weight, net weight, and paper quality as variables are still limited.

Based on this gap, this study applies the Fuzzy Tsukamoto method to determine the unfitness weight of waste paper quality. The proposed assessment uses four input variables, namely vehicle type, gross weight, net weight, and paper quality, while the output variable is the percentage of waste paper quality unfitness weight. The result is expected to support a more systematic, objective, and measurable assessment process, which can be used as a basis for determining the payable weight in waste paper purchasing transactions.

2. RESEARCH METHODS

This study uses an applied research approach with system development. Applied research was selected because this study aims to solve a practical problem in the assessment of waste paper quality unfitness weight at PT Gusti Putra. The research focuses not only on understanding the existing assessment process, but also on developing a system that can assist the assessment process in a more systematic, objective, and measurable manner [7], [8].

The object of this study is the assessment process of waste paper quality unfitness weight in waste paper purchasing activities at PT Gusti Putra. The assessment process is carried out using several input variables, namely vehicle type, gross weight, net weight, and paper quality. The output variable generated from the process is the percentage of waste paper quality unfitness weight. This output is used as a supporting basis for determining the payable weight in waste paper purchasing transactions.

Data collection in this study was conducted through observation, interviews, and literature study:

- **Observation** was carried out by directly observing the waste paper purchasing process at PT Gusti Putra, starting from weighing activities, paper quality inspection, and payment procedures. Through this observation, information was obtained regarding the existing workflow, user needs, and problems in determining the unfitness weight of waste paper quality.
- **Interviews** were conducted with the weighing officer, quality control officer, cashier, and business owner. The interviews aimed to obtain information regarding the paper quality assessment process, the determination of unfitness weight, system requirements, and problems encountered in the calculation process of waste paper purchasing transactions.
- **Literature Study** was conducted by reviewing various references, such as journals, books, and scientific

articles related to decision support systems, the Fuzzy Tsukamoto method, and web-based system development. This activity was carried out to support the theoretical foundation and the implementation of the method used in this study.

2.1. System Development Method

The system development method used in this study is the Waterfall method. This method was selected because it has structured and systematic stages, making it easier to develop the system from the analysis stage to implementation. The Waterfall stages applied in this study are requirement analysis, system design, implementation, testing, and deployment and maintenance.

- **Requirement Analysis stage,** the existing business process at PT Gusti Putra was identified to understand the workflow and the problems that occur in the waste paper purchasing process. System requirements were collected through observation and interviews with related parties. The results of this stage were used to determine the functional and non-functional requirements that must be fulfilled by the system.
- **In the system design stage,** the system was designed using Unified Modeling Language (UML) as a modeling tool. In addition, the database structure was designed to store and manage the data needed by the system. This stage also included the design of the user interface so that the system could be easily understood and used by users.
- **Implementation stage** was carried out by developing a web-based system using the PHP programming language. In the development process, the Laravel framework was used to simplify and accelerate system development. MySQL was used as the database management system, while the Fuzzy Tsukamoto method was integrated into the system to calculate the unfitness weight of waste paper quality [9–12].
- **System Testing:** In the testing stage, each developed feature was examined to ensure that the system functioned properly. Testing was carried out on the data input process, calculation process, and output generation to ensure that the system met user requirements. Black Box Testing was used to test the system functions by evaluating the relationship between the input and output without examining the internal source code.
- **The deployment and maintenance stage** was carried out by implementing the system in the operational environment. After the system was used, improvements were made if errors or bugs were found that could affect system performance. Maintenance was also carried out periodically to ensure that the system continued to run properly and remained aligned with user needs.

2.2. Fuzzy Tsukamoto Method

The Fuzzy Tsukamoto method is applied in this study to calculate the unfitness weight of waste paper quality based on several assessment variables. Fuzzy Tsukamoto is one of the fuzzy logic methods that uses IF-THEN rules and produces a crisp output. In the Tsukamoto method, each rule is represented by a fuzzy set with a monotonic membership function. The final result is then obtained through the weighted average process of all active rules [13].

