

Application of fuzzy TOPSIS in the Analyze phase of the DMAIC cycle to aid decision-making

BY ANDERSON IDACIR DOS SANTOS, DALMARINO SETTI,
AND GILSON ADAMCZUK OLIVEIRA

ABSTRACT: This paper reports the use of multicriteria analysis in the Analyze phase of the DMAIC (Define-Measure-Analyze-Improve-Control) cycle for continuous improvement. The research was carried out in a tissue paper factory located in southern Brazil. A sample of 64 parts of 16 different reels of recycled paper was used. A problem regarding paper quality variability was detected, presenting a scrap index ranging between 9% and 23%, compromising machine productivity and product sales. This motivated the implementation of a structured project supported by the application of the DMAIC cycle.

The project team (machine operators, maintenance staff, supervisor, and data analyst) defined the evaluation criteria and determined the control intervals and their equivalence with linguistic variables to support the necessary evaluations for the application of fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution). The criteria were C1-Longitudinal Strength (Kgf), C2-Longitudinal Elongation (mm), C3-Cross-strength (kgf), C4-Cross-elongation (mm), C5-Weight (g/m²), and C6-Humidity (%).

The results showed that samples with the same ranking had the lowest scrap indexes in the subsequent process. Also, the criterion C5 had a more significant impact on the quality of the product than the other criteria, which was determined from the DMAIC sequence. Improvements related to C5 should be prioritized. The fuzzy TOPSIS method presented is a flexible tool, adapting itself to the solution of the problem and contributing to the decision-making process.

Application: Academics and practitioners will understand the use of the fuzzy TOPSIS method in the DMAIC cycle for continuous improvement in the context of the tissue paper manufacturing process.

The term quality has several definitions in the literature, varying mainly in the way it is used [1]. For example, according to Juran [2], quality is a fitness for use. Mitra [3] has broadened this definition and infers that quality is the suitability of a product or service to meet or exceed the expectation of conformity required by the customer. Ensuring the desired level of quality involves measuring performance, comparing the result with the objectives, and taking corrective actions in case of a negative discrepancy concerning the required quality objectives [3,4].

Process industries are increasingly striving for productivity, environmental responsibility, and the production of high-quality goods. Papermaking is a multidisciplinary area that has progressed significantly in recent decades. Notable advances have been made in all areas of papermaking, such as raw materials, process control, and final products [5]. Between 1962 and 2015, while the rest of the world grew at a rate of 4.58% per year in the production of tissue paper, Brazil registered a growth of 7.48% per year in the same period [6,7]. Tissue paper is used for hygiene purposes, and it includes items such as toilet paper from virgin cellulose or recycled fibers, paper tow-

els, napkins, kitchen towels, tissue, and hospital bed-sheets [8]. For the paper industry to remain competitive and evolving, production processes must have strict quality policies. The control of paper machines focuses on maintaining quality constraints on their target values. The modeling of this type of equipment is intricate, mainly due to the interactions between the different variables of the process [9].

The challenge for a tissue paper manufacturer in the southern region of Brazil was the poor quality of the product generated by its recycled paper machine. In 2017, this company did not meet the expectations of product quality, both for internal and external customers. Thus, it was proposed to carry out a structured project using the DMAIC (Define-Measure-Analyze-Improve-Control) cycle in an attempt to minimize the problem. The DMAIC cycle allows the identification and optimization of the production stages that affect the efficiency of a given process, focusing on continuous improvement [10,11].

DMAIC, a modified version of the PDCA (Plan-Do-Check-Action) cycle, is a well-defined process improvement methodology for Six-Sigma projects. Managers use tools in Six-Sigma projects according to their suitability

PROCESS CONTROL

for a specific phase of DMAIC. In particular, for the Analyze phase, the most popular tool is probably the cause-and-effect diagram [12], whereas in this article we report the use of multicriteria analysis as an efficient way to identify the root causes.

This study focused on identifying which aspects concerning paper quality properties should be prioritized in decision-making for manufacturing improvements. In this context, during the Analyze phase of the DMAIC, the opinions of decision-makers, machine operators, maintenance, management, and technical specialists were necessary to identify the most important quality attributes in the constitution of the tissue paper. For Jing et al. [13], decision-makers often hold different preferences regarding the same evaluation criteria. This fact can result in substantial problems regarding the final decision. Therefore, it turns out to be necessary to predict the solution in terms of the selection of more critical characteristics by using an appropriate decision-making technique.

Multicriteria methods have been widely used in many fields of research to aid in decision-making. Different approaches have been proposed by many researchers, including the analytical hierarchy process (AHP) [14] and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [15]. AHP is the most commonly used technique for multiple criteria analyses. TOPSIS is also widely used to solve many complicated decision-making problems because of its effectiveness in multicriteria problem solving and computational simplicity. Additionally, the seamless building processes of AHP and TOPSIS make them easily understandable by academics and professionals [16].

Even with many benefits in supporting decision-making, AHP and TOPSIS approaches are heavily criticized for their inability to process ambiguous variables [16]. AHP cannot deal with the ambiguity present in the decision of the weights of different attributes due to the use of a discrete scale of one to nine [17]. Likewise, the classic TOPSIS method uses sharp numerical values rather than language assessments, and it may face practical problems due to human cognition and vague judgment [18].

In this study, a fuzzy TOPSIS approach is proposed to aid in more rational decision-making in the Analyze phase of the DMAIC cycle. In addition to traditional multicriteria methods, fuzzy set theory has been used in studies where qualitative variables need to be quantified. It is thus a powerful modeling tool to deal with real situations of imprecision [19,20]. The fuzzy TOPSIS is used when it is necessary to use linguistic values in the measurement scales [21]. The remainder of the paper presents a literature review containing definitions needed to understand the model. Afterward, this paper details the model structure and a case study about the quality of tissue paper, while the final section presents the results and conclusion.

