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ORIGINAL

Predicting the tensile strength of a new fabric using artificial intelligence (fuzzy logic)

Predicción de resistencia a la tracción de un nuevo tejido mediante inteligencia artificial (lógica difusa)

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ABSTRACT

One of the most important characteristics of a warp and weft fabric is its tensile strength. The aim of this research is to develop a practical fuzzy logic model that could anticipate the ideal tensile strength of new fabrics by modifying only the weave structure. An experimental part was carried out on different weave structures to obtain the results that will enable the development of this new model. We then used the fuzzy logic model to compare its results with those of the experimental tests. The calculated mean absolute error of the fuzzy model was 1,83 % for tensile strength in the warp direction and 1,99 % for tensile strength in the weft direction. This result also confirmed that the fuzzy model was not only effective, but also reliable in predicting the strength of the new fabric.

Keywords: Fuzzy Logic; Weave Structures; Tensile Strength; Average Length of Floats; Weave Interlacing Coefficient.

RESUMEN

Una de las características más importantes de un tejido de urdimbre y trama es su resistencia a la tracción. El objetivo de esta investigación es desarrollar un modelo práctico de lógica difusa que pueda anticipar la resistencia ideal a la tracción de nuevos tejidos modificando únicamente la estructura de trama. Se llevó a cabo una parte experimental con diferentes estructuras de tejido para obtener los resultados que permitirán desarrollar este nuevo modelo. A continuación, se utilizó el modelo de lógica difusa para comparar sus resultados con los de las pruebas experimentales. El error absoluto medio calculado del modelo difuso fue del 1,83 % para la resistencia a la tracción en la dirección de la urdimbre y del 1,99 % para la resistencia a la tracción en la dirección de la trama. Este resultado también confirmó que el modelo difuso no sólo era eficaz, sino también fiable para predecir la resistencia del nuevo tejido.

Palabras clave: Lógica Difusa; Estructuras de Tejido; Resistencia a la Tracción; Longitud Media de los Flotadores; Coeficiente de Entrelazamiento del Tejido.

INTRODUCTION

Fabrics have emerged as a vital factor of everyday existence. Today, fabrics serve a lot of functions, unlike in preceding a long time after they have been used as clothing. In fashionable, fabrics need to meet the requirements for colourfastness, tensile strength, aesthetics, and other attributes. These characteristics are vital for ordinary use.

To our knowledge, a few researchers have attempted to forecast the tensile strength of 2D cloth using a realistic method. In 2007, Pelin Gürkan ÜNAL et al.[1] conducted a study to investigate the impact of weave patterns and densities on the tensile strength of fabrics made entirely of polyester. Various types of fabric were generated, incorporating different warp and weft densities, with a particular focus on plain and twill weaves. However, several restrictions were recognised, such as the lack of specified sample sizes and doubts about the representativeness of the fabric samples. Furthermore, measurements were taken after the materials had been washed, which would have affected the tensile strength readings that were obtained.

R. OĞULATA ET F. KADEM[2] created an empirical formula in 2008 to predict the tensile strength of cotton only textiles. This system considered variables such as weave patterns and thread count. However, the examiner only checked the plain and twill weaves and did not take into consideration the measurements taken simply after weaving.

Similarly, M.D. TELI[3] produced a 12-month essay that concentrated on the experimental creation and testing of textiles, the use of different yarns, cloth manufacturing techniques, and pick-out densities. However, the article had certain limitations because it only focused on specific yarn sorts and had restricted warp and weft memory tiers, which affected the accuracy of power predictions.

Helena GABRIJELI[4] studied the consequences of weave styles, perpendicular threads, and weft residences on the elongation and breaking strength of woven textiles in 2008.

The observed that the usage of doubled weft yarns augmented the breaking energy and elongation inside the warp direction. However, obstacles had been determined, such as a restricted range of weaves and the difficulty of precisely calculating the effects ascribed to even less dense systems.

In 2010, Filiz EKERDEN[5] conducted an examination on the influence of weft density, weft count and weave type on the physical and mechanical properties of textiles. However, the study predominantly concentrated on the tensile strength of cloth wefts after washing and sunrising, thereby neglecting the implications for warp yarns.

In 2011, ZULFIQAR ALI MALIK[6] developed models aimed at forecasting the tensile strength of cotton woven fabrics. However, these models were exclusively validated for plain and twill weaves, thereby suggesting their limited applicability to other weaving structures.

In 2013, HAKAN ZDEMIR[7] carried out a comparative evaluation inspecting the tensile, bursting and effect strengths of cell woven fabric in the evaluation of straightforward woven material. The analysis in general focused on fabric structural parameters and did not now delve into other capability factors or versions in yarn materials.

In 2016, Nasrun, F.M. Z[8] investigated the effect of weft density on yarn crimps and the tensile strength of three-dimensional perspective interlocking woven material. However, the look at did not specify how many fabric samples were evaluated, which would have expanded the statistical significance of the outcomes.

In 2017, Jahan I[9] completed studies to discover how numerous weave structures affected the mechanical traits of cotton textiles. The studies discovered sure types and weave patterns that advanced tear power; however, they lacked statistical evaluation to determine the importance of the modifications detected.

In 2020, Million MEBRATE[10] investigated how loom anxiety affected the mechanical traits of the cotton cloth that became absolutely produced.