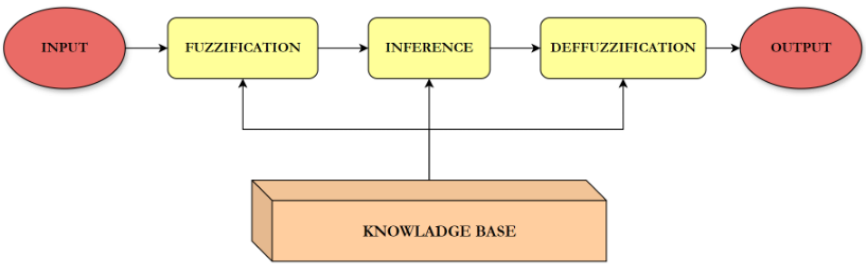

Figure 1. Stages of the Fuzzy Method

The stages of the Fuzzy Tsukamoto method in this study consist of fuzzification, fuzzy rule formation, inference, and defuzzification. Fuzzification is used to convert crisp input values into fuzzy values based on the defined membership functions. After that, fuzzy rules are formed in IF-THEN form to connect the input variables with the output variable. The inference stage is used to obtain the α-predicate value of each rule, while the defuzzification stage is used to generate the final output in the form of the waste paper quality unfitness weight percentage [10].

2.2.1. Membership Degree and Fuzzy Operation

Fuzzy operators are used to connect several input variables in fuzzy rules. In this study, the fuzzy rules use the AND operator because each rule involves several input conditions simultaneously, namely vehicle type, gross weight, net weight, and paper quality. The AND operator works by taking the minimum value from the membership degree of each input variable. This minimum value is used as the α-predicate value for each fuzzy rule [9]. The formula is shown in Equation (1):

$$\alpha_i = \min(\mu(j), \mu(k), \mu(l), \mu(m)) \tag{1}$$

Information:

$$\begin{aligned} \alpha_i &= \alpha\text{-Predicate value of the } i\text{-th rule} \\ \mu(j) &= \text{membership degree of vehicle type} \\ \mu(k) &= \text{membership degree of gross weight} \\ \mu(l) &= \text{membership degree of net weight} \\ \mu(m) &= \text{membership degree of paper quality} \end{aligned}$$

The membership degree is used to show the degree to which a value belongs to a particular fuzzy set. The membership value ranges from 0 to 1, where 0 indicates that a value is not a member of a fuzzy set, while 1 indicates full membership. Membership functions can be represented using linear, triangular, trapezoidal, or other forms according to the characteristics of the variables and fuzzy sets used [10].

In the inference process, the α-predicate value is used to determine the crisp value of each active rule. After all α-predicate values and crisp values are obtained, the final output is calculated through the defuzzification process. The defuzzification formula used in the Fuzzy Tsukamoto method is the weighted average formula, as shown in Equation (2):

$$z = \frac{\sum \alpha_i z_i}{\sum \alpha_i} \tag{2}$$

where:

$$\begin{aligned} z &= \text{final unfitness weight value} \\ \alpha_i &= \alpha\text{-Predicate value of the } i\text{-th rule} \\ z_i &= \text{crisp value generated by the } i\text{-th rule} \end{aligned}$$

The fuzzy variables, fuzzy sets, and domains used in this study are presented in the following tables. These variables consist of input variables and an output variable. The input variables include vehicle type, gross weight, net weight, and paper quality, while the output variable is the unfitness weight of waste paper quality. Each variable is grouped into several fuzzy sets to support the fuzzification process and to convert crisp input values into membership degrees.

Table 2: Fuzzy Variables, Sets, and Domains of Vehicle Type

Variable	Fuzzy Set	Domain
Vehicle type	K1	Motorcycle, cart (1)
Vehicle type	K2	Pickup car (2)
Vehicle type	K3	Colt diesel, tronton, truck (3)

Vehicle type is used as an input variable because each vehicle category has different carrying capacity characteristics. In recycling operations, vehicle capacity utilization, payload, and loading procedures are important factors that influence transport efficiency and load performance [14]. Therefore, vehicle type is considered relevant in this study because it provides an initial description of the transportation category used by customers when delivering waste paper. In this study, vehicle type is represented using crisp categories, where K1 represents motorcycle, cart, and motor trike; K2 represents pickup car; and K3 represents larger vehicles such as colt diesel, tronton, and truck.

Table 3: Fuzzy Variables, Sets, and Domains of Gross Weight

Variable	Fuzzy Set	Domain
Gross weight	Light	100 – 1000 kg
Gross weight	Medium	800 – 1800 kg
Gross weight	Heavy	1500 – 2000+ kg

Gross weight is used as an input variable because it represents the total initial weight of the vehicle and its load before the unloading process. This variable provides an initial indication of the amount of material carried by the vehicle. In recycling transportation operations, vehicle capacity utilization, payload weight, and weight distribution are important factors that influence transport efficiency and load performance [14]. Therefore, gross weight is relevant in this study because it reflects the total load condition before the actual waste paper weight is determined.

