OPTIMIZATION OF CHASSIS DESIGN FOR ASSEMBLY LINE FEEDER USING PROMETHEE AND TAGUCHI METHODS

Nikola Gjeldum, Bozenko Bilic, Zvonimir Tomic

PhD. N. Gjeldum, University of Split, FESB, R. Boskovica 32, 21000 Split, Croatia
Prof. PhD. B. Bilić, University of Split, FESB, R. Boskovica 32, 21000 Split, Croatia
Z. Tomic, University of Split, FESB, R. Boskovica 32, 21000 Split, Croatia

Keywords: learning factory, assembly line, design optimization, taguchi method, promethee

Abstract

The Learning Factory concept presents simulation of a real factory environment through specialized equipment. Mission is to integrate needed knowledge into the engineering curriculum by using of didactic games and production lines which presents simplified real processes from industry. In this paper, design optimization of low cost and low quality equipment for Learning Factory is presented. Using guidelines for Design for Manufacturing and Assembly (DFMA), four different designs of chassis for assembly line feeder are evaluated using PROMETHEE method. For steel chassis, total weight and costs of parts for given load has to be minimized in order to minimize total costs. On the other hand easiness of machining and assembly is also taken in consideration. Subsequent consideration used redesigns of selected design according Taguchi design of experiments. According Finite Element Analysis (FEM) results for estimated loads, the lightest chassis is selected in compromise to minimization of maximal deformation.

1. INTRODUCTION

The project Innovative Smart Enterprise (INSENT), financed by Croatian Science Foundation has the priority to strengthen cooperation between research institutions and entrepreneurship. The main objective of this project is to develop Croatian model of Innovative Smart Enterprise (HR-ISE model) taking into consideration specific regional way of thinking, manufacturing and organizational tradition and specific education. Its results should help Croatian enterprises to bridge the gap between their competencies and EU enterprises' competencies and capabilities [1].

A special learning environment is in establishing process in one Laboratory at University of Split, Faculty of electrical engineering, mechanical engineering and naval architecture (FESB). It will be Lean Learning Factory which represents simulation of a real factory through specialized equipment. Laboratory will be organized to simulate factory based on HR-ISE model. Hence, Laboratory will be learning environment not just for students but for engineers from manufacturing enterprises. It will be a place in which transfer of developed HR-ISE model to the economy subjects will be achieved.

Establishment of Lean Learning Factory at FESB has been encouraged by European Initiative on Learning Factories and project Network of Innovation Learning Factories (NIL) financed by Deutscher Akademischer Austauschdienst German Academic Exchange Service (DAAD), in which FESB took part [2].

The Lean Learning Factory (Fig. 1) is already equipped with didactic and real products for demonstration and learning of Lean tools and methods. Didactic game "Lego flowcar®" is modified to teach students and industry employees by hands-on simulation embedded in learning materials in form of presentations. It covers methods related to efficient warehousing and logistic systems and balanced workload on assembly stations for different game scenarios. Methods for information flow are also included. Another game is developed using bunch of toy trucks and toy formula cars which can be easily assembled. Besides line balancing, assembly process can be analyzed, improved and schematically expressed by using this game. Beer distribution game covers supply chain management tools.

Figure 1. Lean Learning Factory at FESB.

Project named Master studies programme and continuing education network in Product Lifecycle Management with Sustainable Production 144959-TEMPUS-2008-IT-JPCR financed server and eight personal computers, A1 size plotter and 80 licenses for PLM software Siemens (NX, Technomatix and Teamcenter) [3]. This gives opportunities to engage students for problem oriented projects with possibility of manufacturing, assembly and implementation of designed equipment.

2. GEARBOX ASSEMBLY LINE

In effort to make hands-on learning process more familiar to mechanical and industrial engineers and industry employers, assembly stations and conveyer line for gearbox assembly have been developed (Fig. 2). Education on real assembly stations and tools for complex product assembly, together with real products to assembly, gives necessary skils to learners for further development of balanced assembly lines, assembly documentation and procedures, conveyor systems or other transport systems, clamping tools, measurement procedures and quality assurance tests.

