Fuzzy Least-squares Linear Regression Approach for Fatigue Life Estimation of Die-Marked Drill pipes

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Abstract— One of the major problems for the soil project contractors is proper forecasting the Drill pipe fatigue damage. Drill pipe fatigue damage occurs under cyclic loading conditions due to, for instance, rotation in a dogleg region [5]. The present paper used method with linear regressions having independent variables or fuzzy dependent and independent variables to forecast Drill pipe fatigue damage in Iran. The study uses the Least-Squares Linear as an operational criterion. The data required to build the model were collected from observations of 45 places in various projects in Iran. The Mathematica 6 and Lingo 8 soft wares were used to make and implement the model. Comparisons of the model's data with those provide by the manufacturers indicates a significant reduction of error on one hand and the ability of the model in accurately estimating the Drill pipe fatigue damage on the other.

Keywords— Fuzzy linear regression، Fuzzy least-squares Drill pipe, Fatigue damage.

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I. Introduction

Failure due to fatigue is a very costly problem in oil and gas industry [3]. Drill pipe fatigue damage occurs under cyclic loading conditions due to, for instance, rotation in a dogleg region. Usually, failure mechanisms develop in the transition region of the tool joints and the die-marks due to gripping systems intensify it. Many investigators have previously addressed this problem, but its frequency of occurrence is still excessive. Torque and tension can be correctly predicted but computations of fatigue duration are still approximate.

Fatigue is by far the most common cause of drill stem failure. It can occur at stress levels far below normal operating stress in most drill stem components. Fatigue is a complex mechanism that is affected by many factors, such as drilling environment, dogleg severity, axial loads and etc [5].

Fatigue damage accumulates over extended use, so sudden failure may occur any time the drill string is under load.

The followings are the reasons for the use of linear regression techniques for modeling the estimated Drill pipe fatigue damage in the Iranian construction industry. The artificial intelligent models require a variety of historical data for training and evaluation. In this case historical data include real-time efficiency under various operating and project conditions. Given the geographical spread of the projects, the collection of a vast amount of performance-related data is time-consuming, laborious and sometimes impossible task indeed. A linear regression model however can be applied with a comparatively less data requirement.

In this paper, attempt is made to apply an extension one of regression approaches with real numbers. The proposed methodology consist the least-squares method. The proposed method is assumed to be appropriate alternative approaches to productivity estimation of bulldozers in earthwork projects.

The remainder of this paper is outlined as follows: The next section introduce the method used to compute the productivity of bulldozers. The application of the algorithm to collected data set is presented in section 3. In section 4 illustrated this method in detail for the specifically-defined problem of this paper then Computational results are represented. Conclusions and future researches which are presented in section 5.

II. Fuzzy Least-Squares Linear Regression

The rationale for the Fuzzy Theory is briefly reviewed before developing fuzzy Least-squares Linear Regression as follows:

A. Fuzzy arithmetic

First, we briefly review the rationale for the Fuzzy Theory before the development of fuzzy Least-squares Linear Regression as follows:

Definition 3.1. A Fuzzy set M in a universe of discourse *X* is characterized by a membership function $\mu_M(x)$ which associates with each element *x* in *X*, a real number in the interval [0, 1]. The function value $\mu_M(x)$ is termed the grade of membership of *x* in M [12]. The present study uses triangular Fuzzy numbers. A triangular Fuzzy number, M, can be defined by a triplet $M=(\alpha,\beta,\delta)_T$. Its conceptual schema and mathematical form are shown by Eq. (1).

$$\mu_{\tilde{a}}(x)=\begin{cases}0 & x\le\alpha\\ \dfrac{x-\alpha}{\beta-\alpha} & \alpha\prec x\le\beta\\ \dfrac{\delta-x}{\delta-\beta} & \beta\prec x\le\delta\\ 1 & x\succ\delta\end{cases} \qquad (1)$$

Definition 3.2. Let $M=(\alpha,\beta,\delta)_T$ and $N=(\chi,\gamma,\lambda)_T$ be two triangular Fuzzy numbers, then the vertex method is defined to calculate the distance between them, as Eq. (2):

$$d_T^2(X,Y)=(\alpha_x-\alpha_y)^2+(\beta_x-\beta_y)^2+(\delta_x-\delta_y)^2 \qquad (2)$$

The basic operations on Fuzzy triangular numbers are as follows [13]:

For approximation of multiplication [13]:

$$(\alpha,\beta,\delta)_T\times(\chi,\gamma,\lambda)_T\cong(\alpha\times\chi,\beta\times\gamma,\delta\times\lambda)_T \qquad (3)$$

For addition:

$$(\alpha,\beta,\delta)_T+(\chi,\gamma,\lambda)_T\cong(\alpha+\chi,\beta+\gamma,\delta+\lambda)_T \qquad (4)$$

Given the above-mentioned Fuzzy theory, the proposed Fuzzy Least-squares Linear Regression Approaches is then defined as follows:

B. Developed version of the approximate-distance fuzzy least-squares

This is basically an extension of and improvement on the model applied by Yang and Lin [11] above which is expressed by the FLR model as follows:

$$FLR\quad Y_i=A_0+A_1X_{j1}+\cdots+A_kX_{jk},\quad j=1,2,\ldots,n, \qquad (5)$$

Where outputs $Y_j=(\alpha_{Y_j},\beta_{Y_j},\delta_{Y_j})_T$, inputs $X_{ji}=(\alpha_{X_{ji}},\beta_{X_{ji}},\delta_{X_{ji}})_T$ and parameters $A_j=(\alpha_{a_j},\beta_{a_j},\delta_{a_j})_T$ $\forall i=1,2,\ldots,k$, $j=1,2,\ldots,n$ so that the notion $M=(\alpha,\beta,\delta)_T$ is triangular fuzzy number.

The difficulty in treating model (5) of fuzzy input-output data is that A_iX_{ji} may not be of triangular fuzzy number. Although the product of two triangular fuzzy numbers may not be a triangular fuzzy number, Dubois and Prade [14] presented an approximation form. Based on this analytical framework, Yang and Ko [10] further developed the model presented by Dubois and Prade and suggested an approximation type of fuzzy least-squares. What follows here is the application of approximation to present an algorithm for parameter estimation of the FLR model (5).

By assuming $M=(\alpha,\beta,\delta)_T$ and $N=(\chi,\gamma,\lambda)_T$ to be two triangular Fuzzy numbers; therefore, by using the basic operations on Fuzzy triangular numbers, it will be possible to express an approximation of multiplication and addition as follows: $A_0+A_1X_{j1}+\cdots+A_kX_{jk}\cong(\tilde{\alpha}_j,\tilde{\beta}_j,\tilde{\delta}_j)_T$

where

$$\tilde{\alpha}_j=\tilde{\alpha}_{a_0}+\sum_{p=1}^{k}(\tilde{\alpha}_{a_p}*\tilde{\alpha}_{x_{jp}})$$

$$\tilde{\beta}_j=\tilde{\beta}_{a_0}+\sum_{p=1}^{k}(\tilde{\beta}_{a_p}*\tilde{\beta}_{x_{jp}})$$

$$\tilde{\delta}_j=\tilde{\delta}_{a_0}+\sum_{p=1}^{k}(\tilde{\delta}_{a_p}*\tilde{\delta}_{x_{jp}})$$

Since $A_0+A_1X_{j1}+\cdots+A_kX_{jk}$ is of approximate triangular fuzzy number, the distance d_T^2 is defined on two triangular fuzzy numbers. Thus, the following objective function is considered:

$$U(A_0,A_1,\ldots,A_k)=\sum_{j=1}^{n}d_T^2(Y_j,A_0+A_1X_{j1}+\cdots+A_kX_{jk})$$

$$=\sum_{j=1}^{n}\frac{1}{3}\left[(\alpha_{y_j}-\tilde{\alpha}_j)^2+(\beta_{y_j}-\tilde{\beta}_j)^2+(\delta_{y_j}-\tilde{\delta}_j)^2\right]$$

The minimization of $U(A_0, A_1, ..., A_k)$ over A_i subject to $0 \le \alpha_{a_i} 1, \quad 0 \le \beta_{a_i} \le 1, \quad 0 \le \delta_{a_i} \le 1, \quad ,i = 0,1,2,\cdots,k$ is called the developed version of the approximate-distance fuzzy least-squares method.