Table 4: Fuzzy Variables, Sets, and Domains of Net Weight

Variable	Fuzzy Set	Domain
Net weight	Light	100 – 700 kg
Net weight	Medium	500 – 1200 kg
Net weight	Heavy	1100 – 2200+ kg

Net weight is used as an input variable because it represents the actual weight of waste paper after the second weighing process. This value is more specific than gross weight because it shows the amount of waste paper material that will be assessed after the vehicle load has been unloaded. In recycling activities, weighing paper and cardboard waste is an important part of determining material characteristics. Silveira et al. [15] explained that paper and cardboard waste bales were weighed using a scale, and their dimensions were measured to determine weight and volume. In addition, the acceptance of paper and cardboard waste in recycling plants is also related to quality control parameters, such as moisture content. Therefore, net weight is relevant in this study because it represents the actual quantity of waste paper used as one of the input variables in calculating the unfitness weight.

Table 5: Fuzzy Variables, Sets, and Domains of Paper Quality

Variable	Fuzzy Set	Domain
Paper quality	Good	Good quality (7–10)
Paper quality	Medium	Medium quality (3–8)
Paper quality	Poor	Poor quality (1–4)

Paper quality is used as an input variable to represent the physical condition and quality level of waste paper based on the quality control assessment. The quality value is measured using a scale from 1 to 10. A higher value indicates better paper quality, while a lower value indicates poorer paper quality. Le Pera et al. [16] explained that the quality of separately collected packaging waste streams, including paper and cardboard, can be determined based on the quantification of impurities and recyclable fractions. Their study also showed that low-quality materials and foreign materials contained in packaging waste can affect sorting operations and the sustainability of material recovery facility processes. Therefore, paper quality is relevant in this study because it represents the condition of waste paper materials and helps determine the level of unfitness assigned to the material.

Table 6: Fuzzy Variables, Sets, and Domains of Unfitness Weight

Variable	Fuzzy Set	Domain
Unfitness weight	Low	2% – 12%
Unfitness weight	Medium	10% – 24%
Unfitness weight	High	22% – 35%

Unfitness weight is the output variable in this study, representing the final percentage generated by the Fuzzy Tsukamoto method after the input variables have been processed through fuzzification, inference, and defuzzification. Unlike vehicle type, gross weight, net weight, and paper quality, which serve as inputs, unfitness weight reflects the final level of waste paper quality unfitness. In the Fuzzy Tsukamoto method, each IF-THEN rule produces a crisp output based on the α-predicate, and the final result is obtained using the weighted average of all active rules [17]. Therefore, the unfitness weight value is generated automatically from the combination of all input variables through the fuzzy calculation process.

The output variable is classified into three fuzzy sets: low, medium, and high. Low indicates a small level of quality reduction, medium indicates a moderate level of unfitness, and high indicates a greater level of quality unfitness that may require a larger deduction in payable weight. This output serves as a measurable basis for assessing waste paper quality in purchasing transactions.

Based on Tables 2 to 6, the fuzzy variables in this study consist of input variables—vehicle type, gross weight, net weight, and paper quality—and an output variable, namely unfitness weight. Vehicle type is treated as a crisp categorical variable, while gross weight, net weight, and paper quality use membership functions based on their respective fuzzy domains and are processed through fuzzification to obtain membership degrees. The unfitness weight variable serves as the output of the Fuzzy Tsukamoto method, represented as a percentage and classified into low, medium, and high fuzzy sets. Through the inference and defuzzification processes, a crisp unfitness weight value is generated as the final measurable result, representing the level of waste paper quality unfitness based on the combination of all input variables.

2.2.2. Membership Degree of Vehicle Type

The vehicle type variable is divided into three categories, namely K1, K2, and K3. This variable uses a crisp membership function, where the membership value is 1 if the input matches the vehicle category and 0 if it does not match. The membership functions for vehicle type are defined as follows:

$$\mu_{\mathrm{K1}}(j) = \begin{cases} 1, & \text{if } x = 1 \\ 0, & \text{if } x \neq 1 \end{cases}, \quad \mu_{\mathrm{K2}}(j) = \begin{cases} 1, & \text{if } x = 2 \\ 0, & \text{if } x \neq 2 \end{cases}, \quad \mu_{\mathrm{K3}}(j) = \begin{cases} 1, & \text{if } x = 3 \\ 0, & \text{if } x \neq 3 \end{cases} \tag{3}$$

