CONTRIBUTION TO THE PRODUCTION FLEXIBILITY SOLUTION

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Production (manufacturing) flexibility is one of the dominant requirements of the present engineering industry. Automated assembly systems have a special position because of their technical and technological complexity. At the present the problem of determination of existing or planned assembly systems flexibility is elaborating at the many research workplaces. The relations between assembly parts and assembly unit (its gripper) are very important for product flexibility excluding. The article presents the particular results of the first stage of scientific grant project solution. The attention is focused on to elaborating of the base methodical steps for determination of a relative similarity of objects group (assembly parts and assembly grippers) with suitable statistical methods utilisation. The dichotomous parameters were defined for the objects similarity valuation.

Keywords
flexibility, automation, assembly gripper, similarity, clusters analysis.

1. Introduction

Actual development of automation leads to the effective grouping of the production machines with automated material flow and information too, whereupon the system management is realized by the computer. If these production systems are built in frame of bigger integrities we talk about integrated production systems (IPS). There is effective to implement computer aided activities connected with construction, technology, measurement, assembly and products despatch into IPS. Automation of production system assumes the substantial understanding of single components of production system "*machine-tool-work piece*" and relations among them too. The beginning of flexible automation is dated in 1950s, when the first NC machines have been made. The flexible production connects high productivity with law costs. Flexible production system (FPS) integrates one or more technological devices equipped with system for realisation of its activities in automated mode. This system is able to respond to an assortment changing flexible. There the other type of parts can be produced after the control information changing. Therefore the production and additional devices are not specialized ones. The change of production system is solved through the data base changing. IPSs are predetermined for production in lot sizes.

IPSs can be divided according to organizational structure as follows:
- Flexible production cell (FPC);
- Flexible automated line (FPL);
- Flexible automated plant;
- Flexible automated factory.

FPC consists of the autonomously programmed technological device and additional devices as follows: a work pieces magazine equipped with technological pallets, a grip device, tools exchange device, a diagnostic device etc. FPCs are often equipped with industrial robot.

FPL is flexible production system consists of a lot of production cells arranged according to technological sequences. Line consists of several production cells under supervisor controlling. Automation of production processes (manufacturing, forming, welding etc.) is solvable better than automation of assembly processes. Automation of production has a trend of a growth of the assembly labour consumption and a decline of the product production labour consumption in frame of evaluation of product production total labour consumption [Kovac 2000]. The raising of products competitiveness requires shorter time of both product production and assembly. Assembly technique has to be accommodated to the production innovations too [Kovac 2002]. The development trends in assembly automation field lead to the deepening of difference between assembly automatic machine and flexible assembly systems. There is a need of multifunctional modular and flexible assembly devices and systems and simultaneously the changes in assembly technologies solution, material and information flows, logistics etc. are required. Multipurpose assembly robot implemented into automated assembly workplace can contribute to the rise of the workplace flexibility markedly.

One of the key tasks of present industrial concerns is to provide ability for the production flexible changing. "The changing ability" is tactic ability of the concern whole structure to preset itself to the others – most of all – the similar groups of products. This preset implies structural interferences into:
- production, assembly and logistic systems;
- buildings and its facilities;
- operating organization and staff too.

This changing assumes that the flexible, reconfigurable and pre-settable systems exist at the plant. The flexible manufacturing/assembly system requires the higher investments. That is why the planning of its flexibility is needed already in its process designing. Likewise, the evaluation of existing manufacturing/assembly system flexibility is very important too. The flexibility of this one rises by the modular principle application in structure of manufacturing/assembly devices, transport systems, frameworks and control and sensor system too.

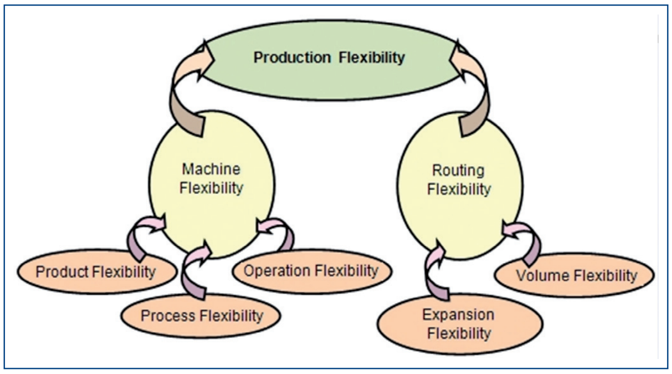

Figure 1. *The relationships among the flexibility type*

The production system flexibility can be evaluated considering to [Shewchuk, 1998]:
- machine (Machine Flexibility);
- alternative ways (Routing Flexibility);
- product (Product Flexibility);
- production operation (Operation Flexibility);
- production process (Process Flexibility);
- production volume (Volume Flexibility);
- material transport (Material Handling System Flexibility);
- ability of system to be extensible (Expansion Flexibility);
- employee (Labour Flexibility).

