Tabatabaei et al., J Fashion Technol Textile Eng 2014, 2:3
http://dx.doi.org/10.4172/2329-9568.1000113

Journal of Fashion Technology & Textile Engineering

Research Article

A SCITECHNOL JOURNAL

Modeling the Performance Properties on Woolen Hand-knotted Carpets using Response Surface Methodology

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Abstract

In this study, the main purpose is to predict the performance properties of woolen hand-knotted carpets using response surface methodology (RSM). We have considered the thickness loss of surface pile yarns (TL) and compression toughness index (TI) as representative of the compression properties, and color difference index of pile yarns (ΔE), tuft size index (TS) and evenness of texture index (ET) as representative of the appearance characteristics. Eighteen woolen hand-knotted carpet samples with different structural specifications were produced. The carpet samples were subjected to 4000, 8000 and 12000 drum revolutions (wear factor) using a Hexapod tumbler tester. Meanwhile, performance properties of samples were investigated in original and worn out carpet samples. Factorial experimental design and response surface method were applied for modeling of each performance property. To optimize some initial models, the Box-Cox transformation was used. In addition, contribution of different variables was determined. The models showed a desirable fit and high adjusted R2 values were resulted. The ANOVA test showed that the obtained models are valid at 5% level significant.

Keywords

Factorial design; Performance properties; Hand-knotted carpet; Modeling; Response surface method

Introduction

Basically, the weaving methods of hand-knotted carpet are the same as procedures used to be hundreds years ago. Only the structures and work technology of the looms have a little change over time. In recent years, the hand-knotted carpet industry has revealed significant improvement and development in appropriate areas such as variety of colors and sizes, standardization, delivery time and the ability to compete with machine-made products. Commonly, in this cut-pile carpet, pile yarns are tied on pairs of warp threads under two knot types, symmetric (Turkish) or asymmetric (Persian) knots that are shown in Figure 1 [1-3].

The lifetime of a carpet is usually determined by deterioration in its appearance and mechanical performance of surface pile yarns in usage. Surface pile yarns are mainly exposed to forces among axial compression, bending, and extension during such human daily activities like standing and walking and also static and dynamic pressure by massive goods such as moving furniture and other household goods [4,5].

Often, primary studies were considered the dynamic mechanical properties of carpets' pile yarns under compressive load. The carpets' compression characteristics such as compressibility and thickness loss measured under or after static and dynamic loading tests [2,5-8]. In this context, several theoretical models were presented by few researchers which the last one has been based on elastic-stored energy to evaluate the compression behavior of cut-pile carpets [9]. Furthermore, other dynamic-compression properties of carpets' pile yarns are characterized by several unique features including compressive modulus in stress-strain compression curve, compressive and recovery energy and energy absorption or hysteresis effect [10,11]. Norton et al. [12] reported that proper compression behavior and mechanical reaction of pile yarns will be effective to better perceived comfort in the human activities on carpet.

Some of the researchers have investigated the main properties of hand-knotted carpets. Panti et al. [1] investigated resiliency, compressibility, thickness loss, abrasion cycles and durability factor as performance or functional properties of carpet samples and indicated that the knot density has significant influence to determine the majority of these properties. Mirjalili and Sharzehee [2] determined the thickness recovery index to investigate the effect of wool quality, knot density and pile height of carpet samples (with Persian knot) under static loading. So, it was found that different structural parameters of carpets, particularly knot density and pile height, and also pile yarn specifications were clearly effective to determine compression properties and thus performance properties of carpets [2,5-7,13].