2.2.3. Membership Degree of Gross Weight

The gross weight variable is divided into three fuzzy sets, namely light, medium, and heavy. The membership functions for gross weight are defined as follows:

$$\mu_{\mathrm{Light}}(k) = \begin{cases} 1, & 100 \leq k \leq 800 \\ \frac{1000-k}{1000-800}, & 800 < k < 1000 \\ 0, & k \geq 1000 \end{cases} \tag{4}$$

$$\mu_{\text{Medium}}(k) = \begin{cases} 0, & k \leq 800 \text{ or } k \geq 1800 \\ \frac{k-800}{1000-800}, & 800 < k < 1000 \\ 1, & 1000 \leq k \leq 1500 \\ \frac{1800-k}{1800-1500}, & 1500 < k < 1800 \end{cases} \tag{5}$$

$$\mu_{\text{Heavy}}(k) = \begin{cases} 0, & k \leq 1500 \\ \frac{k-1500}{1800-1500}, & 1500 < k < 1800 \\ 1, & k \geq 1800 \end{cases} \tag{6}$$

2.2.4. Membership Degree of Net Weight

The net weight variable is divided into three fuzzy sets, namely light, medium, and heavy. The membership functions for net weight are defined as follows:

$$\mu_{\text{Light}}(l) = \begin{cases} 1, & 100 \leq l \leq 500 \\ \frac{700-l}{700-500}, & 500 < l < 700 \\ 0, & l \geq 700 \end{cases} \tag{7}$$

$$\mu_{\text{Medium}}(l) = \begin{cases} 0, & l \leq 500 \text{ or } l \geq 1200 \\ \frac{l-500}{700-500}, & 500 < l < 700 \\ 1, & 700 \leq l \leq 1100 \\ \frac{1200-l}{1200-1100}, & 1100 < l < 1200 \end{cases} \tag{8}$$

$$\mu_{\text{Heavy}}(l) = \begin{cases} 0, & l \leq 1100 \\ \frac{l-1100}{1200-1100}, & 1100 < l < 1200 \\ 1, & l \geq 1200 \end{cases} \tag{9}$$

2.2.5. Membership Degree of Paper Quality

The paper quality variable uses a numerical scale from 1 to 10. The membership functions for paper quality are defined as follows:

$$\mu_{\text{Poor}}(m) = \begin{cases} 1, & m \leq 3 \\ \frac{4-m}{4-3}, & 3 < m < 4 \\ 0, & m \geq 4 \end{cases} \tag{10}$$

$$\mu_{\text{Medium}}(m) = \begin{cases} 0, & m \leq 3 \text{ or } m \geq 8 \\ \frac{m-3}{4-3}, & 3 < m < 4 \\ 1, & 4 \leq m \leq 7 \\ \frac{8-m}{8-7}, & 7 < m < 8 \end{cases} \tag{11}$$

$$\mu_{\text{Good}}(m) = \begin{cases} 0, & m \leq 7 \\ \frac{m-7}{8-7}, & 7 < m < 8 \\ 1, & m \geq 8 \end{cases} \tag{12}$$

2.2.6. Membership Degree of Unfitness Weight

The unfitness weight variable is the output variable in this study. The membership functions for unfitness weight are defined as follows:

$$\mu_{\text{Low}}(z) = \begin{cases} 1, & z \leq 2 \\ \frac{12-z}{12-2}, & 2 < z < 12 \\ 0, & z \geq 12 \end{cases} \tag{13}$$

$$\mu_{\text{Medium}}(z) = \begin{cases} 0, & z \leq 10 \\ \frac{z-10}{24-10}, & 10 < z < 24 \\ 1, & z \geq 24 \end{cases} \tag{14}$$

$$\mu_{\text{High}}(z) = \begin{cases} 0, & z \leq 22 \\ \frac{z-22}{35-22}, & 22 < z < 35 \\ 1, & z \geq 35 \end{cases} \tag{15}$$

3. RESULTS AND DISCUSSION

This section discusses the application of the Fuzzy Tsukamoto method to one transaction data as a case study. The case study is used to demonstrate the calculation process of waste paper quality unfitness weight based on vehicle type, gross weight, net weight, and paper quality. The final result of this process is a percentage value of unfitness weight, which is used as a supporting basis for determining the payable weight in waste paper purchasing transactions.

