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Application of Taguchi Method In Health And Safety (Fire Extinguishing Experiment)

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ABSTRACT
The traditional Taguchi method is widely used for optimizing the process parameters of a single response problem. In this paper, Taguchi method is applied to study the effects of five control variables – training, experience, response to alarm, age, and qualification on extinguishing time and percent damage. An L_{16} orthogonal array (OA) was used to accommodate the experiment. ANOVA and F-tests and regression are used to analyze the results. The study indicated that training and experience have the largest effect on the on extinguishing time and percent damage
Key words: ANOVA analyze, Extinguishing time, Fire extinguishing experiment, orthogonal array (OA), percent damage and Taguchi method.

I. Introduction

Taguchi Method or Robust Engineering, developed by Genichi Taguchi, is an approach to Design of Experiments (DOE) for designing products or processes so that they are robust to environmental conditions such temperature and humidity. The objective of Taguchi method is to model responses (and variance) as a function of controllable (and uncontrollable) factor levels, then choose levels of controllable factors to reduce variation transmitted to the response from variation of the controllable factors and of the uncontrollable factors, in another word reduce product variation by choosing levels of the control factors that dampen the effect of the uncontrollable or noise factors. Quality is improved without controlling or removing the cause of variation, instead, we make the product (or process) robust to variation in the noise factors [4], [5], [6]. Noise factor is measured by signal to noise ratio and it is calculated depends on the objective of the experiment. There are three ways the response could be optimized[6]:

Objective Signal to noise ratio

Minimize response (smaller the better) $-10*\log(Sy^2/n)$

Maximize the response (larger the better) $-10*\log(S(1/y^{2)}/n)$

Nominal is best $-10*\log(s^2)$

Multiplied by 10 to put into “deci” “bel” metric, a terminology used in Electrical Engineering. Taguchi suggested that “quality” should be thought of, not as a product being inside or outside of specifications, but as the variation from the target. He defines quality as the losses a product imparts to the society from the time the product is shipped. To quantify quality loss, write T for the target value and Y for the measured value [5], [6]. We want $E(Y) = T$. Write $L(Y)$ for the loss (in dollars, reputation, customer satisfaction, ……) for deviation of Y from T. The loss function is $L(Y) = K(Y-T)^2$
Where, K is some constant. If $E(Y)$ really is T, then $E(L(Y)) = K\sigma^2$, where σ^2 = Var (Y).

If the product is off target, so that $E(Y) = T + d$, then $E(L(Y)) = k(\sigma^2+d^2)$.

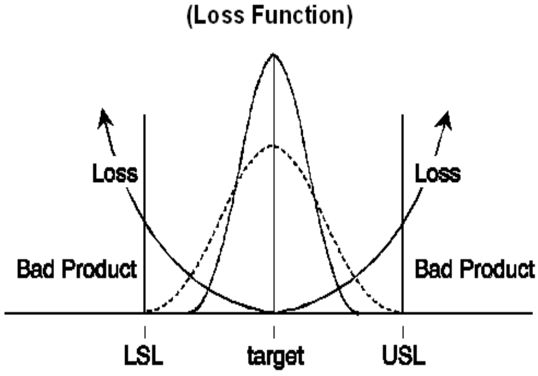

Figure 1. Quality loss function

A Taguchi design, or an orthogonal array, is a method of designing experiments that usually requires only a fraction of the full factorial combinations. An orthogonal array means the design is balanced so that factor levels are weighted equally. Because of the orthogonality, each factor can be evaluated independently of all the other factors, so the effect of one factor does not influence the estimation of another factor.

The Steps followed for Taguchi design are:

1. State your problem and objective
2. List responses, control parameters, and sources of noise
3. Plan the experiment
4. Run experiment and
5. Analyze the experiment and predict improved parameter settings

II. Problem Identification

Fire accidents are common and play an important role amongst major accidents, not only because of their relatively high frequency but also because of their dangerous effects. This makes the control and protection from the fire accidents a vital issue that needs to be studied. Our objective is to determine the effect of employee training, experience, his or her response to alarm, his or her age and qualification and their interactions on how long it takes to extinguish a fire and asses time the percent damage resulted from the fire.