LITERATURE REVIEW

DMAIC methodology

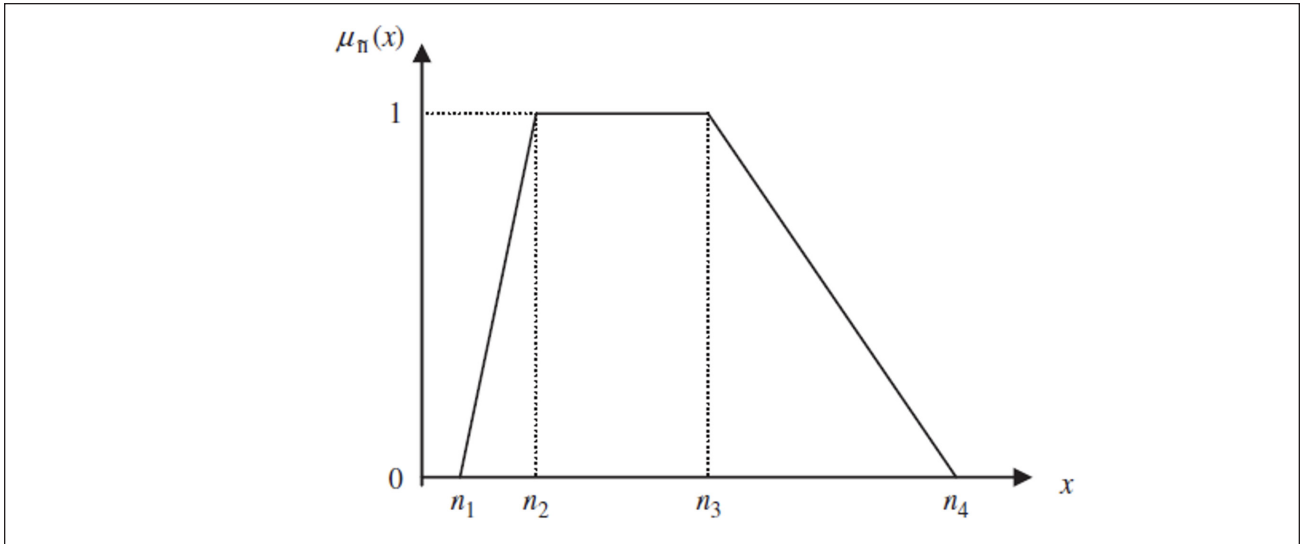
The DMAIC cycle is a closed-loop process. It enables researchers to identify and refine the productive phases and parameters that affect the efficiency of a given process, often focusing on new measurements and applying technology for continuous improvement [10,11]. DMAIC can be considered an expansion of the Deming improvement cycle, PDCA, divided into five stages. The “Define” (i) phase consists of identifying the goals and objectives of the project. The responsibilities and tasks of the team, including the customer, are established, as well as the definition of project boundaries. It includes the products and processes to be analyzed [22]. In “Measure” (ii), the goal is to measure the variability of the system that can create waste [23]. For Cheng and Chang [24], the purpose is to understand and document the current state of processes that need improvement. In “Analyze” (iii), the detailed analysis of the process or problem in question is made based on a group of methods and tools [25]. Barjaktarovic and Jecmenica [26] state that this phase identifies, validates, and quantifies the problem.

In the “Improve” phase (iv), the problems identified in the Analysis phase should be addressed. Therefore, this phase is engaged in identifying potential solutions and also implementing them through the use of different tools [25]. Identification and testing of the proposed solutions are made, contrasting the costs and possible benefits of implementing each one of the solutions. Thus, the best option is established. Finally, the “Control” phase (v) is intended to prevent the return of the original (old/faulty) process. It also has a fundamental role in the transmission of the successful results of the project to the employees. Techniques and achievements are disseminated, ensuring more management support in further implementations [26].

Fuzzy TOPSIS

The TOPSIS method proposed by Hwang and Yoon [15] was adapted by Chen [21] to use fuzzy numbers, which allows the use of linguistic variables as a way of obtaining information. A linguistic variable is one whose values are sentences defined in a natural or artificial language, thereby distinguishing qualifications through gradation bands [27]. The use of linguistic variables requires the definition of a set of linguistic terms to measure their values adequately [28]. The fuzzy set theory allows the managers to incorporate unquantifiable information, incomplete information, and partially ignored facts in the decision model [29]. Fuzzy sets and fuzzy logic are a powerful approach for modeling uncertain systems and capturing tacit knowledge from industry experts. A fuzzy set is also an extension of a crisp set. Crisp sets allow only full adherence or non-adherence, while fuzzy sets allow partial adherence [30,31].

Rathi et al. [32] and Oliveira et al. [33] dealt with similar ideas addressed in the present research, but in different contexts. The first used AHP, fuzzy VIKOR, and fuzzy TOP-



1. Trapezoidal fuzzy number $\tilde{n}$.

SIS to select the critical factors in a production section of an automotive plant, and the second developed an evaluation tool for the new product development enablers for small and medium-sized enterprises (SMEs) using AHP and fuzzy TOPSIS. In an extensive review, Behzadian et al. [34] conducted an extensive literature survey to taxonomize research on TOPSIS applications. The classification scheme for this review contains 266 academic papers, of which only one deals with the problem of improving the design, but with a focus on optimizing product design rather than the process. Therefore, there is a lack of studies using multicriteria analysis in projects to improve the efficiency and quality of manufacturing processes. The contribution of the present research to the literature is therefore justified by introducing the fuzzy TOPSIS multicriteria analysis in the Analyze phase of DMAIC in the context of the tissue paper manufacturing process.

Process for tissue paper manufacturing

Papermaking begins at the disintegrator, which is a blender (between 5 and 20 m³) that disintegrates cellulose fiber into a diluted suspension. The fiber is then directed to the refining step, in which it undergoes a treatment that increases its surface area. Next, the fiber suspension goes to the mixing tank, where it is added with chemical components that will constitute the paper. From the mixing tank, the mass flows to the purification system, composed of centrifugal cleaners and pressurized scrubbers that eliminate possible impurities from the mass by centrifugal force and sieves. After that, the mass is pumped into the inlet. From the inlet, the mass is sprayed onto a screen that is responsible for forming the paper. Upon being poured onto the screen, the fibers are retained on the surface and water passes through the screen, falling into appropriate gutters. This water, rich in fiber particles, recirculates to dilute the mass and refuel the machine. After the forming screen, the

wet sheet suspension enters the pressing sector, which can contain two, three or four presses, depending on the type of machine and the paper present [35-37].

There are several press configurations. However, they are basically composed of the lower roller, upper roller, and a felt for absorbing much of the water that is drawn from the paper. At the exit of the last press, the humidity of the sheet will be around 55% or 60% before going to the drying system. In the final drying of the paper, steam dryer steel cylinders with different pressures are used, depending on the speed of the machine and the weight required for the paper. The cylinders heat the paper, and then the evaporated water is extracted by special hoods coupled in a drying hood [38,39]. The humidity of the paper at the exit of drying varies between 5% and 8% (typical moisture content), depending on the type of paper being manufactured. Some paper machines, such as those used to produce tissue paper (used for sanitary purposes), have only one dryer cylinder, called a Yankee dryer [39,40]. Finally, the paper is wrapped in an axis called a core, which in turn is coupled to another metal axis called a take-up roll, ending the reel spool manufacturing process and releasing it for shipment to the customer or a subsequent process [41].

