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Statistical Model for the Prediction of Loop Length in Knitted Fabrics

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Abstract:*The purpose of this paper is to present a comparative analysis of statistical models to predict the loop length in knitted fabrics,relating this parameter to the stitch cam setting. Four linear regression methods were used;Least Squares, Nonparametric Regression, Least Absolute Deviations and M-Regression. Model performance was tested by the mean absolute deviation (MAD), the coefficient of determination R^2 and the mean squared error (MSE). In order to obtain a model to determine the primary parameter for knitted structures and that controls the dimension of the garment components a study was developed.The results proved M-Regression to be the best performing method for predict the parameter of interest.The study was carried out in a textile company producing knitted garments located in the south of the Mexican state of Guanajuato.*

Keywords: *Loop length, Textile sector, Linearregression, Knitting, SMEs*

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I. Introduction

Mexico is a major textile producer, with an industry based on competitive labor costs and geographic proximity to the United States. According to the Mexican National Institute of Statistics and Geography (INEGI), 63 percent of the Mexican textile industry is concentrated in the central and north eastern parts of the country. The textile sector represents 1.3 percent of Mexico's GDP[1].A large number of companies in this sector are small and medium enterprises (SMEs). These companies play an important role as employment sources and supporting large-scale organizations [2]. In many European countries, SMEs account for almost 80% of the GDP and employment structure [3]. According to SBA (2016) data, small companies represent 99.7% of employment sources in the United States [4]. Similarly, 93.6% of manufacturing companies in Mexico are microbusinesses, whereas the second place is occupied by small companies (4.2 %) and the third place by medium-sized companies (1.5%), according to data by INEGI [5].The work of [6] mentions the importance of providing small and medium-sized enterprises in the textile sector with engineering tools to improve their production and business processes by making informed decisions to enhance their competitive advantage.

Knitting is one of the most important sectors of textile. Knitted fabrics are commonly used because of their excellent mechanical and comfort properties. Because of their integral qualities like softness, coolness, sweat absorbance and durability, such garments are very popular all over the world, particularly in the developed countries [7].

Loop length is the most important specification for fabric quality in knitting. The manufacturers of knitted products are also gradually becoming more aware of the value of consistent loop length. The acceptability of a knitted product largely depends on its quality. Consumers have become more quality conscious. The manufacturer also needs to maintain a uniform standard of quality, as well as to meet the required specification. Effective process and quality control are essential. This can be achieved by regular checking and testing of the raw material, knitting processes and the finished product. Control at all these different stages of manufacture is important. To be effective, the quality control system for knitted fabric must begin with checking the incoming yarn and continue throughout the knitting process. The dimensions of knitted fabrics are determined by the number and size of stitches per unit area; this in turn is determined by loop length. In fact, the most important criteria of quality control in knitting are aimed at controlling the loop length [8].

Loop lengths combine in the form of course lengths and it is these that influence fabric dimensions and other properties, including weight. Variations in course length between one garment and another can produce size variations, whilst course length variations within structures can produce horizontal bareness and adversely affect the appearance of the fabric [9].

The aim of the present study is to obtain a statistical model to determine the loop length parameter of knitted fabrics, relating this parameter with the operating parameter of the stitch cam setting through a simple linear regression model.In this work, four regression methods are compared, through prediction criteria it is possible to determine the best model that explains the relationship between the two parameters of interest. The present study attempts to highlight the importance of knowing the value of the loop length during the knitting process because this is the most important parameter for assuring the quality of the product. The study was conducted in a small company producing knitted garments located in the south Mexican state of Guanajuato.

The textile firm where the study was conducted has the following manufacturing process.Production process begins in the knitting area, where textile fibers are woven as canvases and then basted to facilitate ironing. Ironing is performed using steam ironing machines; this operation stabilizes the fibers and the canvases undergo a certain natural shrinking so that cutting can take place. Garments are assembled in the sewing department and final details are completed in the finishing department. The final product is sold to special types of clients, such as department stores, and is also distributed via retailers and sales points.This paper focuses on the knitting department. In Figure 1 the knitting textile process is shown.

Fig. 1: Knitting textile process.

