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New product similarity index development with application to an assembly system typology selection

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Abstract

The choice of an adapted production system is essential in today's volatile market environment. For this choice the identification of common and distinct assemblies in between the product variants is of high importance. This paper presents four new similarity indices which are aggregated to categorize products. The categorization will support the choice of an assembly system type (dedicated, reconfigurable or hybrid) for a selection of product subassemblies when designing a new production facility. On this way, operational areas for a reconfigurable system can be defined. The novel approach is applied to an industrial case study in automotive industry.

Keywords: assembly system reconfiguration; decision making; aggregation

1. Introduction

First introduced by Koren et al [1], reconfigurable manufacturing systems (RMS) are the next evolution of production systems [2] and have become the upcoming manufacturing paradigm for the industry of the future. RMS is nowadays a well-known topic and in the center of interest of numerous publications which also gain more and more application in the industrial sector [3]. A very recent literature research carried out by Bortolini et al. [4] identifies five ongoing research trends. Out of these, this article focuses on the intersection of the following two trends:

- Reconfigurability level assessment,
- Applied research and field applications on, between others: layout, system configuration and product family formation.

As defined by Koren, reconfigurable manufacturing systems are dedicated to one product family. This implies the need for methods which support the identification of product families and clustering. The common modus operandi is the analysis of a product set in regard of a commonality on the physical level. In general, the objective is to (re)group products in a family for X (e.g. for RMS, for delayed product differentiation, etc.). In contrast, the presented approach is not dedicated to a single production paradigm but aims at identifying the optimum one for a set of products. Even the combination of several paradigms in one production line is possible.

The presented research work is part of a PhD project which aims at measuring and improving the agility of assembly systems. The developed indices base on the product analysis part which has been presented by the authors in a previous publication [5] and contribute on the decision-making concerning assembly system related choices. They are a brick of a future integrated methodology.

This paper is structured as follows: in section 2, common similarity indices are presented and their application is discussed. The new similarity indices to support the choice of an assembly system type are introduced. In section 4, an application on a case study in automotive industry is presented. Section 5 gives the conclusion and describes upcoming research work.

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2. Evolution of similarity indices

The measurement of similarity as presented in literature is marked by a wide range of definitions and methods. A fact also stated by Wazed et al. [6]. In general, commonality is defined as the number of parts/components that are used by more than one product and is determined for all product family [7]. Within a product/process family, the commonality index is a metric which assesses the degree of commonality. Based on the latter, product families can be created.

One simple commonality analysis method is proposed by Abdi and Labib combining Jaccard's similarity coefficient for product family identification with an analytic hierarchy process (AHP) application for evaluation, considering manufacturing and market requirements [8,9]. The Jaccard coefficient measures similarity between finite sample sets and is defined as the size of the intersection divided by the size of the union of the sample sets.

Beside the simple calculation of Jaccard's similarity, more sophisticated indices exist in literature. The most common ones are presented in Table 1, inspired by the comparison presented in [10]. The indices are sorted in order of their apparition, starting with the first publication (DCI – 1986) and finishing with the most recent one (S – 2016).

Table 1. Commonality indices – an overview.

Name and abbreviation		Commonality measure for	Reference
Degree of Commonality Index	DCI	Product family	Collier [11]
Total Constant Commonality Index	TCCI	Product family	Wacker & Treleven [12]
Commonality Index	CI	Product family	Martin & Ishii [13,14]
Percent Commonality Index	%C	Product	Siddique et al. [15]
Product line Commonality Index	PCI	Product family	Kota et al. [16]
Commonality versus Diversity index	CDI	Product family	Alizon et al. [17]
Comprehensive Metric for Commonality	CMC	Product family	Thevenot & Simpson [18]
Component Part Commonality	$CI^{(c)}$	Product family	Jiao & Tseng [19]
Synergy (interfaces)	S	Product family	Lafou et al. [20]

Considering the way of measuring commonality, eight of the nine above mentioned indices (except the CMC) have in common that they examine commonality on the component level, applying a one to one comparison. Therefore, commonality exists if exactly the same component appears in different products. In addition, to the component comparison, the CMC takes also into account material and assembly, but the commonality is fixed also on the criterion "exactly the same".

Some questions remain: How to compare products which vary in number and characteristic of their components? That means how to consider products with a broad range of similar components, for example screws with different length and diameter, which are not the same, but which could be assembled by an adapted (reconfigurable) assembly system? And how to define what is an adapted assembly system?