3.1. Case Study Data

The data used in this case study represent a waste paper purchasing transaction. The details of the transaction data are shown in Table 7.

Table 7: Case Study Data

Variable	Input Value	Information
Vehicle Type	K2	Pickup Car
Gross Weight	1600 kg	Initial weight of vehicle and load
Net Weight	1150 kg	Paper Weight after second weighing
Paper Quality	6	Paper Quality Scale 1–10

Based on Table 7, the transaction data used in this case study consist of vehicle type K2, gross weight of 1600 kg, net weight of 1150 kg, and paper quality value of 6. These data are then processed using the Fuzzy Tsukamoto method to obtain the unfitness weight value of waste paper quality.

3.2. Fuzzification Process

Fuzzification is the process of converting crisp input values into fuzzy membership degrees. At this stage, each input variable is calculated based on the predetermined fuzzy sets and membership functions.

Fuzzification of Vehicle Type:

Since the vehicle type in this case study is K2, the membership degrees are as follows: $\mu_{\text{K1}}(x) = 0$, $\mu_{\text{K2}}(x) = 1$, and $\mu_{\text{K3}}(x) = 0$. Therefore, only the K2 fuzzy set is active in the vehicle type variable.

Fuzzification of Gross Weight:

The gross weight value in this case study is 1600 kg. This value lies in the overlapping area between the medium and heavy fuzzy sets.

$$\mu_{\text{Medium}}(1600) = \frac{1800-1600}{1800-1500} = \frac{200}{300} = 0.67$$
$$\mu_{\text{Heavy}}(1600) = \frac{1600-1500}{1800-1500} = \frac{100}{300} = 0.33$$

Fuzzification of Net Weight:

The net weight value in this case study is 1150 kg. This value lies in the overlapping area between the medium and heavy fuzzy sets.

$$\mu_{\text{Medium}}(1150) = \frac{1200-1150}{1200-1100} = \frac{50}{100} = 0.50$$
$$\mu_{\text{Heavy}}(1150) = \frac{1150-1100}{1200-1100} = \frac{50}{100} = 0.50$$

Fuzzification of Paper Quality:
The paper quality value in this case study is 6. Based on the fuzzy domain of paper quality, this value belongs fully to the medium category. Therefore: $\mu_{\text{Poor}}(6) = 0$, $\mu_{\text{Medium}}(6) = 1$, and $\mu_{\text{Good}}(6) = 0$. Thus, only the medium fuzzy set is active in the paper quality variable. The fuzzification results of all input variables are shown in Table 8.

Table 8: Fuzzification Results

Variable	Fuzzy Set	Membership Degree
Vehicle type	K2	1.00
Gross weight	Medium	0.67
Gross weight	Heavy	0.33
Net weight	Medium	0.50
Net weight	Heavy	0.50
Paper quality	Medium	1.00

3.3. Inference Process

The inference process is carried out by applying IF-THEN rules based on the active combination of input variables. The operator used in this process is the AND operator, which takes the minimum membership degree from each input variable in a rule:

$$\alpha_i = \min(\mu(j), \mu(k), \mu(l), \mu(m)) \tag{16}$$

Based on the fuzzification results, there are four active rules:

- **R1:** IF vehicle type is K2 AND gross weight is Medium AND net weight is Medium AND paper quality is Medium THEN unfitness weight is Medium.

$$\alpha_1 = \min(1, 0.67, 0.50, 1) = 0.50$$

Using $\mu_{\text{Medium}}(z) = \frac{z-10}{24-10} \implies 0.50 = \frac{z_1-10}{14} \implies z_1 = 10 + (0.50 \times 14) = 17$

- **R2:** IF vehicle type is K2 AND gross weight is Medium AND net weight is Heavy AND paper quality is Medium THEN unfitness weight is Low.

$$\alpha_2 = \min(1, 0.67, 0.50, 1) = 0.50$$

Using $\mu_{\text{Low}}(z) = \frac{12-z}{12-2} \implies 0.50 = \frac{12-z_2}{10} \implies z_2 = 12 - (0.50 \times 10) = 7$

- **R3:** IF vehicle type is K2 AND gross weight is Heavy AND net weight is Medium AND paper quality is Medium THEN unfitness weight is Medium.

$$\alpha_3 = \min(1, 0.33, 0.50, 1) = 0.33$$

Using $\mu_{\text{Medium}}(z) = \frac{z-10}{24-10} \implies 0.33 = \frac{z_3-10}{14} \implies z_3 = 10 + (0.33 \times 14) = 14.62$

- **R4:** IF vehicle type is K2 AND gross weight is Heavy AND net weight is Heavy AND paper quality is Medium THEN unfitness weight is Medium.

$$\alpha_4 = \min(1, 0.33, 0.50, 1) = 0.33$$

Using $\mu_{\text{Medium}}(z) = \frac{z-10}{24-10} \implies 0.33 = \frac{z_4-10}{14} \implies z_4 = 10 + (0.33 \times 14) = 14.62$

The α-predicate and z values of each active rule are summarized in Table 9.