The observer became restricted to at least one form of cloth, had a small sample size, and found a strong recognition on anxiety. Finally, Deniz Mutlu ALA performed an experimental study on the performance characteristics of 100 % cotton terry fabrics in 2021.[11] Despite inspecting various fabric structures, the study no longer checks out the effects of finishing techniques and treatments on the material's overall performance, which might also have supplied important information for enhancing the material's sturdiness and first class.

But this type of observer requires an expensive and expensive system for growing samples and performing mechanical checks on these samples. In addition, mechanical testing involves the usage of sources including testing machines, laboratory device, and substances for sample practise, which ends up in additional resource consumption. This has precipitated us to work with fuzzy good judgment fashions that may be educated on present datasets and may be used to quickly make predictions on new tissue with exceptional weave structures.

This kind of mathematical logic known as fuzzy logic permits the use of ambiguous or inaccurate data in reasoning and decision making. Lotfi Zadeh created it in the 1960s to simulate how people think and make decisions.

Fuzzy logic describes how well a proposition or statement applies to a given circumstance using degrees of truth or membership values, as opposed to standard Boolean logic, which is based on binary true/false values.[12] In conventional logic, for example, a proposition can be classified as true or false.[13] The statement may have a membership value of 0,9 in fuzzy logic, which means that it is largely true but not entirely true.

Fuzzy logic may be found in many domains, such as artificial intelligence, pattern recognition, control systems, and decision making. It is especially helpful when judgments must be made based on ambiguous or insufficient information, or when the data available right now are inaccurate or unclear.[14]

The fuzzy set and the concepts of linguistic variables

In a fuzzy set, an element can have a membership value between 0 and 1, indicating the degree to which it belongs in the set. This allows for more nuanced reasoning and decision-making, particularly when dealing with imprecise or uncertain data.

A linguistic variable is a way of expressing a concept or category using natural language terms rather than numerical values. For example, in our case, a weave report could be described as "Smal," "Medium," "High," rather than using specific weave report of 2, 4 or 8... These linguistic terms can be associated with fuzzy sets, allowing more nuanced reasoning and decision making based on imprecise or uncertain data.[15]

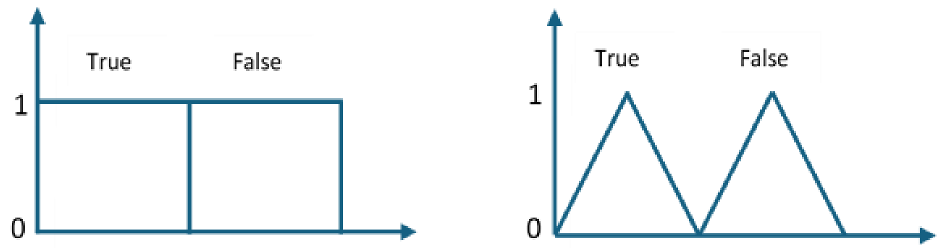

Figure 1. Classic and fuzzy sets

The distinction between the roles of membership in fuzzy reasoning and traditional logic is illustrated in figure 1. Fuzzy logic fundamentally consists of fuzzification, an inference engine, and defuzzification. As depicted in figure 3 below, our research uses inputs such as the weave report, weave interlacing coefficient, and average thread length. The output being measured is the tensile strength.

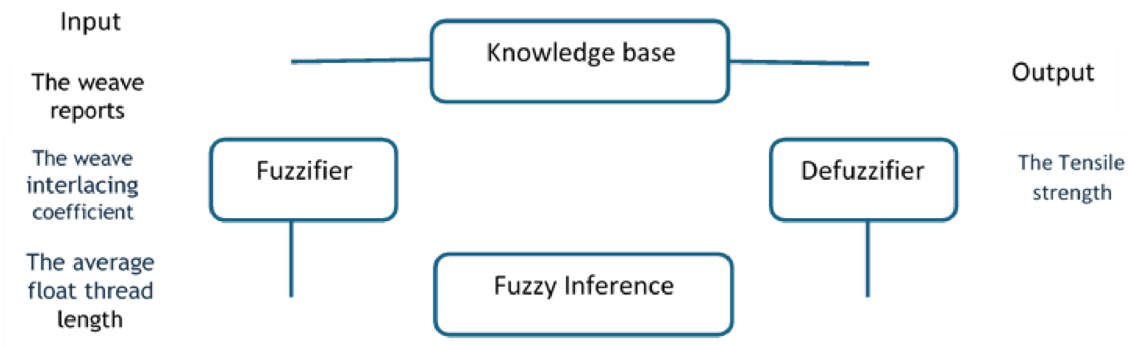

Figure 2. Architecture of a fuzzy logic system[16]

Step 1: Fuzzification of numeric values in fuzzy values

The process of turning clear values into fuzzy ones is known as "fuzzification." Membership functions, which give various linguistic words or fuzzy sets a degree of membership, are used to express variables. The issue and the information at hand determine which membership type is best. Because it is easy to comprehend and interpret and enables straightforward modelling of linguistic factors, the trapezoidal shape (figure 4) is frequently utilized. Nevertheless, depending on the needs of the task and the properties of the data, triangular and Gaussian membership function shapes can also be used.[17] The following equation (1) defines the trapezoidal membership function:

$$\mu(x) = \begin{cases} 0 & \text{si } x \leq a \\ \frac{x-a}{b-a} & \text{si } a \leq x \leq b \\ 1 & \text{si } b \leq x \leq c \\ \frac{d-x}{d-c} & \text{si } c \leq x \leq d \\ 0 & \text{si } x \geq d \end{cases}$$

Where a, b, c, and (d) are the parameters defining the edges of the trapezoid.