The assembly line for real products shows better acceptance by learners, especially from industry employees. But, on the other side, complexity, effort and time necessary to conduct simulation runs, disable assembly line to operate in its full content. On some stations, parts are too heavy, or numerous, which leads to high process time variations dependable on learners skills.

Figure 2. Gearbox assembly line.

Problem presented in this article is upper chase of gear box which is assembled in fifth station on assembly line (Fig 2.). Assembly on this station requires precision position adjusting while holding heavy upper casing. Proposed solution is shown in Fig. 3. Feeder for that station will be installed between conveyer line and supermarket. The supermarket will be redesigned to enable feeding of upper casings in one row. The feeder will have functionality to grip one casing, lift it and bring it down in enough correct position and orientation for assembly. As the feeder is equipment with expected high weight, which will be used in laboratory environment, it should be on wheels. Additional devices should be provided to enable fixing of the feeder to both the supermarket and the conveyor to achieve accuracy of positioning.

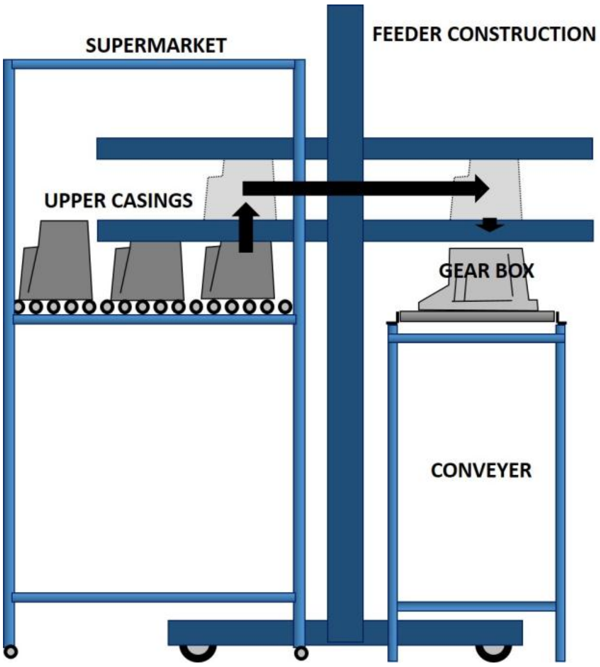


Figure 3. The assembly line feeder position.

3. SELECTION OF OPTIMAL FEEDER DESIGN WITH PROMETHEE METHOD

Using guidelines for DFMA, and taking into consideration machine tools available on FESB, four designs are developed and shown in Fig 4. Every proposed design uses steel profiles and strips, assembled with screws and nuts. By using Multi-Criteria Decision-Making (MCDM) method PROMETHEE, designs are evaluated according to their costs, weights, number of machined parts and simplicity of assembly process.

The MCDM consists of selection of the optimal alternative, comparison and ranking of alternatives, or comparison of alternatives with some referent points (sorting of alternatives). Generally, MCDM methods can be divided into following groups based on their characteristics: based on utility functions – MAUT [4], outranking methods – AHP [5], ELECTRE [6], PROMETHEE [7], TOPSIS [8], and interactive methods – VIMDA [9]. The PROMETHEE method is well accepted by decision-makers because it is comprehensive and has the ability to present results using simple ranking.

