Ergonomic Design Using Quality Function Deployment and Design of Experiments

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Abstract

User needs relating to products are expressed in the language of customers. Designers are facing the challenge of answering the question of how relatively subjective customer needs can be translated into precise target specifications. In most cases, some of these needs can be interpreted as ergonomic requirements. This is especially true for furniture. The question is what a piece of furniture has to do to bring about satisfaction in use. Ergonomic suitability has a number of components, each of which is determined by a given set of product properties. Therefore, ergonomic quality can be satisfied by using complex methods of analysis. Such methods include Quality Function Deployment (QFD). The adaptability of this methodology for the ergonomic design of seats was confirmed as a result of our study. Furthermore, it has been found that the components of ergonomic quality can be treated as dependent variables. The level of these dependent variables is determined by quantitative and categorical product-related independent characteristics. A model for evaluating and designing ergonomic quality on the basis of the method of Design of Experiments was conceived as a complement to the QFD-based approach and is demonstrated for sitting furniture.

The objective of our study was to make the design of sitting furniture more effective via advanced design techniques. This article describes an attempt to satisfy ergonomic design using quality management methods. A three-stage approach was proposed.

The first stage was to clarify the objectives, i.e. to define what ergonomic quality in the case of chairs, sofas, and recliners would mean. According to the literature (Hayes 1999), the major tools for surveying customer satisfaction are different types of questionnaires. It can be established that sitting comfort and contributing to the preservation of health are the two focal points of any ergonomic design. Comfort requires sufficient support of the body and promotes easy activities, such as sitting, eating, reading, and writing. Furthermore, health necessitates effective relaxation, safety, and avoidance of exertion and unhealthy positions during the use of furniture (Westgaard and Winkel 1997, Klein 2004). These two groups of requirements must be inherent properties of sitting furniture.

Having defined the required properties, during the second stage these should be converted into technical specifications, including types of materials, dimensions and angles, and softness or hardness. In these contexts, color and aesthetic form are not considered. During the third stage, the target values of the technical parameters, i.e. the best combination of their levels, should be found. For these two latter stages, in this article we present the tentative utilization of two methods. The first one is based on the technique of Quality Function Deployment (QFD), while the second one uses Design of Experiments (DOE).

Basic textbooks on engineering design emphasize the usefulness of the QFD methodology in the design stage (Ulrich and Eppinger 2004, Cross 2008), yet few authors used QFD to integrate ergonomics in engineering design (Leppänen et al. 2000, Guedez et al. 2001, Kahraman et al. 2004, Marsot 2005, Chen and Ming-Chu 2006). Kahraman et al. (2004) and Chen and Ming-Chu (2006) applied fuzzy logic rather than DOE to complement their QFD-based approach. DOE appeared as a response surface methodology along with virtual manufacturing in chair design in a work

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by Ben-Gal and Bukchin (2002). Brintrup et al. (2008) used genetic algorithms for the same purpose. The joint application of QFD and DOE in ergonomic design has not been researched yet according to the literature. Consequently, this article may contribute to the better ergonomic design of sitting furniture.

Methods

Application of the QFD method for improving ergonomic quality

A product is the carrier of functions corresponding to a set of needs (expectations). The designer tries to cope with those needs through the choice of a multitude of technical (design) parameters characterizing the product. An essential step in the design, based on customer needs, is the interpretation of the requirements by using product-related technical terms. QFD is a suitable method to do this. In a QFD study, customer needs (WHATS) are converted into technical parameters (HOWS). The relative importance of the latter is then determined by setting up an interaction matrix. The final results of the procedure are target levels established for the technical parameters through which customer expectations can be optimally satisfied (Roozenburg and Eekels 1995). Figure 1 schematically represents the so-called House of Quality with the individual ''rooms.'' The left-hand ''terrace'' contains the list of customer needs (WHATS) along with their importance weighting. The annex on the right side is the room in which comparison is made with concurrent products. This section includes WHYS, which are used to justify product improvement. The upper floor comprises all the technical characteristics (HOWS) that have a hold on any of the customer needs. The first floor is the so-called interaction matrix, in which the importance of the technical characteristics (columns of matrix) can be marked in relation to the individual needs (rows of the matrix). The ''roof'' matrix demonstrates the interactions among the technical characteristics. The ''basement'' is the part of the house where the numerals in the first row represent the relative importance of the technical characteristics. These were derived on the basis of the strength of their interaction with the needs. Furthermore, the first-row values were also modified by the weight of customer needs and by the target development ratios. However, it should be noted that the final objective of the QFD methodology is to establish target values of the technical characteristics in view of their relative importance.