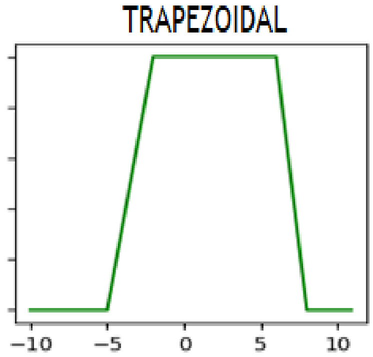

Figure 3. Trapezoidal membership functions[18]

Step 2: Fuzzy inference with Mamdani systems

Now that we have the linguistic variables, we can pass them on to the inference engine. Mamdani systems have demonstrated significant utility in the definition or approximation of functions grounded in IF-THEN rules, each rule of the inference engine is written by the designer of the fuzzy system according to the knowledge he has.[19]

R_1 : if X_1 is A_{11} and X_2 is A_{12} ...and X_n is A_{1n} then y is C_1

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R_m : if X_1 is A_{m1} and X_2 is A_{m2}...and X_n is A_{mn} then y est C_m

$$X = (X_1, X_2, \ldots\ldots\ldots X_n) \text{ : Vector of inference}$$
$$A = [A_{m,n}] \text{ : Characteristic Matrix}$$
$$C = (C_1, C_2 \ldots\ldots\ldots C_m) \text{ : Result Vector}$$

$$\mu_m = \prod_{j=1}^{n} \mu_{mj}(X_n)$$

μ_m : degree to belong of membership function decision class

μ_{mj}: degree to belong of membership function criterion

Figure 4. Operations in fuzzy sets[20]

Fuzzy inference allows us to develop a decision by using the decision rules. The decision rules are described by linguistic terms. For example, in our study:

IF the weave report is low AND the weave interlacing coefficient is high AND the average float length thread is low, then the tensile strength is low.[21]

The inference engine is the step in which we will parameterize our “If..., then...” decision rules. Thanks to this engine, we will be able to apply the rules we have set to our fuzzy input variable.[22]

Step 3: Defuzzification

The defuzzification process converts the aggregated fuzzy set $\mu_{Mamdani|x}$ into a singular crisp value. Conventional Mamdani systems employ equation (2) of Centre of Gravity (COG) defuzzification approach.[23]

$$Y_0 = \frac{\int_y y \times \mu(y)\, dy}{\int_y \mu(y)\, dy}$$

The non-fuzzy value y_0 gives the output in ‘crisp’ or numerical form.

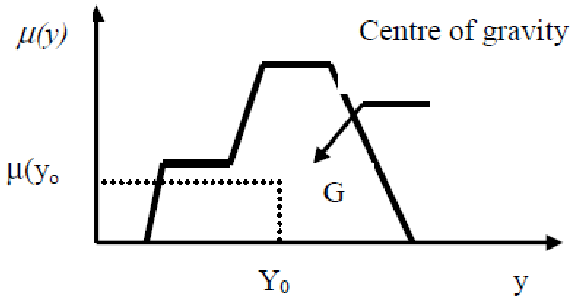

Figure 5. Centre of gravity[24]

Literature review

In our first study[25], a systematic literature review methodology was used to examine the application of fuzzy logic within the weaving process. Data for this study were collected from reputable databases, including ScienceDirect, IEEE Xplore, Textile Research Journal, and Google Scholar.

To pick out relevant articles for this look at, the Prisma framework turned into used, ensuing inside the inclusion of best magazine articles for the literature review. A thorough framework became created to provide an explanation for the outcomes of the use of fuzzy good judgment, and the approach offered on this framework offers a thorough and very a hit way to address the complicated problems of ambiguity, change, and subtlety which might be generally visible within the complex and elaborate procedure of weaving.

To my knowledge, many studies have explored fuzzy logic and used it in various applications in the textile industry to predict its performance and durability based on previous learning data. This minimises the need to produce large numbers of physical samples and conduct costly tests and tests.

In 2003 Xiangyi Zeng et al.[26] presented a method based on fuzzy logic to represent and analysing the outcomes of subjective evaluation of the fabric hand provided by experts in the fields of fashion or quality inspection.

In 2006, EK CEVEN et al.[27] established a fuzzy logic model and principles based on experimental data, facilitating the prediction of the abrasion behaviour of the chenille fabric. The use of fuzzy logic also allowed the optimisation of abrasion resistance to be economically optimised, which has useful implications for the fabric manufacture.

In 2017 Fuzzy logic was chosen as a methodology by THOURAYA Hamdi and al.[28] because it can consider the ambiguity and uncertainty included in the draping behaviour, which could vary between creative designs and types of garments. Fabric samples were categorized into several groups according to the results of the testing phase, which verified the fuzzy logic technique used in this study.

