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Prediction of Polypropylene Yarn Shrinkage in the Heat-Setting Process Using the Fuzzy Inference System

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Abstract
In the carpet industry, yarn shrinkage is a very important specification, the percent of which being affected by heat-setting parameters, time and temperature. In order to obtain the best uniform appearance of carpets, the shrinkage of pile yarns should be minimum in the carpet sizing process. Inappropriately heat-set yarn may cause undesirable shrinkage and uneven pile height on carpets after the sizing process. It could be useful for manufacturers to understand the optimum condition of heat setting to obtain the low shrinkage of heat-set yarns before weaving. Therefore, a fuzzy logic model was designed to predict the shrinkage percentage of polypropylene yarn in different heat-setting conditions. Time and temperature are taken into account as input variables, and yarn shrinkage is predicted as the output. For validation of the model, yarn samples were heat set over various periods of time, at different temperatures, and finally yarn shrinkages were measured experimentally. The results of the fuzzy model prediction compared to regression results show that the fuzzy results present a good and better match with experimental results, with an acceptable $R^2 = 0.97$ *and average error (2.59%).*

Key words: *heat setting, shrinkage, Fuzzy inference system, polypropylene.*

Introduction

In recent years, heat setting has found a tremendous commercial position in the textile industry [1, 2]. Gupta [3] and Hearle [4] classified all types of settings as permanent, semi-permanent and temporary. In fact, through spinning, weaving and finishing processes [4], different stresses are collected in the final products, and a perfect heat-setting process will release the stresses and position the material's internal energy at the lowest level. This classification is a confirmation of heat-setting's importance in the textile industry.

Horrock [5] mentioned that the time–temperature relationship in the heat-setting process will vary depending on the polymer, fabric weight and its construction. A simple way to determine the optimum time–temperature relationship in heat setting is to look at the shrinkage of the finished product. If the material has been correctly heat set, then it should show a residual shrinkage of less than 1% on a 5 min immersion in boiling water [6].

Kish [7] tried to create a formula for the relationship between elongation, load and draw ratio after the cold drawing and heat setting of polypropylene filaments. The results of a research work by Abigail [8] showed different recrystallisation responses of fibres to the thermal annealing applied and, consequently, different shrinkage mechanisms. The existence of nuclei crystallites at temperatures of heat treatments above 120 °C was the major significant factor for Nylon 6 fibre to undergo less shrinkage than Nylon 6.6 fibre. Gao [9] worked on the heat treatment and shrinkage behaviour of POY/FDY polyester yarns, as an important factor for this type of yarn. Hui [10] worked on the characterisation of high modulus and low shrinkage polyester technical yarn by means of the simulation curing method. Jeanette [11] investigated controlling wool fabric shrinkage. Ma [12] and Pelisser [13] studied the effect of different geometric polypropylene and synthetic fibres on the plastic shrinkage cracking of cement. Samui [14] investigated the hysteresis characteristics of high modulus, low shrinkage polyester tire yarn and cord. Headinger [15] researched low shrinkage, dyeable MPD-I yarns.

The above-mentioned researches tried to work on shrinkage and yarn specification either in different atmospheres or at different tensions, while some others tried to predict yarn parameters by means of an artificial intelligence system. Lin [16] predicted yarn shrinkage using Neural Nets. Lin finished woven fabrics and estimated the shrinkages of warp and weft yarn therein by means of the neural net. The neural network is used to find relationships between the shrinkage of yarns and the cover factors of yarns and fabrics.

Çeven [17] worked on the shrinkage of Chenille yarns, where the yarns were put inside boiling water for 15 minutes and then the yarn shrinkage measured, where the yarn count, pile length and twist level were selected as input variables and yarn shrinkage was the output function. This research [17] concluded that chenille yarns with higher twist levels and shorter pile lengths have lower shrinkage values, and that the yarn count has a significant effect on their shrinkage.

With regards to the literature reviewed, generally the most important parameters of the heat-setting process are the temperature, vapour pressure, dew point and time of different heat-setting methods [3, 18-21]. The machine speed can changed depending on the rate of the yarn mass on the belt and on type of material. Many other researchers have studied the time and temperature effect on polypropylene and polyester (yarns and fabrics) shrinkage [16, 22, 23]. Sardag [21] tried to predict the shrinkage of chenille yarn under constant conditions. Regarding the importance of time and temperature, which was concluded from the papers reviewed, in this research the effect of temperature and time on the shrinkage of polypropylene pile yarns of carpet was investigated.