III. Experimental Details

A series of experimental tests were designed to accomplish these objectives and develop baseline for future research. The experiment is conducted by running it at various levels of the factors.

3.1 Determining factors for the study

It was determined the human factors that need to be studies which influence the performance of an employee in using the extinguisher are:

a) Training: it is expected that there is difference between the performance of trained employee and untrained employee.
b) Experience: the employee with more experience may perform better in the extinguishing process. It is worthy to say that the expert employee is already a trained employee.
c) The response to the alarm: the fast response to the alarm may lead us to the best scenarios.
d) Age: the employee age directly affects the physical and mental behavior of the employee in which it affects his performance.
e) Qualification: higher qualification is predicted to lead to better performance.

The response variables to be measured and improved are:

a) Extinguishing time: it is a measure of the employee performance and measured in seconds.
b) Percentage of damage: it will be used to study the relation between the extinguishing time and the damage percentage. It is believed longer extinguisher time leads to more damage.

3.2 Determining the levels of the factors

The Process parameters and their levels used in the experiment summarized in table 1

Table 1. Factors and their levels

Factors	code	Level 0	Level 1
Training	T	Untrained	Trained
Experience	X	without experience	with experience
Response to the alarm	R	>30 sec. (Slow response)	<30 sec. (Fast response)
Age	G	>40	<40 years
Qualification	Q	<Bachelor	>Bachelor

3.3 Taguchi Design

Taguchi Orthogonal Array L_{16} design is used (table 2) which included 5 factors and 16 runs. Columns of L16(2**15) Array are chosen that are 1, 2, 4, 8 and 15. The L16 is a resolution III design which means the main effect is confounding with two factor interaction. The alias structure for L16 is summarized below:

[A] = A - BC - DE - FG - HJ -KL - MN - OP
[B] = B - AC - DF - EG - HK -JL - MO - NP
[C] = **C** - **AB** - DG - EF - HL - JK - MP - NO
[D] = D - AE - BF - CG - HM - JN - KO - LP
[E] = **E** - **AD** - BG - CF - HN - JM - KP - LO
[F] = **F** - AG - **BD** - CE - HO - JP - KM - LN
[G] = **G** - AF - BE - CD - **HP** - JO - KN - LM
[H] = H - AJ - BK - CL - DM - EN - FO - GP
[J] = **J** - **AH** - BL - CK - DN - EM - FP - GO
[K] = **K** - AL - **BH** - CJ - DO - EP - FM – GN
[L] = **L** - AK - BJ - CH - **DP** - EO - FN - GM
[M] = **M** - AN - BO - CP - **DH** - EJ - FK – GL
[N] = **N** - AM -**BP** - CO - DJ - EH - FL – GK
[O] = **O** - **AP** - BM - CN - DK - EL - FH - GJ
[P] = P - AO - BN - CM - DL -EK - FJ - GH

Based on the alias structure, factor C is confounded with AB interaction, Factor E is confounded with AD interaction, factor F is confounded with BD interaction and so on.

The first linear graph for L_{16} (figure 2) assisted in matching factors and column and possible interaction in the experimental matrix [3].

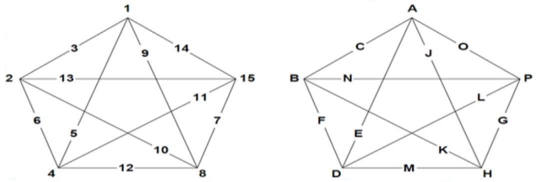

Figure 2. First Linear Graph for L_{16} Array assigns the variables and interactions

No replicates of treatment combinations were done, also the experiment was run in random order to minimize the effect of extraneous variables that might influence the results. Alpha (α) or type I error of 0.05 is used. Alpha is the maximum acceptable level of risk for rejecting a true null hypothesis.