Table 9: Inference Results

Rule	Output	α-Predicate	Value z
R1	Medium	0.50	17.00
R2	Low	0.50	7.00
R3	Medium	0.33	14.62
R4	Medium	0.33	14.62

3.4. Defuzzification Process

Defuzzification is the final stage in the Fuzzy Tsukamoto method. The defuzzification process uses the weighted average formula:

$$z = \frac{\sum \alpha_i z_i}{\sum \alpha_i} \tag{17}$$

Based on the values in Table 9, the defuzzification process is calculated as follows:

$$z = \frac{(0.50 \times 17) + (0.50 \times 7) + (0.33 \times 14.62) + (0.33 \times 14.62)}{0.50 + 0.50 + 0.33 + 0.33}$$
$$z = \frac{8.50 + 3.50 + 4.82 + 4.82}{1.66} = \frac{21.64}{1.66} = 13.04\%$$

Based on the defuzzification result, the final unfitness weight value is 13.04%. This value indicates that the waste paper quality unfitness level in the case study belongs to the medium category. The result also shows that the Fuzzy Tsukamoto method can process several assessment variables systematically and produce a measurable percentage value that can support the waste paper quality assessment process.

3.5. Discussion

The application of the Fuzzy Tsukamoto method in this study successfully demonstrated a systematic and measurable approach to determining the unfitness weight of waste paper. The case study, which involved a pickup car (K2) with a gross weight of 1600 kg, a net weight of 1150 kg, and a paper quality score of 6, yielded a final unfitness weight of 13.04%. This result places the waste paper in the “medium” unfitness category. The calculation reflects a balanced deduction: while the net weight indicates a substantial volume of paper, the medium quality score and the vehicle capacity utilization necessitate a moderate penalty to the payable weight. By translating these multi-dimensional variables into a single, crisp percentage, the method effectively bridges the gap between subjective physical inspection and quantifiable financial deductions [18–20].

Traditionally, the assessment of waste paper quality at recycling facilities like PT Gusti Putra relies heavily on the intuition and experience of quality control officers. This manual estimation often leads to inconsistencies and disputes between sellers and buyers, as the perception of “quality” and “deduction” can vary significantly from person to person. The Fuzzy Tsukamoto method mitigates this subjectivity by mathematically modeling human reasoning through IF-THEN rules. Unlike crisp logic, which might arbitrarily categorize a quality score of 6 without accounting for overlapping boundaries, the fuzzy approach accommodates the inherent uncertainty and gradations in physical waste assessment. The use of the weighted average defuzzification ensures that every active rule contributes proportionally to the final output, resulting in a fairer, more transparent, and defensible evaluation compared to conventional flat-rate deductions.

The findings of this research align with and expand upon previous studies that have successfully implemented the Fuzzy Tsukamoto method for decision support and pricing mechanisms, such as those involving used smartphones, motorcycles, and agricultural products. In those domains, the method proved highly effective in handling multiple conflicting criteria to produce a definitive crisp output. This study extends the applicability of the Tsukamoto model to the waste management and recycling sector, specifically addressing the unique variables of logistics (vehicle type, gross/net weight) combined with material assessment (paper quality). The integration of vehicle type as a crisp categorical variable alongside continuous fuzzy variables (weights and quality) demonstrates the flexibility of the method in handling mixed data types within a single inference engine.

From a managerial and operational perspective, the implementation of this model offers significant benefits for the waste paper trading industry. For PT Gusti Putra, the system provides a standardized pricing justification that can be transparently shown to suppliers, thereby enhancing trust and reducing negotiation time. Furthermore, the web-based system developed using the Laravel framework ensures that this complex mathematical process is accessible to non-technical staff through a user-friendly interface. This digital transformation not only streamlines the purchasing workflow but also creates a historical database of transactions that can be analyzed for market trends, supplier reliability, and operational efficiency.