In new industrial products, manufacturers need to reach a high quality of production with the least cost. If they attempt to achieve favourable shrinkage by trial and error, they will lose and waste expensive materials to accomplish their goals, while by means of predicting systems, they can produce favourable products from prior knowledge and reduce the cost of their products. In carpet pile yarns the heat-setting process, as well as optimum time and temperature can help to increase the efficiency and decrease the cost. The fuzzy model is able to predict these parameters and help industries achieve better productivity. While in recent years there has been growing use of the artificial neural network (ANN) to predict the various properties of textile yarns [24], there has not yet been any research to predict the shrinkage of polypropylene yarns by the fuzzy system. Fuzzy logic is suitable for models that have an indiscrete, subjective and linguistic nature (such as ’shrinkage is high’ and ’that is linguistic and has an indiscrete value for different times’), while ANN matches to models that have discrete numbers as inputs and outputs similar to the prediction time series. In addition, it should be highlighted that the new fuzzy system, which is designed with more input parameters (which could be developed during a practical test in every factory), will be able to help users efficiently predict yarn shrinkage. However, in the present paper, there was a limitation put on sample preparation due to factory resources.

In this research work, first a brief review of the fuzzy inference system is carried out. Then important factors in heat setting are introduced as linguistic variables in the fuzzy system. Input/output variables are fuzzified, the fuzzy rules introduced, and finally defuzzification is carried out. Fuzzy model validation with real data and some other discussions follow in the next steps.

Materials and methods

Theory of Fuzzy Inference System

Fuzzy Inference Systems (FIS) are popular computing frameworks based on the concepts of fuzzy set theory, which have been applied with success in many fields like control, decision support, and system identification [25]. Their success is mainly due to their closeness to human perception and reasoning, as well as their intuitive handling and simplicity. Fuzzy logic theory has emerged over recent years as a useful tool for modelling processes which are too complex for conventional quantitative techniques or when the available information from the process is qualitative, inexact or uncertain. Logically, the variables have been defined as false or true, while fuzzy logic states that variables can be adjusted intermediate values. Pre-defined membership functions help to define uncertainty. If the approximate element of the result is defined as one, there is no doubt that other elements are between zero and one and they are changing continuously. Variation between zero and one is called membership degrees and the variation in a subset is called Membership Function (MF). Membership function is a curve that explains how each point in the input space is mapped to the degree of membership between zero and one [26]. Once the fuzzy sets are chosen, a membership function is created for each. A membership function is a typical curve that converts the input between zero and one, indicating the belongingness of the input to a fuzzy set. This step is known as “fuzzification” [24]. Fuzzification classifies numerical measurements into fuzzy sets [27]. There are various types of MF, such as triangle, trapezoid, sigmoid and Gaussian [24]. Every MF is based on some different parameters such as “mean” and “variance”. In the Matlab fuzzy toolbox the “trimf” and “trapmf” are defined as the simplest membership functions, both of which are formed of straight lines. The simplest function is the triangular membership function, which has the function name “trimf”.

Methodology, fuzzy linguistic rules and defuzzification

It is almost four decades since Lotfi Zadeh [28] introduced fuzzy methodology. Mamdani’s fuzzy inference was among the first control systems built using fuzzy set theory. The Mamdani FIS type was proposed as the first attempt to solve control problems by a set of linguistic rules obtained from experienced human operators [29]. The main feature of such a type of FIS is that both the antecedents and the consequents of the rules are expressed as linguistic constraints [30].