In 2018, EB Priyanka and al.[29] employed fuzzy logic to analyse surface roughness and measure fractal dimension, a commonly used parameter in fabric texture analysis. The combination of fuzzy logic with other techniques, such as genetic algorithms, has been investigated in texture recognition for fabric identification.

In 2019, NAJMEH Dehghan-MANSHADI and al.[30] used a fuzzy logic model that showed efficiency in predicting bending of fabrics using input parameters such as yarn count, yarn diameter, yarn spacing, yarn bending rigidity, and yarn length.

Using fuzzy logic, THOURAYA Hamdi and al.[31] created a prediction model in 2019 that considers different fabric properties and how they affect the drape. In the context of the evaluation of fabric curtains, fuzzy logic offers an adaptable and user-friendly framework to encapsulate the subjective character of human perception and decision making.

Furthermore, in 2020 by Maher Alsayed and al.[32] to forecast the air permeability of multifilament polyester woven textiles. The fuzzy logic model yielded satisfactory and accurate prediction results, with a mean absolute error of 2,32 %.

In 2023, M. EL BAKKALi and al.[33] developed a predictive model using fuzzy logic that helps designers and creators of new fabric to know in advance the problems associated with the difficulty of weaving on looms and to avoid damage and loss of material. It also enables a priori assessment of production yield problems for items close to weaving limits.

However, to the best of our knowledge, no study has yet been carried out on the prediction of the strength of a warp and weft fabric using a fuzzy system. Creating a fuzzy logic-based model to forecast warp and weft fabric strength for a new product is the aim of our study.

Experimental details

To study the influence of weave structures on the tensile strength of fabrics, before beginning the production of the samples to be used in this study, we adjusted the tension on the VAMATEX weaving machine which turns at a speed 440 (ppm) and selected the parameters that will remain unchanged. The raw material: warp yarn

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lighter colour polyester (300/72) denier and weft yarn yellow colour polyester (300 /72) denier, warp density = 26 (threads/cm), Weft density= 19 (picks/cm). The fabrics that were produced will not be subjected to any treatment or finishes. A total of 200 fabric samples with different weaves were produced. These samples were carefully designed and manufactured under identical production conditions.

When examining the tensile strength, the results of our research on fabrics confirm that the weave structure plays a significant role in determining the warp and weft densities, which are influenced by the number of interlacing points and the length of float sections within the repeat of the weave pattern. When the warp and/or weft count increases, the warp and weft strength also tend to increase.[(34)–]

Weave structures	The weave report	The weave interlacing coefficient	The average float length thread	Densitie warp (yarn /cm)	Mean value of the breaking force (N) Warp	Densitie weft (piks/cm)	Mean value of the breaking force (N) weft
Twill 4x4 right Hand	8	0,34375	4,00	27,60	1220	21,40	957
Warp-faced twill 6x2 right Hand	8	0,34375	4,01	27,30	1201	21,32	952
Warp-faced twill 7x1 right Hand	8	0,34375	4,02	27,00	1197	21,20	946
Warp-faced sateen de 8	8	0,34375	4,03	27,00	1196	21,04	935
Warp-faced satin de 8	8	0,34375	4,04	27,00	1192	21,04	933
twill 2x2 right Hand	4	0,62500	2,00	26,80	1186	20,20	899
4 end sateen	4	0,62500	2,01	26,80	1178	19,92	890
Warp-faced twill 3x1 right Hand	4	0,62500	2,02	26,60	1175	19,88	887
Basket 2-2	4	0,50000	2,03	26,60	1171	19,84	878
Plain	2	1,00000	1,00	26,00	1165	19,00	840

Figure 6. The mean value of the breaking force (N) in the warp and weft direction

CASE OF STUDY

Presenting the indicators

In our study, we measured the tensile strength of the fabrics in two directions, warp and weft. For this purpose, we chose linguistic variables, which refer to words, namely the weave report, the weave interlacing coefficient and the average floating yarn length for both directions, because all weave patterns consist of square unit weaves, ensuring an equal number of interlacing between each warp and weft yarn.

The input space has been systematically partitioned into three distinct fuzzy subsets, namely small (S), medium (M), and large (L) for the weave report. Low (L), medium (M), and high (H) for both weaves interlacing coefficient, and Average float length thread for both directions warp and weft.

To derive a fuzzy value for the two output variables, warp tensile strength and weft tensile strength, it has been further categorised into tree fuzzy subsets for each one, specifically low (L), medium (M) and high (H). Furthermore, to facilitate the mapping of the output to a fuzzy subset, trapezoidal membership functions have been employed. The membership functions pertaining to weave report, weave interlacing coefficient, average float length thread, warp tensile strength, and weft tensile strength.

Indicator Modelling

In our study, we measured the tensile strength of the warp and weft directions (figure 7,8). The purpose of these measurements was to demonstrate the relationship between fabric tensile strength and weave structures.

