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Development and utilization of a DFMA-evaluation matrix for comparing the level of modularity and standardization in clamping systems

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1. Introduction

The advantages of standardization and modularization for manufacturing friendly design have been widely reported [1, 2]. In design assessment, numerical evaluation forms are commonly used to evaluate both manufacturability and assembility.

Design for manufacturing and assembly (DFMA) concepts have proved to reduce cost and time in manufacturing and assembly of different constructions up to 70% [2, 3].

The main object of numerical DFMA-evaluation forms is to bring globally designed products into an evaluation environment where they can be compared and to establish which parts of the product structure or details have the potential for improvements regarding manufacturability and assembility. School grade scales, value analysis or methods based on product performance can be used for numerical evaluation of different properties. However, previous work does not prioritize the modularization and standardization points of view or analyze if modularization has led to standardization or existing standard has led to modularization.

This article combines these two perspectives and produces a tool enabling the evaluation and comparison of alternative constructions based on modularity, standardization, manufacturability and assembility.

In theory: Modularity can be seen to base on a product's or part's a) geometrical, b) functional and c) manufacturability details. In this paper's case (a) confirms a standardized joining to the environment (b) is verified with measurements and (c) has been taken into account because of DFMA- views. Standardization starts often with (a) and minimal functional requirements form the terms in which the comparison can be done and the requirements will be met.

2. Materials and methods

This paper consists of two parts. The first part introduces a DFMA-evaluation matrix for evaluation of an assembly's suitability for modularization or standardization. A zero point clamping system is selected to be analyzed. The second part is preliminary validation of the results, which includes accuracy measurements from the selected fixturing system.

2.1. Requirements and wishes, criteria of modularization and standardization

The approach of this research is to prioritize the modularization and standardization points of view in manufacturing and assembling. Naturally, functional requirements (Example in Table 3) must be met. Several possible combinations that fulfill the functional requirements and use the advantages that modularity and standardization offer can be found between functional and manufacturing requirements. Modularization criteria according to [4] are presented in Table 1 and standardization criteria are presented in Table 2.

Table 1

Criteria of modularization [4]

Criteria of modularization	
1 Reducing product complexity	2 Managing the product in smaller assemblies
3 Separate design of assemblies (modules)	4 Separate manufacturing of assemblies (modules)
5 (Easier) control and development of (customer's) requirements to the product	6 Increase of product variation possibilities
7 Forming a product family	8 Creation of parallel assemblies

Table 2

Criteria of standardization [4]

Criteria of standardization	
1 Unambiguous quality limits, better quality	2 Unambiguous tolerance limits
3 Compability of measurements, materials, shapes	4 Interchangeability of parts
5 Better product / system safety	6 Lower cost (production, maintenance, design,storage)
7 Uniformity of production (=efficiency of industrial production, production time)	8 Same product can be manufactured in different places
9 Compatirivity of products of different manufacturers	10 Easier composition of (manufacturing) documents

In addition, it must be noted that modularization can be a result of existing standardized solutions or modularization can create new standardized solutions. This produces two new possible combinations of alternatives between possible modularized and standardized solutions.

In this research, the evaluation of modularity has been divided into eight different criteria, as in Table 1, and the evaluation of standardization into ten criteria as in Table 2. The writers of the article have used a scale of 0 to 5 to evaluate the criteria. Evaluation checks both ways: modularization has led to standardization or an existing standard has led to modularization. A similar analysis method of performance and manufacturability has been used in previous LUT research [5].

The starting point was that traditional manufacturability requirements have already been included into the product's requirement list (Example in Table 3). Requirements such as these include, for example, suitability for certain manufacturing methods and machinery. The solution produced in this research uses the advantages of modularization and standardization and aims to fulfill as many requirements for easy manufacturing as possible. This research does not include the optimization of a tool that is attached to the fixing system. Such research has also been conducted in LUT earlier [6], but this study is limited to the fixing systems in both female and male tools and their connection to the plate and the fixing system's connection to the pressing tool.