This article is structured as follows: The second section presents a review of the literature, the third section presents the research method used in the present study, and the fourth section presents de development of the study. Results and conclusions are presented in the last section.

II. Literature Review

This section presents the literature review related to the study of loop length in knitted fabrics, in these investigations models to determine length were developed and investigate the influence of this parameter on the dimensions, structures or physical properties of knitted fabrics.

Table 1. Literature Review.

Authors	Year	Purpose	Findings
Cuden, Hladnik & Sluga	2013	Conducteda study the impact of material, knitted structure and relaxation process parameters on loop length. In addition, to examine the differences in loop length of single weft knitted fabrics, produced from different types of elasticized and non-elasticized yarns.	For both groups, knitted fabric density and relaxation process influence the loop length most of all. Loop length decreases during the process of consolidation, but this decrease is not substantial. Addition of elastane does not significantly influence the loop length [10].
Çoruh&Çelik	2014	Investigated the effect of fabric density and nozzle type on the structural and performance properties of single jersey knitted fabrics investigated in both a grey and dyed state. In addition to performing a statistical analysis of the results and obtain regression equations.	For grey and dyed samples, the adjusted loop length has a significant effect on the loop length, course density, fabric weight and bursting strength. On the other hand, the nozzle type has a significant effect on the bursting strength [11].
Heravi, Najar, Moavenian, &Yazdanshenas	2014	This research aimed to design, construct and install a new optical IR monitoring system in order to record fluctuations in yarn fed into industrial circular knitting machines and to	Evaluating the fluctuation amplitudes recorded by analysis of variance revealed that an increase in the loop length will cause a highly significant decrease in the

		investigate the effect of the knitted loop length on yarn movement flow.	yarn fluctuation amplitude [12].
Çoruh	2015	Investigated the influence of different loop lengths and different fibre blend ratios of single jersey knitted fabrics on the mechanical and comfort properties thereof.	This study showed that the fibre, yarn structures and their respective loop length were significantly influential factors for single jersey knitted fabric properties, like dimensional properties, comfort, strength and others [13].
Sitotaw& Subramanian	2016	The study focuses on the analysis of twist multipliers effect on single jersey and 1 × 1 rib knitted fabrics dimensional properties.	The results showed that loop length, loop shape, and tightness factors properties of single jersey and 1 × 1 rib knitted fabrics are significantly influenced by twist multipliers variation [9].
Elzaher, Sultan, & Mito	2016	Developed a geometrical theoretical model for the determination of the loop length of single jersey knitted fabrics: a defined simplified equation for the loop length for open to normal knitted structure and for normal to compact structure.	By comparing the value of the loop length predicted from this work with other models, it was found that the calculated values are very near to the *L* value of the case study; so, the developed equations are acceptable [14].
Ghosh, Mal, Majumdar & Banerjee	2017	Conducted research to observe the effect of yarn count, loop length, knitting speed, and yarn input tension in the presence of two uncontrollable noise factors on selected comfort properties of single jersey and 1×1 rib knitted fabrics using the Taguchi experimental design.	It was found that the loop length and yarn count have major impacts on air permeability, thermal absorptivity, and thermal conductivity. Higher loop length and finer yarn count increase the air permeability but reduce the thermal conductivity and thermal absorptivity [15].

The studies presented in the literature review show the importance of the loop length parameter on the structural properties of knitted fabrics, also, factors such as fiber, knitted structure and operating conditions of the machinery significantly influence the loop length. It should be highlighted that none of the reviewed studies directly related the loop length with position of the stitch cam.The main objective of this research is to obtain a statistical model to determine the loop length parameter of knitted fabrics, relating this parameter with the operating parameter of the stitch cam setting through a simple linear regression model.

III. Methodology

Figure 2 shows the method used by this study to accomplish its goals. The statistical models to determine the loop length parameter of knitted fabrics was developed in three phases.