The regression analysis is commonly presented in actual practical cases where there is heterogeneity of observations. In order to overcome the heterogeneous problem, the cluster wise fuzzy regression analysis [15] is adopted. Fuzzy clustering that has been widely studied and applied in a variety of substantive areas [15]-[18], is applied to ward off the heterogeneous problems. Cluster wise fuzzy regression embeds fuzzy clustering into fuzzy regression model fitting at each step in the iterations. Given a data set $\{(X_{j1}, ..., X_{jk}, Y_j), j = 1,2,...,n\}$, a cluster wise FLR model is fitted to the data set $Y_j = A_0 + A_1 X_{j1} + \cdots + A_k X_{jk}, \quad j = 1,2,...,n,$ Let $\mu_{ij} \in [0,1]$ with $\sum_{i=1}^{c} \mu_{ij} = 1 \quad \forall j = 1,.2,...,n$. The notation μ_{ij} is used to represent the membership of the jth data point $(X_{j1}, ..., X_{jk}, Y_j)$ belonging to the ith class. After embedding μ_{ij} to the objective function J, one has a cluster wise objective function as follows:

$$U(\mu, A_{0i}, A_{1i}, ... A_{ki}) = \sum_{i=1}^{c} \sum_{j=1}^{n} \mu_{ij}^m d_T^2 (Y_j, A_{0i} + A_{1i} X_{j1} + \cdots + A_{ki} X_{jk})$$

Where, $m \ge 0$ is the index of fuzziness. According to the Lagrange multiplier, one has the necessary condition for μ_{ij} with

$$\mu_{ij} = \left(\sum_{p=1}^{c} \frac{ \left(d_{LR}^2 (Y_j, A_{0i} + A_{1i} X_{j1} + \cdots + A_{ki} X_{jk}) \right)^{1/(m-1)} }{ \left(d_{LR}^2 (Y_j, A_{0p} + A_{1p} X_{j1} + \cdots + A_{kp} X_{jk}) \right)^{1/(m-1)} } \right)^{-1}, \quad \begin{matrix} i = 1,2,...c, \\ j = 1,2,...n \end{matrix}$$

Outliers always have immense effects in model fitting, especially in regression. e.g., they decrease the accuracy of estimation. Thus, robust regression and outlier detection become an important consideration. Robustness seems to be more important in fuzzy regression. However, the cluster wise fuzzy regression as applied here presents the restriction of membership functions with $\sum_{i=1}^{c} \mu_{ij} = 1 \quad \forall j = 1,.2,...,n$ so that the results will be deteriorated due to outliers and noise. An easy way of modifying this cluster-wise fuzzy regression into detect and tolerate noise and outliers is to apply the idea of Dave's noise cluster [19]. A noise cluster is the one, which contains noise points or outliers so that all the points have equal a priori probability of belonging to a noise cluster [11]. Assume that the cluster (c + 1) is a noise cluster, then the objective function can be expressed as follows:

$$U^0(\mu, A_{0i}, A_{1i}, ... A_{ki}) = \sum_{i=1}^{c} \sum_{j=1}^{n} \mu_{ij}^m d_{ij}^2$$

where

$$d_{ij}^2 = \begin{cases} d_T^2 (Y_j, A_{0i} + A_{1i} X_{j1} + \cdots + A_{ki} X_{jk}), & i = 1,2,...c, \quad j = 1,2,...n \\ \tau^2 & i = 1,2,...c, \quad j = 1,2,...n \end{cases} \quad (6)$$

$$\tau^2 = \lambda \left(\frac{ \sum_{i=1}^{c} \sum_{j=1}^{n} d_{ij}^2 }{ nc } \right), \quad \lambda \succ 0 \quad a\, cons\tan t.$$

The necessary condition for minimization of U^0 over μ is

$$\mu_{ij} = \left(\sum_{p=1}^{c+1} \frac{ (d_{ij}^2)^{1/(m-1)} }{ (d_{pj}^2)^{1/(m-1)} } \right), \quad i = 1,2,...c+1, \quad j = 1,2,...n \quad (7)$$

C. Fuzzy membership function

We deliberately transform the existing precise values to five-levels, Fuzzy linguistic variables very low (VL), low (L), medium (M), high (H), and very high (VH). Among the commonly used Fuzzy numbers, triangular and trapezoidal fuzzy numbers are likely to be the adoptive ones due to their simplicity in modeling easy interpretations. Both triangular and trapezoidal fuzzy numbers are applicable to the present study. We assume that a triangular fuzzy number can adequately represent the five-level Fuzzy linguistic variables, thus, is used for the analysis hereafter.