Recent research have often emphasized that loss of appearance specifications of surface pile yarns in carpet can considerably reduce its useful life. Namely, appearance stability of woven carpets has been a great problem in the carpet industry for years. Perceived changes in carpet appearance are mostly the combined effects of soiling and changes in color and surface texture. Image analysis and techniques of digital image processing have shown great potential as an automated approach for quantitative evaluation of carpet appearance changes [5,14-17]. Onder and Berkalp [8], and Wu et al. [15] investigated the effects of main structural specifications on texture retention and some

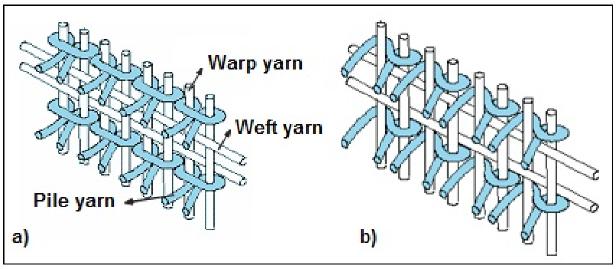

Figure 1: Profiles of two types of hand-knotted carpet knot; (a) symmetrical (Turkish) knot and, (b) asymmetrical (Persian) knot.

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Received: August 12, 2013 **Accepted:** September 27, 2014 **Published:** October 01, 2014 doi:http://dx.doi.org/10.4172/2329-9568.1000113

quality characteristics in original and worn out carpets. Here, it was also found that specifications of pile material, knot density and pile height can be considered as critical construction factors of carpets to achieve the desirable useful life.

In this study, we considered that five categories of properties which possess the highest degree of influence on the useful life of carpets as the performance properties of hand-knotted carpets and applied them in statistical analysis. Thickness loss of surface pile yarns (TL) and compression toughness index (TI) as representative of the compression properties, and color difference index of pile yarns (ΔE), tuft size index (TS) and also evenness of texture index (ET) as representative of the appearance characteristics were chosen. Then, factorial experimental design and response surface method were applied to model each of the performance properties.

Experimental

Carpets materials specifications

Pile yarns are perpendicular to the carpet backing and create carpet surface. Hence, pile yarn is the most important raw material for carpet production [9]. To produce the pile yarn, virgin wool fibers of an Asian breed were selected. Wool fibers specifications are shown in Table 1.

Carpets specifications

In this work, 18 samples of hand-knotted carpets with symmetrical and asymmetrical knots were woven based on a flat pattern. Pile yarns were dyed under similar conditions using a vegetable dyestuff. Knot density was also considered as a variable in production process at three levels. Essentially, depending on the knot density of carpet samples; proportional pile, warp and weft yarns were selected [18]. Details of structural specifications of carpet samples are presented in Table 2.

Due to the significant effect of the pile height on the performance properties of the hand-knotted carpets [5,7], pile heights of produced carpet samples were prepared and adjusted at three levels including 5, 9 and 13 mm. Specifications of 18 samples of woolen hand-knotted carpets are presented in Table 3.

Test methods

In this work, we used the available standard procedures or valid practical methods to test the five performance properties of carpet samples.

Thickness loss (TL): This property was determined according to the ISO 3416 standard; A method for determining the thickness loss of textile floor coverings after prolonged heavy static loading. Percentage of thickness loss was calculated using Equation (1):

$$\%TL=[(T_0-T_{24})/T_0]\times 100 \quad (1)$$

where T_0 is an original thickness and T_{24} is recovered thickness after 24 hours recovery [5].

Compression toughness index (TI): According Figure 2, this index is defined as the area under compression loading curves to locking point (S_{OAB}). Locking point of compressional load-crush curve is practically defined as transition point of low compression modulus region to high compression modulus region (point A). Also, the crush value at the locking point (CL_p) is defined as equal as the crush at the intersecting point of a hypothetical bilinear curve, consisting only of the lowest and highest modulus lines of the compression curve. The compression toughness index can be approximately described the human perceived walking comfort under dynamic behavior of surface pile yarns in compaction [12,19]. Numerical methods in Matlab® program were used to calculate this index.

Fineness (µm)		Length (mm)		Crimps/2.5 cm		Medullated fibers (%)	
Mean	%CV	Mean	%CV	Mean	%CV	Non	Coarsely
35.28	31.18	103.43	23.36	4.8	7.88	88	4

Table 1: Wool fibers specifications.