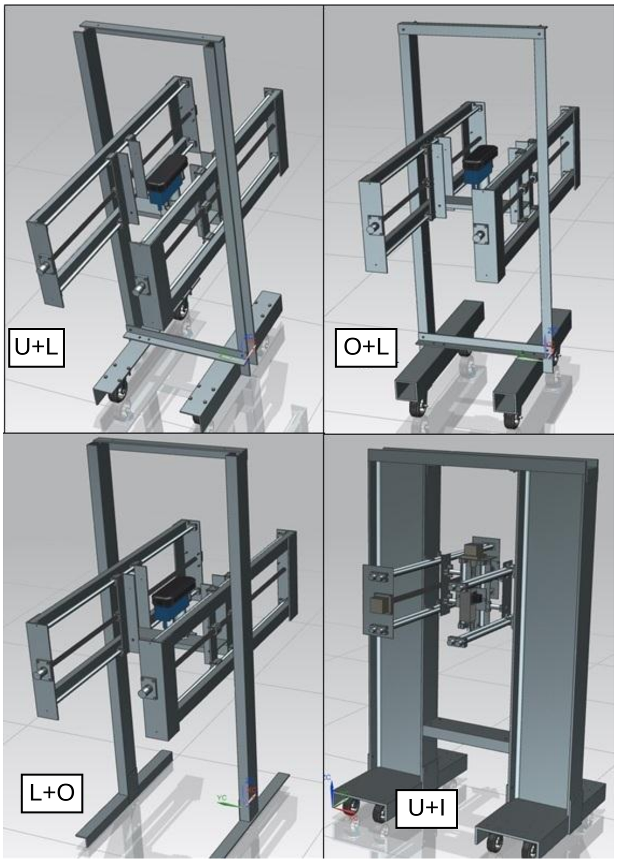


Figure 4. Four designs of the feeder.

The PROMETHEE method was developed by J. P. Brans and B. Mareschal in 1983 [7]. An input for the PROMETHEE method is a matrix consisting of set of potential alternatives (actions) *A*, where each *a* element of *A* has its $\phi(a)$ which represents evaluation of one criterion. Method PROMETHEE I ranks actions by a partial ranking, with the following dominance flows, for the positive outranking flow [7]:

$$\phi^{+}(a)=\frac{1}{n-1}\sum_{x\in A}\Pi(a,x) \tag{1}$$

and for the negative outranking flow [7]:

$$\phi^{-}(a)=\frac{1}{n-1}\sum_{x\in A}\Pi(x,a) \tag{2}$$

where *a* and *x* represent the actions from set of action *A* (during the pairwise comparison of action *a* with all other *n*-1 actions), *n* is the number of actions and Π is the aggregated preference index defined for each couple of actions. There are six types of preference functions proposed by authors of the method [7].

The PROMETHEE I method gives the partial relation, and then net outranking flow is obtained from PROMETHEE II method which ranks the actions by complete ranking calculating net flow [7]:

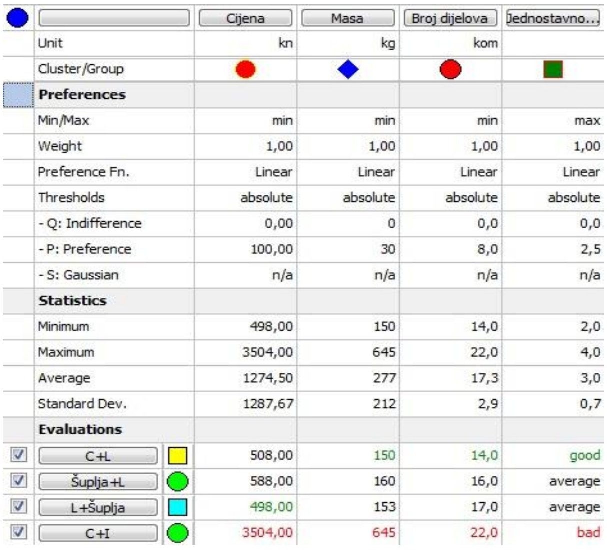
$$\phi(a)=\phi^{+}(a)-\phi^{-}(a) \tag{3}$$

Usually, criteria are weighted using criteria weights w_j and usual pondering technique:

$$\Pi(a,b)=\frac{\sum^{n}{}_{j=1} w_j P_j(a,b)}{\sum^{n}{}_{j=1} w_j} \tag{4}$$

where $P_j(a,b)$ represents preference of *a* over *b* for given preference function of criterion *j*. Recently, authors of the PROMETHEE method presented newest software for its application, Visual PROMETHEE [10].