The relationships among the production flexibility single types are shoved in Fig.1. Automated assembly system (AAS) has a specific place among production systems because of its technical and technological complexity. The assembly unit (robot) is the main element of assembly cell. Mutual dependences among assembly product, assembly process, assembly operations and assembly robot flexibilities are evident (see Fig. 1). If the assembly product is modified or switch to other one then the assembly process, assembly operations and robot assembly gripper are modified too in more cases. There is question: how quickly and easily/difficultly the AAS is able to adapt itself to the new production requirements? This adaptability is qualified as flexibility.

2. Problem describing

The similarity of objects can be evaluated on the base of different aspects. Objects sorting (classification) can be done from the view point of many aspects. Sorting of objects according to ***Rabinovic*** is based on an evaluation of number of the rounds needed for object orientation [Belohoubek 1993]. There the geometrical shape of objects is taken into account. The rotary parts are divided into four classes. The square parts are divided into three classes. Classification method according to ***Boothroyd*** is based on the same requirements on the object orientation as ***Rabinovic*** one [Belohoubek 1993]. The classifier describes a base shape of the part, significant properties and symmetry too. The terms as cover, reduced cover, geometrical similarity, symmetry (***alfa symmetry, beta symmetry***) etc. are considered. The part classification is usually given by three-numerical code, where:

- *the first number* represents code of part according to its cover (rotary, triangular, square etc.) ;
- *the second* and *third numbers* catch up the part symmetry from the view point of possibility of the part orientation in devices for automatic orientation.

Methods, mentioned above, are suitable for classification of objects which can be defined as objects of the same "kind" (parts, tools, machines or actuators etc.).

Group technology (GT) method is suitable for production in lot sizes especially. *GT* represents the code and classification system for sorting the parts into the single groups according to their shape, dimensions, used material, technological process etc. [Kuric 2001]. Geometrical classification goes out from the part dimensions and shape. The technological classification goes out from the operations number and sequences. Coding of part is process of binding set symbols or numbers to the certain properties of the part. On the base of this one the classification of parts – sorting into single groups – is executed. For CA classification of parts there is a problem to determine which behaviour of part is important for the correct classification. There exist no generalised rules.

The particular problems of objects similarity evaluation can be solved with help of other methods too, for example: Neural Networks (NNs), Fuzzy Logic (FL), Cluster Analysis (CA) etc. Clustering is the classification of objects into different groups, or more precisely, the partitioning of a data set into subsets (clusters), so that the data in each subset (ideally) share some common trait – often proximity according to some defined distance measure.

To solve out the automated assembly workplace flexibility totally is very difficult task because of existence of mutual functional dependency among assembly part/product on the one side and all production and additional devices on the other side. The direct functional relations can be described between assembly part and assembly gripper or parts magazine or transport system and indirect ones can be described between assembly part and assembly robot construction. In this article the primary attention is focused to the functional relations identification between assembly part and assembly robot gripper to develop a method for evaluating of their mutual similarity. The evaluation of similarities inside the group of assembly parts and grippers separately are important too. The part is identifiable with its mass, shape, dimensions, gripping faces, strength at the gripping points, etc. Gripper is identifiable with: gripping force per gripper finger, kinematics, gripping finger geometrical shape, opening stroke per gripper finger, repetition accuracy, maximum permissible load values at the gripper jaws, opening and closing times, specifications for its application, etc. The all important properties (attributes) of grippers of modular structure are known and guaranteed by producer for all their dimensional types. The evaluation of similarity among the assembly parts is based on the comparing of x_{iP} – attributes. Alike, the evaluation of the similarity among assembly grippers is based on the comparing of x_{iG} – attributes. The similarity among objects of these two groups can be evaluated on the base of definition of common attributes x_n (see Fig. 2). There is important to identify attributes x_n so suitable to obtain the most exact evaluation of mutual similarity. However, there is the problem: how to identify if the new – similar assembly part or similar assembly product is suitable/unsuitable for assembly at existing automated assembly cell?