As a rule of thumb, each rank is assigned an evenly spread membership function that has an interval of 0.30 or 0.25. Based on these assumptions, a transformation table can be found as shown in Table 1. For example, the Fuzzy variable, very low has its associated triangular Fuzzy number with the minimum of 0.00 mode of 0.10 and maximum of 0.25. The same definition is then applied to another Fuzzy variable Low, Medium, High, and Very High [13].

TABLE 1. Transformation for Fuzzy membership functions.

Rank	grade	Membership function
Very low (VL)	1	(0.00,0.10,0.25)
Low (L)	2	(0.15,0.30,0.45)
Medium (M)	3	(0.35,0.50,0.65)
High (H)	4	(0.55,0.70,0.85)
Very high (VH)	5	(0.75,0.90,1.00)

III. Causes of Failure in Drill String

The main causes of failure in drill string are:

A. Critical Rotary Speed

Rotating equipment has a critical speed which varies with changes in the location of the centre of gravity, mass, alignment between the axis of rotation and gravitational force, and rotational speed. Critical speed problems include bent pipe, bottom hole assembly (BHA) connection failure, fatigue failure, washouts, and severe outer diameter (OD) wear of tool joints and tube sections. The critical speeds are proportional with length and weight of the drill pipes and drill collars and also to Bottom Hole Assembly (BHA).

B. Excessive Tension

When a drill string gets stuck during drilling, operational procedures are applied to release the drill string. These procedures include working the drill string up or down, attempting to rotate the string and pumping mud through the drill bit to aid pipe release. When pulling the string out, by increasing the tension stress from the yield stress of the pipe material, the weakest section of the string or the smaller one become necking. Continuing this situation, will yields to breaking the string from that section.

This type of failure mainly cause in the upper parts of the string that is usually in tension and also bear the tension due to the weight of the string.

C. Fatigue Failure

Fatigue is by far the most common cause of drill stem failure, often taking place in surface notches such as slip cuts, metal tears caused by the pipe turning in the slips, or deep corrosion pits on the pipe internal diameter. It can occur at stress levels far below normal operating stress in most drill stem components.

Two results of fatigue failure are the washout and the twist-off. A washout is a place where a small opening has occurred in the pipe, usually the result of a fatigue crack penetrating the pipe wall, and drilling fluid has been forced through it. Fluid abrasion erodes the metal and enlarges and rounds off the edge of the hole. A twist off is usually caused by a fatigue crack extending around the pipe and causing the pipe to break.

Several studies confirmed that washouts occurred near the end of the Miu, closest to the tube body, the most highly stressed area of the drill pipe during drilling and the most exposed to fatigue failure [5].

Fatigue, by definition is the phenomenon in which a repetitively loaded structure fractures at a load level less than its ultimate static strength. For instance, a steel bar might successfully resist a single static application of a 300 KN tensile load, but might fail after 1,000,000 repetitions of a 200 KN load.

D.Fatigue Failure

Failure due to fatigue in drill pipes can be categorized in three groups:

- ***Pure fatigue:*** break with no previous visible cause,
- ***Corrosion fatigue:*** break due to a pitting in a corrosive environment,
- ***Notch fatigue***: break because of a mechanical cut or notch.

E. Notch Fatigue

Surface imperfections, either mechanical (such as a notch) or metallurgical, greatly affect the fatigue limit. Aside from the initial distortion of the steel grain structure, a notch concentrates the stresses and speeds the breakdown of the metal structure. If a
notch is within 20 inches of a tool joint, where maximum bending takes place, it can form the nucleus of an early fatigue break. A longitudinal notch is less harmful than a circumferential
(Transverse), which leads to failure.

Some of various surface scratches that can cause drill pipe notch failure are

- Slip marks, cuts and scratches
- Tong marks
- Spinning chain marks
- Down hole notching by formation and junk cuts [5].

IV. Application

A. Data collection

The first priority for developing the linear regression model is collection of data which are usually gathered from the expert's views on factors that influence the pipe failures.

The second phase involved measurements of the real-time efficiency of 45 places in 38 projects during a one year period. Since some of the crucial factors of efficiency are measured qualitatively, data collection was carried out by earth-moving experts to improve the reliability and validity components.