Table 3

Example of requirements and wishes

Requirements	Wishes
Positioning accuracy 0.01 mm or better	Hydraulic and pneumatic models available
Withstands 150 kN pressure	Fewer parts than existing system
Same fixing geometry in every tool	Fast fixing and separation of tools
Withstands machining forces	Suitable to current networks (pressure air etc)
	Maintenance free

	Modular 1	Modular 2	Modular 3	Modular 4	Modular 5	Modular 6	Modular 7	Modular 8	Standard 1	Standard 2	Standard 3	Standard 4	Standard 5	Standard 6	Standard 7	Standard 8	Standard 9	Standard 10
Modular 1	5,0	4,5	4,5	4,5	3,2	3,2	3,9	2,2	0,9	5,0	0,9	3,1	2,2	3,2	4,5	5,0	0,0	3,6
Modular 2	4,5	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0
Modular 3	4,5	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0
Modular 4	4,5	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0
Modular 5	3,2	2,8	2,8	2,8	2,0	2,0	2,4	1,4	2,8	3,2	2,8	2,4	1,4	2,0	2,8	3,2	0,0	2,8
Modular 6	3,2	2,8	2,8	2,8	2,0	2,0	2,4	1,4	2,8	3,2	2,8	2,4	1,4	2,0	2,8	3,2	0,0	2,8
Modular 7	3,9	3,5	3,5	3,5	2,4	2,4	3,0	1,7	3,5	3,9	3,5	3,0	1,7	2,4	3,5	3,9	0,0	3,5
Modular 8	2,2	2,0	2,0	2,0	1,4	1,4	1,7	1,0	2,0	2,2	2,0	1,7	1,0	1,4	2,0	2,2	0,0	2,0
Standard 1	3,6	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0
Standard 2	5,0	4,5	4,5	4,5	3,2	3,2	3,9	2,2	4,5	5,0	4,5	3,9	2,2	3,2	4,5	5,0	0,0	4,5
Standard 3	1,8	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0
Standard 4	0,8	3,5	3,5	3,5	2,4	2,4	3,0	1,7	3,5	3,9	3,5	3,0	1,7	2,4	3,5	3,9	0,0	3,5
Standard 5	2,2	2,0	2,0	2,0	1,4	1,4	1,7	1,0	2,0	2,2	2,0	1,7	1,0	1,4	2,0	2,2	0,0	2,0
Standard 6	3,2	2,8	2,8	2,8	2,0	2,0	2,4	1,4	2,8	3,2	2,8	2,4	1,4	2,0	2,8	3,2	0,0	2,8
Standard 7	4,5	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0
Standard 8	5,0	4,5	4,5	4,5	3,2	3,2	3,9	2,2	4,5	5,0	4,5	3,9	2,2	3,2	4,5	5,0	0,0	4,5
Standard 9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Standard 10	0,9	4,0	4,0	4,0	2,8	2,8	3,5	2,0	4,0	4,5	4,0	3,5	2,0	2,8	4,0	4,5	0,0	4,0

Fig. 1 An example evaluation matrix

2.2. Evaluation matrix

In order to evaluate such structural and geometrical solutions where modularity and standardization work together, the evaluation matrix calculates the geometrical average between interacting criteria of modularity and standardization. Between these values and individual criteria, the arithmetic average is calculated. This value describes the suitability of each alternative solution in terms of modularity and standardization. The purpose of this calculation is to separate solutions that utilize both modularity and standardization at the same time. An example of an evaluation matrix is shown in Fig. 1. In this matrix, a zero-point clamping system is compared to the older fixing method, which was tightened with four M12 screws and required positioning with every tool change. This positioning was often time consuming and increased machine down times.

The fields of the matrix describe the following: Only modular criteria are evaluated in the upper left (UL) field and only standardized criteria are evaluated in the lower right (LR) field on a scale from 0 to 5. The upper right (UR) and lower left (LL) fields evaluate solutions where modularity has led to standardization or standardization has led to modularity. In cases where the criteria of modularity and standardization do not get the same grade, a weighted factor is needed. We have assumed that the more significant factor is given the weight factor of 0.8 and the less significant a weight factor of 0.2. This aims to highlight the bilateral priority of modularity and standardization. The tool describes the "succession rate" of both modularization and standardization, but in addition to that, it also describes how much modularization has guided standardization or vice versa.