Fuzzy linguistic rules provide quantitative reasoning that relates input fuzzy sets with output fuzzy sets. Rules are designed based on knowledge of human expertise and experience. A fuzzy rule base consists of a number of if-then rules. For example, for a system with two inputs and one output, it could be written as, “if x is high and y is medium then z is low”. Where x, y and z are variables representing two inputs and one output, high and low are the fuzzy sets of x, y and z, respectively. As can be seen, some logical operations are used for defining fuzzy rules. “AND”,”OR”& “NOT” help to define a fuzzy rule. Every rule in will result in a fuzzy set. These outputs will aggregate to a single fuzzy set. This step has been known as “aggregation” in fuzzy logic. Finally, the resulting set is resolved to a single crisp number by defuzzification; however, defuzzification methods are different. Perhaps the most popular defuzzification method is centroid calculation, which returns the centre of the area under the curve. There are five built-in methods supported: centroid, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum [31, 32].

Data clustering

Clustering problems arise in various areas like pattern recognition and classification, image processing, and bioinformatics. It is considered that the k-means algorithm is the best-known squared error based clustering algorithm. It is very simple and can be easily implemented in solving many practical problems. It uses a two-phase iterative algorithm to minimise the sum of point-to-centroid distances, summed over all k clusters: The first phase uses batch updates, where each iteration consists of reassigning points to their nearest cluster centroid all at once, followed by recalculation of cluster centroids. This phase occasionally does not converge to a solution that is a local minimum, that is, a partition of the data where moving any single point to a different cluster increases the total sum of distances. This is more likely for small data sets. The batch phase is fast but potentially only approximates a solution as a starting point for the second phase. The second phase uses online updates, where points are individually reassigned if doing so will reduce the sum of distances, and cluster centroids are recomputed after each reassignment. Each iteration during the second phase consists of one pass through all the points. The second phase will converge to a local minimum, although there may

Table 1. *Yarn shrinkage data.*

No.	Temperature, °C	Time, seconds	$Sh_{\_e}$, %
1	120	45	2.5
2		60	1.6
3		75	1.5
4		90	1.3
5	130	45	2.3
6		60	1.5
7		75	1
8		90	0.9
9	140	45	1.5
10		60	1.3
11		75	0.7
12		90	0.5
13	150	45	1
14		60	0.4
15		75	0.3
16		90	0.2

be other local minima with a lower total sum of distances. The problem of finding the global minimum can only be solved in general by an exhaustive choice of starting points, but using several replicates with random starting points typically results in a solution that is a global minimum [33].