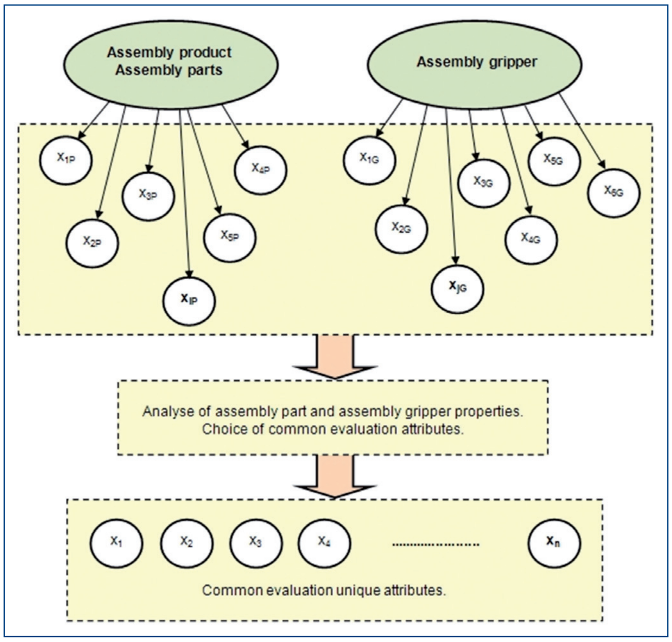

Figure 2. *Generalised method of the common evaluation attributes selection*

3. Used method

At the first step the cluster analysis method was used for "assembly part – assembly gripper" similarity evaluating.

3.1 Cluster analyse methods

Cluster analyse (clustering) can be applied at the set of objects from which everyone is described through the same set of attributes. Similarity of objects and its quantitative exploitation is one of the base problems of cluster analysis. The way how to evaluate the objects mutual similarity is given either by the cluster analysis type directly or by user´s choice with concerning of the both clustered objects and the used cluster analysis types too. Therefore the similarity measure is necessary to introduce as follows:

Non-negative real function sm which binds number sm_{qr} to every pair of vectors $(X_q, X_r) \in E_p$ is the similarity measure of these vectors, if conditions (1), (2) and (3) are fulfil for every pair X_q, X_r:

$$0 \le sm(X_q, X_r) < 1 \qquad \text{for } X_q \neq X_r \tag{1}$$

$$sm(X_q, X_r) = 1 \qquad \text{for } X_q = X_r \tag{2}$$

$$sm(X_q, X_r) = sm(X_r, X_q) \tag{3}$$

Where: $q = 1, 2, \ldots n$ and $r = 1, 2, \ldots n$

Whereas the vectors X_q and X_r are bound to the corresponding objects O_q and O_r explicitly, it has been talk about the similarity measure of objects O_q and O_r too. Values of the similarity measure sm_{qr} calculated for all possible pairs of evaluated objects are used for creation of the symmetric matrix of similarity (*SM*).

If the tested objects can be described with dichotomous attributes (1/0 or Yes/No) explicitly the associate coefficients are suitable for the objects similarity evaluation (Jacquard's (S_J)-(4), Sokal-Michener´s (S_{S-M}) – (5), Dice´s (S_D) – (6), Russel-Rao's (S_{RR}) – (7)).

$$S_J = \frac{a}{a+b+c} = \frac{a}{a+u} \tag{4}$$

$$S_{SM} = \frac{a+d}{a+b+c+d} \tag{5}$$

$$S_D = \frac{2a}{2a+b+c} \tag{6}$$

$$S_{RR} = \frac{a}{a+b+c+d} \tag{7}$$

The association of single pair of objects (O_i, O_j) is given with associate table of two rows and two columns [Lukasova 1985] – see Table 1. Let we have five objects O_x (x = 1,…,5). Their properties are described by ten common evaluating attributes A_y (y = 1,…,10) – see Tab. 2. Number *"1"* means that the object is characterised by the corresponding attribute and number *"0"* means that the one is not characterised by the corresponding attribute. The corresponding associative table – see Table 3 [Kumicak 2005] – is created on the base of Table 2 values and rules cleared up in Table 1.