To answer these questions, four new similarity indices are presented in the following section. Their use is different from the former ones: they aim at giving a decision support concerning the question how to conceive the assembly system architecture optimally for a set of given products.

3. New indices for assembly system type determination

The four new indices are named S_1 to S_4 and form two pairs of indices. One pair, S_1 S_2, impacts decisions on the level of one production line. Instead of a simple one-to-one comparison on the physical level, they compare products also on the functional level which eases the analysis of variety. The other pair, S_3 S_4, has an impact on the production line entity by considering assembly technologies. They are complementary to S_1 S_2. The following Table 2 synthesizes the level and impact of each pair of indices.

Table 2. Similarity indices

System level	Impact on	Indices
Production line	Production paradigm (RMS / DMS) Product range	S_1 & S_2
Production line entity	Manufacturing processes	S_3 & S_4

3.1. Similarity indices S_1 and S_2

The indices S_1 and S_2 are based on the physical and functional architecture (*PHARE*) of the product. It is generated based on a Datum Flow Chain (DFC) with information about functional subassemblies (FSA). These contain the components needed to perform a function. The FSA being in relation to each other, build the physical and functional architecture. The following figure gives an example of a DFC with FSA (named A-E) and its corresponding *PHARE* representation. The detailed *PHARE* approach is described by the authors in [5]. As the method needs a common definition of technical functions, it is limited to products on which the common definition can be applied. It is automatically restricted to products of the same domain depending on the function definition.

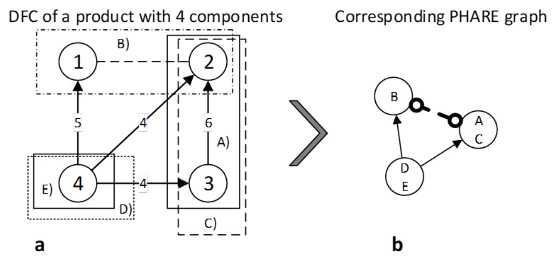

Fig. 1. (a) example of a DFC with FSA; (b) and its *PHARE* graph.

The calculation of S_1 and S_2 itself is based on the FSA matrix, here called GF. It is the matrix representation of the *PHARE* graph. One matrix represents one product. Similarity is evaluated concerning two aspects considering the different types of links: the relations between functional subassemblies (S_1) on the one hand and the existence of common absent links (S_2) on the other hand. A similarity value is calculated for each FSA to identify subassemblies which are similar in both products. Next, the application order is described.

1) Generation of the matrices representing the *PHARE*

2) Binary comparison of two matrices (for two products)
3) Input weighting
4) Similarity by functional group

At first, two different *PHARE* matrices are calculated according to equation (1), gf_{ij} being the entries of GF_1 and gf_{mn} being the entries of GF_2.

$$GF_1 = \begin{pmatrix} gf_{11} & \cdots & gf_{1j} \\ \vdots & \ddots & \vdots \\ gf_{i1} & \cdots & gf_{ij} \end{pmatrix}; GF_2 = \begin{pmatrix} gf_{11} & \cdots & gf_{1n} \\ \vdots & \ddots & \vdots \\ gf_{m1} & \cdots & gf_{mn} \end{pmatrix}; \begin{matrix} gf_{ij} \\ gf_{mn} \end{matrix} = \begin{cases} 3 \text{ si inclusion entrant} \\ -3 \text{ si inclusion sortant} \\ 2 \text{ si partition} \\ 1 \text{ si contact entrant} \\ -1 \text{ si contact sortant} \\ 0 \text{ sinon} \end{cases} \quad \forall \begin{matrix} i,j, \\ m,n \end{matrix} \in \mathbb{N} \quad (1)$$

The proposed approach is a pairwise comparison. During this pairwise comparison, the entries of GF_1 and GF_2 are combined to build a new matrix GF_A for analysis. The entries of GF_A being gf_{op}. The building consists of two steps:

1) Identification of identic elements:

$$gf_{op} = 16 \text{ if } gf_{ij} = gf_{mn} \text{ for } gf_{ij}, gf_{mn} \neq 0 \ \forall \ i = m = o, j = n = p; \quad \forall \ i, j, m, n, o, p \in \mathbb{N}^6 \quad (2)$$

With equation (2), all identical entries which are not zero are identified. Equation (3) identifies all identical entries equal to zero. The distinction is necessary to calculate the similarity indices S_1 and S_2. The value of 16 is needed for the generation of matrix GF_A and is essential for weighting the entries.