Input table for Visual PROMETHEE is in the Fig. 5. It consists of input data calculated and obtained by NX software for all four designs, together with weight factors and preference functions.



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	Unit	kn	kg	kom	
	Cluster/Group	●	◆	●	■
	Preferences				
	Min/Max	min	min	min	max
	Weight	1,00	1,00	1,00	1,00
	Preference Fn.	Linear	Linear	Linear	Linear
	Thresholds	absolute	absolute	absolute	absolute
	- Q: Indifference	0,00	0	0,0	0,0
	- P: Preference	100,00	30	8,0	2,5
	- S: Gaussian	n/a	n/a	n/a	n/a
	Statistics				
	Minimum	498,00	150	14,0	2,0
	Maximum	3504,00	645	22,0	4,0
	Average	1274,50	277	17,3	3,0
	Standard Dev.	1287,67	212	2,9	0,7
	Evaluations				
☑	C+L 🟨	508,00	150	14,0	good
☑	Šuplja+L 🟢	588,00	160	16,0	average
☑	L+Šuplja 🟦	498,00	153	17,0	average
☑	C+I 🟢	3504,00	645	22,0	bad

Figure 5. Visual PROMETHEE input table.

Results, presented in Table 1 shown that optimal design is U+L design as it has the highest net flow.

Table 1. PROMETHEE flow table.

Rank	Design	$\phi(a)$	$\phi^{+}(a)$	$\phi^{-}(a)$
1.	U+L	0,5299	0,5382	0,0083
2.	L+O	0,2715	0,3549	0,0833
3.	O+L	0,0299	0,2729	0,2431
4.	U+I	-0,8313	0,0000	0,8313

4. OPTIMALIZATION OF PROFILE SIZES WITH TAGUCHI METHOD

For selected design of feeder, further consideration is made in order to reduce overall weight and therefore cost. Compromise between weight of construction and maximal deformation has to be taken into consideration in optimization procedure. For optimization purpose, Taguchi approach for Design of Experiments (DOE) is used. The DOE using Taguchi approach can economically satisfy the needs of problem solving and product design optimization projects. By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations [11].

Using the Taguchi experimental design, a L16 (4^5) orthogonal array was selected which is suitable for five factors and four levels for each factor [12]. Four factors are taken into consideration, while fifth factor is omitted. The advantage of using an orthogonal array is the ability to estimate all the main factor effects and all the possible interaction with a minimal number of experiments. This approach is considered as very efficient since much information is obtained from a only few trials [13]. Analysis and optimization is conducted in Design Expert 10 software.

The factors selected are discrete values which represents one reference dimension of four different steel profile sizes from which construction is made (Fig. 6). Preliminary random experiments are conducted to define range of factors. Lower cross connecting L-shape profile is eliminated due to its negligible stress and deformation. In Table 2. Influence factors and levels are listed.

There are three signal-to-noise (S/N) ratios that are available, which can be selected based on the response function and its characteristics. In design of the construction, desired responses considered in this article are minimum weight and minimum deformation. Therefore, smaller the better ratio were selected. The S/N ratio for minimum responses type of characteristic can be calculated as follows:

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (5)$$

where n is the number of trails, and y_i is the observed data at i-th trial. S/N ratio is used to determine the influence parameters on process results. Optimal sets of process parameters can be determined using S/N ratio.

Experiments were done according to the list of experiments shown in Table 3. The factor levels and corresponding response results are also shown in Table 3.