Fuzzy set and fuzzy number

Definition 1

A fuzzy set $\tilde{A}$ in a universe of discourse X is characterized by a membership function $\mu_{\tilde{A}}(x)$, which associates with each element x in X a real number in the interval $[0, 1]$. The function value $\mu_{\tilde{A}}(x)$ is termed the grade of membership of x in $\tilde{A}$ (Kaufmann and Gupta [42]).

Definition 2

A positive trapezoidal fuzzy number (PTFN) $\tilde{n}$ can be defined as (n_1, n_2, n_3, n_4) shown in **Fig. 1**. The membership function $\mu_{\tilde{A}}(x)$ is defined as [42]: For a trapezoidal fuzzy

number $\tilde{n} = (n_1, n_2, n_3, n_4)$, if $n_2 = n_3$, then $\tilde{n}$ is called a triangular fuzzy number. A non-fuzzy number r can be expressed as (r, r, r, r) . By the extension principle used by Dubois and Prade [43], the fuzzy sum $\oplus$ and fuzzy subtraction $\ominus$ of any two trapezoidal fuzzy numbers are also trapezoidal fuzzy numbers; but the multiplication $\otimes$ of any two trapezoidal fuzzy numbers is only an approximate trapezoidal fuzzy number. Given any two positive trapezoidal fuzzy numbers, $\tilde{m} = (m_1, m_2, m_3, m_4)$ and $\tilde{n} = (n_1, n_2, n_3, n_4)$ and a positive real number r , some main operations of fuzzy numbers $\tilde{m}$ and $\tilde{n}$ can be expressed as follows:

$$\tilde{m} \oplus \tilde{n} = [m_1 + n_1, m_2 + n_2, m_3 + n_3, m_4 + n_4] \quad (1)$$

$$\tilde{m} \ominus \tilde{n} = [m_1 - n_4, m_2 - n_3, m_3 - n_2, m_4 - n_1] \quad (2)$$

$$\tilde{m} \otimes r = [m_1 r, m_2 r, m_3 r, m_4 r], r \geq 0 \quad (3)$$

$$\tilde{m} \otimes \tilde{n} \approx [m_1 n_1, m_2 n_2, m_3 n_3, m_4 n_4] \quad (4)$$

Definition 3

A linguistic variable is a variable whose values are expressed in linguistic terms. The concept of a linguistic variable is very useful in dealing with situations that are too complex or not well enough defined to be reasonably described in conventional quantitative expressions (Zimmermann [44]). For example, "weight" is a linguistic variable whose values are very low, low, medium, high, very high, etc. Fuzzy numbers can also represent these linguistic values.

Definition 4

If $\tilde{m} = (m_1, m_2, m_3, m_4)$ and $\tilde{n} = (n_1, n_2, n_3, n_4)$ are two trapezoidal fuzzy numbers, then the distance between them can be calculated by using the vertex method as follows [21]:

$$d_v(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{4}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2 + (m_4 - n_4)^2]} \quad (5)$$

The vertex method is an effective and simple method to calculate the distance between two trapezoidal or triangular fuzzy numbers. According to this method, two trapezoidal fuzzy numbers $\tilde{m}$ and $\tilde{n}$ are identical if and only if $d_v(\tilde{m}, \tilde{n}) = 0$. Let $\tilde{m}$, $\tilde{n}$ and $\tilde{p}$ be three fuzzy numbers. Fuzzy number $\tilde{n}$ is closer to fuzzy number $\tilde{m}$ than the other fuzzy number $\tilde{p}$ if and only if $d_v(\tilde{m}, \tilde{n}) < d_v(\tilde{m}, \tilde{p})$ [21].

The fuzzy TOPSIS method

The fuzzy TOPSIS method is based on choosing the best alternatives concerning their proximity to the positive ideal solution (PIS) and greater distance from the negative ideal solution (NIS). In the execution of this method, the decision problem is initially structured, arranging the decision-making group and determining the criteria and the set of alter-

natives. The appropriate language variables should be chosen to measure the relative importance of the criteria and evaluate the alternatives' performance concerning these criteria. In this paper, linguistic variables are associated with positive trapezoidal fuzzy numbers (PTFNs). This information is described in the illustrative example. In this work, the version of Chen et al. [19] was adapted to develop the fuzzy TOPSIS method.

Let the fuzzy rating and importance weight of the k th decision-maker be $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk})$ and $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$; $i = 1, 2, \dots, m$, $j = 1, 2, \dots, n$, respectively. Hence, the aggregated fuzzy ratings ($\tilde{x}_{ij}$) of alternatives with respect to each criterion can be calculated as:

$$\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij}) \quad (6)$$

where:

$$a_{ij} = \min_k \{a_{ijk}\}, b_{ij} = \frac{1}{k} \sum_{k=1}^k b_{ijk}, c_{ij} = \frac{1}{k} \sum_{k=1}^k c_{ijk}, d_{ij} = \max_k \{d_{ijk}\}$$

The aggregated fuzzy weights ($\tilde{w}_j$) of each criterion can be calculated as:

$$\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4}) \quad (7)$$

where:

$$w_{j1} = \min_k \{w_{jk1}\}, w_{j2} = \frac{1}{k} \sum_{k=1}^k w_{jk2}, w_{j3} = \frac{1}{k} \sum_{k=1}^k w_{jk3}, w_{j4} = \max_k \{w_{jk4}\}$$

As stated before, the decision problem can be concisely expressed in matrix format as follows:

$$\tilde{D} = \begin{bmatrix} A_1 & \tilde{x}_{11} & \tilde{x}_{12} \dots & \tilde{x}_{1n} \\ A_2 & \tilde{x}_{21} & \tilde{x}_{22} \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_m & \tilde{x}_{m1} & \tilde{x}_{m2} \dots & \tilde{x}_{mn} \end{bmatrix}$$

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2 \dots \tilde{w}_n]$$

where $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$ and $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$ $i = 1, 2, \dots, m$, $j = 1, 2, \dots, n$ can be approximated by positive trapezoidal fuzzy numbers.

Remark: If we consider the TOPSIS algorithm, the following step would be the normalization of the matrix, but when utilizing linguistic terms in association with normalized trapezoidal fuzzy numbers. For the evaluation of the alternatives for all the criteria, this step is unnecessary. More information about this step can be found in [19].