The project activities under various topographic and climatic conditions of Iran were selected randomly to include the variability requirements. The main performance criteria were the effective parameters of pipe failures. By dividing the total project by the number of shift work hours, the effective parameters of pipe failures was calculated as can be seen in follows:

1) *Speed drill string*:

Moved away from the rotary table to drilling pipe. The round tube Kelly a pipe section is six or octagonal tube is transferred to

2) *Weight on Bit:*

Hemo drilling pipes. Saws should be kept in a state of tension resulting in Shvndta buckling pressure due to the failure does not occur. This weight control which includes part of the drill pipe weight weightlifting (Drill Collar) is to be provided. Weight on the bit should be standard maximum weight of about 70% weight drill collar is considered to always neutral point placed in the drill collar.[10]

3) *Neutral point:*

Neutral point in the drilling string to tension and pressure boundaries string is defined. End of the string arrangement (BHA) should always be designed so that this point weights placed on the drill collar.

4) *Viscosity drilling fluid:*

The parameters of the factors related to the mud drilling during the drilling process and control is always set. Be more this factor on the torque pipe's and thus be more shear pipe.

5) *Acidity (PH):*

This factor of the drilling fluid properties related to its value should always be kept in the limit. The standard recommended dose is 7.5 to 11. This factor of the corrosive impact of drilling fluid and have low value, the amount More corrosive pipes that its outcome, appearing avulsion (Pitting) and create tensions Nat focus is on the tube.

6) *The output of the drill in Dubai (GPM):*

This factor determines the amount of outflow of drilling fluid is drilling. The cause significant impact on drilling performance and drill also has a drilling rate.

7) *Output from the drill fluid pressure (Pump Pressure):*

It specifies the operating pump output pressure is drilling (drilling fluid increases Fshyar may be accelerated corrosion.

8) *Temperature:*

The corrosion rate by increasing the temperature increases. (During drilling operations due to current flow and turbulence within the drill pipe and heat is produced by drilling and drilling in the heat transfer will increase the track that can be corrosive.)

9) *Exit Speed scored (Annular Velocity):*

Increase the flow rate will increase corrosion rates.

10) *Mud yield point:*

Increasing the yield point of attraction forces, ie flower or flowers into the mud concentration increases thus more torque tube is shear.

11) *Mud Weight:*

What is the weight percent of most mud scored be more solid particles When Mud in pipe increase circulation and corrosion perforation will ultimately suffer

12) *Formation (Formation):*

When drill pipe during rotation in well, the external surface in contact with the surface uneven and rough formations make up the well wall. Is located. Therefore, the possibilities of creating from scratch environmental erode the wall of the pipe drilling pipe there.

13*) The depth of drilling:*

Drilling Depth maximum depth drilled (drill POSITION) failure occurred at the moment (Failure) is.

B. Developing the linear regression model for pipe failures

Independent variables which have entered the model for estimating the pipe failures included factors such as those described in section A. The Temperature (X8) has four different states such as, Good-Average-Rather poor-Poor. From these four varieties, the type "Good" is considered to be the best state (VH), followed by Average (H), rather poor (M) and Poor (L).

V. Numerical Results

In Sections 2 fuzzy least-squares method have been constructed for the estimation of an FLR model with fuzzy input-output data. In this section some numerical examples are given. From the results in Table 4,5 and 6 it is seen that the parameter estimates and sum of squares of residuals (SSR) from the approximate-distance and interval-distance fuzzy least-squares methods are almost the same.

TABLE 4. Parameter estimates and SSR for the model

No.	Apprximate- distance ($\widetilde{Y}$)		
	$\widetilde{\alpha}_y$	$\widetilde{\beta}_y$	$\widetilde{\delta}_y$
1	0.00	0.10	0.25
2	0.35	0.50	0.65
3	0.00	0.10	0.25
4	0.35	0.50	0.65
5	0.00	0.10	0.25
6	0.00	0.10	0.25
7	0.00	0.10	0.25
8	0.35	0.50	0.65
9	0.00	0.10	0.25
10	0.35	0.50	0.65
11	0.00	0.10	0.25
12	0.15	0.30	0.45
13	0.00	0.10	0.25
14	0.00	0.10	0.25
15	0.15	0.30	0.45
16	0.15	0.30	0.45
17	0.00	0.10	0.25
18	0.15	0.30	0.45
19	0.00	0.10	0.25
20	0.00	0.10	0.25
21	0.35	0.50	0.65
22	0.00	0.10	0.25
23	0.15	0.30	0.45
24	0.00	0.10	0.25
25	0.15	0.30	0.45
26	0.15	0.30	0.45
27	0.15	0.30	0.45
28	0.00	0.10	0.25
29	0.35	0.50	0.65
30	0.00	0.10	0.25
31	0.00	0.10	0.25
32	0.00	0.10	0.25
33	0.00	0.10	0.25
34	0.15	0.30	0.45
35	0.35	0.50	0.65
36	0.00	0.10	0.25
37	0.35	0.50	0.65
38	0.00	0.10	0.25
39	0.00	0.10	0.25
40	0.15	0.30	0.45
41	0.15	0.30	0.45
42	0.15	0.30	0.45
43	0.15	0.30	0.45
44	0.00	0.10	0.25
45	0.15	0.30	0.45