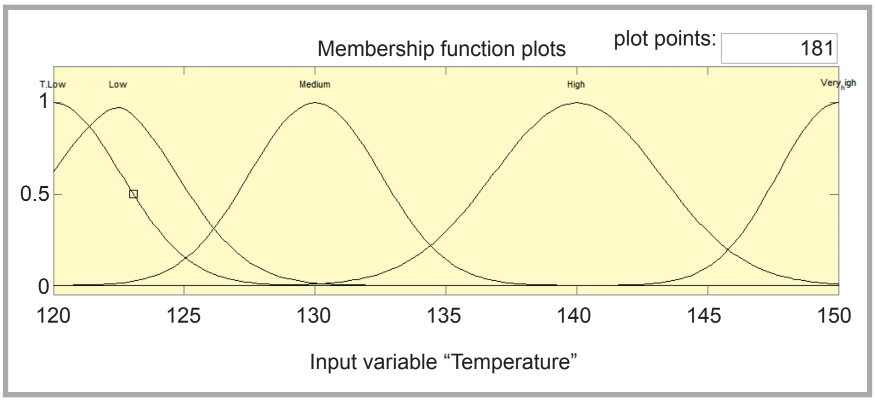

Figure 1. *Temperature mapping diagram.*

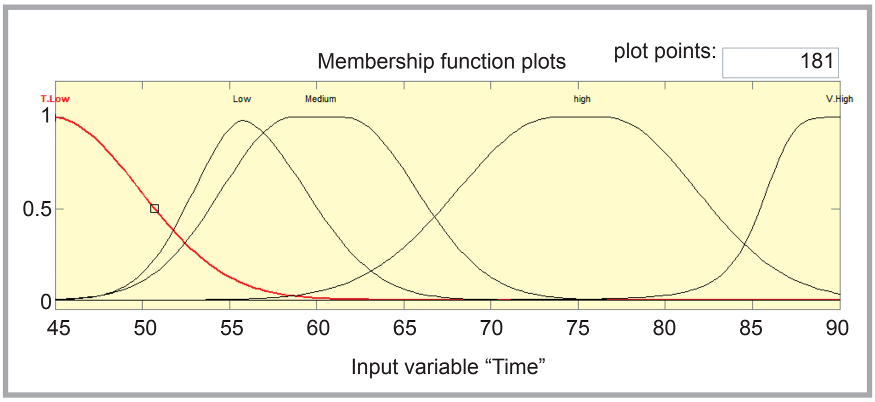

Figure 2. *Time mapping diagram.*

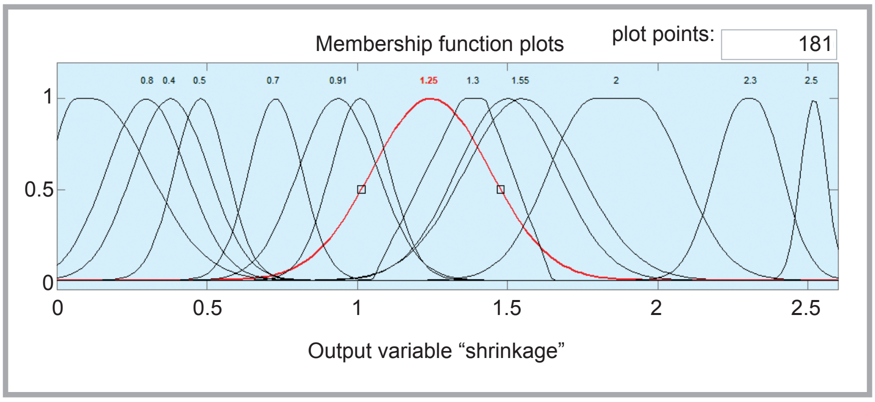

Figure 3. *Shrinkage mapping diagram.*

Experimental

There are three common methods of heat setting, such as saturated steam, dry and wet, to heat set the yarns of carpet pile. Initially, we tried to use a Power-Heat-Set machine, but controlling the temperature was not so accurate, and also high twist yarns twisted together in a free state over the machine belt. Therefore, to achieve better accuracy, the dry heat setting of the oven (equipped with air circulation) was chosen for the heat-setting process. This method was selected because of similarities to the Power-Heat-Set machine, where controlling the temperature with better accuracy is possible. 2800 dtex polypropylene yarn (144 filaments, trilobal filament, 95 TPM, MFI 25, production speed 2500 m/min) produced by a Swisstex BCF spinning machine was used as samples. In BCF spinning of the samples, 2.6% of colour master batches and 1% of a UV stabiliser were used. Samples were heat set at different temperatures of 120, 130, 140 and 150 °C. This range of temperatures was defined regarding the melting point of polypropylene yarns. The maximum temperature that is normally set on the heat setting machine is 150 °C, while lower temperatures are considered to be lower than the maximum temperature. Every test was done for four different times: 45, 60, 75 and 90 seconds, as recommended by the industry. Normally, a yarn passes through the Power-Heat-Set tunnel in one minute. Choosing these ranges for input variables was also considered in other research works [4, 18, 22].

A shrinkage test was performed according to ASTM D2259-02. The lengths of hanks before and after heat-setting treatment were measured and then the value of shrinkage calculated. The number of samples for the shrinkage test was ten due to the statistical significance of data at a 95% confidence level.

Table 1 shows the results of 16 experimental yarn shrinkage values, with all data calculated from the average values of ten experimental tests. In this research, $Sh_{\_e}$ and $Sh_{\_t}$ show the experimental shrinkage and theoretical shrinkage, respectively. The results of the fuzzy model were obtained using the fuzzy logic toolbox of Matlab software version 2013.