Considering the different importance of each criterion, the weighted normalized fuzzy-decision matrix is constructed as:

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (8)$$

where:

$$\tilde{v}_{ij} = \tilde{x}_{ij} \otimes \tilde{w}_j$$

According to the weighted normalized fuzzy decision matrix, normalized positive trapezoidal fuzzy numbers can also approximate the elements $\tilde{v}_{ij}$. Then, the fuzzy positive-ideal solution (FPIS, A^*) and fuzzy negative-ideal solution (FNIS, A^-) can be defined as:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*) \quad (9)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-) \quad (10)$$

where:

$$\tilde{v}_j^* = \max_i \{v_{ij4}\} \text{ and } \tilde{v}_j^- = \min_i \{v_{ij1}\}, \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n$$

The distance of each alternative from A^* and A^- can be currently calculated as:

$$d_i^* = \sum_{j=1}^n d_v(\tilde{v}_{ij}, \tilde{v}_j^*), \quad i = 1, 2, \dots, m \quad (11)$$

$$d_i^- = \sum_{j=1}^n d_v(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1, 2, \dots, m \quad (12)$$

where d_v (Eq. 5) is the distance measurement between two fuzzy numbers.

A closeness coefficient is defined to determine the ranking order of all alternatives once d_i^* and d_i^- of each alternative $A_i (i = 1, 2, \dots, m)$ have been calculated. The closeness coefficient represents the distances to the fuzzy positive-ideal solution (A^*) and the fuzzy negative-ideal solution (A^-) simultaneously by taking the relative closeness to the fuzzy

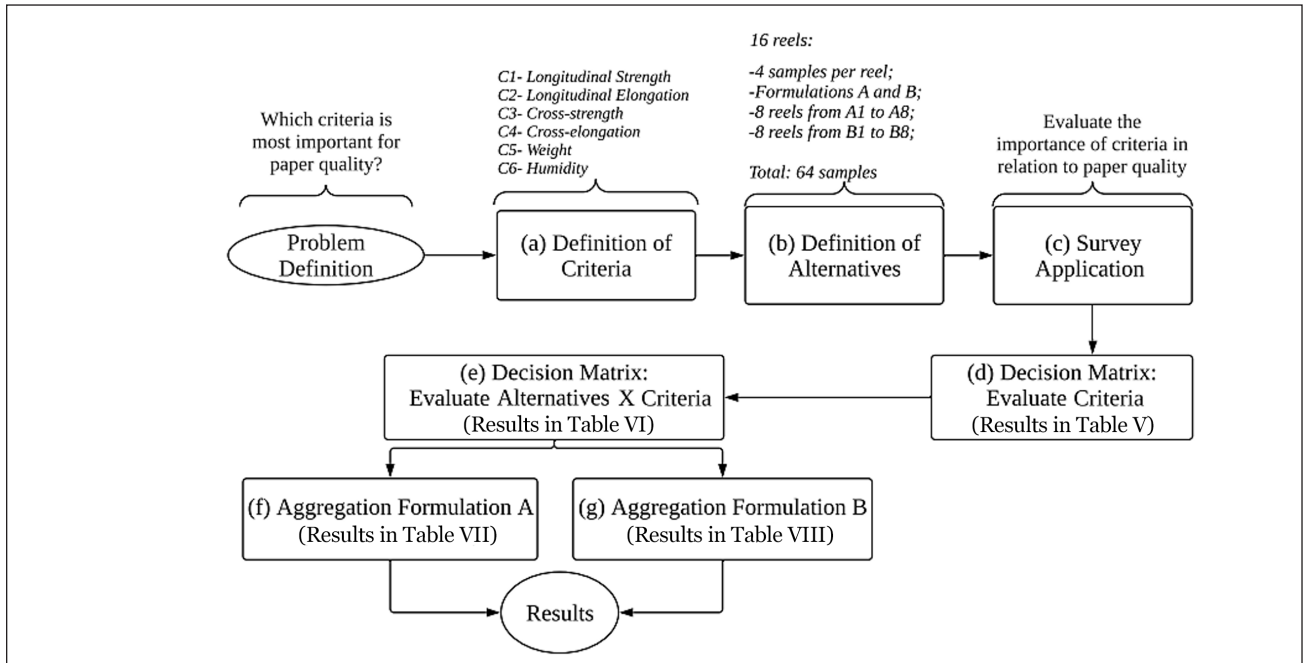
positive-ideal solution. The closeness coefficient (CC_i) of each alternative is calculated as:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}, \quad i = 1, 2, \dots, m \quad (13)$$

Finally, the alternatives are ranked in descending order by the CC_i , sequentially obtaining the most important factors for good product quality. Thus, it leads the “Improve” phase of the DMAIC cycle to a sequence of improvement actions to be adopted, considering the ranking of product quality characteristics. **Figure 2** presents the framework of the general process proposed to apply the fuzzy TOPSIS methodology in this research, followed by the details of the case study and its results.

ILLUSTRATIVE EXAMPLE

The factory selected for analysis is located in the southern region of Brazil. The plant has a monthly manufacturing capacity of approximately 2 million kg of paper, 65% of which is from pure cellulose, while 35% of the production is made from recycled material. The installed capacity for converting this raw material into toilet paper is over 1.4 million kg per month, while the remainder is allocated to other plants that only process jumbo reels. It was decided to apply the DMAIC cycle to tackle the root causes of quality issues in recycled paper from the machine responsible for its manufacture. The problem was identified through the efficiency indicators computed by the company, which pointed to a significant increase in the scrap index generated by the paper conversion process. In the case of recycled paper, the waste limit should be 8.5%. Indexes ranging from 9% to 23% were mapped from January to September



2. Fuzzy TOPSIS process to prioritize improvement actions in the Analyze phase of the DMAIC cycle.

PROCESS CONTROL

DEFINE	MEASURE	ANALYZE	IMPROVE	CONTROL
Project charter	Measurement systems evaluation	Process flowchart	Brainstorming	SIPOC
Scope	Data collection plan	Product map	Ishikawa diagram	Capacity indexes
Economic analysis	Process flowchart	Cycle time analysis	5W2H	KPI
GRIP analysis	Reset goals and earnings	5 Whys	Priority matrix	Poka-Yoke
Voice of customer (VOC)	Sampling	Stratification	Stakeholders analysis	Check sheet
Suppliers, inputs, process, outputs and customers (SIPOC)	Key performance indicators (KPI)	Brainstorming	Investment project analysis (MMIA)	SOP
	Brainstorming	Ishikawa diagram	Gantt	Meetings
	Ishikawa diagram	Multicriteria analysis fuzzy TOPSIS	Standard operational procedure (SOP)	

I. Toolbox used per DMAIC cycle phase.

2017. To mitigate this problem, a structured project was started using tools and procedures from the DMAIC cycle. **Table I** shows the arrangement of the tools used per phase of the cycle.