TABLE 5. Catalog productivity and actual productivity

No.	catalog productivity ($\hat{Y}$)	actual productivity (Y)
1	**VL**	**VL**
2	**M**	**VL**
3	**VL**	**VL**
4	**VH**	**M**
5	**VL**	**VL**
6	**VL**	**VL**
7	**VL**	**VL**
8	**H**	**L**
9	**L**	**VL**
10	**VH**	**L**
11	**VL**	**VL**
12	**VL**	**VL**
13	**L**	**L**
14	**L**	**VL**
15	**L**	**VL**
16	**VL**	**VL**
17	**VL**	**VL**
18	**M**	**L**
19	**H**	**M**
20	**L**	**L**
21	**L**	**VL**
22	**L**	**VL**
23	**VL**	**VL**
24	**L**	**L**
25	**L**	**L**
26	**L**	**L**
27	**L**	**L**
28	**VL**	**VL**
29	**L**	**VL**
30	**VL**	**VL**
31	**VL**	**VL**
32	**VL**	**VL**
33	**VL**	**VL**
34	**L**	**VL**
35	**VL**	**VL**
36	**VL**	**VL**
37	**M**	**L**
38	**M**	**L**
39	**VL**	**VL**
40	**VL**	**VL**
41	**L**	**VL**
42	**M**	**L**
43	**L**	**VL**
44	**VL**	**VL**
45	**M**	**L**

TABLE 6. SSR FOR THE MODEL

No.	SSR based on Apprximate- distance $d_T^2\left(Y,\widetilde{Y}\right)$	$d_T^2\left(Y,\hat{Y}\right)$
1	**0**	**0**
2	**0.1475**	**0**
3	**0**	**0**
4	**0**	**0.1475**
5	**0**	**0**
6	**0**	**0**
7	**0**	**0**
8	**0.04**	**0.04**
9	**0**	**0.034167**
10	**0.04**	**0.1475**
11	**0**	**0**
12	**0.034167**	**0.034167**
13	**0.034167**	**0.034167**
14	**0**	**0.034167**
15	**0.034167**	**0**
16	**0.034167**	**0.034167**
17	**0**	**0**
18	**0**	**0.04**
19	**0.1475**	**0.340833**
20	**0.034167**	**0.034167**
21	**0.1475**	**0.04**
22	**0**	**0.034167**
23	**0.034167**	**0.034167**
24	**0.034167**	**0.034167**

25	0	0
26	0	0
27	0	0
28	0	0
29	0.1475	0.04
30	0	0
31	0	0
32	0	0
33	0	0
34	0.1475	0
35	0.034167	0.1475
36	0	0
37	0.04	0
38	0	0.1475
39	0	0
40	0.034167	0.034167
41	0.034167	0
42	0	0.04
43	0.034167	0
44	0	0
45	0	0.04
Sum	**1.233337**	**1.512503**

At the same time measuring the real-time pipe failures of a 45 places, their failure was calculated from the manufacturers' manual data. The failures of these pipes were also calculated by the linear regression models. Calculation of the failures of method including the manuals, regression model and their comparisons with the real-time pipe failures, the deviation were obtained the results of which are described in the following figure 1.