Table 1. General association table of a single pair of objects (Oi, Oj)

		O_j	
		1	0
O_i	1	a	b
	0	c	d

a = number of cases of positive equality; O_i = 1 and O_j = 1
d = number of cases of negative equality; O_i = 0 and O_j = 0
b = number of cases of inequality; O_i = 1 and O_j = 0
c = number of cases of inequality; O_i = 0 and O_j = 1

Table 2. Example of dichotomous table

O_2	1	1	0	0	0	1	1	1	1	0
O_3	1	0	1	0	0	1	0	1	0	1
O_4	0	1	1	0	0	0	1	1	0	1
O_5	1	0	0	1	1	0	1	1	0	0

Table 3. Associative table of relations among objects O1 – O5

Object	O_1		O_2		O_3		O_4		O_5	
O_1	5	0	3	2	1	4	2	3	4	1
	0	5	3	2	4	1	3	2	1	4
O_2	3	3	6	0	3	3	3	3	3	3
	2	2	0	4	2	2	2	2	2	2
O_3	1	4	3	2	5	0	3	2	2	3
	4	1	3	2	0	5	2	3	3	2
O_4	2	3	3	2	3	2	5	0	2	3
	3	2	3	2	2	3	0	5	3	2
O_5	4	1	3	2	2	3	2	3	5	0
	1	4	3	2	3	2	3	2	0	5

The corresponding associative matrix ***S*** is created on the base of application of the suitable associative coefficient formula and values of associative table too. For example, associative matrix S_J (8) created with the utilisation of Jacquard´s associative coefficient formula (7) and values of Table 3 will be:

$$S_J = \begin{pmatrix} 1{,}000 & 0{,}375 & 0{,}111 & 0{,}250 & 0{,}667 \\ 0{,}375 & 1{,}000 & 0{,}375 & 0{,}375 & 0{,}375 \\ 0{,}111 & 0{,}375 & 1{,}000 & 0{,}429 & 0{,}250 \\ 0{,}250 & 0{,}375 & 0{,}429 & 1{,}000 & 0{,}250 \\ 0{,}667 & 0{,}375 & 0{,}250 & 0{,}250 & 1{,}000 \end{pmatrix} \tag{8}$$

Associative matrix elements placed in a matrix diagonal are equal value *"1"*. There these values represent the maximal measure of the similarity and correspondent to the mutual comparing of the single pair of objects (O_i, O_j), where ***i = j***. The minimal value ***"0,111"*** represents the least measure of the similarity of pairs of objects (O_1, O_3) and (O_3, O_1). These two objects are the least similar to each other from all evaluated objects O_x (x = 1,…, 5).

S_{ij} values are input data for cluster analyse methods of statistical software (***Statgraphics***, ***NCSS*** etc.). Outputs are in the form of the tree diagram (dendrogram) which shows clusters of similar objects and measure of its dissimilarity/similarity.

Statistical software NCSS offers eight clustering methods for the hierarchical clustering. Algorithm of the clusters creating is described by the next steps [NCSS 2007]:

Let the distance between clusters ***i*** and ***j*** be represented as d_{ij} and let cluster ***i*** contain n_i objects. Let ***D*** represent the set of all remaining d_{ij}. Suppose there are **N** objects to cluster.

1. Find the smallest element remaining in ***D***.
2. Merge clusters ***i*** and ***j*** into a single new cluster, ***k***.
3. Calculate a new set of distances using d_{km} the following distance formula.

$$d_{km} = \alpha_i\, d_{im} + \alpha_j\, d_{jm} + \beta\, d_{ij} + \gamma\, |d_{im} - d_{jm}| \tag{9}$$

   Here ***m*** represents any cluster other than ***k***. These new distances replace d_{im} and d_{jm} in ***D***. Also let $n_k = n_i + n_j$. Note that the eight algorithms available represent eight choices for α_i, α_j, β a γ.
4. Repeat steps 1 – 3 until ***D*** contains a single group made up off all objects. This will require ***N-1*** iterations.