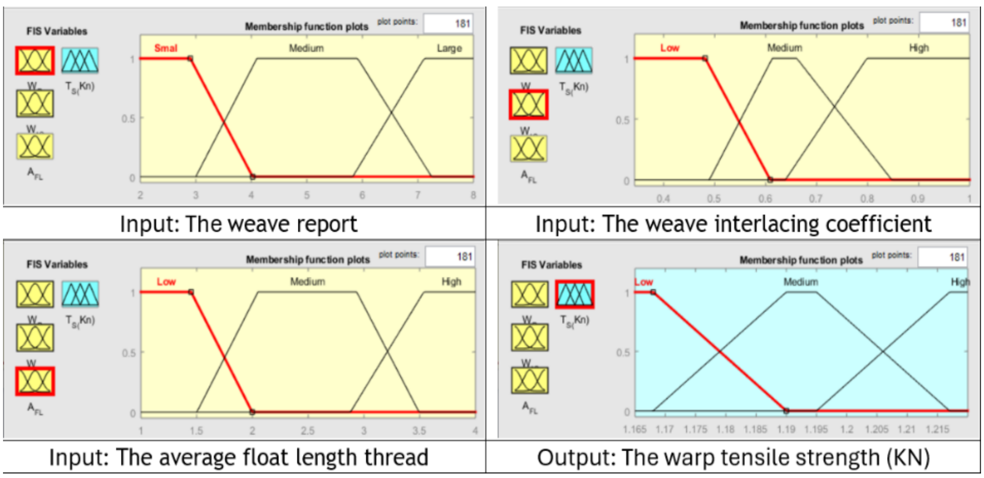

Figure 7. Membership functions for warp direction

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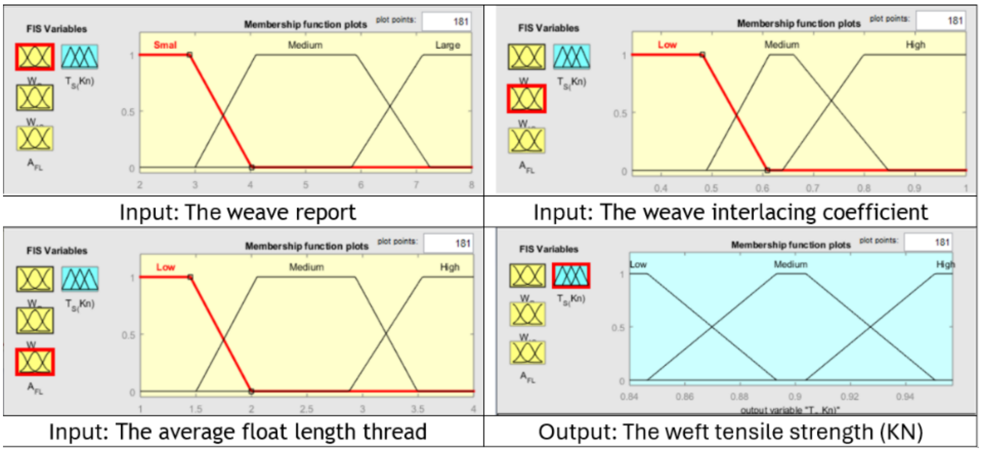

Figure 8. Membership functions for weft direction

Fuzzy Inference

The part where the experts define the fuzzy rules using the set of input indicators. To establish a correlation between the tensile strength and the process parameters, a total of 27 rules have been created. The IF THEN rule base, along with its corresponding output, has been catalogued in figure 9.