The evaluation is carried out by the geometrical averages of individual values. Finally, the average of all graded values in the table is calculated. This average describes the suitability of the alternative. An analog solution to the table is the analysis of the adhesion of different materials to each other, and in some ways it is an application of cross-tabling in which all possible combinations are graded. For analytical review, the DFMA grade produced by the table can be expressed according to Eq. (1) where x is the DFMA grade of the solution.

$$x = \frac{1}{4}\left(\frac{n_{UL1} + n_{UL2} + n_{UL3} + ... + n_{UL64}}{64} + \frac{n_{UR1} + n_{UR2} + n_{UR3} + ... + n_{UR80}}{80} + \right.$$

$$+\frac{n_{LL1}+n_{LL2}+n_{LL3}...n_{LL80}}{80}+\frac{n_{LR1}+n_{LR2}+n_{LR3}...+n_{LR100}}{100}\Bigg) \quad (1)$$

For the preliminary evaluation of standardization and modularization, a simplified fourfold table according to Fig. 2 can be used. This table shows only the occurrence of combinations in a construction. Constructions with many recognized features take advantage of modularity and standardization effectively. If upper right and lower left fields are highlighted, the construction also has a functional connection between modularization and standardization. An analog to this is selecting polymers to applications where they need to fill several different requirements. [5]

	Modular 1	Modular 2	Modular 3	Modular 4	Modular 5	Modular 6	Modular 7	Modular 8	Standard 1	Standard 2	Standard 3	Standard 4	Standard 5	Standard 6	Standard 7	Standard 8	Standard 9	Standard 10
Modular 1	x	x																
Modular 2	x	x	x															
Modular 3		x	x										x					
Modular 4		x	x										x		x			
Modular 5													x					
Modular 6					x	x					x							
Modular 7			x												x			
Modular 8								x										
Standard 1									x	x								
Standard 2					x				x	x								
Standard 3					x												x	
Standard 4						x										x		
Standard 5				x	x						x	x				x		
Standard 6				x	x									x			x	
Standard 7					x					x			x		x			
Standard 8																x		x
Standard 9																		
Standard 10																x		x

Fig. 2 An example of a simplified evaluation matrix

2.3. Validation and accuracy test of the zero-point clamping cylinder

The first stage of the validation research was to research if the zero-point clamping system can achieve the necessary repeating accuracy. A machining center was used to machine a positioning surface geometry required by the clamping cylinder (Figs. 3-5).

The clamping cylinders used were AMF K20 series square shaped cylinders:

- Type AMF 6370EQ-20HA-001;
- Locking force: 20 kN;
- Holding force 55 kN;
- Hydraulic locking;
- Air blow.

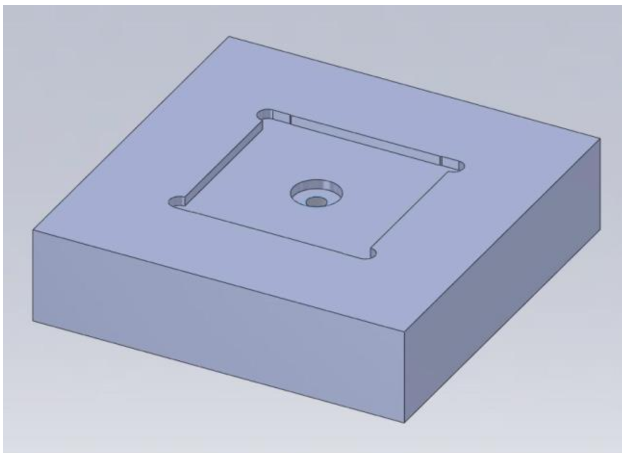

Fig. 3 3D- model of the positioning surface geometry

AMF 6370S2-20HA-002 embedded cylinders were used in the machining stage. The palette size was 400 × 200 mm and the distance between cylinder center-points was 200 mm.