Despite its promising results, this study has several limitations that must be acknowledged. First, the validation was restricted to a single case study, which, while illustrative of the method's mechanics, does not represent the full variance of daily transactions. Second, the model currently relies on four primary variables. In real-world recycling operations, other critical factors such as moisture content, the presence of foreign contaminants (e.g., plastics, metals), and the specific grade of cardboard versus office paper significantly impact the actual recyclable yield. Future research should aim to incorporate these additional parameters into the fuzzy rule base. Additionally, expanding the dataset to include hundreds of historical transactions would allow for the optimization of the membership function domains using machine learning techniques, such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS). Finally, integrating the system with Internet of Things (IoT)-enabled weighbridges and moisture sensors could automate data input, further eliminating human error and creating a fully autonomous Decision Support System (DSS).

4. CONCLUSION

Based on the research results and the case study that has been conducted, the Fuzzy Tsukamoto method can be applied to calculate the unfitness weight of waste paper quality based on vehicle type, gross weight, net weight, and paper quality. In the case study using vehicle type K2, gross weight of 1600 kg, net weight of 1150 kg, and paper quality value of 6, the final unfitness weight value obtained was 13.04%. This value indicates that the unfitness level of the waste paper quality in the case study belongs to the medium category. The calculation result shows that the unfitness weight value of 13.04% represents the level of waste paper quality unfitness based on the assessment variables used in this study. This result indicates that the Fuzzy Tsukamoto method can support the unfitness weight assessment process in a more systematic, objective, and measurable manner. Therefore, the resulting percentage value can be used as a supporting basis for determining the payable weight in waste paper purchasing transactions. This study is still limited to one calculation case study and uses four main variables, namely vehicle type, gross weight, net weight, and paper quality. Future studies may develop the system by adding other variables that affect waste paper quality, expanding transaction data, and testing more samples so that the calculation results can be validated more comprehensively.

DECLARATIONS

Author Contributions:

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Use Statement:

During the preparation of this manuscript, the authors used Gemini solely for language refinement and readability improvement and used ChatGPT as an assistant for programming support in the Arduino IDE, including code suggestions, debugging assistance, and code optimization. All scientific content, analysis, interpretations, conclusions, and final program implementations were developed, verified, and validated by the authors. Following the use of these tools, the authors carefully reviewed and edited the manuscript and assume full responsibility for the content of the published article.

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REFERENCES

[1] A. Z. Saputra and Ah. S. Fauzi, "Pengolahan Sampah Kertas Menjadi Bahan Baku Industri Kertas Bisa Mengurangi Sampah di Indonesia," *J. Mesin Nusantara*, vol. 5, no. 1, pp. 41–52, 2022, doi: 10.29407/jmn.v5i1.17522.

[2] M. Marwondo, A. H. Nugroho, T. Hidayah, and D. A. Nugraha, "Penerapan Fuzzy Multi Criteria Decision Making untuk Menentukan Bibit Ikan Lele Unggul di Kabupaten Bandung," *INTERNAL (Information System Journal)*, vol. 7, no. 1, pp. 66–75, 2024, doi: 10.32627/internal.v7i1.993.

[3] S. Kevin and S. Kosasi, "Implementasi Fuzzy Metode Tsukamoto Dalam Sistem Penentu Harga Jual Smartphone Bekas," *e-Jurnal JUSITI (Jurnal Sistem Informasi dan Teknologi Informasi)*, vol. 11, no. 1, pp. 47–58, 2022, doi: 10.36774/jusiti.v11i1.910.

[4] A. P. Aulia Manurung, M. Amin, and H. Herdianto, "Rancang Bangun Aplikasi Sistem Pendukung Keputusan Cleaning Service Menggunakan Metode Fuzzy Multiple Attribute Decision Making," *J. Sistim Inf. dan Teknol.*, vol. 5, no. 3, pp. 52–62, 2023, doi: 10.60083/jsisfotek.v5i3.285.

[5] R. K. Fitri and A. I. Nurhidayat, "Sistem Pendukung Keputusan Dalam Memprediksi Harga Sewa Kos Menggunakan Fuzzy Tsukamoto Pada Kos Daerah Universitas Airlangga Kampus B," *J. Univ. Negeri Surabaya*, pp. 1–10, 2024.

[6] A. Letsoin and A. S. Purnomo, "Pengembangan Sistem Penunjang Keputusan Untuk Menentukan Harga Motor Bekas Menggunakan Metode Fuzzy Tsukamoto Berbasis Web," *IJIS - Indonesian Journal On Information System*, vol. 9, no. 1, p. 60, 2024, doi: 10.36549/ijis.v9i1.311.