Table 2 L_{16} orthogonal array design matrix and the results

Run #	**Factors**					**Extinguishing Time**	**Damage percentage**
	T	X	R	G	Q	**(seconds)**	**%**
	1	2	4	8	15		
1	0	0	0	0	0	**253**	**84**
2	0	0	0	1	1	**229**	**82**
3	0	0	1	0	1	**219**	**75**
4	0	0	1	1	0	**171**	**73**
5	0	1	0	0	1	**150**	**52**
6	0	1	0	1	0	**125**	**49**
7	0	1	1	0	0	**115**	**18**
8	0	1	1	1	1	**107**	**16**
9	1	0	0	0	1	**160**	**51**
10	1	0	0	1	0	**120**	**26**
11	1	0	1	0	0	**116**	**15**
12	1	0	1	1	1	**96**	**12**
13	1	1	0	0	0	**110**	**20**
14	1	1	0	1	1	**108**	**13**
15	1	1	1	0	1	**96**	**12**
16	1	1	1	1	0	**92**	**8**

3.4 Equipment

- Extinguishers: Class A&B extinguishers will be used. (Foam Extinguisher)
- The burned material: Crib of wooden sticks will be used as a burned material.
- Tray containing heptane to light the fire.
- Personal protective equipment.

3.5 Experiment Assumptions

The experiments are conducted in the same conditions, which mean that the place; the burning material and the extinguishing method are the same in all the trials. In addition to that, the time for starting the extinguishing is the same.

3.6 Experiment Conditions

The test room where the experiment was conducted was closed with the exception of a small opening at the base of the door (Provided for ventilation). The wood cribs description is shown in Table 3.

Table 3*: Wood Description*

CLASS	DIMENSIONS (m)
White Wood	0.5*0.5*0.5

The wood cribs are fixed at 50 cm above floor level. A properly sized tray is placed beneath the crib at 30 faraway from the wood cribs (see Figure 3 and Figure 4). The appropriate heptane starter charge is poured into the tray. The heptane charge is ignited and allowed to ignite the wood crib above [2]. The wood crib is allowed to burn for a period of 30 seconds before extinguishing (see Figure 5).

For each run, the following steps should be followed:

- Put the wood crib at the center of the experiment room, and place a tray full of heptane under it to light the fire.
- Ignite the heptane.
- Start the extinguishing process after 30 seconds from removing the tray.
- Write down the time spent in the extinguishing process, and the percentage of damage in the wood for each trial.

Figure 3: Wood Crib Set up

Figure 4: Wood Crib Dimension

Figure 5*:* Fire before Extinguishing

IV. Experimental Analysis and Discussion

4.1 Graphical Analysis

4.1.1 Graphical Analysis for Extinguishing Time

The main effects plot for extinguishing time (figure 6) shows that extinguishing time decreases for a trained and experienced employee, also it decreases for a response to alarm for less than 30 seconds, concluding that training, experience and response to alarm variables are significant factors while age and qualification factors are not as significant. Qualification could be ignored and it may not be used as factor to improve extinguishing time.

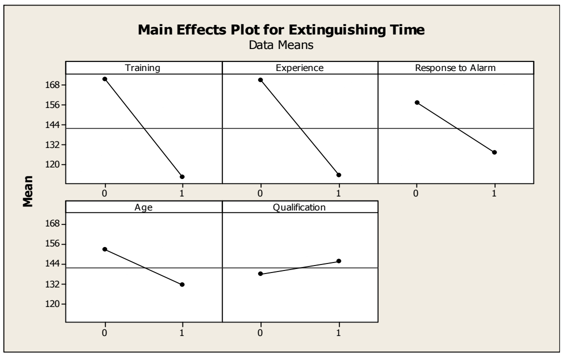

Figure 6. The main effect plot for extinguisher time.

The interactions plot for extinguishing time (figure 7) shows that there is a significant interaction between training and experience. The plot indicates that there is no other interaction exists. We will only include the Training * Experience interaction as a term in the statistical analysis.