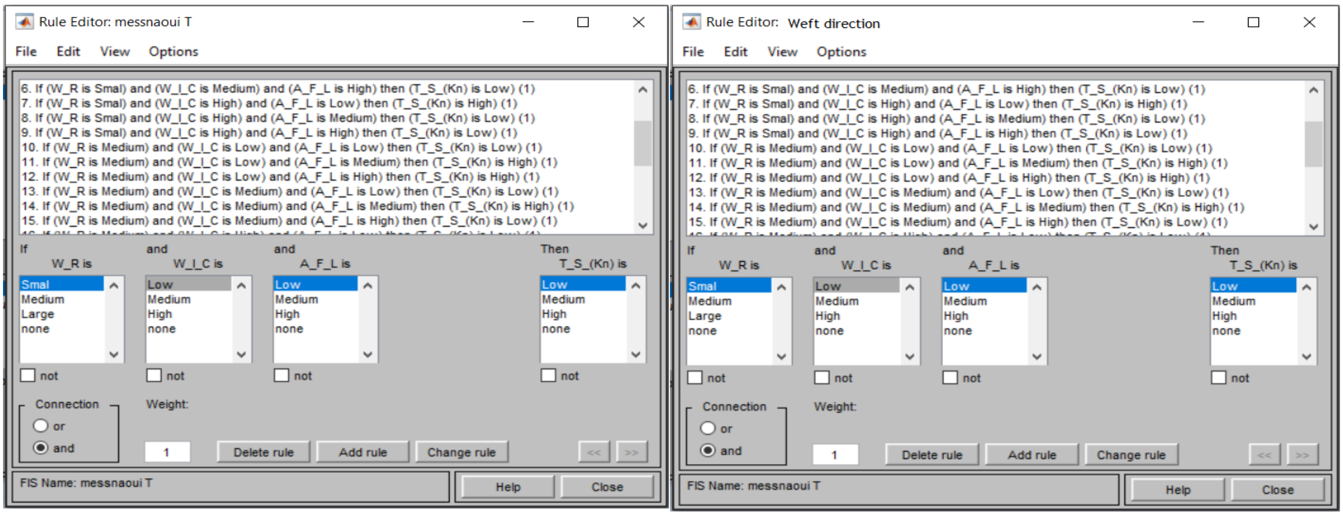

Figure 9. Rule viewer of developed fuzzy model for warp and weft directions

Defuzzification

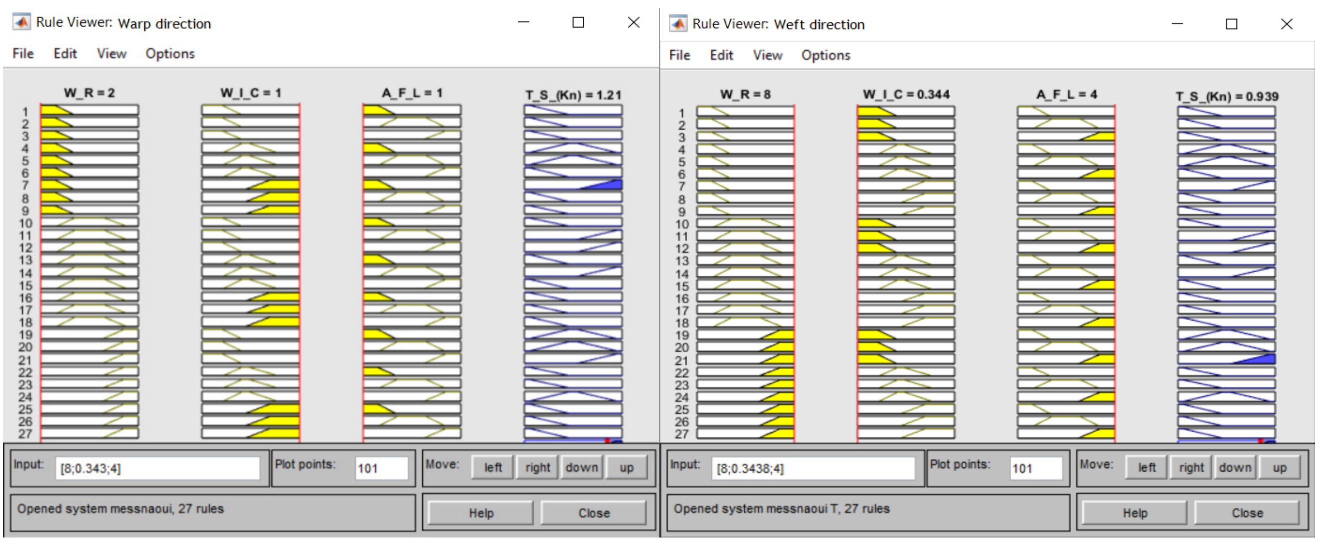

Figure 10. Defuzzification process for warp and weft direction

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Graphically, the following figure shows the defuzzification step, which consists of transforming the fuzzy set associated with the inputs: the weave report, the weave interlacing coefficient, and the average floating yarn length into a net value by applying the centre of gravity method. The results are represented in figure 10 which clearly explain the process.

One example of prediction: if the weave report = 8 and the weave interlacing coefficient = 0,3438 and the average floating yarn length= 4 then the tensile strength = 9,39 (KN).

Surface Viewer

The simulated surfaces below reflect the dependency relationship between the input indicators and the output indicator. Nevertheless, the weighting of these inputs is not the same, among which there is one more influential than the others.

To analyse the surfaces, we work with only 2 inputs, and we fix the third one on a constant value (abscissa axis) and we visualise the result of the output on the coordinate axis.

Case N°1: the weave report indicator is set as Medium

X (input)	Y (input)	Z (output)
(WCI) the weave interlacing coefficient	(AFYL) the average floating yarn length	(WTS) warp tensile strength

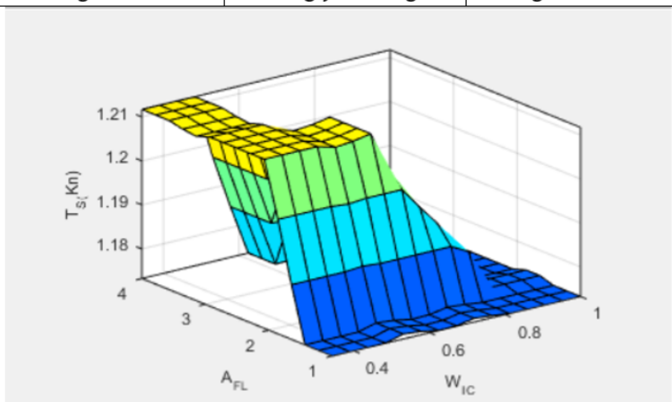

Figure 11. The Surface Viewer of Warp Tensile Strength

Although the average floating yarn length has less impact in some ranges, the graph indicates that maintaining the weave interlacing coefficient at lower levels will result in higher tensile strength.

Tensile strength is higher and more stable when the interlacing coefficient is low (for example, 0,2–0,4), indicating ideal performance conditions. Tensile strength quickly decreases as the interlacing coefficient gets closer to 0,8–1, suggesting a critical threshold beyond which performance deteriorates.