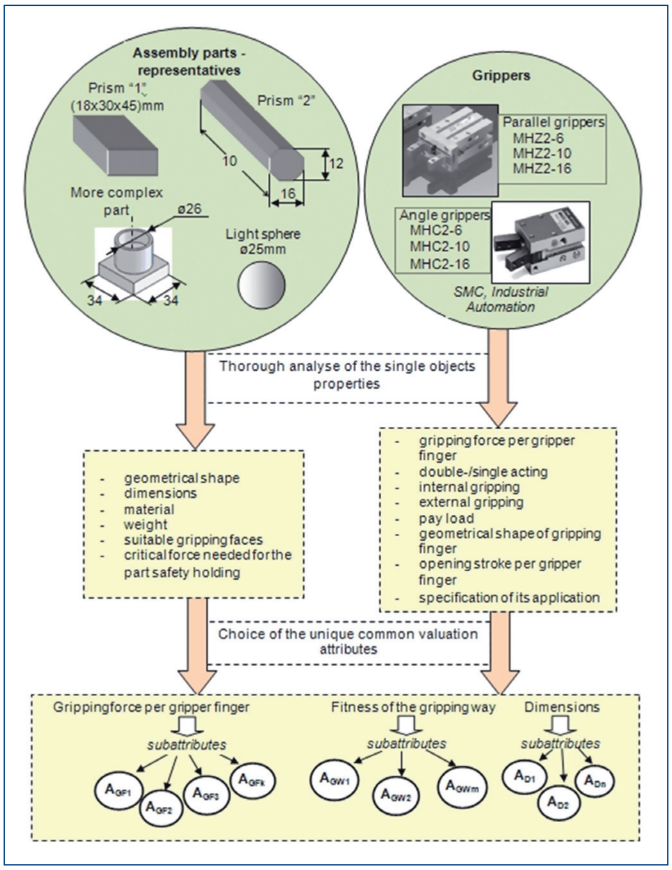

Figure 3. *The base principle of the choice of evaluating attributes.*
AGFi – sub-attributes for deep detailing of gripping force
AGWi – sub-attributes for deep detailing of gripping way
AGDi – sub-attributes for deep detailing of gripping way

3.2 Methodology of objects similarity identification.

The mutual similarity of objects is based on the comparing of their external attributes as geometrical shape, dimensions etc. most of all. The similarity evaluation among assembly parts and assembly grippers can't be based only on these attributes. Hence the attention was focusing to the searching of common attributes that could explain these objects mutual functional dependency.

The methodology of the object similarity determining can be summed into next steps:

1. Analyse of the single objects properties – the defining of evaluating attributes in frame of each objects group.
2. Defining of unique attributes common for all evaluated objects.
3. Creating of dichotomous table for evaluated objects and chosen common attributes too.
4. Creating of association table of relations among objects.
5. Creating of association matrixes for chosen associative coefficients (S_J, S_{S-M}, S_D *and SRR*).
6. Application of available cluster methods for the objects mutual similarity evaluation.
7. Dendrogram evaluation.

The first three steps are very important for the correct results obtaining.

The methodology principles were creating gradually in frame of example of two groups of evaluated objects:

Table 4. Dichotomous table for ten objects (O1 – O10)

Objects/ Attributes	Gripping force																		Gripping fitness/ surface shape								
	Double type									Single type									YES				NO	Dimensions (mm)			
Part No.:	2,8	3,8	7	10	28	30	6,2	17	40	1,7	2	5	6,5	20	25	3,8	12,5	31	Rovinná plo.	Von. Valec	Vnt. Valec	Prizma	Iné Uchop.	5 – 11	12 – 18	19 – 24	25 – 32
1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
3	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0
4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0
Gripper No:																											
5	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
6	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	1	0	1	1	1	1	0	1	0	0	0
7	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	0	0	1	0	0
8	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
9	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0
10	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	1	0

Table 5. Associative table of relations among objects (O1 – O10)

	O1		O2		O3		O4		O5		O6		O7		O8		O9		O10	
	3	0	0	3	0	3	1	2	0	3	1	2	3	0	0	3	1	2	1	2
O1	0	24	2	22	4	20	3	21	5	19	8	16	6	18	4	20	4	20	5	19
	0	2	2	0	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2
O2	3	22	0	25	4	21	4	21	5	20	9	16	9	16	4	21	5	20	6	19
	0	4	0	4	4	0	0	4	1	3	1	3	2	2	0	4	0	4	1	3
O3	3	20	2	21	0	23	4	19	4	19	8	15	2	16	4	19	5	18	3	18
	1	3	0	4	0	4	4	0	0	4	1	3	3	1	0	4	1	3	2	2
O4	2	21	2	21	4	19	0	23	5	18	8	15	6	17	4	19	4	19	4	19
	0	5	0	5	1	4	0	5	5	0	1	4	0	5	1	4	1	4	1	4
O5	3	19	2	20	3	19	4	18	0	22	8	14	9	13	3	19	4	18	4	17
	1	8	0	9	1	8	1	8	1	8	9	0	4	5	2	7	2	7	2	7
O6	2	16	2	16	3	15	3	15	4	14	0	16	5	13	2	16	3	15	4	14
	3	6	0	9	2	7	3	6	0	9	4	5	9	0	1	8	2	4	2	7
O7	0	18	2	16	2	16	1	17	5	13	5	13	0	18	3	15	3	18	4	14
	0	4	0	4	0	4	0	4	1	3	2	2	1	3	4	0	2	2	2	2
O8	3	20	2	21	4	19	4	19	4	19	7	16	8	15	0	23	3	20	4	19
	1	4	0	5	0	5	1	4	1	4	2	3	2	3	2	3	5	0	3	2
O9	2	20	2	20	4	18	3	19	4	18	7	15	7	15	2	20	0	22	3	19
	1	5	0	6	1	5	2	4	1	5	2	4	2	4	2	4	3	3	6	0
O10	2	18	2	19	3	18	2	19	4	17	7	14	7	14	2	19	2	19	0	21