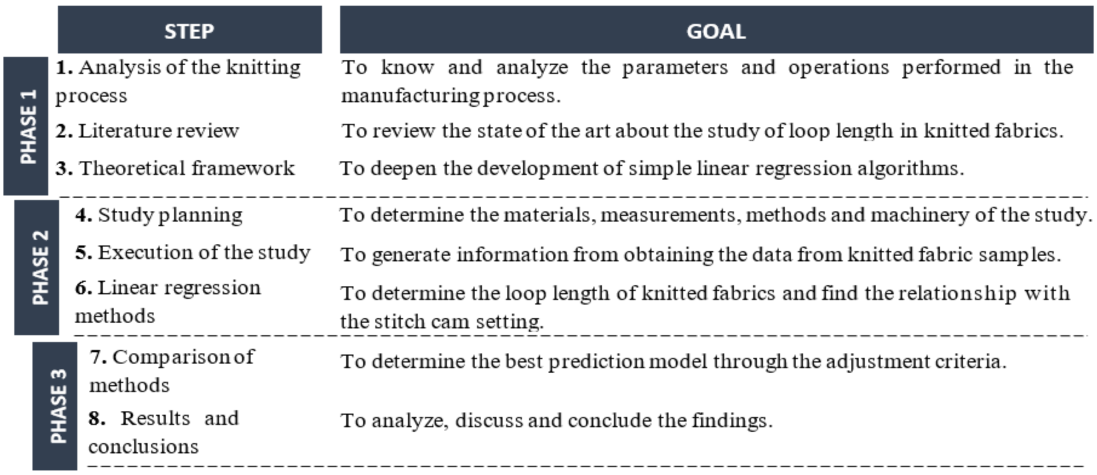


Fig. 2: Research method.

IV. Development

The first variable of interest in this study is the loop length, and this is the most important parameter in the manufacture of knitted fabrics, the dimensions and the appearance of the components of the garment depend on this parameter.The basic unit of a knitted structure is the loop, the length of yarn contained in a knitted loop is called loop length.

Knitting is the process of fabric formation by producing series of intermeshed loops.The newly-fed yarn is converted into a new loop in each needle hook. The needle then draws the new loop head first through the old (fabric) loop, which it has retained from the previous knitting cycle. The needles, at the same time, release, (cast-off or knock-over) the old loops so that they hang suspended by their heads from the feet of the new loops whose heads are still held in the hooks of the needles [16], and in Figure 3 the loop formation is shown.

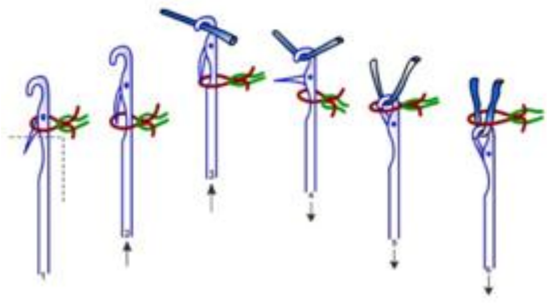


Fig. 3: Loop formation[17].

The second variable of interest in this study is the operation parameter of the stitch cam setting.The loop length is graduated by the position of the stitch cam, which defines the path of the needle drop from the top of the needle bed ("flush-jack") to the detachment of the previous loop [18]. Each stitch cam is raised and lowered by its own step motor, so a wide range of stitch lengths can be achieved during the knitting of a garment [16].

4.1 Materials and machinery

For the collection of the data, 20 sample knitted fabrics were manufactured.Single jersey knitted fabric was selected for this study, since it is widely used.The single jersey is a classic structure, made in a needle bed and is the simplest of knitted fabrics.The structure of this technique is presented in Figure 4.

Fig. 4: Single jersey [19].

Acrylic fiber in this study was used. Acrylic fiber is a synthetic fiber that closely resembles wool in its character (lightweight, soft, and warm). According to the definition of the BISFA (International Synthetic Fiber Standardization Office), contain a minimum of 85% acrylonitrile in their chemical structure, is composed of acrylonitrile and a comonomer [20].

All the fabrics were knitted at the same machine setting, the operating parameters (take-down tension, time, machine speed) were kept constant during knitting.The stitch cam settingwas considered with values of 48 to 67, this operating range is the most used in the company under study for the single jersey structure.The specifications of fiber and machinery are presented in Table 1.