In the first phase of the cycle (Define), in October 2017, we defined the scope of the project, the project team (machine operators, maintenance staff, supervisor, and data analyst), and the customer needs. In the Measure phase, in November 2017, the focus was determined by surveying the data that defined the problem and setting targets for the proposed case (reducing the scrap to 8.5%). In the Analyze phase (between December 2017 and January 2018), some potential causes were analyzed that could lead to the high scrap generated, all of which linked to the condition of the manufacturing machine. However, to prioritize the improvement actions, it was necessary to identify which of the characteristics of the paper should be prioritized for a better quality of product. Since several members of the project team differed in the opinion of which factor would be more beneficial, we chose to use the fuzzy TOPSIS methodology as the guiding principle in the decision-making process, thereby enriching the DMAIC cycle portfolio of options. Each parameter influencing the final quality of recycled paper manufacturing has a degree of importance. Therefore, there is uncertainty as to which criteria should be prioritized in actions to improve the final product. This led us to tackle this uncertainty using fuzzy logic.

The need for fuzzy logic is an issue that is associated with a long history of discussions and debate. There are many misconceptions about fuzzy logic. It is a precise logic of imprecision and approximate reasoning. More precisely,

fuzzy logic may be considered an attempt at the formalization (mechanization) of two remarkable human capabilities. The first is the capability to converse, reason and make rational decisions in an imprecision environment with ambiguity, incompleteness of information, conflicting information, partiality of truth, and partiality of possibility. The second is the capability to execute a wide variety of physical and mental tasks without any measurements or computations [45].

Returning to the sequence proposed by the framework of Fig. 2, the first phase (a) was the identification of a set of specific criteria used in the papermaking context, along with those involved in the DMAIC project. The members of the project team who participated in this phase were: two mechanical maintenance workers (one being electrical maintenance), three machine operators, one production supervisor, one data analyst, and two process managers. The criteria defined were C1-Longitudinal Strength (measured in Kgf); C2-Longitudinal Elongation (measured in mm); C3-Cross-strength (measured in kgf); C4-Cross-elongation (measured in mm); C5-Weight (measured in g/m²), and C6-Humidity (measured in %). In the second phase (b), to define the alternatives, data collection was performed in the field during the conversion of jumbo reels into toilet paper in the subsequent process. Data were collected from 16 recycled paper reels at four different points of each reel (beginning, middle 1, middle 2, and final), totaling 64 samples, which were analyzed concerning criteria C1, C2, C3, C4, C5, and C6. The samples were collected on different days of November 2017 in order to be able to collect information from different lots. These samples represent ap-

Linguistic Variables	Trapezoidal Fuzzy Number
None (N)	(0.0, 0.0, 0.1, 0.2)
Very Low (VL)	(0.1, 0.2, 0.2, 0.3)
Low (L)	(0.2, 0.3, 0.4, 0.5)
Moderate (M)	(0.4, 0.5, 0.5, 0.6)
High (H)	(0.5, 0.6, 0.7, 0.8)
Very High (VH)	(0.7, 0.8, 0.8, 0.9)
Absolute (AB)	(0.8, 0.9, 1.0, 1.0)

II. Linguistic variables for importance weight of each criterion.

proximately 16 metric tons of paper. The reels were divided into Formulation A and Formulation B due to the formulation change during the research period, resulting in eight reels numbered from A1 to A8 for Formulation A and eight other reels numbered from B1 to B8 for Formulation B.

To measure longitudinal, cross strength and longitudinal, and cross elongations, a calibrated digital dynamometer was used, measuring the two quantities in the desired direction. One-square-meter samples of paper were cut to measure the weight, folded, and inserted on the tray of a digital precision scale that was calibrated and had a capacity of 1000 g. For the humidity question, a moisture meter for tissue paper was used, which was also calibrated and assessed. To validate the quality of the result obtained, the percentage of scrap that each of the 16 reels generated in the paper conversion process was measured. In the measurement of the scrap, all rejected paper in the production of each sample was packed in bales and weighed on a calibrated digital scale with a capacity of 500 kg.

The decision-makers of the study were the people involved with the DMAIC project who were focused on improving the product quality and efficiency of the paper

machine. Those who knew the process answered the questionnaire, evaluating the criteria regarding product quality using linguistic terms, which corresponds to the third step of sequence (c), according to Fig. 2. The need for the questionnaire arose from the divergence of opinion among the experts about which of the criteria would have more impact on the quality of the product. Then, in the fourth step (d), the fuzzy numbers of the linguistic terms defined for the completion of the evaluation are presented according to **Table II**. The terms were expressed by trapezoidal pertinence functions to capture the uncertainty of language assessments [19,46].

In the fifth step (e), to evaluate each reel used (alternatives) in the research, value ranges were defined that fit each sample analyzed with the specific metrological equipment. These levels were used to define each linguistic variable. **Table III** shows the ranges of values used to relate each sample to the respective linguistic variable.

Thus, in the sixth (f) and seventh (g) steps, it was possible to analyze each sample belonging to each alternative in relation to the different criteria. The linguistic variables and equivalent trapezoidal fuzzy number for the evaluation of the different alternatives are shown in **Table IV**.

Linguistic Variables	Trapezoidal Fuzzy Number
Terrible (T)	(0.0, 0.0, 0.1, 0.2)
Very Bad (VB)	(0.1, 0.2, 0.2, 0.3)
Bad (B)	(0.2, 0.3, 0.4, 0.5)
Reasonable (R)	(0.4, 0.5, 0.5, 0.6)
Good (G)	(0.5, 0.6, 0.7, 0.8)
Very Good (VG)	(0.7, 0.8, 0.8, 0.9)
Great (GT)	(0.8, 0.9, 1.0, 1.0)

IV. Linguistic variables for evaluating alternatives.

Criteria	Terrible (T)	Very Bad (VB)	Bad (B)	Reasonable (R)	Good (G)	Very Good (VG)	Great (GT)
C1	0-0.44	0.45-0.59	0.6-0.74	0.75-0.89	0.9-1.04	1.05-1.29	>1.3
C2	9-10.4	10.5-11.9	12-13.4	13.5-14.9	15-16.4	16.5-17.99	>18
C3	0-0.44	0.45-0.59	0.6-0.74	0.75-0.89	0.9-1.04	1.05-1.29	>1.3
C4	0-1.49	1.5-1.99	2-2.49	2.5-2.99	3-3.49	3.5-3.99	>4
C5	<15.5; >20	15.6-16; 19.5-20	16.1-16.5; 19.1-19.5	16.6-17	18.6-19	17.1-17.5; 18.1-18.5	17.6-18
C6	<5; >10.5	5-5.4; 10-10.4	5.5-5.9; 9.5-9.9	6.5-6.9; 9-9.4	6.5-6.9; 8.6-9	7-7.5; 8.1-8.5	7.6-8