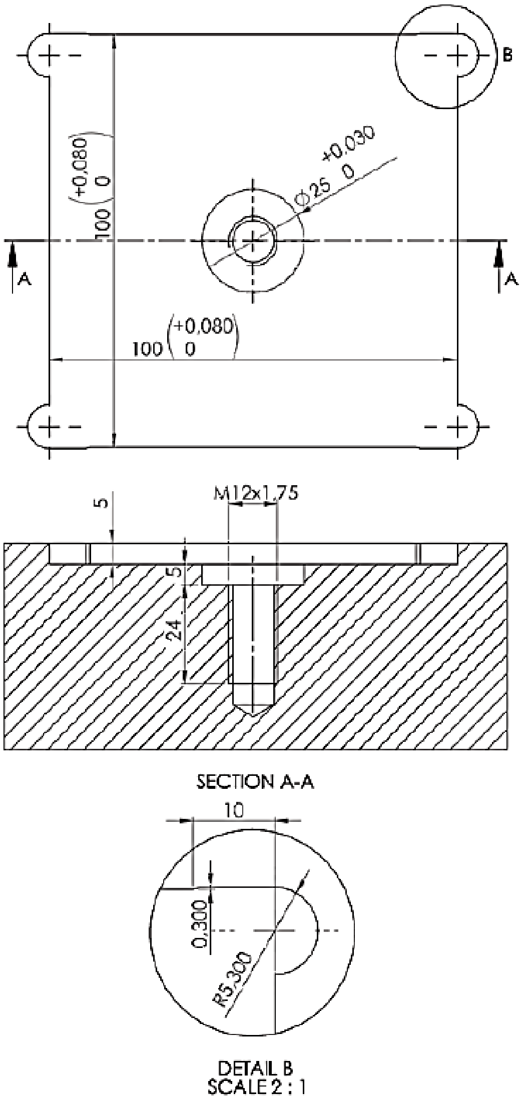

Fig. 4 Positioning surface and its dimensions

After the part with this attachment geometry was machined, it was attached to the clamping cylinder, which was positioned inside the machining center (Fig. 6). This attachment required attaching the clamping nipple onto the part's thread hole. Several tests were performed to measure the accuracy and repeatability of the fixing with the zero-point clamping cylinder.

The test part's outer edges were machined with symmetrical surfaces which were equidistant to the programmed center point. These edges were measured and the test piece was then repeatedly removed from and re-attached to the cylinder. The measuring system was constructed by attaching a dial gauge into the machining center's spindle (Fig. 7). While measuring the coordinate of the part, the part was always approached from the same direction to eliminate the error from the machining center's clearances. Once the spindle was in the correct position, the dial gauge showed the change in coordinates while the part was removed or turned.

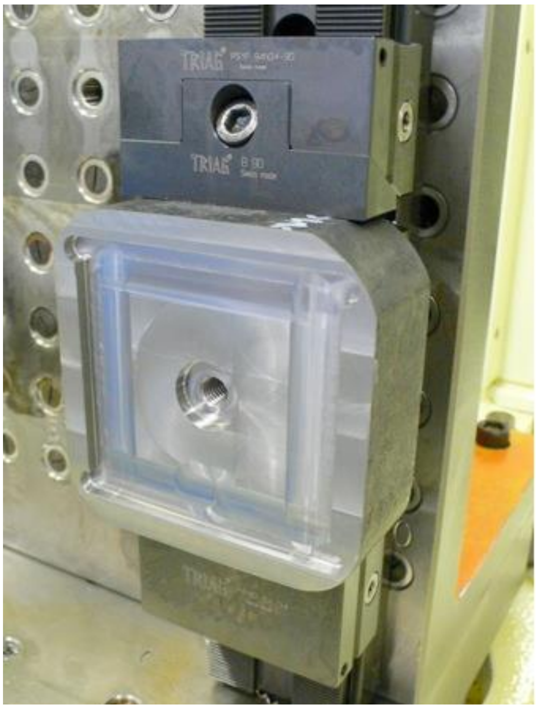

Fig. 5 Machined part in the machining center

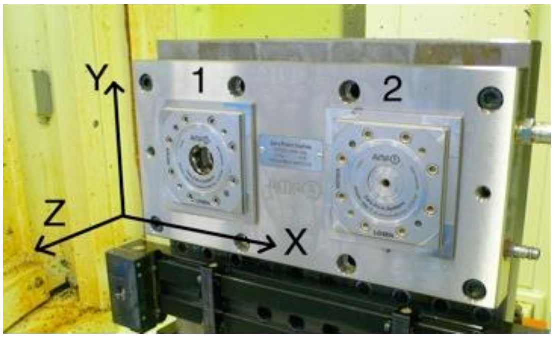

Fig. 6 Two clamping cylinders inside the machining center and the directions of the machining center's axes

Additional tests were carried out when the clamping nipple was unscrewed from the part and screwed back onto it. The results in these tests did not differ from the test results shown below.

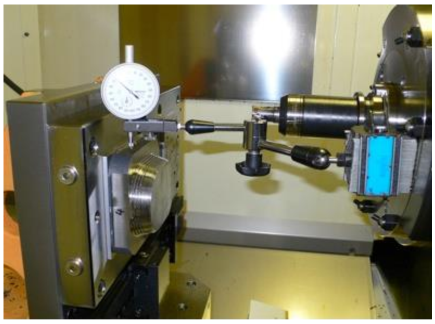

Fig. 7 Measuring system in the machining center

Table 4

Results of accuracy measurements with square shaped test piece

Square side	Measurement	Dial gauge reading
1	1	0.031
	2	0.034
	3	0.038
	4	0.038
	5	0.038
2	1	0.062
	2	0.063
	3	0.062
	4	0.062
	5	0.062
3	1	0.065
	2	0.065
	3	0.065
	4	0.066
	5	0.065
4	1	0.027
	2	0.027
	3	0.027
	4	0.026
	5	0.026