$$gf_{op} = -16 \text{ if } gf_{ij} = gf_{mn} \text{ for } gf_{ij}, gf_{mn} = 0 \ \forall \ i = m = o, j = n = p; \quad \forall \ i, j, m, n, o, p \in \mathbb{N}^6 \quad (3)$$

2) Identification of similar elements (equation (4)):

$$gf_{op} = |gf_{ij}| \cdot |gf_{mn}| \ if \ gf_{ij} \neq gf_{mn} \ \forall \ i = m = o, j = n = p; \quad \forall \ i, j, m, n, o, p \in \mathbb{N}^6 \quad (4)$$

The theoretic maximum absolute value of the operation $gf_{ij} \cdot gf_{mn}$ is 16. To create the matrix GF_A, according to equation (5), all the entries are normalized by dividing them by 16.

$$GF_A = \begin{pmatrix} \frac{gf_{11}}{16} & \cdots & \frac{gf_{1p}}{16} \\ \vdots & \ddots & \vdots \\ \frac{gf_{o1}}{16} & \cdots & \frac{gf_{op}}{16} \end{pmatrix} \quad (5)$$

Therefore, identical elements have the value 1, identic elements modelling a common absent link have the value -1 and non-identical entries are in the range $0 \leq x < 1$. All possible values for gf_{op} are added in Table 3.

Table 3. Values for GF_A

Combination		Equation	Absolute value	Normalised value
Entry 1	Entry 2			
Identity	Identity	Fixed value	16	1
Composition	Composition	Fixed value	16	1
Partition	Partition	Fixed value	16	1
Contact	Contact	Fixed value	16	1
No link	No link	Fixed value	-16	-1
Identity	Composition	$4 \cdot \|\pm3\|$	12	0,75
Composition	Composition^{-1} (inverse)	$3 \cdot \|-3\|$	9	0,5625
Identity	Partition	$4 \cdot 2$	8	0,5
Composition	Partition	$\|\pm3\| \cdot 2$	6	0,375
Identity	Contact	$4 \cdot \|\pm1\|$	4	0,25
Composition	Contact	$\|\pm3\| \cdot \|\pm1\|$	3	0,1875
Partition	Contact	$2 \cdot \|\pm1\|$	2	0,125
Contact	Contact^{-1}	$1 \cdot \|-1\|$	1	0,0625
No link	Identity	$0 \cdot 4$	0	0
No link	Composition	$0 \cdot \|\pm3\|$	0	0
No link	Partition	$0 \cdot 2$	0	0
No link	Contact	$0 \cdot \|\pm1\|$	0	0

Fixed value means that the value is automatically set without calculations. The sign of the values depends on the direction of the arcs in the *PHARE*. If there is no sign, the arcs are undirected.

Now, the two similarity indices can be calculated. The first one, S_1, considers the similarity based on existing links between functional subassemblies, the second one, S_2, takes also into account the absence of links in both physical and functional architecture representations. The following formula (6) describes the way to calculate these indices for one functional subassembly, represented by one line in the GF_A matrix.

$$S_1 = \frac{\sum values > 0}{Nb. of\ values \geq 0} \quad S_2 = \frac{\sum values > 0 + Nb.\ of\ values = -1}{27} \quad (6)$$

The indices S_1 and S_2 take only into account the functional and physical product architecture, but they do not give any information about the assembly technologies which are used. This additional knowledge is necessary to decide the assembly system type to select.

3.2. Similarity indices for assembly technology

In the following, the indices S_3 and S_4 for assembly technology similarity are introduced. A value is calculated for each FSA to identify similar assembly technologies.

Index S_3 evaluates the internal similarity of each functional subassembly. It considers the assembly technologies used in the functional subassembly and determines thus the way how it is realized. Index S_4 evaluates the external similarity, i.e. the similarity in the relations which one functional group has to the others. It considers all assembly technologies which are used to position a functional subassembly, i.e. all entering arcs. In this way, the similarity of how de functional subassembly is assembled to the whole product is examined. The general approach to calculate is as follows:

1) Generation of a DFC (Whitney [21]) with functional subassemblies and assembly technology information on the arcs, as presented by the authors in [5]
2) Selection of arcs to evaluate
3) Generation of a matrix containing assembly technology and functional groups
4) Binary comparison of two matrices (representing the comparison of two products) to calculate S_3 and S_4
5) Similarity by functional group

Fig. 2 gives an example of a functional subassembly in a DFC with its different links and their signification. For S_3, all arcs belonging to a functional subassembly are evaluated (here called “internal arcs”). For S_4, the entering arcs are considered (“external” arcs).