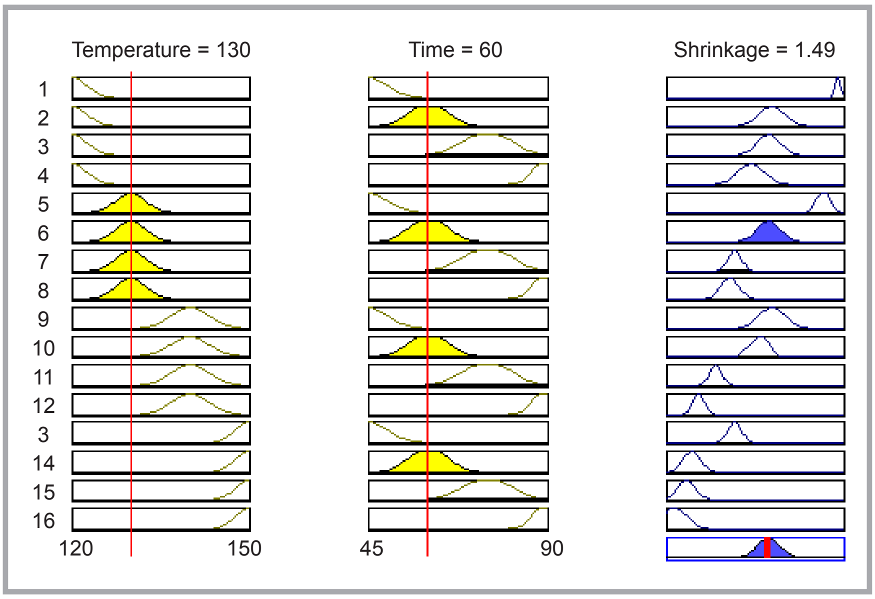

Figure 4. *Prediction of the percentage of yarn shrinkage by the fuzzy system.*

Table 2. *Fuzzy rules.*

No.1	If	Temperature	Is	T.Low	And	Time	Is	T.Low	Then	Shrinkage	Is	L14
No.2								Medium				L11
No.3								High				L10
No.4								High				L8
No.5				Medium				T.Low				L13
No.6								Medium				L12
No.7								High				L7
No.8								T.High				L6
No.9				High				T.Low				L11
No.10								Medium				L9
No.11								High				L5
No.12								T.High				L4
No.13				T.High				T.Low				L7
No.14								Medium				L3
No.15								High				L2
No.16								T.High				L1

Table 3. *Comparison results of "Gaussian MF" and "Gbell MF".*

No.	Temperature, °C	Time, seconds	Sh_e, %	Sh_$_t$_Centroid, %	Error_Ex&Cen, %	Sh_$_t$_Gbellmf_ Shrinkage, %	Error_Ex &Gbellmf_ Shrinkage, %
1	120	45	2.5	2.46	1.6	2.48	0.8
2		60	1.6	1.55	3.125	1.55	3.125
3		75	1.5	1.5	0	1.5	0
4		90	1.3	1.25	3.84	1.25	3.846
5	130	45	2.3	2.28	0.86	2.28	0.86
6		60	1.5	1.49	0.66	1.49	0.66
7		75	1	1.02	0.02.	1.02	2.
8		90	0.9	0.933	3.66	0.933	3.66
9	140	45	1.5	1.55	3.33	1.55	3.33
10		60	1.3	1.34	3.07	1.36	4.61
11		75	0.7	0.739	5.57	0.743	6.14
12		90	0.5	0.494	1.2	0.492	1.6
13	150	45	1	1.02	2.	1.02	0.02.
14		60	0.4	0.424	6.	0.411	2.75
15		75	0.3	0.318	6.	0.318	6.
16		90	0.2	0.2	0	0.136	0.32
Average Error, %					2.68		4.58

Operation of fuzzy expert system

All of the variables that are introduced as important factors in heat setting are considered as linguistic variables. This is investigated by changing the heat-setting conditions of time and temperature with a constant type of yarn which is designed to simulate the heat-setting condition. Therefore, changing the input parameters can present the results. With two input parameters, there are many states, and FIS can result in a proportional state for outputs. Each of the input variables was assigned with a combination of Gaussian fuzzy MF. However, it is possible to use various types of membership functions (MF) in the model. The Gaussian type was chosen because of better results fit by Gaussian MF. The temperature range chosen is from 120 to 150 °C and the time range from 45 to 90 seconds.