III. Value ranges for correlation of linguistic terms.

PROCESS CONTROL

Criteria	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	Aggregated Fuzzy Weights ($\tilde{w}_j$)
C1	VH	M	H	VH	H	M	H	AB	H	AB	(0.40, 0.68, 0.74, 1.00)
C2	H	H	M	VH	M	M	M	H	L	H	(0.20, 0.55, 0.60, 0.90)
C3	M	M	H	VH	M	H	M	AB	M	H	(0.40, 0.60, 0.64, 1.00)
C4	M	H	M	H	M	M	M	M	VL	H	(0.10, 0.50, 0.53, 0.80)
C5	AB	AB	AB	M	M	VH	H	VH	VH	AB	(0.40, 0.76, 0.81, 1.00)
C6	H	M	M	M	L	VH	VH	VH	H	AB	(0.20, 0.63, 0.67, 1.00)

V. Evaluation of the criteria by decision-makers.

RESULTS AND DISCUSSION

After defining the criteria, decision-makers, alternatives, and linguistic variables, the next step was to construct the fuzzy decision matrix to analyze the criteria evaluated by the decision-makers, assigning a weight to each criterion. The linguistic values assigned by the decision-makers for each criterion were associated with trapezoidal fuzzy numbers, aggregated using Eq. 7, and they are presented in **Table V**.

The criterion C5-Weight was more prominent compared to the others, being evaluated by the decision-makers as more influential in the quality of the product. Subsequently, each of the beginning, first half, second half, and final samples of each of the alternatives were analyzed. **Table VI** displays the matrix generated for each of the formulations (Formulation A and Formulation B) made with the ranges of values defined by the decision-makers, which were previously shown in Table IV.

Subsequently, the sample values were aggregated to generate only one value related to each of the six criteria for each reel of the different formulations. Thus, through Eq. 11 and Eq. 12, it was possible to determine the distance of each alternative from FPIS (d_i^+) and FPIS (d_i^-) and, through Eq. 13, the coefficient of proximity (CC_i) was found for each

of the alternatives. **Table VII** and **Table VIII** show the results obtained for each formulation, with the percentages of scrap from each sample, to validate the quality of the result obtained.

The results show that the reel denoted A2 is more prominent than the others. Its characteristics are those that most benefit the quality of the product. The percentage of scrap generated by each reel was measured in the subsequent manufacturing process. It can be seen that reel A2 had the lowest percentage. This supports the result obtained in the CC_i analysis, since the lower the percentage of scrap generated, the better the quality of the product. For reels A7 and A8 ranked in 3rd and 2nd places, the similarity in their values is verified, both in the percentage of scrap and CC_i .

The percentage of scrap varies significantly between the reels. For this reason, the DMAIC project was implemented, with the choice of fuzzy TOPSIS to assist in the decision-making in the Analyze phase. In the same way the reels of Formulation A were analyzed, the process for Formulation B was carried out. The formulations differ in the composition of the raw material used for paper production. To make sure that the results of the analysis of the reels of one formulation did not interfere with the

Formulation A	d_i^+	d_i^-	CC_i	Ranking	Scrap
A1	3.923	2.264	0.366	8	17.3%
A2	3.157	3.161	0.500	1	9.5%
A3	3.697	2.483	0.402	6	15.7%
A4	3.633	2.499	0.408	5	16.0%
A5	3.794	2.211	0.368	7	16.2%
A6	3.485	2.695	0.436	4	12.1%
A7	3.437	2.779	0.447	3	9.9%
A8	3.455	2.822	0.450	2	9.8%

VII. Results obtained for Formulation A.

Formulation B	d_i^+	d_i^-	CC_i	Ranking	Scrap
B1	3.509	2.655	0.431	6	15.6%
B2	3.597	2.661	0.425	7	16.0%
B3	3.340	3.058	0.478	1	11.0%
B4	3.398	2.874	0.458	4	15.1%
B5	3.673	2.623	0.417	8	17.2%
B6	3.421	2.896	0.458	3	14.9%
B7	3.508	3.049	0.465	2	13.1%
B8	3.464	2.705	0.439	5	15.8%

VIII. Results obtained for Formulation B.

Formulation A		C1	C2	C3	C4	C5	C6	Formulation B		C1	C2	C3	C4	C5	C6
BEGINNING	A1	VB	R	R	B	R	B	BEGINNING	B1	G	B	VG	B	G	GT
	A2	VG	VB	G	G	GT	VG		B2	G	VG	B	VG	R	VG
	A3	VB	G	VB	B	R	VG		B3	B	GT	G	GT	GT	VG
	A4	G	VG	R	R	T	G		B4	VG	R	VG	R	GT	GT
	A5	R	VB	VG	G	R	R		B5	VG	VG	R	VG	G	R
	A6	G	VB	R	G	T	R		B6	G	R	G	R	GT	GT
	A7	VG	R	GT	B	G	GT		B7	R	VB	GT	VB	G	GT
	A8	G	R	G	B	G	GT		B8	VG	VB	R	VB	GT	VG
FIRST HALF	A1	R	VG	G	B	T	B	FIRST HALF	B1	R	R	R	R	G	GT
	A2	G	VG	B	G	GT	VG		B2	R	VG	R	VG	R	VG
	A3	VB	R	G	G	T	VG		B3	B	VG	R	VG	GT	VG
	A4	G	G	R	R	G	G		B4	VG	B	G	R	R	GT
	A5	VB	VB	R	R	B	R		B5	G	VG	R	VG	G	R
	A6	R	VB	R	G	GT	R		B6	R	G	R	G	GT	GT
	A7	G	VB	VG	B	T	GT		B7	VB	R	G	R	B	GT
	A8	B	B	R	B	G	GT		B8	VG	VB	B	VB	GT	VG
SECOND HALF	A1	B	VG	R	VB	GT	B	SECOND HALF	B1	R	R	R	R	G	GT
	A2	GT	VG	VG	G	R	VG		B2	R	G	G	G	R	VG
	A3	B	R	G	G	T	VG		B3	G	GT	G	GT	G	VG
	A4	R	VG	R	R	T	B		B4	G	B	G	B	GT	GT
	A5	B	R	R	R	B	R		B5	VB	VG	G	VG	T	R
	A6	GT	R	G	G	G	R		B6	VB	R	G	R	G	GT
	A7	VG	B	VG	R	T	GT		B7	VG	VG	G	VG	B	GT
	A8	R	T	VB	G	GT	GT		B8	GT	R	R	R	VG	VG
FINAL	A1	T	R	VB	VB	T	B	FINAL	B1	G	B	R	B	G	GT
	A2	R	VB	G	G	R	VG		B2	VB	R	B	R	R	VG
	A3	R	VG	G	R	T	VG		B3	R	B	G	B	G	VG
	A4	B	VG	VB	R	T	G		B4	R	B	R	B	GT	GT
	A5	VB	B	R	VB	R	R		B5	R	R	R	R	G	R
	A6	R	B	R	G	GT	R		B6	B	R	G	R	G	GT
	A7	R	B	G	VB	T	GT		B7	VG	GT	GT	GT	T	GT
	A8	VB	T	VB	G	GT	GT		B8	GT	B	B	B	VG	VG