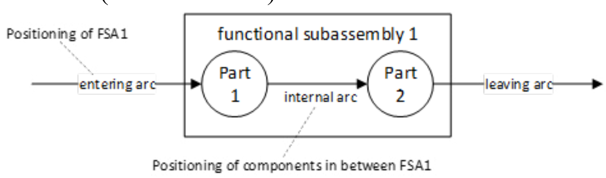

Fig. 2. Functional subassembly with its components.

The technology matrix T is built, where the rows represent all assembly technologies and the columns stand for functional subassemblies. The entries of matrix T are 1 if one technology *i* is used for a functional group *j*, and 0 else. The considered technologies are identified as described above. Two matrices T^{int} and T^{ext} have to be built for each product. Equation (7) illustrates two matrices T.

$$T_1^{int/ext} = \begin{pmatrix} t_{11} & \cdots & t_{1j} \\ \vdots & \ddots & \vdots \\ t_{i1} & \cdots & t_{ij} \end{pmatrix}; T_2^{int/ext} = \begin{pmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots & t_{mn} \end{pmatrix} \quad (7)$$

For the technology comparison, an analysis matrix T_A with its entries t_{op} is generated. If two entries in the compared matrices T_1 and T_2 are identic and equal to 1, i.e. the same assembly technology is used, the entry in T_A is 1, if the two entries are 0, i.e. no technology is used, then the entry in T_A is 0 and if the two entries differ, then t_{op} is -1. Equation (8) below details the entries t_{op} and equation (9) shows the analysis matrix T_A.

$$t_{op} = \begin{cases} 1 \; if \; t_{ij} = t_{mn} \neq 0 \\ 0 \; if \; t_{ij} \neq t_{mn} \\ -1 \; else \end{cases} \quad \forall i{=}m{=}o, j{=}n{=}p; \forall i, j, m, n, o, p \in \mathbb{N}^6 \quad (8)$$

$$T_A^{int/ext} = \begin{pmatrix} t_{11} & \cdots & t_{1p} \\ \vdots & \ddots & \vdots \\ t_{o1} & \cdots & t_{op} \end{pmatrix} \quad (9)$$

Based on this, the similarity indices S_3 and S_4 are calculated. S_3, presented in equation (10), is based on T_a^{int}. It is calculated per functional subassembly, represented by a line in the matrix.

$$S_3 = \frac{Sum \; of \; all \; entries \; > \; 0}{Number \; of \; entries \; \geq \; 0} \quad (10)$$

S_4, presented in equation (11), is based on T_a^{ext}. It is also calculated per functional subassembly, represented by a line in the matrix.

$$S_4 = \frac{Sum \; of \; all \; entries \; > \; 0}{Number \; of \; entries \; \geq \; 0} \quad (11)$$

The indices S_3 and S_4 compare the assembly technologies which are common of both products with the overall number of different assembly technologies which are used in both products. To homologize the vocabulary used to describe the assembly technology, the following list of different technologies has been identified in cooperation with the industrial partner.

3.3. Similarity index interpretation

The two indices S_1 and S_2 can be interpreted in the following way:

- 100% for S_1 and 100% for S_2: The functional subassembly (FSA) exists within a similar architecture.
- 0% for S_1 and 100% for S_2: The FSA does not exist in the examined products. Therefore, it is no longer considered.
- 0% for S_1 and for S_2 < 100%: FSA exists only in one of the two examined columns. Thus, it is not considered for further analysis.
- 0% < x < 100% for both indices: Domain of interpretation submitted to some uncertainty. Possible conclusions are shown in Fig. 3.

The conclusions have been verified through an industrial case study on two steering columns for the automotive industry. The interpretation scheme in Fig. 3 represents thus a first link of the developed indices with an industrial expert viewpoint. During this first evaluation, the combination of S_1 and S_2 leads, apart from the extreme values, to domains with overlapping frontiers. The indices S_3 and S_4, however, can be interpreted in a simple way: if more than fifty percent of the assembly technology is used in common, then an integration of the two products on the same installation can be envisaged.

