ISSN 1847-7917

The application of Taguchi method for choosing the optimal table construction

Marina CRNJAC

Nikola GJELDUM

Boženko BILIĆ

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Department for Production Engineering
Sveučilište u Splitu, Fakultet elektrotehnike, strojarstva i brodogradnje,
R. Boskovica 32, 21 000 Split, Croatia

mcrnjac@fesb.hr
ngjeldum@fesb.hr
bbilic@fesb.hr

Keywords

Taguchi method
Optimization
Table construction
Design of experiment

Ključne riječi

Taguchi metoda
Optimizacija
Konstrukcija stola
Planiranje pokusa

Original scientific paper

Abstract: New trends in the world show that 3D modeling and simulation of different variants of the product are very often used during the development phase and design of the product. It is very important to shorten the time spent on development and construction of product in today's market conditions. Modelling and simulation can contribute to this. This paper shows the application of the Taguchi method in order to model the table for machining. The table for machining will be used in Lean Learning Factory at Faculty of electrical engineering, mechanical engineering and naval architecture (FESB). The Taguchi method is often used to solve engineer problems, especially in the area of product quality. By using the Design Expert software, a plan for experiments was made for three different versions of the table. According to the plan of experiments, different versions of the table were drawn in the NX Siemens software. The simulations have been made to determine a displacement of each table during the action of vertical and horizontal force. The analysis of displacement and mass was made and the optimal solution was proposed.

Izvorni znanstveni rad

Sažetak: Novi trendovi u svijetu danas pokazuju da se vrlo često prilikom razvoja i konstruiranja proizvoda koristi 3D modeliranje i simuliranje različitih izvedbi proizvoda. S obzirom na vrlo turbulentno tržište, vrlo važno je skratiti ciklus proizvodnje. Modeliranje i simulacija mogu u tome mnogo doprinijeti. U ovom radu je prikazano korištenje Taguchi metode u modeliranju stola za strojnu obradu. Stol za strojnu obradu će biti korišten u Tvornici za učenje na Fakultetu elektrotehnike, strojarstva i brodogradnje (FESB). Metoda je često korištena za rješavanje inženjerskih problema, posebno u području kvalitete proizvoda. Primjenom programskog paketa Design Expert je napravljen plan pokusa za tri različite izvedbe stola. Prema planu pokusa, nacrtane su izvedbe stolova u programskom paketu NX Siemens i napravljene su simulacije kako bi se utvrdio progib pojedine konstrukcije prilikom djelovanja vertikalne i horizontalne sile. Cilj je bio pronaći konstrukciju stola koja ima minimalan progib i minimalnu masu. Provedena je analiza progiba i mase konstrukcije te je predloženo optimalno rješenje.

1. Introduction

Today every organization tries to find different methods to increase their productivity, reduce losses and maximize profits. The project Innovative Smart Enterprise (INSENT) was launched to find different methods for improvement of the production process and product development. Since 2009, Lean Learning Factory has been establishing at Laboratory for Industrial Engineering at Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB) in Split. Lean Learning Factory at FESB is based on a didactical concept emphasizing experimental and problem based learning using tools and methods from Lean management [1]. This concept of Lean Learning Factory presents a simulation of real factory environment. It is also important to establish Digital Factory as part of Lean Learning Factory. The main aim is to "see" the product before it is produced, or production system before it is made [2]. There is special equipment that enables students to learn about real processes through simulations. The Taguchi method, 3D modeling, and simulations are used for learning purposes. Whole process is used to show students how different methods and software solutions can help organizations to reduce the time for development and construction and thereby choose an optimal variant of the product. Here in this paper whole process is shown on simple product – table. With optimal construction, it is possible to avoid an oversized product that results with inappropriate weight and higher construction costs. There are three important design stages in the Taguchi method [3]:

1. System Design is characterized by definition of the problem and application of knowledge and achievements to develop a prototype that represents the initial state of the product or process features.
2. Parameter design determines the initial states of all features, which will minimize product or process variations. The orthogonal field is selected depending on the number of controlled parameters, the experiments are performed based on the orthogonal field, the data are analyzed and the optimal state is identified.
3. Tolerance design determines the tolerances of features, which will minimize product or process variations.
Part of Taguchi's method, related to parameter design is a systematic method that applies statistical procedures and tests for shaping function and optimization of shape. P-diagram is used as the base model for Taguchi method, it is shown in figure 1.