Adaptation of the method for ergonomic design is illustrated next through a case study. The first room contains surveyed costumer needs and their importance ranking. Table 1 compiles user needs regarding sitting furniture, surveyed by the authors.

From the list in Table 1, it appears that user needs demonstrate limited clear technical requirements only. Instead, they relate the actual use and the relationship with the surrounding environment of the product.

As part of the QFD procedure, the individual customer needs must be weighted. In this study, we used paired comparison and checked the results of assessment for consistency as proposed in the KIPA method (Kindler and Papp 1977). Weights are based on decisions on preference between two criteria when each criterion is compared pairwise.

Columns of the HOWS represent the next ''room'' of the House of Quality. Table 2 shows the technical details and parameters having importance in satisfying customer needs. These technical parameters characterize a chair from an ergonomic point of view. To these individual attributes, actual values or ranges, or perception levels positioned in

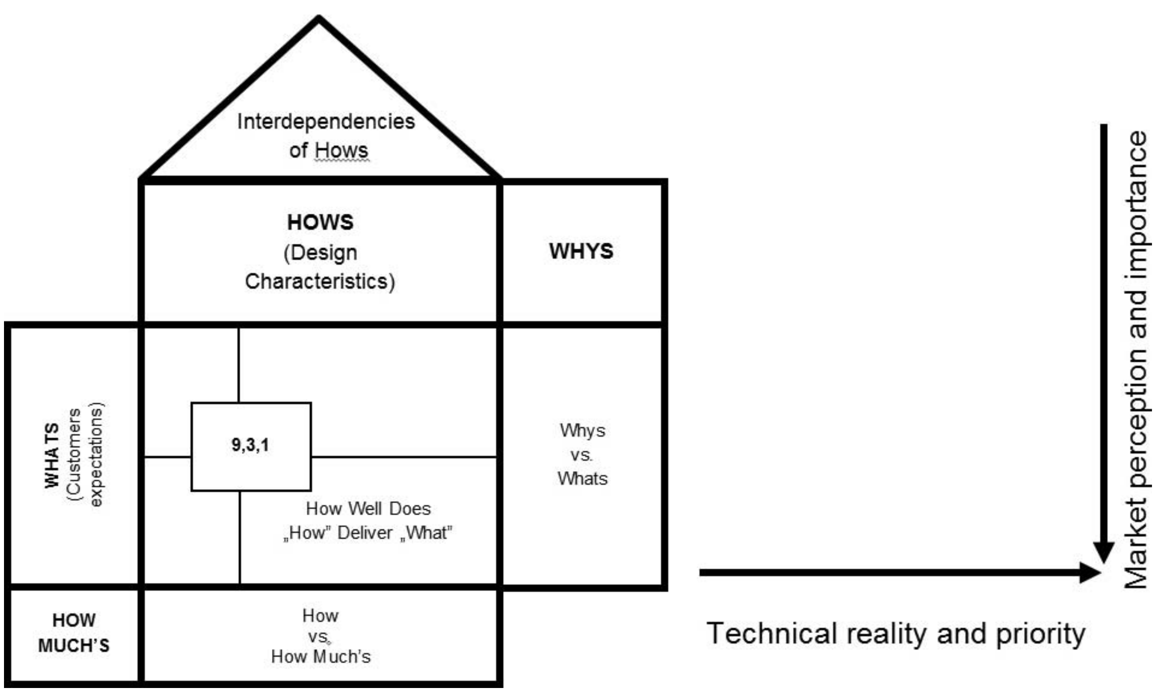

Figure 1.—Schematic representation of the Quality Function Deployment (QFD) method: House of Quality. The first-floor room contains the interaction matrix, where each element is assigned to the importance of a technical parameter in relation to a customer need, such as marked in the box with 9,3,1. The vertical arrow indicates the exploration of market perception and parameter importance. The horizontal arrow represents the survey of technical performance providing quality.