Figures 1 and ***2*** show that both the temperature and time are graded by five levels: Too Low, Low, Medium, High, and Very High. This type of input parameter classification is common in fuzzy models and can be defined differently. The aggregation will result in a fuzzy set as input data for the defuzzified process. In this research, the defuzzification method is centroid, which is one of the usual methods of defuzzification in the fuzzy logic system. In ***Figure 3***, the percentage of yarn shrinkage is mapped by fourteen MFs. As is shown, the membership functions are named with their centres. ***Figure 4*** is a pictograph of the rules of a fuzzy sample; a sample of a fuzzy model was accomplished using the fuzzy logic toolbox of Matlab software. In ***Figure 4***, the yellow sections are the input

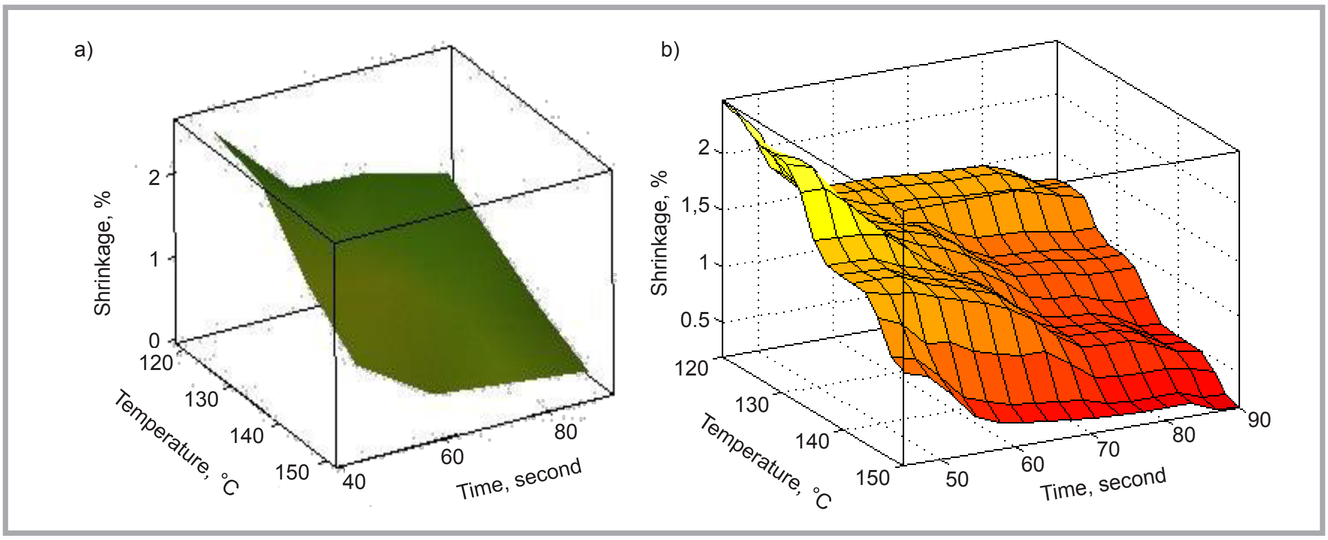

Figure 5. *Shrinkage variation versus temperature and time of heat setting: a) experimental, b) output of model.*

coverage zone, and the level of appropriate shrinkage is shown in the blue diagram.

Table 2 shows the defined rules for this model. As is clear, for a low temperature and time, the shrinkage will be placed in the first level, and this procedure continues proportionally to the input levels. Of course, the description of this process can be from a very good to very poor heat setting as appropriate. In the model, all output data are the result of the input variables.

Results and discussion

Comparison of membership functions

Differences in membership functions were investigated by testing two membership functions for the output parameter. A comparison of the error results of Gaussian and *Gbell* MFs is listed in ***Table 3***. The purpose of *Gbell MF* is a generalised bell-shaped built-in MF. These membership functions with *Centriod* defuzzification methods were compared. The error percentage of *Gbell MF* is more than that of *Gaussian MF* (***Table 3***). Finally, the table results depict a lower error percentage for the Centroid method (2.68%) in comparison to the *Gbell MF* method (4.58%).

Comparison of defuzzification methods

This fuzzy system was developed based on the centroid (centroid of area) method. The results of other defuzzification methods (*bisector*: bisector of area method; *mom*: mean of maximum method; *som*: smallest of maximum method; *lom*: largest of maximum method) were compared and contrasted with those herein, showing that the average error between the experimental data and the two defuzzification methods (*Centriod* and *Bisector*) is the same, while there is a difference between the average errors of these defuzzification methods and the other three defuzzification methods. Meanwhile, the error of the centroid method is the lowest. Thus, the fuzzy model structure was designed based on all items that result in the lowest errors.