Knot density (knot/dm²)	Pile yarn				Warp yarn		Thick weft yarn		Thin weft yarn	
	N_m*	%CV	TPM**	%CV	N_e*	%CV	N_e*	%CV	N_e*	%CV
39×39	4/2	3.23	152/75	3.12/4.26	20/15	3.87	10/20	3.72	20/5	2.63
54×54	6/2	3.56	167/90	3.17/3.57	20/12	2.57	10/14	2.73	20/3	2.14
69×69	8/2	2.18	184/110	2.14/2.88	20/9	3.11	10/10	2.18	20/2	3.21

Note: * Count of ply yarn, ** Twist of single/plied pile yarn (twist/m).

Table 2: Structural specifications of woolen hand-knotted carpet samples.

Knot type: Turkish				Knot type: Persian			
No. of samples	Knot density (knot/dm²)	Pile height (mm)		No. of samples	Knot density (knot/dm²)	Pile height (mm)	
	Adjusted	Mean	%CV		Adjusted	Mean	%CV
1	39 × 39	5.08	2.96	10	39 × 39	5.38	2.75
2	39 × 39	9.15	3.12	11	39 × 39	9.28	3.18
3	39 × 39	13.12	2.55	12	39 × 39	13.10	3.05
4	54 × 54	5.12	3.78	13	54 × 54	5.27	2.55
5	54 × 54	9.18	3.45	14	54 × 54	9.11	2.87
6	54 × 54	13.18	3.05	15	54 × 54	13.24	3.20
7	69 × 69	5.04	2.38	16	69 × 69	5.17	2.06
8	69 × 69	9.10	2.84	17	69 × 69	9.08	2.38
9	69 × 69	13.20	3.19	18	69 × 69	13.15	3.11

Table 3: Specifications of woolen hand-knotted carpet samples.

doi:http://dx.doi.org/10.4172/2329-9568.1000113

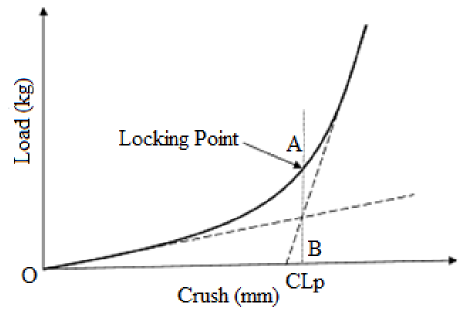

Figure 2: Definition of locking point and compression toughness index.

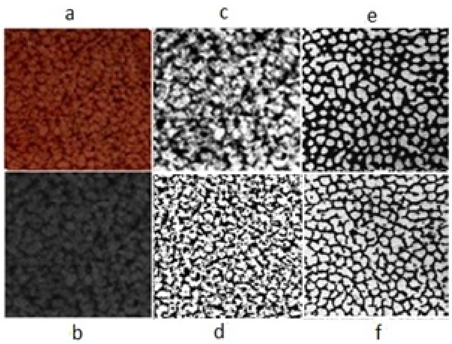

Figure 3: Image processing techniques: (a) original, (b) median filtering, (c) sharpening, (d) opening, (e) binary conversion, (f) erosion.

The compression tests under constant rate of crush were carried out using a Zwick universal testing machine (Model 144660). In order to apply maximum compression force of 70 kg (average weight of a person), additional attachments i.e. circular and square plates were employed. The area of the circular plate linked to upper jaw was considered equal to effective area of the human foot (145 cm^2) which in this case, the maximum compression stress value was calculated as 4.73 N/cm^2. Moreover, a 23×23 cm square plate was applied to link the bottom jaw. Crosshead speed of machine was adjusted to 50 mm/min [9].