$$S_J = \begin{pmatrix} 1 & 0 & 0 & 0{,}17 & 0 & 0{,}09 & 0{,}33 & 0 & 0{,}14 & 0{,}13 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0{,}13 & 0{,}08 & 0{,}33 & 0 & 0 & 0{,}14 \\ 0{,}17 & 0 & 0 & 1 & 0 & 0{,}08 & 0{,}3 & 0 & 0{,}13 & 0{,}25 \\ 0 & 0 & 0{,}13 & 0 & 1 & 0{,}08 & 0 & 0{,}13 & 0{,}11 & 0{,}11 \\ 0{,}09 & 0 & 0{,}08 & 0{,}08 & 0{,}08 & 1 & 0{,}29 & 0{,}18 & 0{,}17 & 0{,}15 \\ 0{,}33 & 0 & 0{,}18 & 0{,}3 & 0 & 0{,}29 & 1 & 0{,}08 & 0{,}22 & 0{,}15 \\ 0 & 0 & 0 & 0 & 0{,}13 & 0{,}18 & 0{,}08 & 1 & 0{,}29 & 0{,}25 \\ 0{,}14 & 0 & 0 & 0{,}13 & 0{,}11 & 0{,}17 & 0{,}17 & 0{,}29 & 1 & 0{,}38 \\ 0{,}13 & 0 & 0{,}11 & 0{,}25 & 0{,}1 & 0{,}15 & 0{,}15 & 0{,}25 & 0{,}38 & 1 \end{pmatrix}$$

$$S_D = \begin{pmatrix} 1 & 0 & 0 & 0{,}29 & 0 & 0{,}17 & 0{,}5 & 0 & 0{,}25 & 0{,}22 \\ 0 & 1 & 0{,}29 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0{,}22 & 0{,}15 & 0{,}5 & 0 & 0 & 0{,}25 \\ 0{,}29 & 0 & 0 & 1 & 0 & 0{,}15 & 0{,}46 & 0 & 0{,}22 & 0{,}4 \\ 0 & 0 & 0{,}22 & 0 & 1 & 0{,}14 & 0 & 0{,}22 & 0{,}2 & 0{,}2 \\ 0{,}17 & 0 & 0{,}15 & 0{,}15 & 0{,}14 & 1 & 0{,}44 & 0{,}31 & 0{,}29 & 0{,}27 \\ 0{,}5 & 0 & 0{,}31 & 0{,}46 & 0 & 0{,}44 & 1 & 0{,}15 & 0{,}36 & 0{,}27 \\ 0 & 0 & 0 & 0 & 0{,}22 & 0{,}31 & 0{,}15 & 1 & 0{,}44 & 0{,}4 \\ 0{,}25 & 0 & 0 & 0{,}22 & 0{,}2 & 0{,}29 & 0{,}29 & 0{,}44 & 1 & 0{,}55 \\ 0{,}22 & 0 & 0{,}2 & 0{,}4 & 0{,}18 & 0{,}27 & 0{,}27 & 0{,}4 & 0{,}55 & 1 \end{pmatrix}$$

$$S_{SM} = \begin{pmatrix} 1 & 0{,}81 & 0{,}74 & 0{,}81 & 0{,}7 & 0{,}63 & 0{,}78 & 0{,}74 & 0{,}78 & 0{,}74 \\ 0{,}81 & 1 & 0{,}78 & 0{,}78 & 0{,}74 & 0{,}59 & 0{,}59 & 0{,}78 & 0{,}74 & 0{,}7 \\ 0{,}74 & 0{,}78 & 1 & 0{,}70 & 0{,}74 & 0{,}59 & 0{,}82 & 0{,}7 & 0{,}67 & 0{,}76 \\ 0{,}81 & 0{,}78 & 0{,}7 & 1 & 0{,}67 & 0{,}59 & 0{,}74 & 0{,}7 & 0{,}74 & 0{,}78 \\ 0{,}7 & 0{,}74 & 0{,}74 & 0{,}67 & 1 & 0{,}56 & 0{,}48 & 0{,}74 & 0{,}7 & 0{,}69 \\ 0{,}63 & 0{,}59 & 0{,}59 & 0{,}59 & 0{,}56 & 1 & 0{,}63 & 0{,}67 & 0{,}63 & 0{,}59 \\ 0{,}78 & 0{,}59 & 0{,}67 & 0{,}74 & 0{,}48 & 0{,}63 & 1 & 0{,}59 & 0{,}74 & 0{,}59 \\ 0{,}74 & 0{,}78 & 0{,}7 & 0{,}7 & 0{,}74 & 0{,}67 & 0{,}59 & 1 & 0{,}81 & 0{,}78 \\ 0{,}78 & 0{,}74 & 0{,}67 & 0{,}74 & 0{,}7 & 0{,}63 & 0{,}63 & 0{,}81 & 1 & 0{,}81 \\ 0{,}74 & 0{,}7 & 0{,}7 & 0{,}78 & 0{,}67 & 0{,}59 & 0{,}59 & 0{,}78 & 0{,}81 & 1 \end{pmatrix}$$