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Table 1.—List of user needs termed WHATS in Quality Function Deployment analyses.[a]

WHATS (what users are asking for)
Stability
Load-bearing capacity
Easy standing up
Comfortable sustained sitting
No risk of injury
Prevention of unhealthy position
Easy to move without exertion
Pleasant to touch
Easy to clean surfaces
Provision of relaxing posture
Relaxation of the upper body
Relaxation of legs
Durable
Fits to the table

[a] Each item is assigned an importance weight reflecting customers' opinions.

interval scales, can be assigned. For example, hardness of upholstery can be soft, semisoft, semihard, etc.

The next step was to fill in the interaction matrix. The applied scale was as follows: 9 = strong correlation, 3 = medium correlation, and 1 = weak correlation.

Values in the cells of the interaction matrix multiplied by the weights of the criteria in each row were summed over each column to get an indication of the importance of the individual technical parameters. The higher the relative importance, the more expedient it is to shift a parameter's value toward its optimum level. Studying the values of the technical parameters of a few competitive products, one can assess target values through which the planned level of satisfaction becomes attainable. It is comparatively easy to weight costumer needs and to establish the relative importance of technical parameters algorithmically. However, determination of target values requires individual judgment and remains subjective. The DOE is frequently used to optimize product performance. This research applied the QFD method to identify the dependent and independent variables. On the other hand, the target values were explored and computed via DOE. Because this DOE is based on regression analysis, all statistical procedures used a 95 percent confidence level ($\alpha = 0.05$).

Table 2.—List of technical parameters involved in the ergonomic chair design study.[a]

HOWS
How to deliver WHATS (measurable quantities)
Structural stiffness
Strength of structural joints
Resistance to abrasion of the surfaces
Width of seat
Depth of seat
Height of seat
Slope of seat
Distance of armrests
Height of armrest
Inclination angle of back
Width of armrests
Height of back
Length of armrests
Curvature of back
Radius of file on frame members
Thickness of upholstering
Hardness of upholstering
Weight of the chair
Surface quality
Air permeability of the cover fabric
Thermal conductivity of upholstery
Vapor resistance of the cover fabric
Resistance of surfaces to chemicals
Sole

[a] Parameters make up the HOWS of Quality Function Deployment methodology, referring to the means by which the product can fulfill user needs.

Designing ergonomic quality into the product

Product performance as perceived by the users depends on several measurable properties and attributes of the product and its parts. These variables can be treated as design parameters. From our point of view, the components of the ergonomic quality are considered as dependent variables, each of which is influenced by a group of continuous and categorical independent variables. Therefore, they can be studied by the methodology of DOE and, more specifically, by using factorial experiments. The next section of our study demonstrates how the relationship between design parameters and customer satisfaction can be analyzed by DOE.

DOE determines the purposeful setting of levels for each variable in conducting individual experimental setups. Thus, the best combination of setting levels for variables may be found. Moreover, it may include the quantification of the effects of independent variables on dependent ones. In cases of continuous variables, a mathematical model describing the relationship between dependent and independent variables is of interest.

Some of the experimental settings during this work were defined on the basis of samples selected from a pool of chairs immediately available for testing. Others were obtained by purposeful modifications made on suitable pieces when the statistically determined settings of design parameters could not be found in existing chairs. A group of volunteer evaluators gave their assessment on ergonomic quality.

Two of the ergonomic quality assessment criteria studied during this research were as follows.

Comfortable sustained sitting.—When using our seats continuously for a longer period, we take all three positions of relaxation, neutral, and active sitting (Orbay 2003). For an easy change of position, the seat must support dynamic sitting and at the same time should alleviate the strains caused by static loading. Sitting itself serves for unloading the lower limbs and should ensure the support of body weight at optimal locations. These include the support of thighs, the lumbar region, and the back. Occasionally, armrests may become necessary. These supports must be of uniform intensity and physiologically right so that no adverse effect on blood circulation or unwanted muscle tone occurs. Additionally, airing of supported body surfaces should be maintained.

Relaxation of the upper body.—Muscles of the optimally supported upper body need less balancing effort, and the load on the lumbar section of the trunk is lessened. Nevertheless, support may be adequate only when the pressure on the intervertebral discs remains uniform by keeping the S-form curvature of the spine.

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Effects of five design parameters (factors) have been studied in relation to the two customer-need items discussed above. Table 3 compiles the two setting levels for the design parameters for each factor.