S1	0%	0%	1%-50%	30%-80%	60%-100%	100%
S2	100%	< 100%	30%-85%	60%-90%	80%-100%	100%

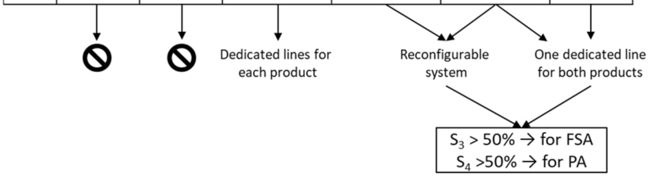

Fig. 3. Interpretation scheme of the similarity indices.

If S_3 > 50% than a common installation for functional subassembly (FSA) can be recommended and if S_4 > 50% than a common installation for the product assembly (PA), i.e. the connection of a functional subassembly with the other parts of the product, can be recommended. The values of 50% percent have been fixed during a first analysis with the industrial partner

4. Case study application

In this section, a similarity analysis with the above described four indices is applied on an industrial case study provided by thyssenkrupp Presta France, manufacturer of steering columns in the automotive sector. This case study is exemplary as the method is developed to be applicable also to other domains than the automotive sector. A preliminary analysis of their technical functions has revealed that a steering column can fulfill up to 22 different sub-functions belonging to seven main functions. Here, two steering columns which are related to two different product families are compared using the four new similarity indices.

Fig. 4. Case study steering columns – column 1 (left) and column 2 (right).

The first column, called “column 1”, is a mechanical column allowing height and length adjustment and having comfort components. The second one, called “column 2”, is a more basic mechanical column which does not possess any comfort components, and which allows only height adjustment. The former one is composed of 59 components fulfilling 25 different sub-functions. The latter one consists of 22 components fulfilling 19 sub-functions.

The two steering columns are illustrated in Fig. 4. The method application follows the description presented in section 3: based on the physical and functional architecture, the matrices $GF_{column1}$ and $GF_{column2}$ are generated and the analysis matrix GF_A^{12} is deduced. Finally, the similarity indices are calculated and interpreted. The interpretation has been confronted with the industrial practices.

Fig. 5 shows an excerpt of the matrix GF_A^{12} of the two columns. In detail the comparison of functional subassemblies FSA 12-16 (out of 22) with others. It illustrates the use of different values according to Table 3. Based on this matrix, the similarity indices S_1 and S_2 can be calculated for the two columns in our example.

Column 1-2	FSA12	FSA13	FSA14	FSA15	FSA16	FSA17
FSA16	-1,00	-1,00	-1,00	-1,00	-1,00	-1,00
FSA17	0,00	0,00	0,00	-1,00	-1,00	-1,00
FSA18	0,375	0,1875	0,375	-1,00	-1,00	-1,00

Fig. 5. Excerpt of analysis matrix GF_A^{12}.

For the calculation of S_3 and S_4 the matrices T^{int} and T^{ext} have to be generated. The figure below shows and extract of the matrix T^{ext} of the two steering columns in the case study.

Column 1-2	Bolted Assembly	Fitting	Charging Positioning	Riveting
FSA4	0	0	-1	-1
FSA5	0	1	1	1
FSA6	0	0	-1	0
FSA7	-1	-1	-1	0

Fig. 6. Excerpt of Matrix T^{ext} for the case study steering column.

Now, with help of the three matrices GF_A, T^{int} and T^{ext}, the indices S_1-S_4 can be calculated. The results are shown in Table 4 which contains the indices for the 22 functional subassemblies.

Table 4. Case study result: Similarity indices

Functional subassemblies	S_1	S_2	S_3	S_4
FSA 1	67%	91%	0%	100%
FSA 2	67%	91%	0%	100%
FSA 3	30%	68%	0%	100%
FSA 4	0%	41%	partial function	
FSA 5	40%	70%	0%	100%
FSA 6	0%	77%	partial function	
FSA 7	0%	73%	partial function	
FSA 8	48%	76%	67%	0%
FSA 9	34%	70%	0%	0%
FSA 10	0%	77%	partial function	
FSA 11	0%	50%	partial function	
FSA 12	34%	58%	25%	67%
FSA 13	36%	83%	50%	50%
FSA 14	15%	65%	0%	0%
FSA 15	0%	100%	absent function	
FSA 16	0%	95%	partial function	
FSA 17	0%	68%	partial function	
FSA 18	59%	91%	0%	0%
FSA 19	50%	95%	0%	50%
FSA 20	26%	60%	0%	100%
FSA 21	75%	95%	0%	100%
FSA 22	14%	73%	0%	100%

The following conclusions can be taken, according the interpretation scheme as presented in Fig. 3.