1. Different types of assembly parts.
2. Parallel and angle gripper types including its dimensional types (producer: SMC, Industrial Automation).

The important attributes were defined to describe objects properties of single groups. The definition of the similarity evaluating attributes was done on the base of the standard methods of the gripper type choice and SMC, Industrial Automation hints too. The first dichotomous table had 9 main evaluation attributes. Every attribute had a lot of sub-attributes to possible its deeper detailing. Total number of evaluated attributes was 43. After revaluating of the single attributes importance the final table was modified and number of attributes was reduced in 3 main and 27 additional attributes – see Fig. 3 and Table 4. The gripping force attribute is of the highest weight. Dichotomous table for these 10 objects is showed in Table 4.

The ***gripping force attribute*** is considered for two types of grippers according to their design production. Numeric values of sub-attributes correspondent to the catalogue values of SMC Industrial Automation. Values of gripping forces needed for the real parts grasping were calculated by the standard way. Attribute ***Gripping fitness/surface shape*** represents whether the object is suitable for the gripper grasping (Yes/No) from the view point of gripped surfaces (planar, external cylindrical, internal cylindrical V-shape, other). Attribute ***Dimensions*** represents the dimensional intervals for gripped size of object on one side and for total opening stroke of the gripper fingers on the other side. Dichotomous table was created in MS Windows Excel 2003 environment. Relations among objects are showed in Table 5. Three associative coefficients (4), (5) and (6) were applied for calculation of elements of associative matrixes (S_J, S_{SM} and S_D).

The special environment was created in frame of MS Windows Excel environment where all tables have been connected with mathematical relations. Therefore the every change made in dichotomous table has been transmitted into all consecutive steps of solution.

The elements of three associative matrixes have been used as input data for cluster analysis in NCSS statistical software. There have been applied all eight methods of cluster analysis. Values of coefficients: ***Delta0.5 (D0.5). Delta1 (D1)*** and ***Cophenetic Correlation (CC)*** were used for evaluation of fitness of the single methods utilisation for the similarity objects evaluation. Advised values for coefficients ***D0.5*** and ***D1*** could be the nearest to ***"zero"*** and values for coefficient **CC** could be greater than ***0.75,*** but better, the nearest to value "1" [NCSS 2007]. On the base of graphical results (see Fig. 4) the best fulfilled conditions mentioned above are for the first four methods: ***Simple Linkage, Complete Linkage, Simple Average*** and ***Group Average*** and for associative matrixes S_J and S_D ***too.***

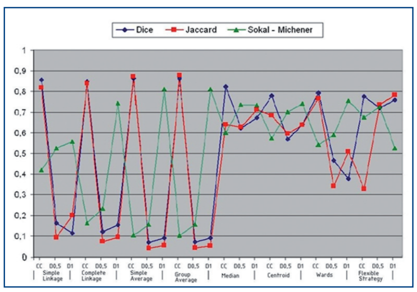

Figure 4. *Graphical comparing of values D0.5, D1 and CC for used cluster analysis methods*

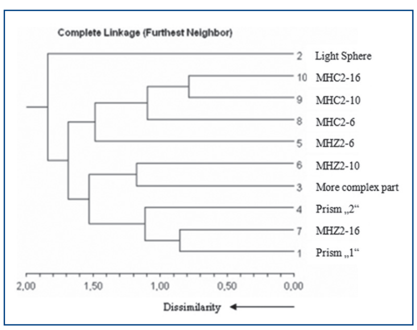

Figure 5. *Dendrogram for Complete Linkage clustering method and elements of associative matrix SJ*