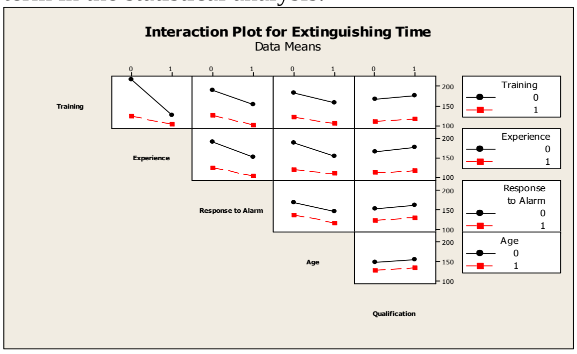

Figure 7. The interaction plot for extinguisher time

4.1.2 Graphical Analysis for Percent Damage

The main effects plot for the percent damage (figure 8) shows % damage decreases for a trained and experienced employee, also it decreases for a response to alarm for less than 30 seconds, concluding that training, experience and response to alarm variables are significant factors while age and qualification factors are not statistically significant.

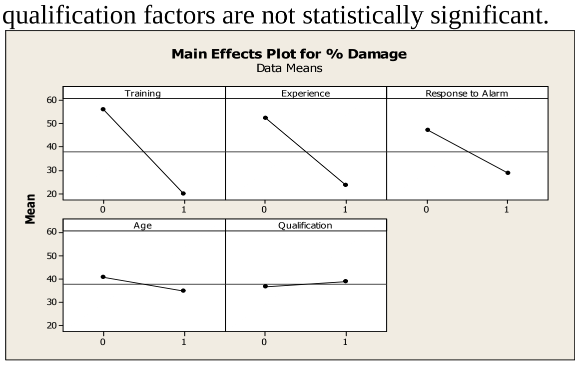

Figure 8. Main Effects Plot for Percent Damage.

The interaction plot (figure 9) shows that there is a significant interaction between training and experience, and between age and qualification. We will include the training * experience and age qualification interactions as terms in the statistical analysis.

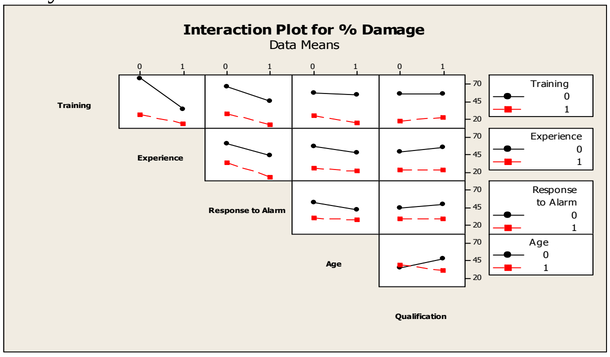

Figure 9. Interactions plot for percent damage

4.2 Statistical Analysis

ANOVA or analysis of variance and multiple regression statistical methods were used to analyze the data generated by our experiment. ANOVA is useful for determining the influence of any giving input parameter from a series of experimental results for the fire experiment. In general, ANOVA compares the variation between groups and the variation within samples by analyzing their variances. It partitions the total variation into its appropriate components[1].

Total variance = between groups variance + variance due to the errors

It follows that: Total sum of squares (SST) = Sum of squares between the groups (SSG) + Sum of squares due to the errors (SSE)

Where **SST** = Total Sum of Squares; **SSG** = Treatment Sum of Squares between the groups; **SSE** = Sum of Squares of Errors. Just think of 'sums of squares' as being a measure of variation. The method of measuring this variation is **variance**, which is standard deviation squared.

There are 3 assumptions for the ANOVA Statistical F-test to be valid which involve the ε_{ij}'s (the error terms) and are summarized below:

1. The ε_{ij}'s are normally distributed.
2. The ε_{ij}'s have mean zero and a common variance, σ^2.
3. The ε_{ij}'s are independent across observations.

Similar to Analysis of variance (ANOVA), multiple linear regression is used to model the relationship between response variables and one or more independent variables and variables. The β_i are the regression parameters and ε is an error. The least square regression method is used for fitting model.
Similar to Analysis of variance (ANOVA), multiple linear regression is used to model the relationship between response variables and one or more

independent variables and their relevant interactions [1]. The model for the multiple regression equation is: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \dots\dots\dots \beta_n X_n + \varepsilon$

Where y is the response or the dependent variable and are the independent X_1, X_2, X_3, X_4 ....and X_n are independent variables. The β_i are the regression parameters and ε is an error. The least square regression method is used for fitting model.