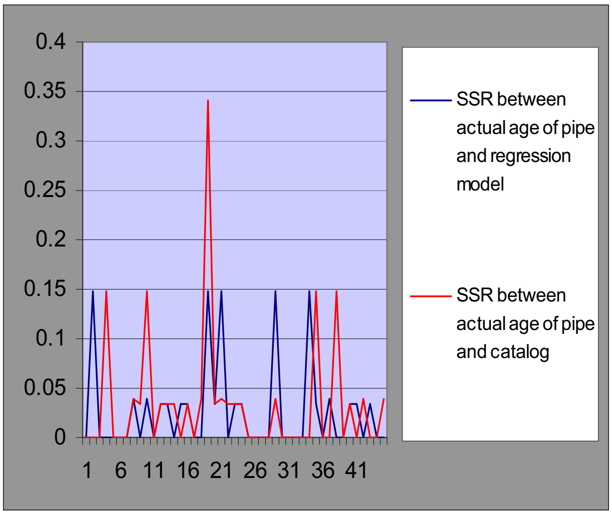

Figure 1. SSR between actual productivity and catalog, with actual productivity and regression model.

VI. Conclusions

In the present study, a Developed version of the approximate-distance fuzzy least-squares is suggested for solving the problem. The application of the fuzzy logic in this study provided a solution which seems to be closer to the real world. Results also indicated that the method used in this investigation presented better answer than the data on pipe failures in industrial Projects which are obtained from the company documents. Under the circumstances where the inputs, outputs and parameters are vague and stochastic, the fuzzy linear regression is preferred to other methods. Furthermore, it would be viable to apply this method in future investigations by using trapezium fuzzy numbers, LR numbers and other related factors to address and solve similar industrial problems.

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APPENDIX

Table 1. Results of variable for the 60 machine

variable / machine	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	VL	H	H	H	VH	VL	VH	VH	VH	VH	VH	VH	VH	VH	H	VH	VH	M	M
2	L	H	M	VH	H	VH	M	VH	H	VH	VH	VL	VL	VH	M	VH	M	H	VL
3	VL	VH	H	VH	VH	VL	VH	H	VH	VH	VH	H	M	VH	H	VH	VH	M	L
4	L	M	M	VH	M	VL	VL	VH	H	M	VH	H	M	H	VH	H	VH	M	VL
5	M	H	H	H	H	VL	M	H	H	H	VH	H	VH	VH	H	H	M	M	VL
6	L	VH	L	M	VH	VH	VH	H	VH	H	VH	VL	M	H	M	H	VH	H	VL
7	M	H	H	H	H	VL	M	H	H	M	VH	M	M	VH	M	M	M	VL	VL
8	H	VH	M	L	H	VH	M	H	H	H	VH	H	VH	H	H	H	M	VL	VL
9	VL	H	H	H	VH	VL	VH	M	VH	VH	VH	M	VH	VH	M	M	VH	H	VL
10	L	M	H	VH	H	VH	VH	H	VH	VH	VH	VL	VL	VH	H	H	VH	M	VL
11	M	H	M	H	VH	VH	M	H	H	H	VH	L	M	H	VH	VH	M	M	VL
12	VL	L	H	VH	H	VL	M	H	H	M	H	VH	M	H	M	H	VL	H	VL
13	L	H	H	VH	VH	VH	VH	VH	VH	H	VH	M	VL	VH	H	H	M	H	VL
14	L	VH	H	VH	VH	VL	VH	M	L	L	VH	M	M	VH	VH	VH	VH	H	VL
15	M	H	M	VH	H	VH	M	VH	H	VH	VH	H	M	VH	H	VH	VH	H	L
16	VL	VH	H	H	VH	VL	M	H	H	M	VH	VL	VH	VH	H	H	VH	VL	VL
17	H	VH	H	VH	H	VH	VH	VH	VH	H	VH	VL	VL	VH	H	VH	VH	H	VL
18	M	H	H	H	VH	VL	VL	M	H	M	VH	VL	M	H	H	M	M	VL	VL
19	L	VH	H	VH	VH	VH	VH	VH	H	VH	VH	VH	M	VH	M	VH	VH	M	M
20	VL	H	M	L	VH	VL	VL	H	H	M	H	VH	VH	VH	M	M	VH	H	VL
21	VL	VH	H	H	VH	VL	VH	VH	VH	H	H	L	VH	M	H	M	VH	M	VL
22	VL	L	H	VH	VH	VL	M	M	H	M	VH	M	M	H	H	H	M	M	VL
23	M	VH	H	VH	VH	VH	VH	H	VH	H	VH	VH	M	VH	H	VH	M	M	L
24	M	VH	H	H	H	VL	M	H	VH	H	VH	VL	M	H	VH	VH	M	M	VL
25	VH	H	H	VH	VH	VH	VH	VH	H	H	VH	VH	M	VH	VH	VH	VH	H	L