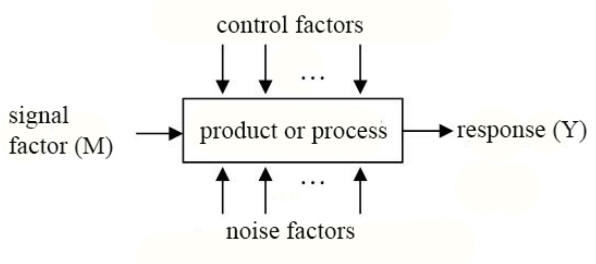

Figure 1. P-diagram [1]
Slika 1. P-dijagram [1]

There are several stages in the planning of experiment:
1) Clear definition and formulation of the problem
2) Review and analysis of all available information about the problem
3) Preparation and selection of the strategy (model use, factor selection, plan of experiments)
4) Performance of first experiment (test)
5) Corrections
6) Performance of other experiments
7) Evaluation of results and comparison with similar research
8) Interpretation of results
9) Conclusion

In this paper, Taguchi method is used to find the optimal construction. The orthogonal arrays are used to organize collected information about effects of controlled factors and about effects of uncontrolled factors and their required levels. With orthogonal arrays and analysis, it is possible to find optimal construction for the table. The optimal construction includes the minimal weight of the table and minimal displacement during the action of vertical and horizontal force. The oversize of construction and big displacement present problems so optimization will be done between three table variants. The basic procedure of this method is by varying the levels of controlled factors, observe their impact on a system response. This approach reduces time and costs of experimenting. The optimization with Taguchi method will be realized through several steps:
1) Defining target values for table construction
2) Determination of control factors
3) Selection of appropriate orthogonal arrays for defined factors that affect table construction (Selection of orthogonal array depends on a number of factors and their levels. In this case, the standard orthogonal array is used but if factors and their levels are not appropriate for standard array there are rules for modification of standard arrays.)
4) Performance of experiments according to conditions in selected orthogonal arrays (Collection of data about influence of selected factors and their levels on defined problems)
5) Analysis of data to select optimal solution

The aim is to achieve a minimal total weight of the table and minimal deflection of the table during the action of horizontal and vertical force.

2. Definition of factors and creation of plan for experiments

According to the defined problem (or target values of the construction), factors of construction are determined. Factors that have the biggest influence on achieving the aim are being considered. They are shown in table 1.

Table 1. Factors and each level
Tablica 1. Parametri i svaka razina

factors	level 1.	level 2.	level 3.
A – frame dimension	80	100	120
B – leg dimension	40	50	60
C – stiffener dimension	40	50	60

The table material is not taken as a factor because it is predefined as well as table height. Table material is constructional steel (St 44-2) and table hight is 900 mm. There are three factors with three levels so orthogonal array L9 is selected. It means that is necessary to do 9 experiments. The software package Design Expert was used for planning experiments and analysis [4]. Three table variants are taken for analysis, the variants are shown in figure 2.

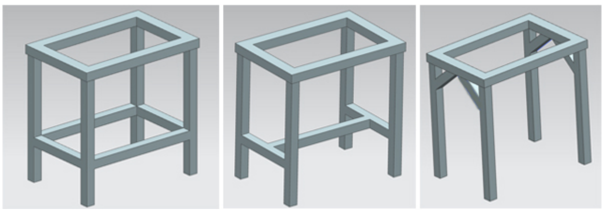

Figure 2. Table variants, experiment 1
Slika 2. Izvedbe stola, pokus broj 1

Three different table variants have been considered, each variant has 9 experiments so there will be 27 experiments. The experiment plan for each table variant is shown in table 2. All data mentioned later in the paper are data relating to the first table variant because of clarity. The procedure is equally done for each other variant in order to find the optimal solution.

Table 2. The plan of experiments
Tablica 2. Plan pokusa

Factor 1 A:A: dim.frame mm	Factor 2 B:B: dim.leg mm	Factor 3 C:C: dim.stiffener mm
80	40	40
80	50	50
80	60	60
100	40	50
100	50	60
100	60	40
120	40	60
120	50	40
120	60	50

Each experiment has three factors: frame dimension, leg dimension and stiffener dimension. The frame of the table is made with tubes that have a rectangular cross section, legs and stiffeners are made with tubes that have a quadratic cross section, where thickness is pre-defined and its amount is 2 mm. The table high is defined in advance and it affects the smaller dimension of rectangular cross section, which is always equal to 60 mm. For each table variant displacement and mass are calculated by using the NX Siemens 10.0 software. The first step is a construction of the 3D model in software module for modeling and the second step is a simulation by using the Finite Element Method – FEM. The Finite Element Method has a wide application in various engineering tasks [5]. The Finite Element Method divides the body into the finite number of simple shape elements that are merged in nodes, figure 3. The displacement in a node is unknown but it is determined by interpolation [6].