4.2.1 Statistical Analysis for Extinguishing Time

Statistical outputs for extinguishing time are summarized in table 4 and 5. Regression analysis provides the coefficients for the factors and their p-values and an analysis of variance table. The order of the coefficients by absolute value indicates the relative importance of each factor to the response; the factor with the biggest coefficient has the greatest impact. The sequential sums of squares in the analysis of variance table also indicate the relative importance of each factor; the factor with the biggest sum of squares has the greatest impact.

Table 4. Regression analysis for Extinguishing Time .

The regression equation is:				
Extinguishing Time = 240 - 95.0 Training - 93.8 Experience - 30.4 Response to Alarm - 21.4 Age + 7.87 Qualification + 72.3 T*X				
Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	**239.938**	**7.725**	**31.06**	**0.000**
Training	**-95.000**	**8.258**	**-11.50**	**0.000**
Experience	**-93.750**	**8.258**	**-11.35**	**0.000**
Response to Alarm	**-30.375**	**5.839**	**-5.20**	**0.001**
Age	**-21.375**	**5.839**	**-3.66**	**0.005**
Qualification	**7.875**	**5.839**	**1.35**	**0.210**
T*X	**72.25**	**11.68**	**6.19**	**0.000**
S = 11.6789 R-Sq = 96.9% R-Sq(adj) = 94.8%				

Table 5. Analysis of Variance for Extinguishing Time

Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	6	38133.9	6355.6	46.60	0.000
Residual Error	9	1227.6	136.4		
Total	15	39361.4			
Source	DF	Seq SS			
Training	1	13865.1			
Experience	1	13282.6			
Response to Alarm	1	3690.6			
Age	1	1827.6			
Qualification	1	248.1			
T*X	1	5220.1			

The regression analysis shows that the P-value for Training, Experience, Response to Alarm, Age, and the Training*Experience interaction are 0, 0, 0.001, 0.005, and 0 respectively which are much smaller than Alpha of 0.05, indicating statistical significance, while the P-value for Qualification is 0.21 which is greater than Alpha of 0.05, indicating non statistical significance.

The prediction equation is:

$Y_{Time} = 240 - 95X_T - 93.8X_X - 30.4X_R - 21.4X_G + 7.87\,X_Q + 72.3X_TX_X \dots$ (Equation (1))

The residual plot (figure 10) indicates that there is no violation of the analysis of variance assumptions. The residuals are normally distributed, the residuals have equal variances, and the residual are independent. This concludes that our model is valid.

4.2.2 Statistical Analysis for Percent Damage

Statistical outputs for percent damage are summarized in table 6 and 7. The regression analysis shows that the P-value for training, experience, response to alarm, training*experience interaction, and age*qualification interaction are 0, 0, 0, 0, and 0.004 respectively which are much smaller than Alpha of 0.05, indicating statistical significance, while the P-value for age, and qualification are 0.056 and 0.379 respectively which are greater than Alpha of 0.05, indicating non statistical significance.

Table 6. Regression analysis for % Damage.

The regression equation is				
% Damage = 84.1 - 52.5 Training - 44.8 Experience - 18.5 Response to Alarm + 4.75 Age + 13.3 Qualification + 32.0 T*X - 21.5 G*Q				
Predictor	Coef	SE Coef	T	P
Constant	84.125	3.793	22.18	0.000
Training	-52.500	3.793	-13.84	0.000
Experience	-44.750	3.793	-11.80	0.000
Response to Alarm	-18.500	2.682	-6.90	0.000
Age	4.750	3.793	1.25	0.246
Qualification	13.250	3.793	3.49	0.008
T*X	32.000	5.365	5.96	0.000
G*Q	-21.500	5.365	-4.01	0.004
S = 5.36482 R-Sq = 98.1% R-Sq(adj) = 96.4%				

Table 7. Analysis of Variance for % Damage.

Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	7	11659.5	1665.6	57.87	0.000
Residual Error	8	230.2	28.8		
Total	15	11889.8			
Source	DF	Seq SS			
Training	1	5329.0			
Experience	1	3306.3			
Response to Alarm	1	1369.0			
Age	1	144.0			
Qualification	1	25.0			
T*X	1	1024.0			
G*Q	1	462.3			

The prediction equation is:

Y_{Damage} $=84.1–52.5X_T –44.8X_X –18.5X_R+ 4.75 X_G+ 13.3 X_Q+32X_T X_X –21.5X_GX_Q$ ….. (Equation (3))

The residual plot (figure 11) indicates that there is no violation of the analysis of variance assumptions. The residuals are normally distributed, the residuals have equal variances, and the residuals are independent. This concludes that our model is valid.

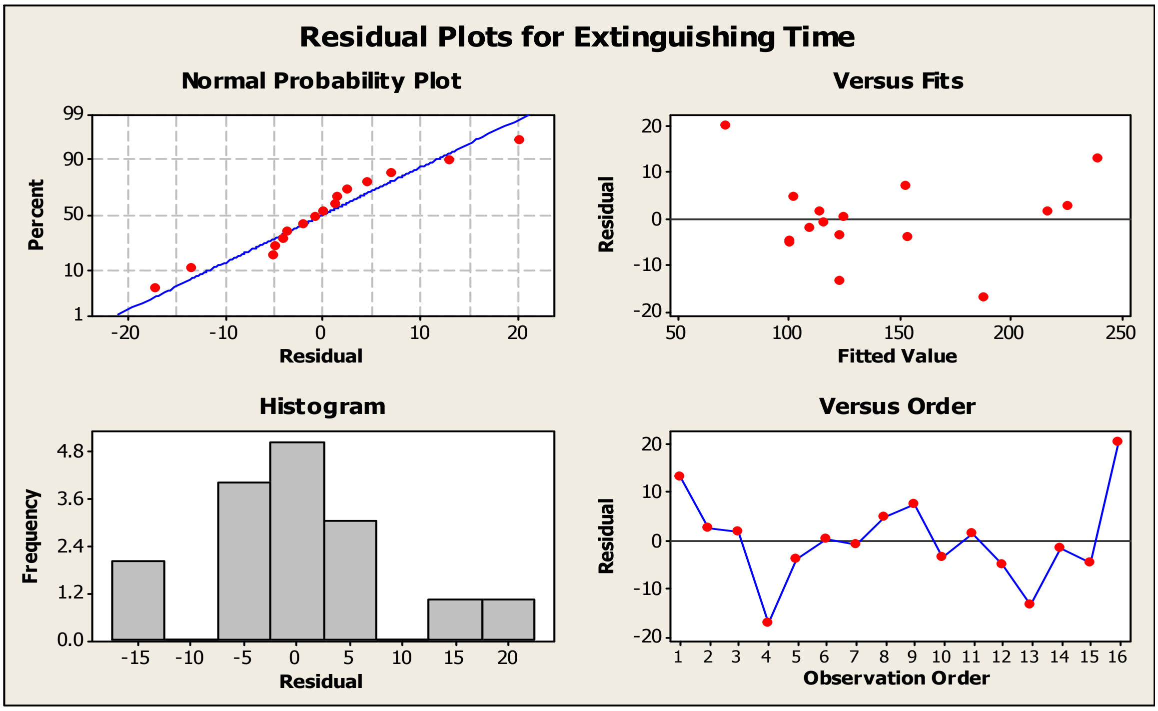

Figure 10. Residual analysis for extinguishing time

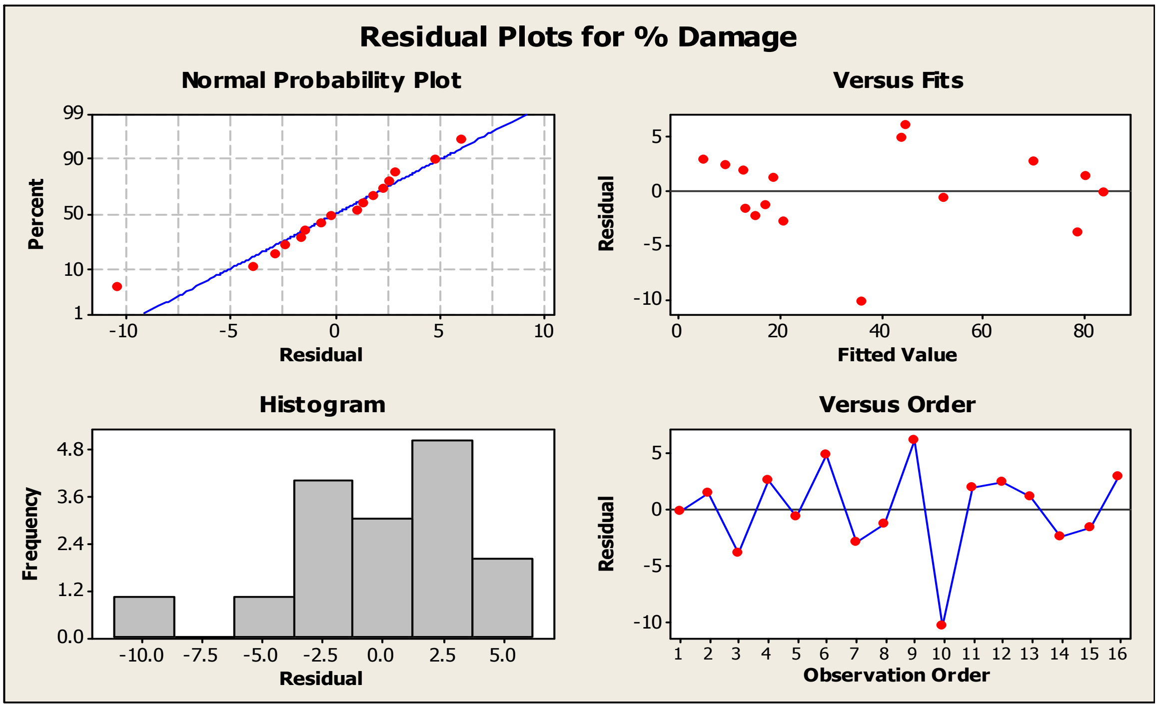

Figure 11. Residual analysis for % damage model

4.3 Relation between the time of extinguishing and the damage :

Correlations: Extinguishing Time,% Damage

Pearson correlation of Extiguishing Time and % Damage = 0.945
P-Value = 0.000

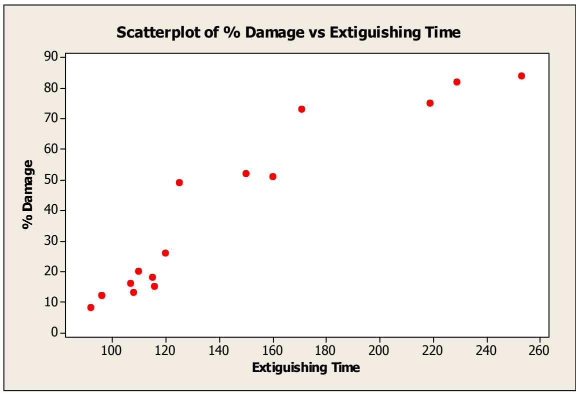

Figure 1 : Extinguishing Time vs Damage Percentage

Figure 12 clarifies the relation between the time of extinguishing and the damage percentage. It is obvious that the damage percentage increase with increasing the time. From the results in the last section, it is concluded that the training, the experience , the response to alarm and the interaction between the training and the experience have the most influence in decreasing the percentage of damage, the age has small influence and the qualification approximately has no influence.

V. Conclusions

Our goal is to decrease extinguishing time and percent damage, the factor levels should be set to that produce the lowest mean. Examining the main effects plots and interaction, the factor levels that decrease extinguishing time and percent damage are summarized in table below

Factors	Level
Training	1
Experience	1
Response to Alarm	1
Age	1
Qualification	1

In conclusion:

a) The training has the highest effect in regard of the performance of the employees in fire extinguishing.

b) The experience factor is ranked in the second stage according to its effect in the performance of the employee in fire extinguishing.

c) The interaction between the training and the experience was also a significant factor.

d) The age has small affect in the performance of the employees in fire extinguishing.

e) The qualification's effect on the performance of the employees in fire extinguishing can also be neglected.

A trained employee, less than 40 years of age, with a bachelor degree and experience, and with fast response leads to the best result in extinguishing time and percent damage.

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