26	L	H	M	M	H	VL	M	H	H	L	VH	M	VH	L	H	H	M	VL	VL
27	VL	H	H	H	VH	VH	VH	H	VH	H	H	M	M	VH	VH	M	VH	H	VL
28	VL	L	H	VH	H	VL	M	VH	VH	H	VH	L	VH	VH	H	VH	VH	M	L
29	VL	H	H	H	VH	VL	VH	H	H	M	H	L	M	VH	H	H	VH	M	VL
30	L	VH	H	VH	VH	VH	VH	VH	H	VH	VH	VL	M	VH	H	H	VH	M	VL
31	L	H	H	VH	H	VH	VH	H	VH	H	VH	VL	VL	H	H	H	VH	H	VL
32	L	M	H	VH	H	VL	VH	H	VH	M	VH	VL	M;	VH	VH	M	M	M	VL
33	M	H	M	M	H	VL	M	M	H	H	VH	H	VH	VH	VH	VH	VH	H	L
34	M	M	M	VH	H	VL	VL	VH	VH	H	VH	H	VH	VH	H	VH	VH	M	M
35	L	H	H	H	H	VL	VL	VH	VH	H	H	L	M	VH	H	VH	VH	M	L
36	M	H	H	H	VH	VL	M	VH	H	H	VH	M	VH	VH	M	VH	VH	M	VL
37	L	VH	M	L	VH	VL	VH	H	VH	VH	M	H	M	H	VH	H	VH	H	VL
38	M	H	H	H	VH	VL	VH	VH	H	H	VH	VH	VH	VH	M	H	VH	M	VL
39	M	M	M	VH	VH	VL	VL	H	H	H	H	VH	M	VH	H	VH	VH	H	L
40	VH	H	H	VH	H	VL	VL	VH	VH	H	VH	VH	M	VH	M	VH	VH	M	L
41	L	VH	VH	VH	VH	VL	VH	H	VH	H	VH	VH	M	VH	H	H	M	M	L
42	VL	M	H	VH	H	VL	VH	H	VH	VH	VH	VH	VH	VH	VH	H	M	H	L
43	H	H	H	VH	H	VL	M	M	VH	H	VH	H	M	VH	H	M	VH	VL	VL
44	L	VH	H	VH	VH	VH	VH	VH	VH	H	VH	VL	M	VH	M	H	VH	M	VL
45	VL	H	M	H	VH	VH	M	VH	H	VH	M	VH	VH	VH	M	M	M	H	VL
46	VH	VH	M	L	H	VH	M	VH	VH	VH	VH	VL	VL	VH	M	VH	VH	H	VL
47	M	H	L	M	VH	VH	VL	H	H	VH	VH	VL	VL	VH	M	H	VH	H	VL
48	VH	VH	M	H	H	VL	M	VH	H	VH	VH	VL	VL	H	M	VH	VH	M	VL
49	M	H	M	VH	H	VH	M	VH	H	VH	VH	VL	M	VH	M	VH	VH	H	VL
50	VL	VH	M	H	H	VL	VH	H	M	H	VH	M	VH	VH	VH	H	VH	H	VL
51	L	H	H	VH	VH	VL	M	VH	VH	H	VH	M	VH	VH	H	VH	M	H	VL
52	VH	VH	M	H	H	VH	VH	VH	H	VH	VH	M	M	VH	H	VH	VH	H	L
53	L	M	H	VH	H	VL	M	H	H	M	VH	H	VH	VH	H	VH	VH	M	L
54	M	H	L	H	VH	VL	VH	VH	VH	VH	VH	VL	VL	VH	H	VH	VH	M	VL
55	VL	VH	M	H	VH	VL	VH	H	H	H	VH	H	VH	H	VH	H	VH	M	VL
56	VL	VH	M	H	H	VL	VH	VH	VH	VH	H	VH	VH	VH	VH	VH	M	H	L
57	VH	VH	M	VH	VH	VL	VH	H	H	VH	VH	VH	VH	VH	H	H	M	H	VL
58	L	H	M	VH	H	VH	VH	VH	VH	H	VH	VL	M	VH	VH	H	VH	M	VL
59	M	VH	M	VH	H	VH	VH	H	H	M	VH	VL	VL	H	M	M	VH	H	VL
60	VL	VH	H	H	VH	VL	VH	H	VH	H	H	M	VH	VH	VH	VH	VH	H	L