Table 1. Study specifications

Operation parameters	*Stitch cam setting* 48-67	*Take-Down* 45	*Time* 3.18 min	*Speed* 65 m/s
Raw material	*Composition* Acrylic	*Caliber* 2/30	*Supplier* Galtex	*Color* Coral 123
Machinery specifications	*Manufacturer* Shima Seiki	*Mode* SES254-S	*Gauge* 8	

4.2 Measurements

The single jersey fabric samples were manufactured on flat knitting machine, employing the same needle bed width (97 working needles).The samples measured between 29.3 cm long and 29.0 cm wide. After the knitting process, all samples were statically dry relaxed and then placed unloaded to the standard environment for 48 hours.

After dry relaxation, loop length was measured, the analytical method was used; it consists of unraveling a complete course, yarn consumed in said course is stretched considerably and the length is determined, which is divided by the number of wales (needles) to obtain the loop length in centimeters as shown in Equation 1.

$$\textbf{Looplength} = \frac{\text{Yarn consumed}}{\text{Number of wales}} \quad (1)$$

Machine setting, knitting process and dry relaxation are shown in Figure 5.

Fig. 5: Execution of the study.

The results of the measurements of knitted fabric samples are shown in Table 2, the value of the stitch cam setting (explanatory variable), the yarn consumed in each course and the loop length (response variable) are presented.

Table 2. Data collection.

Sample No.	Stitch cam setting (x)	Course/cm	Loop length (Y)	Sample No.	Stitch cam setting (x)	Course/cm	Loop length (Y)
1	60	127	1.309	**11**	53	115	1.186
2	52	115	1.186	**12**	66	133	1.392
3	50	114	1.175	**13**	49	113	1.165
4	55	122	1.258	**14**	63	129	1.330
5	56	123	1.268	**15**	59	127	1.309
6	58	125	1.289	**16**	61	129	1.330
7	65	133	1.371	**17**	67	135	1.392
8	57	125	1.289	**18**	51	117	1.206
9	48	113	1.165	**19**	62	129	1.330
10	64	133	1.371	**20**	54	116	1.196

The scatter plot with the 20 data pairs is shown in Figure 6. It is possible to observe that there is a positive linear relationship, to the extent that stitch cam setting increases the loop length also increases.In the plot a significant increase in the level of loop length is observed from the value 55, a second increase in the level from the value 64. Therefore, it is feasible to assume that a regression model describes the relationship between the two variables of interest.

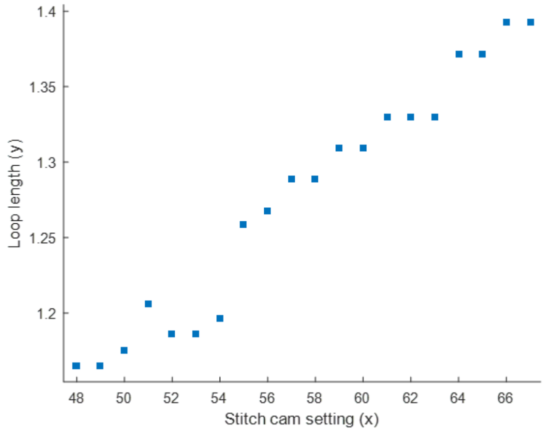


Fig. 6: Scatter plot

To measure the intensity of the relationship between the two variables, the correlation coefficient was obtained (see Equation 2). The value *r = 0.98* indicates a strong positive relationship.

$$r = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}} = \frac{8.726}{\sqrt{(665)(0.118)}} = 0.98 \quad (2)$$

4.3 Linear regression methods

This section presents the linear regression methods that were used in this investigation. The traditional method of least squares is widely used due to its ease in calculating the regression coefficients, also three alternative methods and considered robust are developed.All algorithms were implemented using MATLAB software.