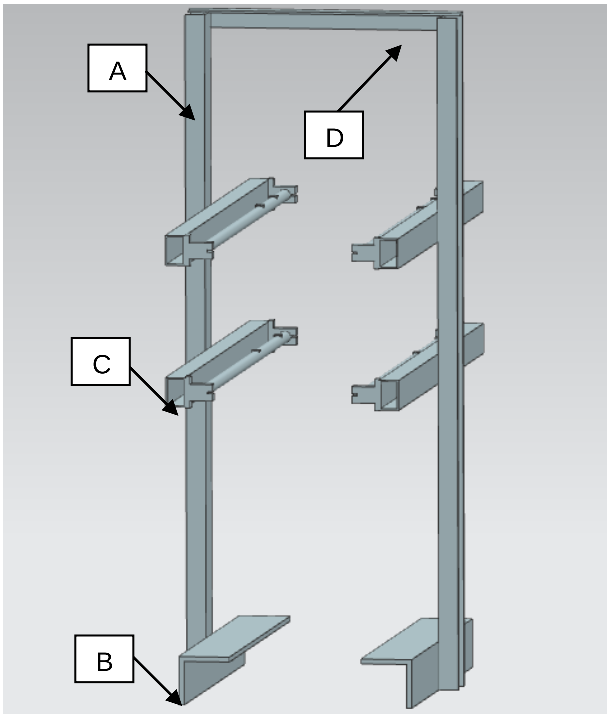

Figure 6. Factors that define size of profiles.

Table 2. Influence factors and levels.

Factor	Level 1	Level 2	Level 3	Level 4
A	80	100	120	140
B	70	90	110	130
C	40	60	80	100
D	40	50	60	70

Table 3. Response values for experiment plan.

Exp.	A	B	C	D	Mass [kg]	Displa-cement [mm]
1.	80	70	40	40	78,14	0,597
2.	80	130	100	70	190,31	0,182
3.	80	110	80	60	145,40	0,201
4.	80	90	60	50	102,27	0,287
5.	100	70	60	60	101,57	0,265
6.	100	90	40	70	99,32	0,547
7.	100	110	100	40	178,99	0,13
8.	100	130	80	50	164,69	0,12
9.	120	90	100	60	183,23	0,119
10.	120	130	60	40	141,23	0,243
11.	120	110	40	50	114,84	0,49
12.	120	70	80	70	145,83	0,14
13.	140	90	80	40	160,34	0,077
14.	140	110	60	70	141,20	0,225
15.	140	70	100	50	181,14	0,059
16.	140	130	40	60	140,13	0,467

The first response result is weight of the constructions. It is calculated according dimensions from working drawing and specific weight of selected profiles. The second response result is maximal displacement which is obtained by finite element method. The finite element method (FEM) is a widely used numerical method for solving problems in engineering field which include structural analysis. While the analytical solution of structural analysis generally require the solution to boundary value problems for partial differential equations, the finite element method formulation of the problem results in a system of algebraic equations [14]. Used Siemens software NX has embedded module for FEM analysis. For every experiment run, new construction design is modeled and analyzed with FEM to obtain maximal displacement. Visualization of FEM analysis results confirm that maximal displacement is achieved in linear guide rails for handling device.

A main effect plots were used to visualize performance changes as each individual factor level is changed (Fig. 7 and Fig. 8).