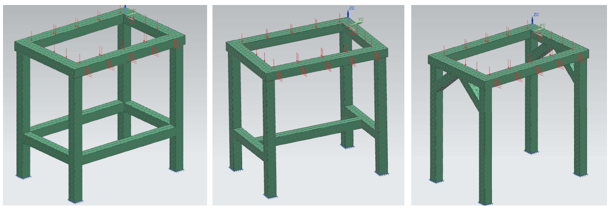

Figure 3. The body of the table divided into the finite number of simple shape elements
Slika 3. Tijelo stola podijeljeno na konačne elemente

The forces for the table load are taken as an example, so vertical force is 1000 N and horizontal force is 300 N. The fixed constraint is set on the surface of legs that lay on the floor. The 27 simulations are completed in the program package NX Siemens 10.0, so the results about displacement and mass were obtained. The results of FEM analysis and displacement are shown in Figure 4.

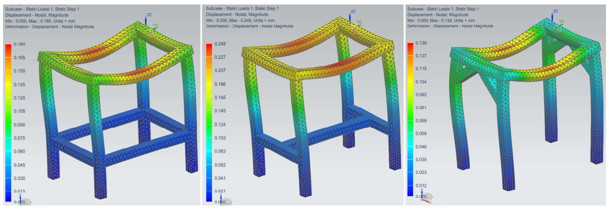

Figure 4. The FEM analysis of different variants, experiment number 1
Slika 4. FEM analiza različitih izvedbi, za pokus broj 1

The results collected from analysis were entered in program package Design Expert 10.0.3. The program uses Taguchi method to find the optimal factors and optimal table variant. The collected data about displacement and mass, as well as dimension of the construction profile are shown in Table 3.

Table 3. The data entered in Design Expert 10.0.3. for second table variant
Tablica 3. Podaci uneseni u Design Expert 10.0.3. za drugu izvedbu stola

Factor 1 A:A: dim.frame mm	Factor 2 B:B: dim.leg mm	Factor 3 C:C: dim.stiff... mm	Response 1 R1 displace... mm	Response 2 R2 mass kg
80	40	40	0.26	23.49
80	50	50	0.157	26.42
80	60	60	0.1075	29.24
100	40	50	0.237	31.11
100	50	60	0.144	33.82
100	60	40	0.142	30.36
120	40	60	0.214	35.2
120	50	40	0.185	30.67
120	60	50	0.131	32.97

3. Analysis and results

The results of experiments are analyzed through determination of the influence of certain factor on a response, depending on which level factor is observed. The analysis of variance (ANOVA) verifies the influence on system response when factors are changing [7]. When all data are entered, the program shows design summary of the process. Figure 5. shows the minimum and maximum level of each factor A, B and C. The "Main effects" model is selected although the program offers more features. The reason for choosing a "Main effects" model is that the system factors are not interdependent. The "Main effects" model is selected although the program offers more features.

Study Type	Factorial		**Subtype**	Randomized		
Design Type	Taguchi OA		**Runs**	9		
Design Mode	Main effects		**Blocks**	No Blocks		
Center Point	0					

Factor	Name	Units	Type	Subtype	Minimum	Maximum
A	A: dim.frame	mm	Categoric	Nominal	80	120
B	B: dim.leg	mm	Categoric	Nominal	40	60
C	C: dim.stiffene	mm	Categoric	Nominal	40	60

Response	Name	Units	Obs	Analysis	Minimum	Maximum
R1	R1 displaceme	mm	9	Factorial	0.1075	0.26
R2	R2 mass	kg	9	Factorial	23.49	35.2

Figure 5. Design summary, for the second table variant
Slika 5. Sažetak podataka, za drugu izvedbu stola

The analysis of variance for displacement shows the probability of 1.21% that value "F" could appear because of noise, figure 7. The value "F" is 81.89, what implies that the model is significant. Values of "$Prob > F$" less than 0.05 indicate that model terms are significant, so here are significant terms B and C, while A is not significant.

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.021	6	3.578E-003	81.89	0.0121
A-A: dim.fran	*9.056E-006*	*2*	*4.528E-006*	*0.10*	*0.9061*
B-B: dim.leg	*0.019*	*2*	*9.499E-003*	*217.40*	*0.0046*
C-C: dim.stifi	*2.461E-003*	*2*	*1.230E-003*	*28.16*	*0.0343*
Residual	8.739E-005	2	4.369E-005		
Cor Total	0.022	8			

Figure 6. Analysis of the variance for displacement, for the second table variant
Slika 6. Analiza varijance za odziv progib, za drugu izvedbu stola

Each model has "AdeqPrecision" or "S-N" ratio greater than 4, what means that each model can be used to navigate the design space. A main effect plots are shown graphically in figure 7. for each factor. The first graph in figure 7. shows that A is not a significant factor.