Color difference index (ΔE): This test was done according to the ISO 105-J03 standard; Tests for color fastness–calculation of color differences. CIE LAB colorimetric system was applied for determination of color change between original and worn out carpet samples using a spectrophotometer machine (Tex-Flash model). Color difference index was calculated as:

$$\Delta E^{*}=[(\Delta L^{*})^2 + (\Delta a^{*})^2 + (\Delta b^{*})^2]^{1/2} \quad (2)$$

where ΔL^* is the lightness difference, Δa^* is red/green difference and Δb^* is yellow/blue difference between original and worn out carpet samples [17,20]. In this study, the effects of color changes of pile yarns due to soiling and staining in use was neglected and wear out effects of carpet's surface pile yarns was only considered.

Tuft size index (TS): In order to determine changes of tufts geometry in carpet, we recognized top of tufts as individual objects and made them more detectable by using digital image processing techniques, and removing uninteresting details [15,21]. The typical protocol of processing the carpet images is provided in Figure 3. Number-based mean of individual tuft size (at pixels) in a certain area of carpet surface was calculated [21].

Evenness of texture index (ET): In order to determine changes in evenness of tuft spatial distributions, tuft gravity centers of individual tufts (Figure 3f) were identified. Scatter plot of tuft gravity centers was prepared (black dots in Figure 4a). The uniformity of spatial distribution or evenness index was practically expressed as:

$$E = \frac{1}{n}\sum\nolimits_{i=1}^{n} E_i \quad (3)$$

where E_i is defined as the standard deviation of di_1 through di_n (Figure 4b), and n is actual number of all neighboring's tufts that we identified within a distance of 20 pixels from the edges of reference point. Here, the less evenness index value indicates an even distribution of tufts on surface appearance of carpet [15,21]. Image processing and calculations in sections IV and V were performed by numerical methods in Matlab® programs, separately.

In this study, carpet samples were subjected under a mechanical wear process to simulate traffic exposure by a Hexapod tumbler tester. This test was performed according to the ISO 10361 standard; Production of changes in appearance by means of Vettermann drum and Hexapod tumbler testers. Each hand-knotted carpet sample (a rectangle with dimensions of 20 by 22.5 cm) was worn under 4000, 8000 and 12000 drum revolutions [8]. Wear intensity was also considered as an independent variable at four levels. Figure 5 shows images of a typical hand-knotted carpet at original and after worn out under 4000, 8000 and 12000 drum revolutions, respectively.

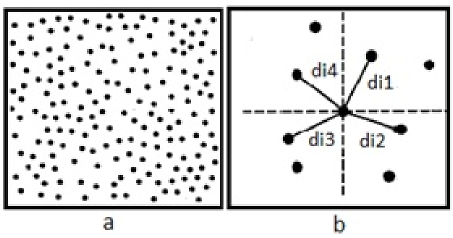

Figure 4: (a) Spatial distribution of tuft gravity center, (b) Characteristics of tuft spatial distribution.

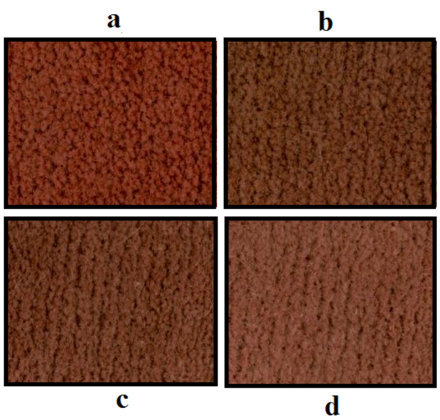

Figure 5: Images of hand-knotted carpet sample No. 5; at (a) original, and after worn out under (b) 4000, (c) 8000, (d) 12000 drum revolutions.

Three replications were used to test the five performance properties on each type of carpet samples.

Statistical Methods

Experimental design and response surface methodology

Factorial design is the most commonly used experimental designs for determining the response surface. It is largely used in cases where the determination of reciprocal and simultaneous effect of a number of variables on response is important [22]. In this study, the experiments were carried out according to a factorial design.