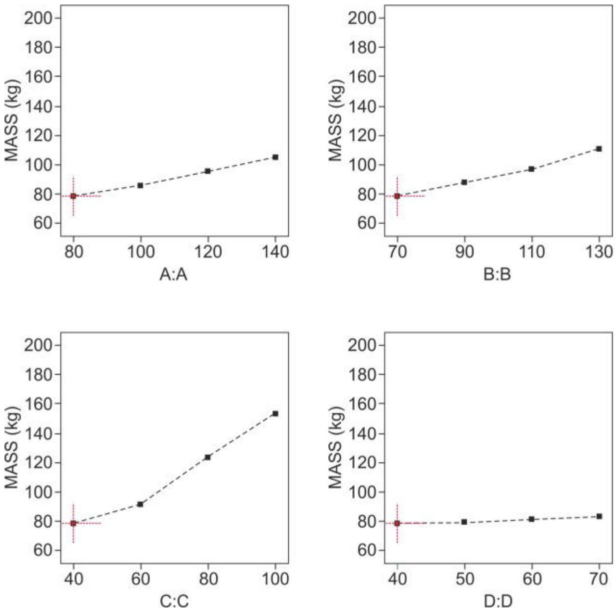

Figure 7. Main effects plot for mass

After conduction of the Taguchi approach, for given importance of four for mass minimization and importance of three for displacement minimization, optimal construction is selected. Dimension of the optimal construction profile sizes are listed in Table 4. Models derived for mass and displacement prediction have 0,996 and 0,977 prediction R^2 respectively. Therefore afterward calculation of mass and displacement has been done. Results in comparison with predicted values are shown in Table 4. Although difference of the actual results and results of Taguchi method prediction is 1,4% and 6,6%, reduction of experimentation efforts by reducing number of experiments for full factorial design in comparison to Taguchi experiment plan is significant and favorable. Design of optimal construction is shown in Fig. 9. Displacement visualization is shown in Fig. 10.

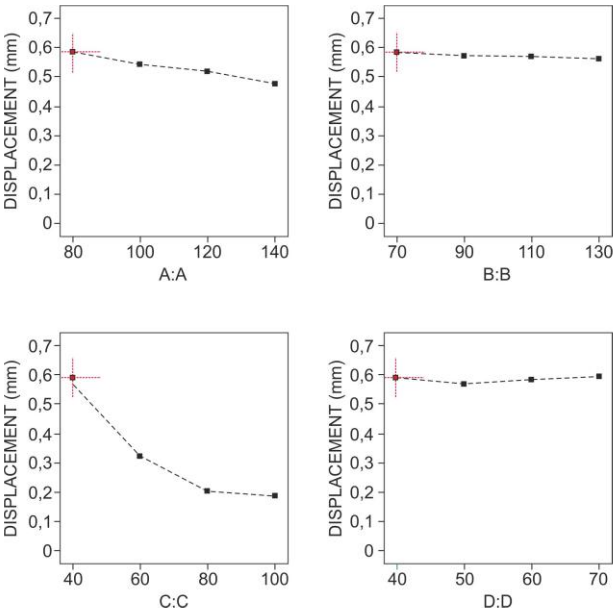

Figure 8. Main effects plot for displacement

Table 4. Dimension and response values of optimal construction

	A	B	C	D	Mass [kg]	Displa-cement [mm]
Pred.	80	70	40	40	99,74	0,247
Act.	80	130	100	70	101,14	0,266

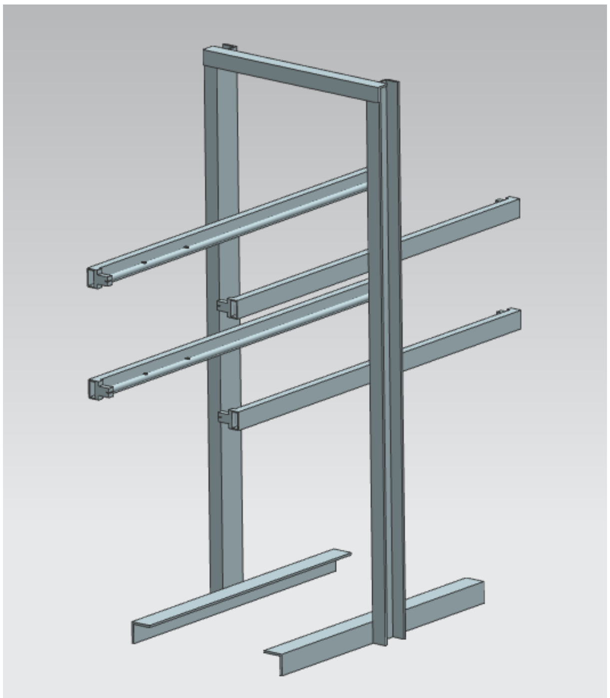

Figure 9. Optimal construction.