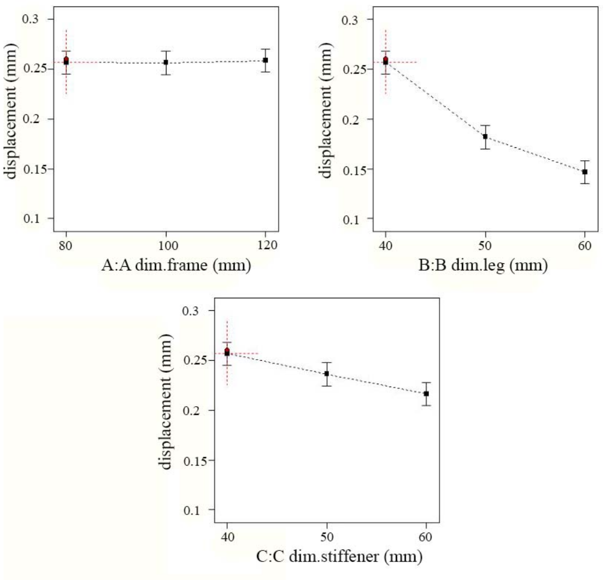

Figure 7. Main effects for response displacement, change of each factor depending on level
Slika 7. Grafički prikaz promjena pojedinog faktora ovisno o razinama, osnovne značajke za odziv progib

The analysis of variance for mass shows that factors with value "$Prob > F$" less than 0.05 indicate that model terms are significant, so here are significant terms A and C, while B is not significant, figure 8. There is "AdeqPrecision" or "S-N" ratio greater than 4, what means that signal is adequate, so the model can be used to navigate the design space.

Analysis of variance table [Classical sum of squares - Type II]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	106.36	6	17.73	73.20	0.0135
A-A: dim.fran	*73.42*	*2*	*36.71*	*151.59*	*0.0066*
B-B: dim.leg	*1.30*	*2*	*0.65*	*2.67*	*0.2721*
C-C: dim.stifi	*31.64*	*2*	*15.82*	*65.33*	*0.0151*
Residual	0.48	2	0.24		
Cor Total	106.84	8			

Figure 8. Analysis of the variance for mass, for the second table variant
Slika 8. Analiza varijance za odziv masa, za drugu izvedbu stola

Graphical display of each factor for response mass, depending on the level, is in figure 9. It is visible on the second graph, in figure 9., that factor B is not significant.

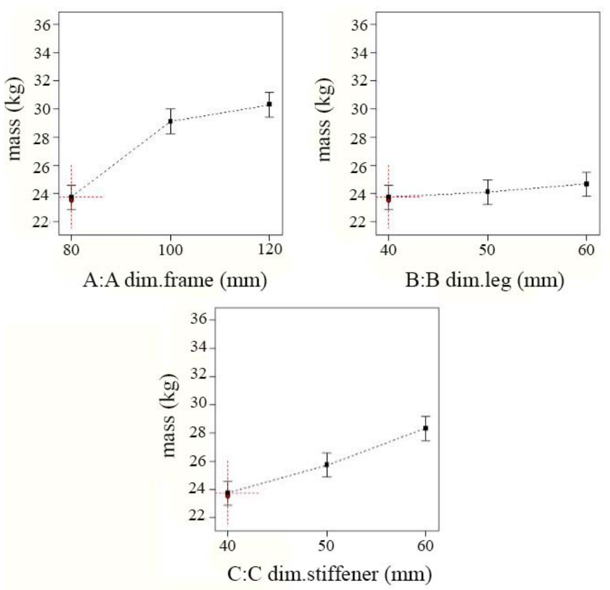

Figure 9. Main effects for response mass, change of each factor depending on level
Slika 9. Grafički prikaz promjena pojedinog faktora ovisno o razinama, osnovne značajke za odziv masa

4. Optimization between table variants

The main aim of this optimization is to find out how different combination of factors influences on the construction of the table, if there are responses mass and displacement that should be minimum. The used method does not provide a mathematical function that describes a problem, it provides an optimal combination according to a given targets, figure 10.