Response surface methodology (RSM) is often used to model and analyze the engineering problems. Generally, if all variables are supposed to be measurable, the response surface can be denoted as follows:

$$y = f(x_1, x_2, x_3, \ldots, x_k) \quad (4)$$

where, $x_1, x_2, x_3, \ldots, x_k$ are the independent variables which influence the dependent variable, y. In this technique, the aim is to optimize the dependent or response variable. So, it is required to find an appropriate approximation for the proper functional relationship between independent variables and the dependent variable [22,23].

Statistical analyses

We analyzed individually the performance properties of hand-knotted carpet samples for each of knot types, as follows:

A) Modeling the relationship between variables.

The data was analyzed by ANOVA test and then a response surface model was obtained.

B) Investigation of models adequacy.

C) Data transformation.

We used the most common family of transforms, i.e. Box-Cox transformation technique. This technique suggested a maximum likelihood procedure to identify an appropriate exponent (lambda, λ) for transforming the response data into a normal variable or stabilize its variance. The lambda value assigns the power for which all data should be raised. This power is equal to minimizing the square root of MSE over the choices of λ [22,23].

D) Relative importance of proper variables using extra sum of squares.

E) Validation of model by press residuals for new observations.

Press statistic is applied as a criterion for validity of regression model and its predictive ability which defined as:

$$Press = \sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 \quad (5)$$

where $\hat{y}_i$ is predictive value of the ith observed response based on the model fitted to the remaining *n-1* sample points. Moreover, press statistic can be used for calculating an R^2-like statistic for prediction by the following Equation:

$$R^2_{predict} = 1 - \frac{Press}{S_{yy}} \quad (6)$$

where, $S_{yy} = \sum_{i=1}^{n} \left(y_i - \bar{y}_i\right)^2$ [24,25].

In this work, statistical analyses were performed using the statistical software package, Minitab 16 at 5% level of significant.

Data collection

In this study, the main purpose is to predict the performance properties of woolen hand-knotted carpet samples with maximum accuracy, minimum random error and actual value using its main structural specification and wear out effect. 18 different hand-knotted carpet samples with symmetrical and asymmetrical knots produced. Five performance properties of the new carpet samples and similarly after worn out at the 4000, 8000 and 12000 revolutions by a Hexapod tumbler tester were measured. The measurements of the five performance properties (dependent variables; y_j) are presented in Table 4.

Knot type of carpets is considered as an important qualitative variable. Therefore, predictive models of each performance property were separately designed for Turkish and Persian knots. In predictive regression models, independent variables; x_i, are wear factor (wear level: 1/1000 drum revolutions; x_1) and main structural or production factors (knot density index: knot/dm; x_2, and pile height: mm; x_3).

Results and Discussion

Polynomial regression modeling

Preliminary analyses and response surface methodology showed that the second-order polynomial regression model should be employed as a model for fitting the suitable relationship between variables. Polynomial regression models based on significant variables and also R^2 and R^2_{adj} values of any models are presented in Table 5.

The results showed that the parameters of obtained models are similar for both types of Turkish and Persian knots. Adequacy of any polynomial regression models depends on the validity of general statistical assumptions for its error term (ε), especially normality of errors [24]. Preliminary analysis suggested the necessity to perform the transformation on TL, ΔE and TS properties data for both types of carpet knot. We used the Box-Cox transformation to modify and introduce new orthogonal variables. The lambda (λ) values were estimated with the lowest MSE that a sample of obtained Box-Cox plot and determined lambda is shown in Figure 6.

The selected λ values to modify the TL, ΔE and TS properties data were 0, 3/2, and 1/2, respectively. Therefore, we used the new modified data in statistical analysis as y_1=Ln y^*_1, $y_3=(y^*_3)^{3/2}$, and $y_4=(y^*_4)^{1/2}$. Polynomial regression models based on Box-Cox transformation are presented in Table 6. The validity of modified data was also evaluated. Evaluation of normality of errors and stability the variance on residual plots showed that transformations were suitable. As an example, values of MSE of related regression models in the case of Persian knot (y_{jp}, j=1, 3, 4) decreased as 0.983 to 0.01, 0.214 to 0.013, and 1.09 to 0.07, respectively. The R^2 and R^2_{adj} values of models were