In a simple linear regression, the most uncomplicated deterministic mathematical relationship between two variables x and y is a linear relationship (see Equation 3). The set of pairs (x, y) for which the equation determines a straight line with a slope β and the intersection with the y axis as $\boldsymbol{\alpha}$is defined as:

$$\mathrm{Y} = \alpha + \beta x + \varepsilon \quad (3)$$

The slope and intercept of the line are called regression coefficients.More generally, the variable whose value is set by the experimenter and is represented with x is termed independent, predictive, or explanatory variable. The second variable is random; this random variable and its observed value are represented by Y and y, respectively, and it is referred to as the dependent or response variable [21]. In equation 3, where $\boldsymbol{\varepsilon}$is a random error with mean zero and (unknown) varianceσ^2. The random errors corresponding to different observations are also assumed to be uncorrelated random variables[22].

4.3.1 Least Squares

This method determines a regression equation by minimizing the sum of squared vertical distances between real and forecasted values of *Y*(see Equation 4). The resulting regression line is known as the best-fitting line [23].

$$\sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n}\left[y_i - \left(\hat{\alpha} + \hat{\beta}x_i\right)\right]^2 \quad (4)$$

To find the least squares estimators of the intercept and the slope, the formulas of equations 5 and 6 were used.

$$\hat{\beta} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{(\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n}}{\sum_{i=1}^{n} x_i^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}} \quad (5)$$

$$\hat{\alpha} = \bar{y} - \hat{\beta}\bar{x} \quad (6)$$

where the values of the slope and intercept are: $\hat{\beta} = 8.726/665 = 0.0131$ and $\hat{\alpha} = 1.276 - [(0.0131)(57.500)] = 0.5213$. Therefore, the model that best explains the relationship between stitch cam setting and loop length is given by equation 7.

$$Looplength = 0.5213 + 0.0131\ (Stitchcamsetting) \quad (7)$$

4.3.2Least Absolute Deviations (LAD)

This is an alternative method and is considered a robust estimation method. LAD finds the slope and Y intercept that minimize the sum of the absolute values of the residuals (see Equation 8).

$$\sum_{i=1}^{n}|\hat{e}_i| = \sum_{i=1}^{n}\left|y_i - \left(\hat{\alpha} + \hat{\beta}x_i\right)\right| \quad (8)$$

Since there are no exact formulas for LAD estimation, an algorithm proposed by Birkes& Dodge [24] was used to iteratively obtain the estimate of the parameters, the algorithm is shown in Figure 7. After three iterations and with Equations 9 and 10, the estimators of the model were found. Therefore, through the LAD method, the model that best explains the relationship between stitch cam setting and loop length is given by Equation 11.

$$\hat{\beta} = \frac{(y_k - y_0)}{(x_k - x_0)} = \frac{1.165 - 1.330}{49 - 62} = 0.0127 \quad (9)$$

$$\hat{\alpha} = y_0 - \hat{\beta}x_0 = 1.165 - (0.0127)(49) = 0.5427 \quad (10)$$