VI. Evaluation of alternatives for each criterion.

PROCESS CONTROL

other, both were separated. This makes it possible to compare what formulation leads to more quality problems in the final product. Table VIII displays the results obtained for Formulation B.

It is observed that the reel of Formulation B that obtained the best result in the ranking was B3. However, this same reel generates a percentage of scrap higher than the best result of Formulation A. In the case of Formulation B, the problem is more pronounced, but the proximity of the CC_i obtained is even higher among its first three values relative to the case of Formulation A.

CONCLUSIONS

In the context of the importance of efficiency in the management and improvement of the competitiveness of organizations, the present study focuses on a tissue paper mill in the Southern region of Brazil. It aimed to apply fuzzy TOPSIS as an aid for decision-making. The improvements identified in the Analyze phase of the project following the premises of the DMAIC cycle were applied to the company's recycled papermaking machine.

The study met the objectives as proposed. The intrinsic criteria for papermaking quality were identified through the application of the fuzzy TOPSIS decision support method. The analyzed reels that served as samples were classified in the respective matrices in relation to each of the identified criteria. Decision-makers defined these as crucial to product quality. They also validated the results found and confirmed the effectiveness of the model, which provided strategic information for project management and sequencing. In this way, from the analysis performed, it is possible to trace the ideal profile of parameters in paper manufacturing. The weights assigned for each criterion ranked the improvement actions relative to each criterion.

The reels indicating better performance concerning the final quality, defined by obtaining the lowest scrap index in both cases, support the conclusions of the decision-makers. Thus, in case of doubt for the prioritization of improvement actions, preference is given to those related to the improvement of parameter C5-Paper Weight, as observed in Table IV. At the end of this research, it is clear that the model elaborated is flexible in dealing with the problem, being robust concerning the results produced and capable of efficiently capturing the judgment of the specialists about uncertainties. The research becomes relevant precisely for testing the usage of a tool—one that is used little in structured design—as an essential component for prioritizing actions given the complexity of factors related to papermaking. For further studies, we suggest an expansion of this research involving a larger number of samples and a longer duration. Therefore, it would be possible to evaluate how the indexes can vary over time and study the influence of scrap indexes on equipment efficiency indicators. **TJ**

LITERATURE CITED

1. Beatty, J., *Int. J. Product. Qual. Manag.* 1(12): 139(2005). <https://doi.org/10.1504/IJPM.2006.008378>.
2. Juran, J.M., Godfrey, B., Hoogstoel, R.E., et al., *Juran's Quality Handbook*, 5th edn., McGraw-Hill, 1999.
3. Mitra, A., *Fundamentals of Quality Control and Improvement*, 4th edn., John Wiley & Sons, Hoboken, NJ, USA, 2016.
4. Yong, J. and Wilkinson, A., *Total Qual. Manag.* 13(1): 101(2002). <https://doi.org/10.1080/09544120120098591>.
5. Bhatia, A., Bansal, M.C., and Mukherjee, S., "Fuzzy modeling and control of basis weight of paper using simulink," *10th WSEAS Int. Conf. FUZZY Syst.*, WSEAS, Athens, Greece, 2009.
6. da Costa, L. and Bacha, C., *Revista Teoria E Evidência Econômica* 23(48): (2017). <https://doi.org/10.5335/rtee.v23i48.7362>. [Portuguese]
7. Ibá, "Relatório 2017," Indústria Brasileira de Árvores, Brazil, 2017. Available [Online] https://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf <13April2021>. [Portuguese].
8. Bracelapa, "Relatórios estatísticos anuais de 1998 a 2013," Brazilian Pulp and Paper Association, Brazil, 2011. [Portuguese]
9. Gowrisankar, M. and Nirmal Kumar, A., *Res. J. Appl. Sci., Eng. Technol.* 10(4): 385(2015). <https://doi.org/10.19026/rjaset.10.2502>.
10. Kwak, Y.H. and Anbari, F.T., *Technovation* 26(5-6): 708(2006). <https://doi.org/10.1016/j.technovation.2004.10.003>.
11. Srinivasan, K., Muthu, S., Devadasan, S.R., et al., *Procedia Eng.* 97: 2064(2014). <https://doi.org/10.1016/j.proeng.2014.12.449>.
12. Akmal Hanafi, N., Tan, O.K., and Goh, C.F., *J. Inf. Syst. Technol. Manage.* 4(13): 1(2019). <https://doi.org/10.35631/JISTM.413001>.
13. Jing, S., Niu, Z., and Chang, P.C., *J. Intell. Manuf.* 30: 2901(2019). <https://doi.org/10.1007/s10845-015-1152-3>.
14. Saaty, T.L., *The Analytic Hierarchy Process*, McGraw-Hill, New York, 1980.
15. Hwang, C-L. and Yoon, K., *Multiple Attribute Decision Making: Methods and Applications*, Springer-Verlag, Berlin/Heidelberg/New York, 1981.
16. Wang, X. and Chan, H.K., *Int. J. Prod. Res.* 51(10): 3117(2013). <https://doi.org/10.1080/00207543.2012.754553>.
17. Chan, F.T.S. and Kumar, N., *Omega* 35(4): 417(2007). <https://doi.org/10.1016/j.omega.2005.08.004>.
18. Bao, Q., Ruan, D., Shen, Y., et al., *Knowledge-Based Syst.* 32: 84(2012). <https://doi.org/10.1016/j.knosys.2011.08.014>.
19. Chen, C.T., Lin, C.T., and Huang, S.F., *Int. J. Prod. Econ.* 102(2): 289(2006). <https://doi.org/10.1016/j.ijpe.2005.03.009>.
20. Kar, A.K. and Pani, A.K., *Manag. Res. Rev.* 37(1): 89(2014). <https://doi.org/10.1108/MRR-10-2012-0230>.
21. Chen, C-T., *Fuzzy Sets Syst.* 114(1): 1(2000). [https://doi.org/10.1016/S0165-0114\(97\)00377-1](https://doi.org/10.1016/S0165-0114(97)00377-1).
22. Ismail, A., Ghani, J.A., Ab Rahman, M.N., et al., *Arabian J. Sci. Eng.* 39(2): 1449(2014). <https://doi.org/10.1007/s13369-013-0678-y>.
23. Bunce, M.M., Wang, L., and Bidanda, B., *Int. J. Prod. Res.* 46(23): 6701(2008). <https://doi.org/10.1080/00207540802230520>.
24. Cheng, C-Y. and Chang, P-Y., *Total Qual. Manag. Bus. Excell.* 23(3-4): 431(2012). <https://doi.org/10.1080/14783363.2012.663880>.
25. Tenera, A. and Pinto, L.C., *Procedia - Soc. Behav. Sci.* 119: 912(2014). <https://doi.org/10.1016/j.sbspro.2014.03.102>.
26. Barjaktarovic, L. and Jecmenica, D., *Acta Tech. Corviniensis* 4(4): (2011).