Properties	Min	Max	Mean	SD	Index
TL_{24h} (%)	4.48	16.11	8.741	2.873	y_1
TI (N.m)	174.17	656.11	391.17	112.07	y_2
ΔE (None)	1.11	7.31	3.94	2.25	y_3
TS (Pixels)	218	629	420.3	124.1	y_4
ET (None)	0.17	0.48	0.295	0.075	y_5

Table 4: Summary of statistical results for performance properties of carpet samples.

doi:http://dx.doi.org/10.4172/2329-9568.1000113

Models		R^2	R^2_{adj}
y_{1T} =	$31.52 - 1.614x_1 - 0.246x_2 - 1.763x_3 + 0.021x_1^2 + 0.002x_2^2 + 0.085x_3^2 + + 0.006x_1x_2 + 0.005x_2x_3$	0.867	0.874
y_{1P} =	$28.96 - 1.574x_1 - 0.252x_2 - 1.215x_3 + 0.024x_1^2 + 0.002x_2^2 + 0.061x_3^2 + 0.008x_1x_3 + 0.004x_2x_3$	0.913	0.917
y_{2T} =	$-489.69 - 8.77x_1 + 22.58x_2 + 39.86x_3 - 0.155x_2^2 - 0.652x_3^2 - 0.202x_1x_2 - 0.087x_2x_3$	0.948	0.950
y_{2P} =	$-214.46 - 12.42x_1 + 11.17x_2 + 46.34x_3 - 0.042x_2^2 - 0.727x_3^2 - 0.103x_1x_2 - 0.130x_2x_3$	0.950	0.953
y_{3T} =	$1.997 + 0.333x_1 - 0.01x_2 - 0.299x_3 + 0.02x_1^2 + 0.015x_3^2 + 0.0027x_1x_3 + 0.0012x_2x_3$	0.948	0.948
y_{3P} =	$2.104 + 0.317x_1 - 0.01x_2 - 0.286x_3 + 0.022x_1^2 + 0.015x_3^2 + 0.002x_1x_3 + 0.0012x_2x_3$	0.947	0.948
y_{4T} =	$845.94 + 8.28x_1 - 9.69x_2 - 21.47x_3 - 0.118x_1^2 + 1.27x_3^2 - 0.318x_1x_3$	0.953	0.954
y_{4P} =	$803.11 + 12.99x_1 - 9.62x_2 - 16.93x_3 - 0.235x_1^2 + 1.023x_3^2 - 0.136x_1x_3$	0.951	0.952
y_{5T} =	$0.4 + 0.019x_1 - 0.002x_2 - 0.032x_3 + 0.00037x_1^2 + 0.0014x_3^2 - 0.00013x_1x_2 - 0.0002x_1x_3 + 0.00012x_2x_3$	0.939	0.943
y_{5P} =	$0.357 + 0.02x_1 - 0.0011x_2 - 0.019x_3 + 0.00049x_1^2 + 0.00086x_3^2 - 0.00019x_1x_2 - 0.00014x_1x_3 + 0.00015x_2x_3$	0.919	0.924

Table 5: Primary polynomial regression models.

Modified models		R^2	R^2_{adj}
$Ln(y_{1T})$ =	$4.94 - 0.157x_1 - 0.013x_2 - 0.195x_3 + 0.0011x_1^2 + 0.00013x_2^2 + 0.01x_3^2 + 0.00033x_1x_3 + 0.00035x_2x_3$	0.886	0.891
$Ln(y_{1P})$ =	$5.30 - 0.249x_1 - 0.035x_2 - 0.199x_3 + 0.0031x_1^2 + 0.00034x_2^2 + 0.011x_3^2 + 0.0011x_1x_3 + 0.00088x_2x_3$	0.911.	0.915
$y^{3/2}_{3T}$ =	$9.3 - 0.606x_1 - 0.029x_2 - 1.049x_3 + 0.169x_1^2 + 0.055x_3^2 + 0.0097x_1x_3 + 0.0013x_2x_3$	0.946	0.948
$y^{3/2}_{3P}$ =	$10.33 - 0.789x_1 - 0.03x_2 - 1.078x_3 + 0.194x_1^2 + 0.059x_3^2 + 0.012x_1x_3 - 0.0073x_2x_3$	0.945	0.946
$y^{1/2}_{4T}$ =	$30.61 + 0.236x_1 - 0.24x_2 - 0.526x_3 - 0.0033x_1^2 + 0.031x_3^2 - 0.0036x_1x_3$	0.963	0.966
$y^{1/2}_{4P}$ =	$29.52 + 0.344x_1 - 0.237x_2 - 0.413x_3 - 0.0059x_1^2 - 0.025x_3^2 - 0.0034x_1x_3$	0.962	0.963