$$Looplength = 0.5427 + 0.0127\ (Stitchcamsetting) \quad (11)$$

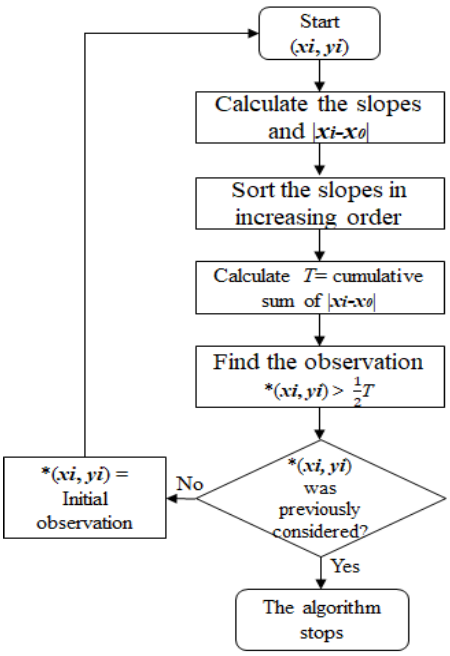


Fig. 7: LAD regression algorithm

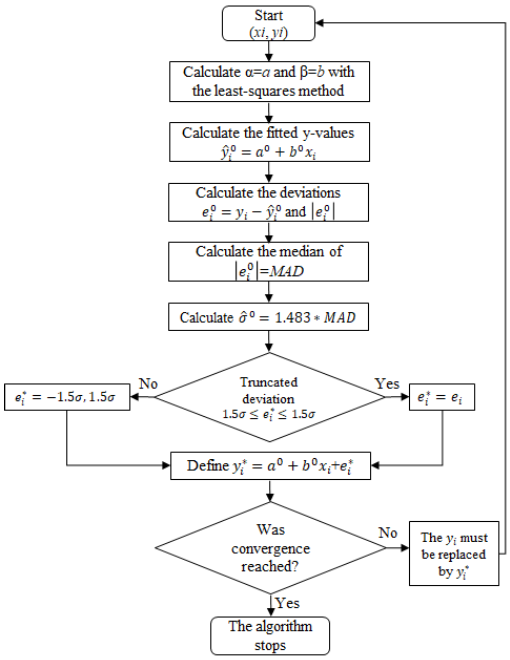


Fig. 8: M-regression algorithm

4.3.3 M-Regression

The M-estimates, also called *Huber M-estimates*, is a simple approach from the theoretical and computational point of view,the basic idea resides in assigning a quadratic weight to the small residuals and to the large residuals a linear weight [25].In M-estimation, this idea is generalized and $\hat{\alpha}$and $\hat{\beta}$are chosen so that $\sum p(\hat{e}_i)$is as small as possible (see Equation 12).

$$\sum_{i=1}^{n}\rho(\hat{e}_i) = \sum_{i=1}^{n}\rho\left(y_i - \left(\hat{\alpha} + \hat{\beta}x_i\right)\right) \quad (12)$$

Least-squares and least absolute deviations estimation can be regarded as the particular cases of M-estimation in which $p(e) = e^2$and $p(e) = |e|$.We can try to combine the advantages of both methods by defining$p(e)$:

$$p(e) = \begin{cases} e^2, si -k \leq e \leq k \\ 2k|e| - k^2, sie < -kok < e \end{cases} \quad (13)$$

Following a suggestion of *Huber* we take k =1.5$\hat{\sigma}$, where $\hat{\sigma}$ is an estimate of the standard deviation $\sigma$of the population of random errors [24].The algorithm developed in this paper is presented in Figure 8.After six iterations (see Table 3), the relative difference between the updated estimate and the previous estimate is less than 10^{-4} forα. Thus, to an accuracy of about four significant digits, the values of $\hat{\alpha}$and $\hat{\beta}$are:0.05247 and 0.01307 respectively.

Table 3. Iterations / M-regression algorithm

Iteration	$\hat{\beta}$	$\hat{\alpha}$	Convergence$\hat{\alpha}$
-	0.01312	0.5213	-
1	0.01303	0.5277	0.00639
2	0.01309	0.5233	0.00440
3	0.01305	0.5263	0.00302
4	0.01308	0.5243	0.00205
5	0.01306	0.5256	0.00138
6	0.01307	.05247	0.00091

The model through the *Huber* M-estimation is presented in the Equation 14.

$$Looplength = 0.5247 + 0.01307\ (Stitchcamsetting) \quad (14)$$

4.3.4 Nonparametric Regression

A "nonparametric" procedure is intended to perform reasonably well for almost any possible distribution of the errors. The estimates of α and β should be chosen so that the residuals $\hat{e}_i = y_i - (\hat{\alpha} + \hat{\beta}x_i)$ are small. A sensible way to measure their smallness is by means of a weighted sum of the absolute values of the residuals. Rather than choose estimates that minimize $\sum rank(|\hat{e}_i|)|\hat{e}_i|$, we choose them to minimize Equation 15 [24].

$$\sum_{i=1}^{n} w_i(R|\hat{e}_i|) = \sum_{i=1}^{n} \left[R(\hat{e}_i) - \frac{n+1}{2}\right] \hat{e}_i \quad (15)$$