The evaluation of similarity of the objects ($O_1 - O_{10}$) through clusters created by the ***Complete Linkage (Furthest Neighbor***) is showed in Fig. 5. There we can see single clusters (groups) of objects which are most similar to each other. There are three main clusters. The first one includes 3 parts (***Prism "1", Prism "2"*** and ***More complex part***) and 2 types of parallel gripper (***MHZ2-10, -16***). It means that these two grippers are suitable for these objects gripping. The second one consists of 3 angle grippers (***MHC2 -6, -10, and 16***) and one parallel gripper (***MHZ-6***) which are not suitable for the considered application. The last cluster consists of one object (***Light sphere***) only. This object is not suitable for gripping by mechanical gripper way.

4. Discussion and conclusions

The methodology was verified in conditions of the automated assembly workplace where the assembly of four real parts into one assembly product was realised – see Fig. 6.

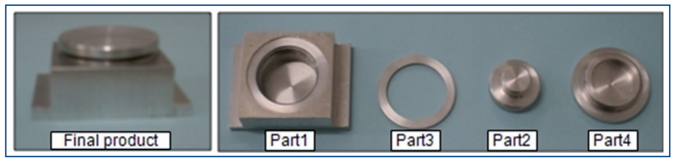

Figure 6. *Assembly parts and final assembly product*

This practical realisation of the preliminarily developed method had required some changes in the attributes definition. Number of main attributes was raised for 4 ones. The attribute ***Application fitness*** (Yes/No) have been added to simulate a human thinking at the griper choice starting. The sub-attributes of ***Gripping force*** were expanded with sub-attributes which correspond to both inner and outer gripping ways. Summary in new dichotomous table is 4 main attributes and 29 sub-attributes. The values of matrix S_D were used for three methods of cluster analysis application. Dendrogram for ***Complete Linkage (Furthest Neighbor)*** method and values of associative matrix S_D is showed in Fig. 7.

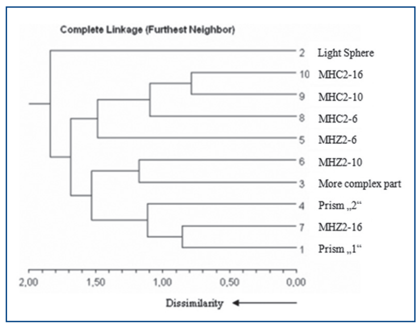

Figure 7. *Dendrogram*

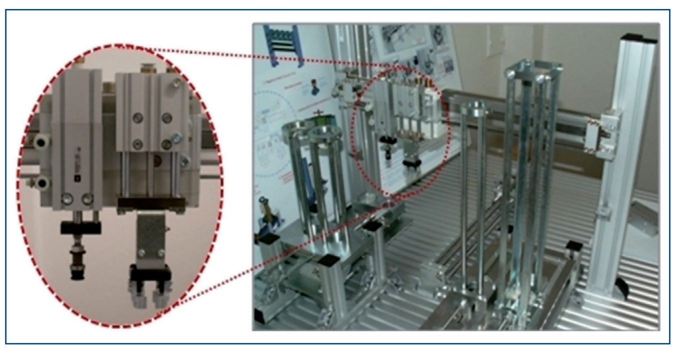

Figure 8. *Laboratory workplace equipped with assembly multifunctional unit (Note: Presented knowledge was obtained in frame of VEGA 1/4150/07 project solution).*

From the dendrogram is follows that two parallel grippers (***MHZ2 -10, -16***) are bond to two the most similar parts (1 and 3). To the next two parts (2 and 4) is bond gripper ***MHZ2 -6***. Angle grippers (***MHC2***) are out of all clusters. They have the highest measure of dissimilarity from the all evaluated objects. These results have the next consequence for practical application:

- We can use only parallel grippers for this application;
- For the all parts grasping can be used two assembly units. One

of them can be equipped with ***MHZ2 -10*** or ***MHZ2 -16*** and other one with ***MHZ2 -6***.

The dividing of the group of parts and parallel grippers into two clusters was caused by big differences in frame of attribute "***Dimensions***" especially. Therefore the problem can be solved with single assembly unit equipped with one gripper ***MHZ2-10*** (or ***MHZ2– 16***) too. In frame of the laboratory workplace designing the problem of automation of the product assembly was solved by single multifunctional as…sembly unit. This one consists of two end effectors (see Fig. 8): ***MHZ2-10*** with specially shaped fingers (grasping of parts 1, 2 and 3) and suction cup (grasping of part 4).

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