Table 6: The modified models based on polynomial regression.

Variables	TL_{24h} (y_1)		TI (y_2)		ΔE (y_3)		TS (y_4)		ET (y_5)	
	Turkish	Persian	Turkish	Persian	Turkish	Persian	Turkish	Persian	Turkish	Persian
x_1	65.18	71.39	20.59	16.36	88.87	88.51	12.71	13.12	81.76	88.22
x_2	13.41	14.17	19.73	24.79	0.20	0.22	85.46	84.43	7.84	9.17
x_3	3.55	2.63	51.15	52.64	4.03	4.02	0.12	0.03	0.53	0.73
x_1^2	0.96	1.01	-	-	3.06	3.38	0.03	0.10	0.69	1.18
x_2^2	0.43	0.55	2.15	0.44	-	-	-	-	-	-
x_3^2	6.37	3.58	0.19	0.22	0.33	0.31	0.59	0.39	1.94	0.77
x_1x_2	-	-	0.98	0.23	-	-	-	-	0.82	2.09
x_1x_3	0.83	1.42	-	-	0.02	0.02	0.04	0.03	0.13	0.21
x_2x_3	0.22	0.22	0.10	0.20	0.02	0.01	-	-	0.40	0.35
$SS_R(\beta)^a$	16.744	46.03	256513	286311	5710.3	6803.1	1345.1	1313.9	0.739	0.709
$SS_T^{\,b}$	18.79	50.37	270145	300733	5732.5	6832.5	1345.9	1323.2	0.784	0.767

a: Sum of squares regression coefficient, *b*: Total sum of squares, in ANOVA table.

Table 7: Extra sum of squares, contribution amounts (%) of independent variables.

Knot type of carpet	TL_{24h} (y_1)		TI (y_2)		ΔE (y_3)		TS (y_4)		ET (y_5)	
	Prees st.	$R^2_{Pred.}$	Prees st.	$R^2_{Pred.}$	Prees st.	$R^2_{Pred.}$	Prees st.	$R^2_{Pred.}$	Prees st.	$R^2_{Pred.}$
Turkish	2.275	0.879	150456	0.944	25.168	0.946	10.64	0.951	0.0518	0.934
Persian	4.713	0.906	161588	0.946	33.832	0.945	10.53	0.962	0.0661	0.914

Table 8: Result of press statistic and $R^2_{Pred.}$ for any final model.

desirable which are also shown in Table 6.

Relative importance of independent variables

Moreover, in order to obtain relative importance and contribution of each independent variable, we used the statistical method of extra sum of squares. Summary of contribution amounts of independent variables for any models is presented in Table 7.

The results revealed that the wear factor has a considerably relative importance and contribution to determine the TL, ΔE and ET properties. Moreover, knot density and pile height factors have significant contribution to determine the TS and TI properties, respectively. Illustriously, color difference index of pile yarns (ΔE) with more than 88% contribution, and tuft size index (TS) with more than 84% contribution, have the highest correlation with wear and knot density factors, respectively. Consequently, it is expected that further wearing out of carpets, will decline most appearance specifications and properties of pile yarns [9,15]. The results are similar for both types of Turkish and Persian knots.