Case N°2: The weave report indicator is set as Medium

X (input)	Y (input)	Z (output)
(WCI) the weave interlacing coefficient	(AFYL) the average floating yarn length	(WTS) weft tensile strength

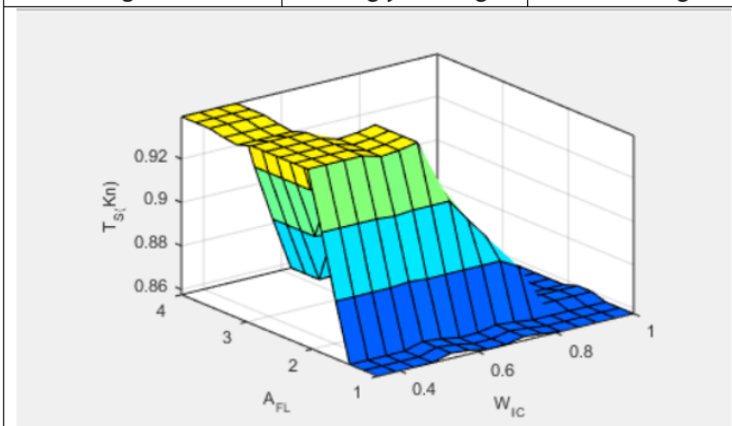

Figure 12. The Surface Viewer of Weft Tensile Strength

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Tensile strength appears to be extremely sensitive to variations in the weave interlacing coefficient, particularly when it shifts from low to a high range, according to the graph. When the weave interlacing coefficient is held constant, the tensile strength varies comparatively little as the average floating yarn length varies, suggesting a limited or gradual effect of this parameter.

RESULTS

In the context of tensile strength analysis, the outcomes of our cloth experiments verify that the weave structure has a full-size impact on warp and weft densities. These densities are laid low with the amount of interlacing and the extent of floating yarns inside the weave's repetitive pattern. An increase in warp or weft density is generally associated with an improvement in warp and weft tensile strength (figures 13 and 14). This variant in yarn density is reflected by in the higher number of interlacing in the fabric. These interlacing increase the overall strength of the textile by inducing greater mutual pressure on the yarn, thus improving the bonding effect. For ease of graphical representation in figures 13 and 14, we have replaced the weave structures with the corresponding numbers of warp and weft yarns (figure 6).

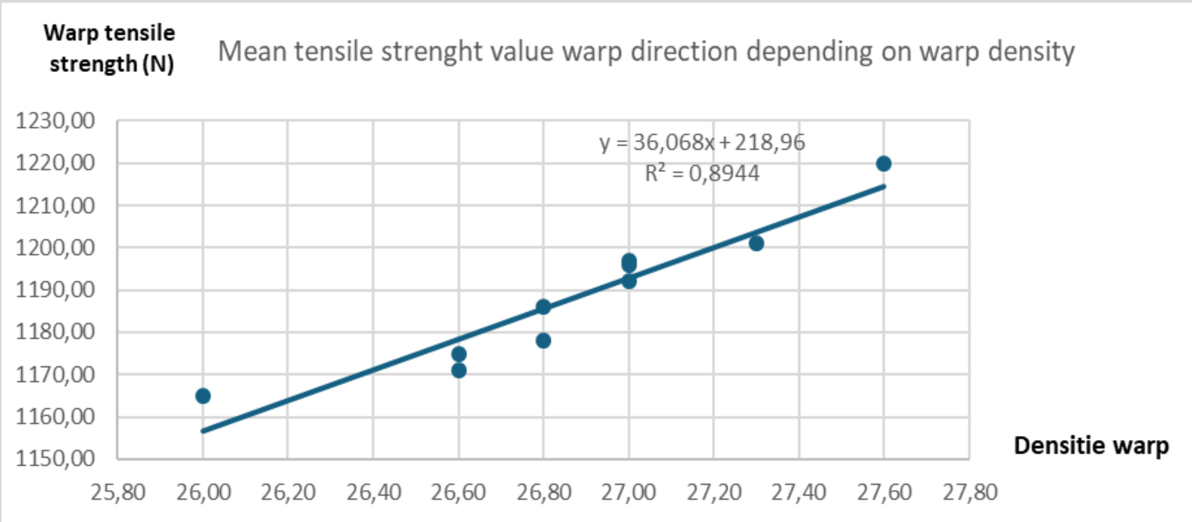

Figure 13. Mean tensile strength value warp direction depending on warp density

The R2 value is 0,8944, which indicates a robust positive correlation. An R2 fee close to 1 suggests that most of the version in warp tensile power may be explained by using changes in warp density.