Statistical analysis

Table 4 shows the results of 16 experimental groups and yarn shrinkage values predicted using the fuzzy system ($R^2 = 0.97$, average error – 2.59%.). ***Table 5*** shows ANOVA results of the time and temperature analysis, showing that their differences are significant from a statistical point of view. ***Table 5*** confirms the significance of shrinkage versus time and temperature, and the R-square is acceptable. Moreover, the regression ***Equation (1)*** for predicting the shrinkages of polypropylene yarns does so with lower accuracy ($R^2 = 0.91$, R-Adjust = 0.90). In ***Equation (1)***, *TMP* is the temperature in Celsius and *TIM* is the time of the heat setting in seconds.

$$Sh\% = 8.42375 - TMP * 0.04175 - 0.02417 * TIM \qquad (1)$$

The input levels in the MF will distinguish the output levels. For example, when the temperature is 130 °C and the time 60 seconds, the predicted shrinkage is 1.49%. The results of predicted shrinkages are shown in ***Table 4***. The differences between the experimental and predicted results of the final fuzzy structure achieved are shown as the error percentage. In ***Table 4***, the error percentage “E_r” is calculated by ***Equation (2)***, with other statistical methods for evaluating errors indicating similar results.

$$Er = (Sh_{\_e} - Sh_{\_t})/Sh_{\_e} \qquad (2)$$

Where, $Sh_{\_e}$ is the experimental shrinkage and $Sh_{\_t}$ the theoretical shrinkage predicted from the fuzzy model. The surface plot obtained from experimental and fuzzy logic results is shown in ***Figure 5***. In the general view, increasing the temperature in more seconds can result in a lower shrinkage percentage. The effect of temperature in the range of 140 to 150 °C on the shrinkage is very notice-

Table 4. *Yarn shrinkage data.* ***Note:*** *$Sh_{\_e}$ – experimental shrinkage, $Sh_{\_t}$ – theoretical shrinkage, Er – error percentage.*

No.	$Sh_{\_e}$ – experimental shrinkage, %	$Sh_{\_t}$, %	Er, %
1	2.5	2.46	1.6
2	1.6	1.55	0.64
3	1.5	1.5	2.59
4	1.3	1.25	0
5	2.3	2.28	0.86
6	1.5	1.49	2.61
7	1	1.02	2
8	0.9	0.933	3.66
9	1.5	1.55	1.97
10	1.3	1.34	3.07
11	0.7	0.739	5.57
12	0.5	0.494	2.92
13	1	1.02	2
14	0.4	0.424	6
15	0.3	0.318	6
16	0.2	0.2	0
Average Error			2.59

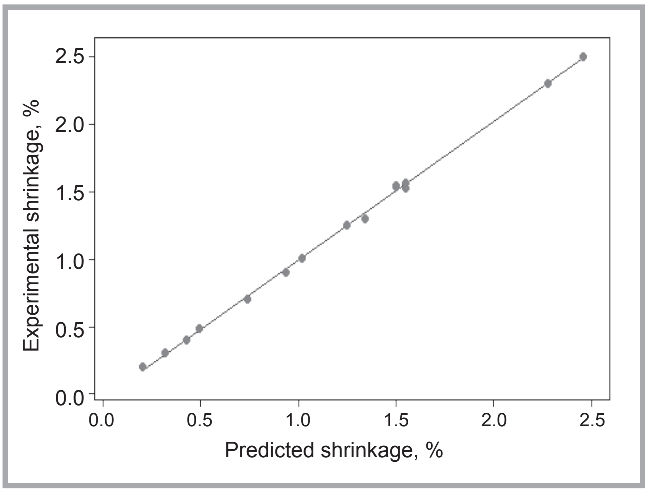

Figure 6. Values of experimental and predicted shrinkage values.