3. Results

3.1. Evaluation matrix results

The clamping system scored 2.8 points on a scale from 0 to 5. This indicates that the system fulfills the criteria of modularization and standardization moderately compared to the old system, which was poorly standardized or modularized

3.2. Accuracy measurements

Table 4 shows that the maximum positioning error was 0.007 mm and the usual accuracy proved to be 0.001 mm. This accuracy is enough for tool clamping in machining and pressing systems and is better than the old clamping system.

4. Conclusions

The 18 × 16 DFMA matrix developed in this research gives the possibility to compare the modularization and standardization of two alternative constructions from the DFMA point of view. The functionality and suitability of a construction can be concluded from the matrix values. A more accurate setting of the weighting factors would enable the recognition of the strongest and weakest interactions regarding modularization and standardization. Even though filling in the scores in the matrix takes more time than checking the criteria in the simplified system, it is recommended because it includes the value analysis. For preliminary evaluation, the simplified matrix can be used.

The same idea can also be applied more widely than just for the comparison of two solutions. It can be used to optimize and to recognize potential changes that need to be made in a construction. Its limitation is the dependence of the matrix on the selected criteria and their suitability for the solution. If roughly half of the criteria give an uncertain result, the matrix yields an inadequate result.

The accuracy of the analyzed and selected fixing system is greater than in the old system, which is partly due to the modularization and standardization of the system. The inaccuracies of interlaced parts in this system do not iterate, unlike in unstandardized or unmodularized construction. The evaluation score of the system (2.8) would have been better if the clamping systems of different manufacturers were compatible. However, every manufacturer uses different geometries, making the system difficult to standardize.

Finally, in the practical test sample we noticed that the main advantages of the selected zero-point clamping system are accuracy, short tool change times (downtimes), and the shortened and simplified design process of the attached tools.

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V. Leminen, H. Eskelinen, S. Matthews, J. Varis

GAMYBOS IR SURINKIMO PROJEKTAVIMO VERTINIMO MATRICOS KŪRIMAS IR NAUDOJIMAS UŽSPAUDIMO SISTEMOS MODULIŠKUMUI IR STANDARTIZAVIMO LYGIUI VERTINTI

R e z i u m ė

Gamtai nekenksmingos gamybos ir surinkimo projektavimo standartizavimo ir moduliavimo privalumai yra visuotinai pripažįstami. Projektavimo procese skaitmeninės vertinimo formos naudojamos pagaminimo ir surinkimo galimybėms vertinti. Straipsnis apima šias abi sritis ir siūlo priemonę, leidžiančią vertinti ir palyginti alternatyvas, pagrįstas moduliškumu, standartizavimu, galimybe pagaminti ir surinkti konstrukcijas.

Pirmojoje dalyje pateikiama gamybos ir surinkimo projektavimo vertinimo matrica, leidžianti įvertinti surinkimo tinkamumą moduliuoti ir standartizuoti. Antroji dalis yra preliminarus rezultatų patvirtinimas, kuris apima parinktos įtvirtinimo sistemos tikslumo matavimus.

Įvertinimo matrica patvirtina vertinimo metodų tinkamumą moduliškumui ir standartizavimo lygiui vertinti.

V. Leminen, H. Eskelinen, S. Matthews, J. Varis

DEVELOPMENT AND UTILIZATION OF A DFMA-EVALUATION MATRIX FOR COMPARING THE LEVEL OF MODULARITY AND STANDARIZATION IN CLAMPING SYSTEMS

S u m m a r y

The advantages of standardization and modularization for manufacturing-friendly design are widely acknowledged. In design assessment, numerical evaluation forms are commonly used to evaluate both manufacturability and assembility. This article combines these two perspectives and proposes a tool enabling the evaluation and comparison of alternative constructions based on modularity, standardization, manufacturability and assembility.

The first part introduces a DFMA-evaluation matrix which considers an assembly's suitability for modularization or standardization. The second part is preliminary validation of the results which includes accuracy measurements from the selected fixturing system.

The evaluation matrix proves to be a working evaluation method for evaluating levels of modularity and standardization.

Keywords: design for manufacturing, DFMA, evaluation, matrix, fixturing, clamping.

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