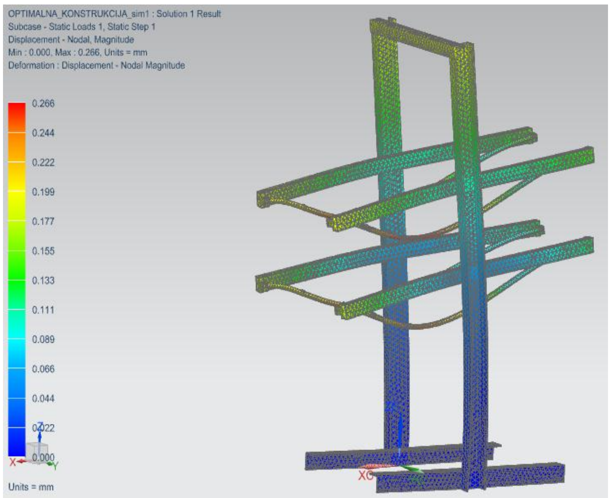

Figure 10. Displacement visualization of optimal construction.

5. CONCLUSION

The Learning Factory concept presents simulation of a real factory environment by using of didactic games and production lines which presents simplified real processes from industry. In this paper, design optimization of low cost and low quality equipment for Learning Factory is presented, which will be integrated in existing gearbox assembly line. Presented assembly line feeder is developed to reduce the effort needed for assembly of gearboxes for manipulation and assembly of heavy gearbox chassis. Two stage optimization method is used. In the first stage, by using PROMETHEE method, optimal design of construction is selected. In the second stage, Taguchi approach and design of experiments are used to optimize mass of construction in relation to maximal displacement. FEM analysis is used to determine displacement of construction. Optimization process results with optimal construction with low weight of 101,14 kg, which gives maximal displacement of only 0,266 mm for given load.

ACKNOWLEDGEMENT

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

6. REFERENCES

[1] Gjeldum, N., Mladineo, M., Veža, I., 2016, Transfer of Model of Innovative Smart Factory to Croatian Economy using Lean Learning Factory, Procedia CIRP, Vol. 54, p. 158-163.

[2] Tisch M., Hertle C., Cachay J., Abele E., Metternich J., Tenberg R., 2016, A systematic approach on developing action-oriented, competency-based Learning Factories. Procedia CIRP; Vol. 7, p. 580-585.

[3] Gecevska V., Lombardi F., Cus F., Anisic Z., Angelidis D., Veza I., Popovska Vasilevska S., Cosic P., 2010, PLM-Product Lifecycle Management Strategy for Innovative and Competitive Business Environment. Innovative Production Systems Key to Future Intelligent Manufaturing. Univerza v Mariboru, p. 193-208.

[4] Farquhar, P. H., 1977, A survey of multi attribute utility theory and applications. Multiple Criteria Decision Making - TIMS Studies in the Management Sciences, Vol. 6, p. 59-90.

[5] Saaty, T. L., 1980, The Analytic Hierarchy Process: planning, priority setting, resource allocation. New York: McGraw Hill.

[6] Roy, B., 1968, Classement et choix en présence de points de vue multiples (la méthode ELECTRE). La Revue d'Informatique et de Recherche Opérationelle (RIRO), Vol. 8, p. 57-75.

[7] Brans, J.P., Mareschal, B., Vincke, P.H., 1984, PROMETHEE - a new family of outranking methods in multicriteria analysis. Operational Research IFORS 84, Amsetrdam.

[8] Yu, C. X., Wong, T. N., 2011, A TOPSIS-based pre-selection method supporting multiple products partner selection in a virtual enterprise. 21st International Conference on Production Research - Conference Proceedings, p. 1162-1167.

[9] Olson, D. L., 1996, Decision Aids for Selection Problems. New York: Springer.

[10] Mareschal, B., 2017, Visual PROMETHEE. http://promethee-gaia.net Accessed: 01/04/2017.

[11] Charantimath, P. M., 2011, Total quality management, 2nd Edition, Pearson, Dorling Kindersley, India.

[12] Roy, R. K., 2001. Design of Experiment Using the Taguchi Approach: 16 Steps to Product and Process Improvement. 1st Edition, Wiley Interscience, New York, USA.

[13] Peace, G.S., 1992. Taguchi Method: A Hands-on Approach. 1st Edn., Addison-Wesley Publishing, Massachusetts, USA.

[14] Reddy, J.N., 2006, An Introduction to the Finite Element Method (Third ed.). McGraw-Hill.