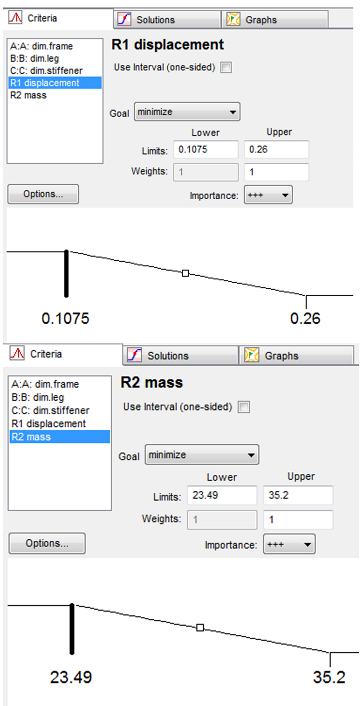

Figure 10. Example of limits for displacement and mass, goal is minimization

Slika 10. Primjer granica za progib i masu, cilj mimimzacija

The used method and mentioned analysis resulted with three table variants that are optimal, figure 11. For each table variant, nine experiments were carried out and the best solution was chosen.

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:A: dim.frame	is in range	80	120	1	1	3
B:B: dim.leg	is in range	40	60	1	1	3
C:C: dim.stiffer	is in range	40	60	1	1	3
R1 displaceme	minimize	0.1158	0.237	1	1	5
R2 mass	minimize	25.36	35.09	1	1	3

Solutions for 27 combinations of categoric factor levels

Number	A: dim.frame	B: dim.leg	C: dim.stiffer	R1 displacem	R2 mass	Desirability
1	80	60	40	0.140	26.974	0.814

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:A: dim.frame	is in range	80	120	1	1	3
B:B: dim.leg	is in range	40	60	1	1	3
C:C: dim.stiffer	is in range	40	60	1	1	3
R1 displaceme	minimize	0.1075	0.26	1	1	3
R2 mass	minimize	23.49	35.2	1	1	3

Solutions for 27 combinations of categoric factor levels

Number	A: dim.frame	B: dim.leg	C: dim.stiffer	R1 displacem	R2 mass	Desirability
1	80	60	40	0.147	24.684	0.817

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:A: dim.frame	is in range	80	120	1	1	3
B:B: dim.leg	is in range	40	60	1	1	3
C:C: dim.stiffer	is in range	40	60	1	1	3
R1 displaceme	minimize	0.0758	0.195	1	1	3
R2 mass	minimize	21.76	28.19	1	1	3

Solutions for 27 combinations of categoric factor levels

Number	A: dim.frame	B: dim.leg	C: dim.stiffer	R1 displacem	R2 mass	Desirability
1	80	50	40	0.112	23.766	0.692

Figure 11. Solutions for each table variant
Slika 11. Rješenja za svaku varijantu stola

The third table variant is chosen for Lean Learning Factory, that variant has optimal mass with minimum displacement, figure 12. The table will be integrated into the assembly line that exists already in Lean Learning Factory. It is an assembly line for karet.

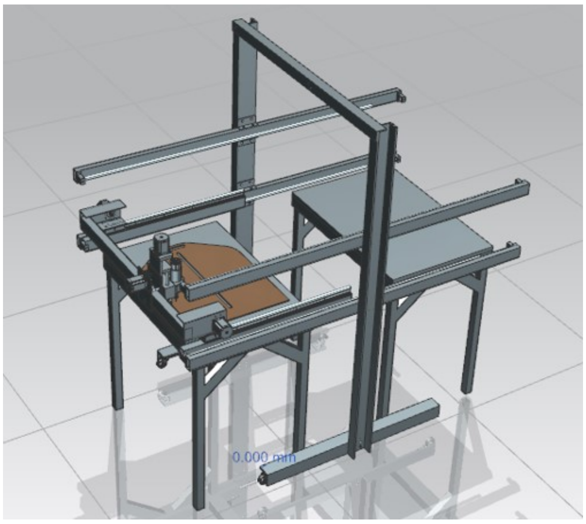

Figure 12. Solution for Lean Learning factory
Slika 12. Rješenje za Lean Learning factory

5. Conclusion

The Lean Learning Factory is a simulation of the real factory environment. This paper presents methods used for the improvement of equipment in Lean Learning Factory. Table variant that is chosen will be integrated into existing karet assembly line. The first step for the whole process was the definition of factors. The second step was Taguchi method and design of experiments, so after that step FEM analysis for each combination of factors was made according to the plan of experiments. The mentioned process resulted with optimal table variant that will be used in Lean Learning Factory. The purpose of this paper is to find out best solutions for improvement of equipment using several methods and software support.

6. Acknowledgement

This work has been fully supported by Croatian Science Foundation under the project Innovative Smart Enterprise – INSENT (1353).

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