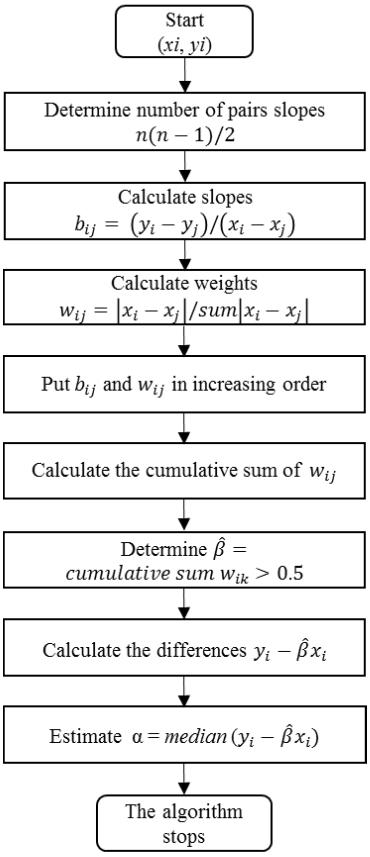


Fig. 9: Nonparametric regression algorithm

Through the algorithm of Figure 9, 190 pairwise slopes were calculated,each slope was assigned a weight w_{ij}, the value of the cumulative sum of the weights that exceeds (½) is 0.0129 and this value corresponds to the estimator$\hat{\beta}$.The 20 differences $y_i - \hat{\beta}x_i$were calculated, $\alpha = 0.5394$was obtained from the median of these differences.Finally, in Equation 16 the regression model is presented.

$$Looplength = 0.5394 + 0.0129 * (Stitchcamsetting) \quad (16)$$

V. Results

Once the study was developed, the adequacy of the regression models was verified.The mean absolute deviation (MAD), the coefficient of determination R^2 and the mean squared error (MSE) were used as prediction criteria.

Table 4. Comparison of methods

METHOD	$\hat{\alpha}$	$\hat{\beta}$	R^2	MAD	MSE
Least Squares	0.5213	0.0131	**0.9626**	0.0122	0.00022
Nonparametric Regression	0.5394	0.0129	0.9463	0.0119	0.00025
Least Absolute Deviations	0.5427	0.0127	0.9316	0.0126	0.00024
M-Regression	0.5247	0.0130	0.9524	**0.0119**	**0.00022**

Table 4 shows the comparison of the coefficients obtained through the four regression methods, as well as fitting quality criteria.As can be appreciated, the best method is the *M-Regression*when MSE and MAD are used as criteria, when considering information from the R^2 coefficient, the best method is*Least Squares*.A widely used measure for a regression model is the R^2, in fact, the four methods have a significant coefficient of determination, greater than 0.93, however, research by [26] and [27] demonstrates that the best model, as indicated by this criteria, does not necessarily result in lower MSE values. Consequently, the best model was selected as indicated by MSE and MAD prediction criteria, and *M-Regression* was found to be the method with the best performance for predictive purposes.

With the above, it is possible to conclude that the intercept of the straight line is 0.5427, for each unit of increment in the cam position of the knitting machine, the loop length will increase 0.0130centimeters, considering Jersey knit fabric.