For our five factors, we chose the Taguchis L8 design (Barker 1990), originally developed for a maximum of seven factors. Table 4 represents the actual design matrix. The columns of the matrix were selected to minimize the influence of possible interactions. Furthermore, the process requires randomization for the sequence of experiments to alleviate any systematic errors.

The chairs were physically tested by four expert evaluators for the criteria of sustained comfortable sitting and relaxation of the upper body, respectively. The selected evaluators had professional expertise in furniture design, ergonomics, and anthropometry as well as experience in furniture testing. They expressed their level of satisfaction on an interval scale ranging from 1 to 5 for each criterion; later, the scores with respect to a customer need in question were averaged.

Table 3.—Experimental design factors and levels used in the analysis.

Factor	Level 1	Level 2
F1: Width of seat (mm)	370–425	426–480
F2: Depth of seat (mm)	360–409	410–460
F3: Width of back (mm)	330–429	430–530
F4: Height of back (mm)	335–467	468–600
F5: Inclination of back (°)	90–97	98–105

Table 4.—Design matrix for the experiments, shown in standard sequence of experimental runs.

Run[a]	F1	F2	F3	F4	F5
8	1	1	1	2	2
7	1	1	1	1	1
2	2	2	1	2	2
3	2	2	1	1	1
6	1	2	2	2	1
5	1	2	2	1	2
4	2	1	2	1	2
1	2	1	2	2	1

[a] Indicates the randomized order of execution.

The conformity levels were based on the two sets of criteria as follows:

1. Comfortable sustained sitting
   - Does uncomfortable pressure develop at any point in the supports?
   - How easy is it to change sitting position?
   - Do sweats develop?
   - How can a pleasant sitting position be taken?
   - Can different activities while sitting be done easily?
   - Does pain in the waist occasionally develop?
   - Does the chair provide a headrest?
   - Does the user like sitting in the respective piece of furniture?
2. Relaxation of the upper body
   - Can the sitting person breathe with unchanged ease?
   - How much muscle tension does the user experience in the upper body?
   - To what extent does the sitting prevent any intended activities?
   - Does the seat keep the occupant in a natural position?
   - Is it easy to find the right supporting position for someone's own needs?
   - Are supporting surfaces adequate, and is any additional support needed?

Results and Discussion

Results of the QFD analysis

Table 5 summarizes the results of this procedure. These include the WHATS, HOWS, and the interaction matrix. The column of weights in the WHATS area contains importance indicators obtained by pairwise comparisons.

Table 5.—Interaction matrix, containing the indices of the strength of correlation between each user need and technical parameter.

		Technical parameters[a]:																		
Customer needs	Weights	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Stability	0.51	1	1	1		3	1	3								3				
Load-bearing capacity	0.54															3				
Easy to stand up	0.70	1	9	9	9	3	3	1			3			3	3					
Comfortable sustained sitting	0.68	9	9	9	9	9	9	9	9	9	9	9	9	9	9			9	9	9
No risk of injury	0.80												9				3			
Impedes unhealthy position	0.56	3	9	9	9	9	9	9	3	9	3	9	3	3	3		3			
Easy to move without exertion	0.77	3	3	3			1			1	1					9				
Pleasant to the touch	0.23												3	1	1		9			
Easy-to-clean surface	0.15																			
Provides relaxing posture	0.58	9	9	9	9				9	9	9			3	3			3	3	
Relaxation of upper body	0.54			3																
Relaxation of legs	0.58	3	3		3	3	3	3				3								
Durable	0.37																			
Fits the table	0.47			9						3				1	1					
Absolute importance of the parameters		18	27	31	24	17	16	15	13	19	16	13	15.6	12	12	10	6.1	7.86	7.9	6.1
Importance ranking		5	2	1	3	7	8	11	13	4	9	14	10	15	15	17	20	18	18	19

[a] Explanation of technical parameters' codes: 4 = width of seat; 5 = depth of seat; 6 = height of seat; 7 = slope of seat; 8 = distance of armrests; 9 = height of armrests; 10 = inclination angle of back; 11 = width of armrests; 12 = height of back; 13 = length of armrests; 14 = curvature of back; 15 = radius of file on frame members; 16 = thickness of upholstering; 17 = hardness of upholstering; 18 = weight of the chair; 19 = surface quality; 20 = air permeability of the cover fabric; 21 = thermal conductivity of upholstery; 22 = vapor resistance of the cover fabric.