FSA 15 is absent in the two columns which means that their respective function is not realized. Thus, the indices S_3 and S_4 are not evaluated. The FSA 4, 6, 7, 10, 11, 16 and 17 are partially realized, i.e. they exist only in one of the two columns. Therefore, the indices S_3 and S_4 are not evaluated either. In these two cases, the assembly system has either to be separated for the assembly of the FSA or it contains modules which are not used at full charge.

For FSA 9 and 14, the values for S_1 and S_2 are poor. In addition, there is no common assembly technology used. So, it can be deduced that a separated dedicated assembly system is to envisage.

In the case of FSA 18, the values S_1 and S_2 indicate the need of a reconfigurable system. However, a closer look on S_3 and S_4 reveals that no common assembly technology is used which complexifies the reconfigurability of the assembly system.

The FSA 3, 5, 19, 20 and 22 have intermediate values of S_1 and S_2, heading for a reconfigurable solution. The S_3 indicator being 0%, the reconfigurable assembly solution is for the product assembly. The values of S_4 being either 50% or 100% indicate that the reconfiguration task is more (50%) or less (100%) complex. The case of FSA 8 is similar, with the only difference that the assembly system is for the assembly of the FSA ($S_3 > 0\%$, $S_4 = 0\%$).

FSA 12 and 13 have intermediate values for each of the four similarity indicators. This evokes a reconfigurable solution which, on the one hand, has to cope with different assembly technologies, and on the other hand should be able to create the functional subassemblies as well as to assemble them with the rest of the product. This makes the reconfiguration task in this case the most complex in comparison with the other cases.

Finally, FSA 1, 2 and 21 have high values for S_1 and S_2. This leads to the conclusion that a dedicated line for both products can be convenient. Analysis of S_3 and S_4 indicates that the assembly line is for the assembly of the FSA on the product ($S_4 = 100\%$).

The conclusions have been presented to and discussed with industrial partner. They present a first interpretation of the four similarity indices. The confrontation with a real case permitted to identify that the conclusions indicated by the four indices are about to match with the experience of the industrial partner. Overall, the indices S_1 and S_2 have been calculated in 17 pairwise comparisons of steering columns and the indices S_3 and S_4 have been calculated in ten pairwise comparisons.

5. Conclusion and perspectives

For the design of manufacturing and assembly systems, it is important to know which products will be sent on one line, which production paradigm to choose and where in the assembly system the reconfiguration has its optimum placement. To answer the question of product mix, several commonality indices have been proposed in the past, ranging from simple part-by-part comparisons to evolved indices considering additional aspects as for example material.

But all these indices fail to answer the question which production paradigm to choose and where to integrate reconfigurability.

Addressing this research gap, a new similarity analysis approach is proposed in this article, based on the parallel analysis of four similarity indices:

- S_1 and S_2 for a general view on the similarity of the product structure (functional and physical) which guide towards the production paradigm to choose and which give an idea about the complexity of the products in terms of technical functions.
- S_3 and S_4 which detail the similarity on an assembly level. They give an information on the difficulty of reconfiguration (different or identic technologies) on the level of the assembly system installations.

The product modelling approach on which the similarity analysis is based has already been introduced by the authors in another publication [5].

In cooperation with the industrial partner, several case studies have been carried out. One is presented in this article. It underlines that a comparison of different products (differing in number and characteristics of their components) is possible. The confrontation of this first case study results with the experience of the industrial partner has revealed that the propositions are in concordance with what is considered possible and reasonable by the industrial partner.

As the indices are newly developed, the presented case study and results cannot be other than the beginning of the verification of the indices. Other case studies, comparing up to ten different products, will follow to verify the findings.

In addition, the calculations and interpretation domains are done by hand for instance. An automation of the calculus would be helpful in terms of reducing calculation time and avoiding input mistakes. A long-term perspective might be the link of the method with an CAD program to extract directly information about mechanical assemblies and technologies used. Concerning the uncertain domains, future work will consist of the determination of their frontiers. This work will be done in cooperation with the industrial partner in order to assure the correct interpretation. The frontiers can be determined by establishing fuzzy rules or using classification tools as for example support vector machine (SVM).

As the similarity indices are only a brick in the research work on the design of reconfigurable assembly systems, they will be integrated into the global approach. The next step after the similarity analysis, leading to a production paradigm and permitting clustering, will be the detailed design taking into account the system constraints and process information.

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