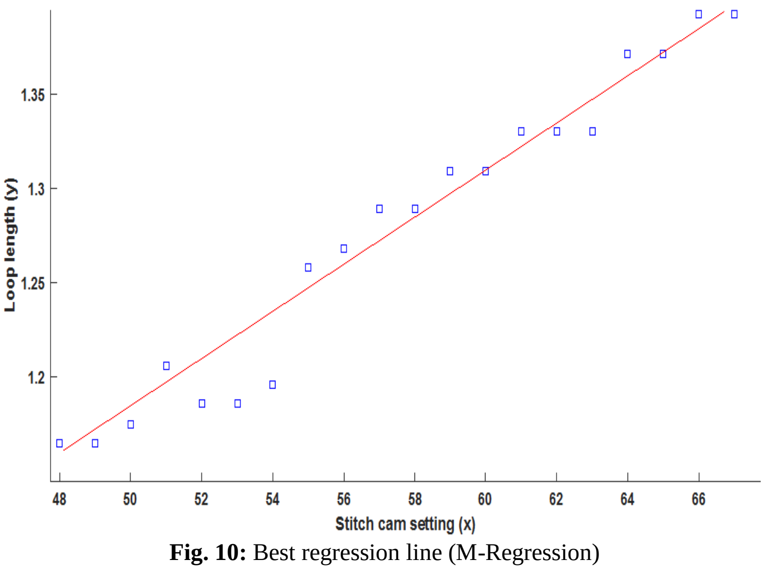
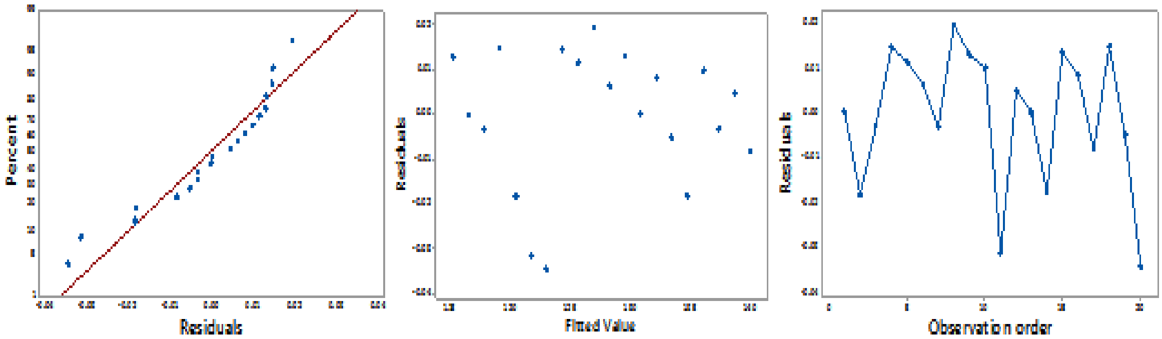


Fig. 10: Best regression line (M-Regression)

After fitting the regression model, it is necessary to analyze the residuals.The analysis of the residuals allows to verify: the assumption that the errors are approximately normally distributed, with constant variance and independence.In Figure 11.a) the probability plot is presented, the residuals fit to the straight line considerably, however, the *Anderson-Darling* test was conducted,because the *p-value* is 0.075, which is greater than the significance level of 0.05, therefore, it is possible to conclude that the residuals of loop length follow a normal distribution.



a) Normality b) Constant Variance c) Independence

Fig. 11: Model assumptions

To verify the assumption of constant variance, residuals versus fits plot was used, Figure 11.b) shows the distributed data without any clear pattern. Finally, residuals versus order plot was used to verify the assumption that the residuals are independentfrom one another, the plot is presented in Figure 11.c).The observations in the plot do not follow a clear pattern, however, to complement this assumption, the *Durbin Watson* statistic test was used to test the presence of autocorrelation in the errors the regression model. Since the statistic $d = 1.79$is greater than the upper limit$d_u = 1.41$, no correlation exists.

VI. Conclusion

Four different statistical models were developed and compared for the prediction of the loop length.Twenty sample knitted fabrics on an industrial knitting machine were manufactured, single jersey knitted fabric was selected for this study.The study was carried out in a small and medium-sized company in the South of Guanajuato.

Knowing this parameter during the knitting process is very important, because of this parameter depend the dimensions (length, width and weight) of the canvas, as well as the structural properties.

In this work, we used the most popular method called least squares,however, this method has weaknesses, so also, alternative regression methods were used, such as, M-regression, nonparametric regression and least absolute deviations. The model obtained through the LAD method only required three iterations to find the estimates, as a characteristic of this method, the best regression line passes through two of the data points, (49,1.165) and (62,1.330). The prediction model of the loop length obtained through the nonparametric regression method is based on the idea of using the ranks of numbers instead of the numbers themselves, the calculations are simple, but at the same time, the algorithm generated a large amount of information.The best model was obtained through the *M-Regression*method; this algorithm required six iterations for finding the estimators, each method was evaluated using MSE, MAD, and R^2 fitting criteria to verify the performance of the different models.

With the regression model it is possible to determine to what extent the canvases acquire the main dimensions;when the level in the stitch cam increases, the length of yarn in each column also increases and therefore fiber consumption is higher.As future work is considered, develop a quality system that has as a fundamental basis to control the parameter of the loop length during the knitting process in the rectilinear machines.

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