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The range of these importance indicators extends from 0.15 to 0.80. The randomly selected two customer needs for further analysis had a higher-than-midrange level of importance (i.e., 0.68 for sustained comfortable sitting and 0.54 for relaxation of the upper body).

The last row in Table 5 contains the ranking of the absolute importance values computed for the individual technical parameters. These values were derived using the strength of relations and the weights of customer needs.

In Table 5, 19 technical parameters are listed from which five were ranked the most important as follows in descending order of importance:

Sitting height (6)
Depth of sitting (5)
Inclination of the sitting (7)
Height of back support (12)
Width of the sitting surface (4)

Importance indicators of these technical parameters (18.00 and above) fall in the upper third of the range of 0 to 27.29 covered; thus, these particular parameters require special attention during design.

Results of the DOE procedure

In Table 5, for the two customer needs (sustained comfortable sitting and relaxation of the upper body), we evaluated the strength of interrelations with the technical parameters. Based on the findings, we selected the technical parameters as factors F1 through F5 listed in Table 3. The resulting evaluation scores may be studied in Table 6 for the customer need of sustained comfortable sitting. A similar table could be arranged for relaxation of the upper body; however, it is not shown here.

The evaluation method included regression analysis. The assumptions of normality of the residuals and the equal variances were checked and accepted. After running the multiple regression procedure, the resulting parameter estimations are listed in Table 7 along with the t and P values of significance testing.

The multiple regression procedure resulted in Equation 1. In the regression equations, the factors are represented as x_1 to x_5:

$$y = 3.9296 + 0.2734 \cdot x_1 + 0.1328 \cdot x_2 + 0.2266 \cdot x_3 + 0.1016 \cdot x_4 + 0.0703 \cdot x_5 \quad (1)$$

Table 6.—Average of the scores given by the four evaluators for the eight chairs tested for sustained comfortable sitting.

	Design: Five factors at two levels					
Run	F1	F2	F3	F4	F5	Independent mean
1	1	1	1	1	1	3.5
2	1	1	1	2	2	3.5
3	1	2	2	1	2	3.5
4	1	2	2	2	1	4.5
5	2	1	2	1	2	4.5
6	2	1	2	2	1	4.5
7	2	2	1	1	1	3.3
8	2	2	1	2	2	4.5
All runs						3.96875

Table 7.—Model parameters and their test of significance relating to the comfort of sustained sitting.

	Parameter estimates (comfort of sustained sitting)			
Effect	Level	Parameter	t	P
Intercept		3.929688	39.30536	0.000000
F1	1	−0.273437	−2.73497	0.011085
F2	1	0.132812	1.32841	0.195585
F3	1	−0.226563	−2.26611	0.032000
F4	1	−0.101563	−1.01584	0.319064
F5	1	−0.070313	−0.70328	0.488134

After eliminating the insignificant factors, the equation takes the following form:

$$y = 3.9296 + 0.2734 \cdot x_1 + 0.1328 \cdot x_2 + 0.2266 \cdot x_3 \quad (2)$$

However, the depth of seat (x_2) is statistically nonsignificant; we kept this parameter for practical reasons. Extremely long seat depth can cause discomfort for short-legged persons. Furthermore, this parameter provided the lowest P value after the significant ones. However, for simplifying the model, x_2 can be eliminated.

A similar analysis of the factor effects, relating to the relaxation of the upper body, results in the mathematical model below:

$$y = 3.5313 + 0.2813 \cdot x_1 + 0.1875 \cdot x_2 + 0.3125 \cdot x_3 + 0.1875 \cdot x_5 \quad (3)$$

These models may be useful for predicting ergonomic suitability of a chair for a given user expectation. The optimization of technical parameters is another advantage of the method. This can be performed by the simpler Taguchi (2000) method based on a study of factorial effects. However, in the case of continuous variables, the regression equations can be analyzed by the more complicated response surface methodology (Montgomery 1991, Denes 2005).

With the use of DOE equations, only simple measurements are needed to relate customer requirements to technical parameters, and the performance of the chair can be optimized. However, the resulting linear models may be different in terms of the sign of particular independent variables; that is, the increase of a given dependent variable may favor one requirement, and it may be disadvantageous for another one. For example, with our two customer requirements, the advantageous settings of the variables (technical parameters) are as shown in Table 8.

Conclusions

Ergonomic suitability of chairs has a number of components, each of which is determined by a given set

Table 8.—Favorable setting of the influential technical parameters in the cases of the two investigated customer requirements.