27. Zadeh, L.A., *IEEE Trans. Syst. Man Cybern.* SMC-3(1): 28(1973). <https://doi.org/10.1109/TSMC.1973.5408575>.
28. Lima Jr., F.R. and Carpinetti, L.C.R., " *Gestão Produção* 22(1): 17(2015). <https://doi.org/10.1590/0104-530X1190>.
29. Alcan, P., Balin, A., and Başlıgil, H., *Energy Build.* 67: 624(2013). <https://doi.org/10.1016/j.enbuild.2013.08.048>.
30. Arabzad, S.M., Ghorbani, M., Razmi, J., et al., *Int. J. Adv. Manuf. Technol.* 76(5-8): 803(2014). <https://doi.org/10.1007/s00170-014-6288-3>.
31. Torlak, G., Sevkli, M., Sanal, M., et al., *Expert Syst. Appl.* 38(4): 3396(2011). <https://doi.org/10.1016/j.eswa.2010.08.125>.
32. Rath, R., Khanduja, D., and Sharma, S.K., *J. Ind. Eng. Int.* 12(3): 377(2016). <https://doi.org/10.1007/s40092-016-0143-0>.
33. Oliveira, G.A., Tan, K.H., and Guedes, B.T., *Int. J. Prod. Econ.* 205: 62(2018). <https://doi.org/10.1016/j.ijspe.2018.08.026>.
34. Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., et al., *Expert Syst. Appl.* 39(17): 13051(2012). <https://doi.org/10.1016/j.eswa.2012.05.056>.
35. Campos, S.E., *Curso de Fabricação de Papéis Tissue*, ABTCP, São Paulo, 2012. [Portuguese]
36. Drummond, D.M.D., "Otimização do setor de prensagem por meio de planejamento de produção em uma indústria de papel," UNICAMP, Campinas, SP, Brazil, 2008. [Portuguese]
37. Gallo, C., "Conceitos de máquinas para a fabricação de papéis tissue de alta qualidade," *34o Congresso e Exposição Anual de Celulose e Papel*, ABTCP, São Paulo, 2001. [Portuguese]
38. Alexandre, G., "Redução do material orgânico do lodo final na fabricação de papel tissue através de otimização do processo," Ph.D. dissertation, Federal University of Paraná, Curitiba, PR, Brazil, 2012, p. 83. [Portuguese]
39. D'Almeida, M.L.O., *Celulose E Papel: Tecnologia de fabricação da pasta celulósica*, 2a edição, IPT/SENAI, São Paulo, 1988. [Portuguese]

ABOUT THIS PAPER

Cite this article as:

Dos Santos, A.I., Setti, D., and Oliveira, G.A., *TAPPI J.* 20(4): 277(2021). <https://doi.org/10.32964/TJ20.4.277>

DOI: <https://doi.org/10.32964/TJ20.4.277>

ISSN: 0734-1415

Publisher: TAPPI Press

Copyright: ©TAPPI Press 2021

[About this journal](#)

40. Bajpai, P., *Green Chemistry and Sustainability in Pulp and Paper Industry*, Springer, Cham, Switzerland, 2015. <https://doi.org/10.1007/978-3-319-18744-0>.
41. Androni, J.L., *Fabricação de Papel-Formação da Folha*, 2a edição, SENAI, Curitiba, PR, Brazil, 2006. [Portuguese]
42. Kaufmann, A. and Gupta, M.M., *Introduction to Fuzzy Arithmetic: Theory and Applications*, Van Nostrand Reinhold, New York, 1991.
43. Dubois, D. and Prade, H., *Fuzzy Sets and Systems: Theory and Applications*, Academic Press, New York, 1980.
44. Zimmermann, H.J., *Fuzzy Set Theory and Its Applications*, 2nd edn., Kluwer Academic Publishers, Boston/Dordrecht/London, 1991.
45. Zadeh, L.A., *Inf. Sci. (N.Y.)* 178(13): 2751(2008). <https://doi.org/10.1016/j.ins.2008.02.012>.
46. Eslamian Shiraz, S., Şengül, Ü., and Eren, M., *Asian Soc. Sci.* 10(4): 183(2014). <https://doi.org/10.5539/ass.v10n4p183>.

ABOUT THE AUTHORS

As practitioners of quality management and Six Sigma, we propose a fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach in this study to aid in more rational decision-making in the Analyze phase of the DMAIC (Define-Measure-Analyze-Improve-Control) cycle. The most challenging aspect was to bridge multiple-criteria decision-making (MCDM) to the context of paper manufacturing. We managed it using an intervention research approach; therefore, we worked in an in-depth longitudinal study with a team of experts.

We found that using fuzzy logic associated with MCDM is a powerful tool to apply in industrial applications. Our most interesting finding was that the intrinsic criteria for papermaking quality may be identified through the application of the fuzzy TOPSIS decision support method.

The application/method presented can be applied in other contexts of industrial environments. We intend to expand this research by involving a larger



dos Santos



Setti



Oliveira

number of samples and a longer duration. Therefore, it would be possible to evaluate how the indexes can vary over time and to study the influence of scrap indexes on equipment efficiency indicators.

Dos Santos is a Master's student and Setti and Oliveira are full professors at the Federal University of Technology (UTFPR), Pato Branco campus, in Pato Branco, Paraná, Brazil. Email dos Santos at anderson.i.s@hotmail.com.br.