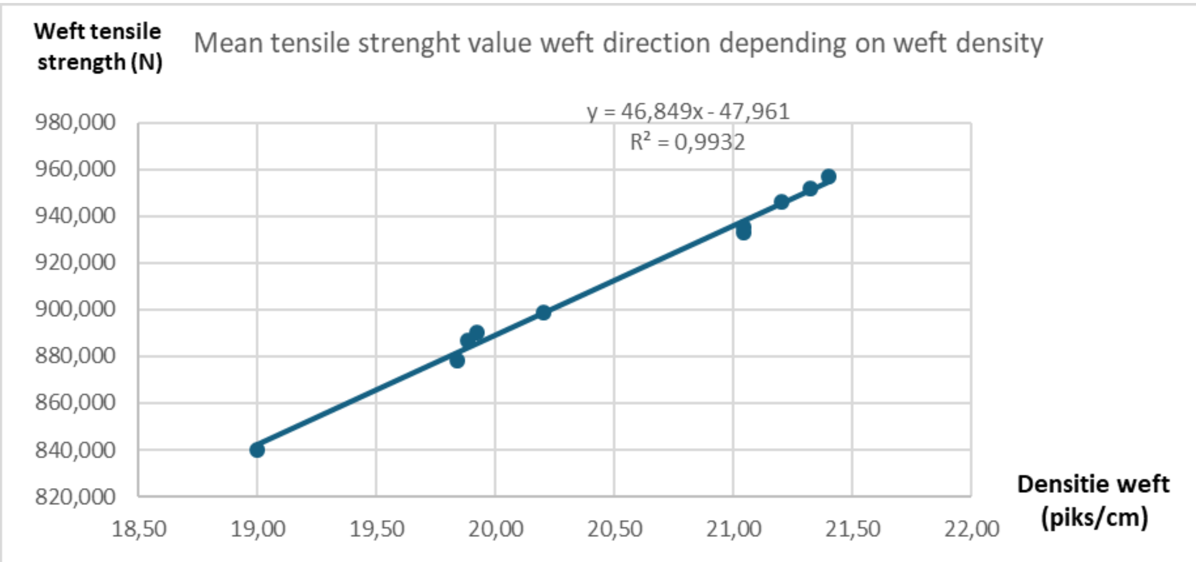

Figure 14. Weft mean tensile strength value depending on weft density

The R2 value is 0,9932, which suggests a sturdy superb correlation. An R2 price close to 1 shows that most of the variant in weft tensile electricity can be defined by way of changes in weft density.

The energy increase is regular (linear relationship). As warp or weft density will increase, fabric turns into more potent inside the warp and weft direction, which is anticipated due to the fact higher density regularly manner tighter or extra several yarns or weft in keeping with unit region, leading to stepped forward load resistance.

Figure 15 shows the experimental effects for fabric tensile energy in each warp and weft direction and the corresponding values of the identical parameter, as expected by means of the fuzzy logic model.

The discrepancy among the experimental effects and the fuzzy logic model was calculated, revealing a mean absolute mistake of 1,83 % for the tensile strength inside the warp direction and 1,99 % for the tensile strength inside the weft direction. This suggests that the predictions generated by the the fuzzy logic model version are remarkably in keeping with actual experimentation.

In other phrases, it efficiently validated the relationships among tensile and weave structures. The low errors fee of the fuzzy logic model shows that it's reliable and able to generate accurate predictions in the subject.

				Mean value of the breaking force (N) Warp			Mean value of the breaking force (N) weft		
Weave structures	The weave report	The weave interlacing coefficient	The average float length thread	Experience	Fuzzy logic	Error %	Experience	Fuzzy logic	Error %
Twill 4x4 right Hand	8	0,34375	4,00	1220	1220,20	1,64%	957	957,25	2,61%
Warp-faced twill 6x2 right Hand	8	0,34375	4,01	1201	1201,10	0,83%	952	952,10	1,05%
Warp-faced twill 7x1 right Hand	8	0,34375	4,02	1197	1197,50	4,18%	946	946,18	1,90%
Warp-faced sateen de 8	8	0,34375	4,03	1196	1196,11	0,92%	935	935,31	3,32%
Warp-faced satin de 8	8	0,34375	4,04	1192	1192,30	2,52%	933	933,09	0,96%
twill 2x2 right Hand	4	0,62500	2,00	1186	1186,12	1,01%	899	899,15	1,67%
4 end sateen	4	0,62500	2,01	1178	1178,14	1,19%	890	890,08	0,90%
Warp-faced twill 3x1 right Hand	4	0,62500	2,02	1175	1175,09	0,77%	887	887,42	4,74%
Basket 2-2	4	0,50000	2,03	1171	1171,42	3,59%	878	878,16	1,82%
Plain	2	1,00000	1,00	1165	1165,19	1,63%	840	840,08	0,95%
						1,83%			1,99%

Figure 15. Comparison of predicted and experimental values for tensile strength in warp and weft directions

Although the study demonstrates the effectiveness of the fuzzy logic model in predicting the tensile strength of fabrics based on weave structures, it has some limitations: the study primarily focuses on the impact of weave structures on the tensile strength of fabrics. While this is relevant, other factors, such as working with the same texture (warp count and weft count), using only polyester yarns for the warp and weft, working with a limited number of binding methods even though it covers the three main families of weaves, and, finally, the fact that the samples were not subjected to any treatments or finishes, are not taken into account.

CONCLUSIONS

Globalization has led to faster and more streamlined global delivery chains while growing the aggressive demand to shorten manufacturing timelines in the textile area.

However, even after designing and generating new fabric, we must conduct tests to assess tensile strength in each warp and weft direction, leading to wasted time, materials, and resources. Our fuzzy common-sense version, developed using MATLAB, can predict the test outcomes with minimal common absolute error.

Several experiments have correctly hired the evolved model. It has been validated to be able to resolve tricky problems and produce specific and truthful results. Users have expressed pride with the version's overall performance, which has aided in expediting the layout and development of recent merchandise (fabric).

Given its encouraging performance, the version will undergo testing in a weaving mill earlier. This segment is essential to assess the version's performance in an actual fabric manufacturing process.

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