[7] R. H. Pratama, Juhartini, and B. Imran, "Sistem Pakar Diagnosa Penyakit Pada Ayam Menggunakan Expert System To Diagnose Disease in Chicken Using Certainty," *J. Kecerdasan Buatan dan Teknol. Inf.*, vol. 2, no. 2, pp. 106–114, 2023.

[8] A. Z. Nirmala, N. Rahmania, and B. Imran, "Pre-Crime Dan Teknologi: Mengantisipasi Terorisme Sebelum Terjadi Di Indonesia," *J. Kecerdasan Buatan dan Teknol. Inf.*, vol. 9, no. 2, 2024.

[9] R. Hadinata and Khairunnisa, "Beyond the Black Box in Computer Vision: A Traceable Architecture for Reproducible Canny Contour Identification," *J. Comput. Technol.*, vol. 4, no. 1, pp. 53–63, 2026.

[10] R. S. Lubis and N. I. Syahputri, "Synergizing Historical Similarity and Probabilistic Attributes: A Dual-Engine Machine Learning Model for Subsidized Housing Credit Risk," *J. Comput. Technol.*, vol. 4, no. 1, pp. 43–52, 2026.

[11] M. Raihan and Tommy, "Majority-Class Collapse in E-Commerce Emotion Mining: A Diagnostic Evaluation of LSTM Under Severe Class Imbalance and Noisy Text," *J. Comput. Technol.*, vol. 4, no. 1, pp. 1–13, 2026.

[12] S. Sharma and A. A. Waoo, "Customer Behavior Analysis in E-Commerce using Machine Learning Approach: A Survey," *Int. J. Sci. Res. Comput. Sci. Eng. Inf. Technol.*, vol. 9, no. 2, pp. 163–170, 2023.

[13] Moh. Faisol, "Klasifikasi Tingkat Kerawanan Banjir di Kabupaten Bangkalan Menggunakan Metode Fuzzy Tsukamoto," *J. Ilm. Matematika*, vol. 13, no. 2, pp. 198–199, 2025.

[14] I. Harris, D. E. Bermudez Bermejo, T. Crowther, and J. McDonald, "Factors Affecting Truck Payload in Recycling Operations: Towards Sustainable Solutions," *Logistics*, vol. 8, no. 4, 2024, doi: 10.3390/logistics8040118.

[15] A. Silveira, J. Cardoso, M. J. Correia, and G. Martinho, "Moisture measurement in paper and cardboard packaging waste bales for recycling," *Appl. Sci.*, vol. 11, no. 10, 2021, doi: 10.3390/app11104586.

[16] A. Le Pera, M. Sellaro, G. Grande, E. Bencivenni, and M. Migliori, "Effect of quality of separately collected glass, paper plus cardboard and lightweight packaging waste on environmental, energetic and economic sustainability of the material recovery facility operations," *J. Clean. Prod.*, vol. 425, p. 138973, 2023, doi: 10.1016/j.jclepro.2023.138973.

[17] Y. Ghoniyyan Purba and D. Avianto, "Implementation of Fuzzy Logic Tsukamoto to Optimize the Quantity of Packaged Ice Cube Production," *Inst. Ris. dan Publ. Indonesia (IRPI)*, vol. 5, no. 1, pp. 119–129, 2024.

[18] F. I. Hadi, R. W. P. Pamungkas, and F. Sinlae, "Optimization of Fuzzy Tsukamoto for Waste Paper Quality Unfitness Weighting," *J. Kecerdasan Buatan dan Teknol. Inf.*, vol. 5, no. 3, pp. 450–462, 2026.

[19] R. P. Nugroho, B. D. Setiawan, and M. T. Furqon, "Penerapan Metode Fuzzy Tsukamoto untuk Menentukan Harga Sewa Hotel (Studi Kasus: Gili Amor Boutique Resort, Dusun Gili Trawangan, Nusa Tenggara Barat)," *J. Pengemb. Teknol. Inf. dan Ilm. Komput.*, vol. 3, no. 3, pp. 2581–2588, 2019.

[20] F. D. Ragestu and A. J. P. Sibarani, "Penerapan Metode Fuzzy Tsukamoto Dalam Pemilihan Siswa Teladan di Sekolah," *Teknika*, vol. 9, no. 1, pp. 9–15, 2020, doi: 10.34148/teknika.v9i1.251.