Results of contribution of independent variables show that the knot density and pile height factors are two structural specifications to predict the performance properties of hand-knotted carpets. These results are compatible with the previous studies on the machine made cut-pile carpets [5,8,21].

Predictive capability of regression models

The press statistic and $R^2_{Pred.}$ Values were calculated according to Equations (5) and (6) and presented in Table 8. Typical scatter plot of predictive values versus experimental values with regression curve

doi:http://dx.doi.org/10.4172/2329-9568.1000113

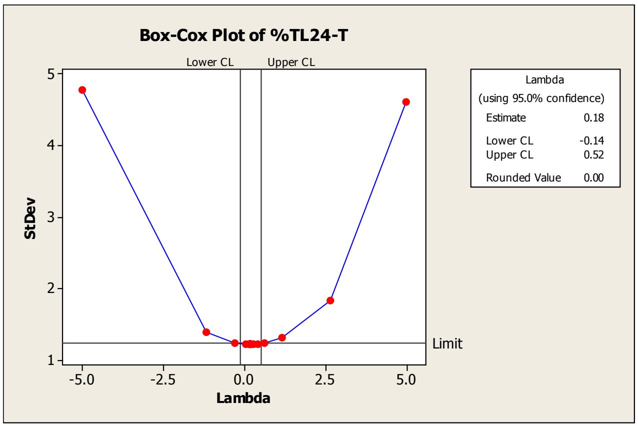

Figure 6: A typical Box-Cox plots for determination of estimated lambda (λ) for y_{1T} model.

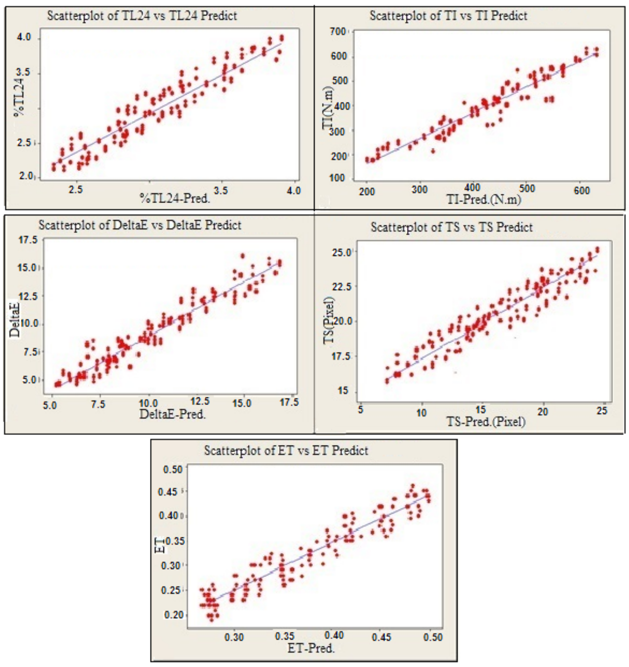

Figure 7: Plots of regression models against of their predicted values.

of models in the case of Persian knot (y_{jp}, j=1-5) are shown in Figure 7. We found that the predictive capability of the most of models is very acceptable. For example in the y_{4P} model, we expected this model to be about 96.2% of the variability in predicting new observations. Among all the models, y_{1T} model has lowest value ($\%R^2_{Pred.}$=87.9), but the predictive capability of this model is good.

Conclusion

The results of this work show that the performance properties of hand-knotted carpets can be modeled through response surface regression. The values of R^2 and R^2_{adj} of the obtained models indicate that the models enjoy a good fit. It was also found that the obtained models show considerable similarity for both types of Turkish and Persian knots.

Among various model parameters, wear factor show a remarkable importance and contribution on response variables. Furthermore, knot density and pile height factors were found as two structural specifications of carpet with significant relative importance. Performance properties of hand-knotted carpets can be improved simply by choosing appropriate structural parameters. Using the proposed models, the optimal values of knot density and pile height factors can be determined at various wear level in order to produce the carpet with desirable custom profile; particularly expected lifetime.

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