	Dependent variable at optimal setting				
Requirement	x_1	x_2	x_3	x_4	x_5
Sustained comfortable sitting	+	−	+	0[a]	0
Relaxation of the upper body	+	+	+	0	+

[a] 0 = nonsignificant parameter.

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of product properties (technical parameters). Components of the ergonomic quality are described by customer needs in an indirect way and can be satisfied by using complex methods of analysis. Such a method could be the QFD procedure. Our study confirmed its usefulness for ergonomic design with respect to mapping the relevant technical parameters and exploring their relative importance.

Taking the individual components of ergonomic quality as independent variables, they can be described as functions of the technical parameters. In determining the target values of technical parameters, DOE proved to be the more precise and effective. However, application of DOE is more labor intensive than the QFD methodology. It does appear that the combination of the two methodologies may provide consumer satisfaction with reasonable compromises of technical and comfort requirements.

Literature Cited

Barker, T. B. 1990. Engineering Quality by Design. Marcel Dekker, New York. 250 pp.

Ben-Gal, I. and J. Bukchin. 2002. The ergonomic design of workstations using virtual manufacturing and response surface methodology. *IIE Trans*. 34:375–391. http://www.eng.tau.ac.il/~bengal/Ergonomics_Paper.pdf. Accessed August 5, 2012.

Brintrup, A. M., J. Ramsden, H. Takagi, and A. Tiwari. 2008. Ergonomic chair design by fusing qualitative and quantitative criteria using interactive genetic algorithms, evolutionary computation. *IEEE Trans. Evol. Comput*. 12(3):343–354.

Chen, L.-H. and W. Ming-Chu. 2006. An evaluation approach to engineering design in QFD processes using fuzzy goal programming models. *Eur. J. Oper. Res*.172(1):230–248.

Cross, N. 2008. Engineering Design Methods—Strategies for Product Design. 4th ed. John Wiley & Sons, Chichester. 217 pp.

Denes, L. 2005. Development of a new veneer based composite using the experimental design method. PhD thesis. University of West Hungary, Sopron. (In Hungarian.)

Guedez, V., P. Mondelo, A. Hernandez, and L. Mosquera. 2001. Ergonomic design of small containers using the Quality Function Deployment (QFD). http://www.cenea.eu/pdf/Ergonomic%20design%20of%20small%20containers%20using%20the%20Quality%20Function%20Deployment%20(QFD).pdf. Accessed January 22, 2012.

Hayes, B. E. 1999. Measuring Customer Satisfaction, Development and Use of Questionnaires. ASQC Quality Press, Milwaukee, Wisconsin.

Kahraman, C., E. Tijen, and B. Gülcin. 2004. A fuzzy optimization model for QFD planning process using analytic network approach. *Eur. J. Oper. Res*. 17(2):390–411.

Kindler, J. and O. Papp. 1977. Methods for comparing complex systems: Application of the KIPA method. Postdiploma Education Institute of the Budapest University of Technology, Budapest.

Klein, S. 2004. Work Psychology. EDGE 2000, Budapest. 872 pp. (In Hungarian.)

Leppänen, M., M. Markku, and J. Kivistö-Rahnasto. 2000. Designing the ergonomic properties of pruning shears using Quality Function Deployment (QFD). *Proc. Hum. Factors Ergon. Soc. Annu. Meet*. 44(22):647–650.

Marsot, J. 2005. QFD: A methodological tool for integration of ergonomics at the design stage. *Appl. Ergon*. 36(2):185–192.

Montgomery, D. C. 1991. Design and Analysis of Experiments. 3rd ed. John Wiley, New York.

Orbay, P. 2003. Design of Kitchen Furniture. Invest-marketing B.t, Budapest. (In Hungarian.)

Roozenburg, N. F. M. and J. Eekels. 1995. Product Design. John Wiley & Sons, New York. 408 pp.

Taguchi, G. 2000. Robust Engineering, McGraw-Hill, New York.

Ulrich, K. T. and S. D. Eppinger. 2004. Product Design and Development. 3rd ed. McGraw-Hill/Irwin, New York. 366 pp.

Westgaard, R. H. and J. Winkel. 1997. Ergonomic intervention research for improved musculoskeletal health: A critical review. *Int. J. Ind. Ergon*. 20(6):463–500.

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