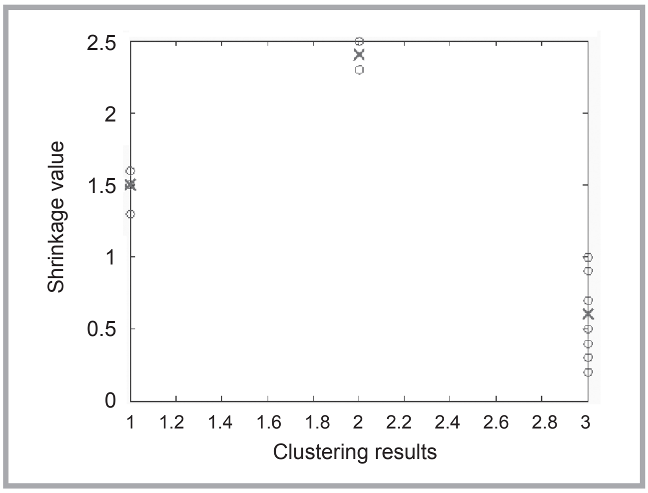

Figure 7. Clustering results of shrinkage.

able, while under 140 °C the shrinkage is not noticeable, and the importance of time is less than that of temperature in all ranges.

Figure 6 shows there is an acceptable relationship between the experimental and predicted shrinkage values. The correlation coefficient between predicted and experimental values is about 0.97, and the average error percentage between them is 2.59%.

These results show that the fuzzy model designed is reliable enough to predict the shrinkage of carpet pile yarns of polypropylene. According to the results, the temperature and time of the heat-setting process are adjustable to obtain a defined yarn shrinkage percentage.

As a final step, it is useful to understand the shrinkage results by forming three groups according to the Hearl classification (permanent setting, semi-permanent setting and temporary setting) [4]. This process was done by means of the K-Means algorithm. ***Table 6*** depicts the centre of every class and its members. The coordination of Hearl and this classification of samples was achieved with regard to the range of temperature. The lower the final effectible temperature that is practical in industry, the higher the level of temperature that is near the softening point of polypropylene materials. Focusing on the clustering results of shrinkage characterises their outcomes, as depicted in ***Figure 7***. As can be seen, three classes are chosen to understand the samples located in every heat-setting class.

Clustering results are given in ***Table 6***. As can be seen, the centre of clusters is different in every class. The first class has the lowest level of heat setting (samples 1, 5). This sample was heat set at 120 and 130 °C for a time of 45 seconds. The second and third levels of heat setting are mentioned in ***Table 6***. As can be seen, increasing the temperature resulted in a better heat setting. One important industrial application of these predictions and clustering methods is finding the optimum cost benefit point for setting the heating and timing condition, due to the importance of energy consumption in industry, especially when a specific level of residual shrinkage satisfies customers and manufacturers.

Table 5. *ANOVA test, shrinkage percentage versus time (second) and temperature (^{o}C).* ***Note:*** *DF – degree of freedom, SS – sum of squares, MS – mean square error, F – Fisher's test, P – value of significance level.*

Source	DF	SS	MS	F	P
Time	3	2.85687	0.95229	30.01	0.000
Temperature	3	3.53687	1.17896	37.15	0.000
Error	9	0.28563	0.03174		
Total	15	6.67938			
S = 0.1781		R – Sq = 95.72%		R – Sq(adj) = 92.87%	

Table 6. *Details of clustering results.*

Test method/clustering	Cluster centre	Samples
Dry heat setting	2.4	1, 5
	1.5	2, 3, 4, 6, 9, 10
	0.6	7, 8, 11, 12, 13, 14, 15, 16

Conclusions

In this research work, a new fuzzy model was designed to predict the effect of heat-setting parameters on the yarn shrinkage of a carpet pile of polypropylene. The results show that the heat-setting parameters of time and temperature affect yarn shrinkage. Correctly selected rules of the fuzzy model designed can give correct output corresponding to the input values. It shows that increasing the temperature and time decrease the shrinkage percentage. As shown, temperature is more important than time for shrinkage properties of polypropylene yarns.

There is an exact relationship between experimental and predicted values. The comparison between the predicted and experimental results show an acceptable average error of 2.59%, and the determination coefficient (R^2) between them is about 0.97. Consequently, this high correlation confirms the reliability of the new fuzzy model designed.

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