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SYSTEMATIC IDENTIFICATION OF REPRESENTATIVE SOLUTIONS TO SUPPORT THE CONCEPT SELECTION PHASE

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ABSTRACT

In the concept selection phase a high number of solutions has to be reduced to one single overall concept. The challenge of this step is to handle the resulting complexity and to ensure that a best fitting concept is chosen. One approach to support these aims is the identification of representative solutions. These representatives give a compressed overview of the solution field and can be used for a preselection. Thereby the overall number of solutions and the complexity is reduced.

In case of large solution fields it is a problem for the designer to identify these representatives because there is no indication of the necessary number and abstraction level. The presented approach allows for a systematic guideline to identify a manageable number of representative solutions out of a large solution field. Therefore the pair wise similarity of all generated partial solutions is determined and represented in a matrix. A cluster analysis is applied to identify groups of solutions which base on the similar basic solution principle. Proper graphical representations support to identify representatives for each cluster which can be analyzed and evaluated in detail with reduced effort.

Keywords: Engineering design, concept selection, similarity analysis, handle complexity, DSM

1 INDTRODUCTION

At the beginning of the conceptual design phase a high number of creative solutions is generated to achieve a solution field as wide as possible. These solutions and fragments differ in their abstraction level, feasibility and the sub problems they deal with. A major task during the following concept selection is to handle the resulting complexity and reduce the large number of solutions to a manageable level [8, 14]. Thereby it has to be ensured that the best fitting solution is selected.

One promising approach to deal with the complexity is the use of representing solutions instead of analyzing the complete solution field. For that purpose groups of solutions have to be identified which are similar in their basic working principle and afterwards summarized under an abstract superordinate concept. In case of large solution fields the appliance of this method is quite difficult because there is no indication how many representatives are necessary and which abstraction level is sufficient.

A feasible solution for the problem is the transfer of the “Concept Mapping” approach [11] which is used for planning and the evaluating of projects within the engineering design process. This method allows for a comprehensible representation of complex structures and the identification of perceived regularity in events and objects [7, 11]. Furthermore a variety of methods in engineering design exists, like the Design Structure Matrix [10], which deal with complexity and the identification of relations and structures in complex systems [3, 5].

In this work an approach is presented which combines some of these ideas to support the concept selection phase. The presented approach allows for the systematic identification of representative solutions or concepts on a suitable abstraction level. The representatives illustrate a superordinate principle or idea and thereby characterize a complete group of solutions or fragments. With the help of these representatives the designer is able to achieve a compact and comprehensible overview of the complete solution field. In a following preselection process these representatives are evaluated and eliminated. Afterwards the remaining concepts are refined and during the next iterations they are steadily reduced to the desired level.

2 MOTIVATION

The development of modern technical products is characterized by a high time pressure and an increasing number of requirements and restrictions. In addition today's companies see themselves faced with a high number of competitors in globalized markets. This leads to a high time and cost pressure for new products. Therefore it is very important for the companies to develop products that meet the customer or market requirements best.

Referring to the engineering design process this leads to a high emphasis on the early development phases, especially the conceptual design phase. Here the basic working principles of the final product are defined [8, 14]. The decisions made in this step are very important because they effect subsequent activities in multiple ways. In [14] it is exposed that "a good concept is sometime poorly implemented, but a poor concept can rarely be manipulated to achieve commercial success". So it is very important to ensure that the "right" concept is chosen during the concept selection phase.

In support of achieving the specified goals many solutions are generated during the concept generation phase. This helps to ensure that an optimal concept is selected at the end of the process. There are a lot of methods available for the systematic and creative generation of a high variety of solutions [8, 14]. In the next step this large solution field has to be reduced to a manageable number. The major difficulty of this elimination process is the high complexity due to the different levels of abstraction and the vastness of the created solutions. Another restriction poses the limited resources (time and individuals) to carry out this task [8].

Under these circumstances the use of representative solutions seems to be a suitable method to reduce the number of solutions to an acceptable level which is necessary for a more detailed evaluation. The advantages of representatives are that they provide a compressed representation of the complete solution field by showing the main superordinate principles and that a holistic evaluation is realizable with a small number of solutions. The use of representatives also follows the basic ideas of concept mapping [11]. This approach has been used for planning and evaluating different projects and in that way shown the advantages of this method [12].

To sum it up, there is a necessity to support the iterative process of concept selection and thereby help to ensure that the best solution is select for the subsequent development activities. Given the presented boundary conditions the usage of representative solutions is a feasible method to fulfill this task.

3 BASIS AND RELATED RESEARCH

As already stressed the selection of the "right" product concept is very important for the subsequent development activities in different ways. According to [8] and [14] the concept of a product is a "concise description of how the product will satisfy the customer needs". In other words the concept of a product describes the basic working principles or the fundamental idea of the future product. The input of this phase is the basic specifications of the final product. The output is one or a small set of concepts from which one is selected for further treatment [14].

Further on the conceptual design can be divided into two sub-phases, the concept generation and concept selection phase (see figure 1) [14]. During the first phase many creative (partial-) solutions are generated which are able to satisfy the customer needs. Thereby often functional decomposition [9] and modeling as well as a variety of creativity techniques are used. A very common method during this phase (there are others as well) is the appliance of functional decomposition in combination with a concept combination table [8, 14]. This method is also known as Zwicky Box or morphological matrix [16]. The morphological matrix is a one dimensional ordering scheme in which the identified sub problems correspond to the columns of the matrix. The entries of the columns are the generated possible solutions for this sub problem. A solution for an overall concept is generated by the combination of one solution from each column [16]. By applying this method a very large number of overall solutions can be created out of a small number of sub problems and belonging solutions. One problem with this method is that most of the generated concepts are not feasible for further treatment because the selected partial solutions are incompatible or the overall solution does not fulfill the specifications. At the same time the high number of theoretical solutions leads to a high complexity because the designer is not able to overview the complete generated field.

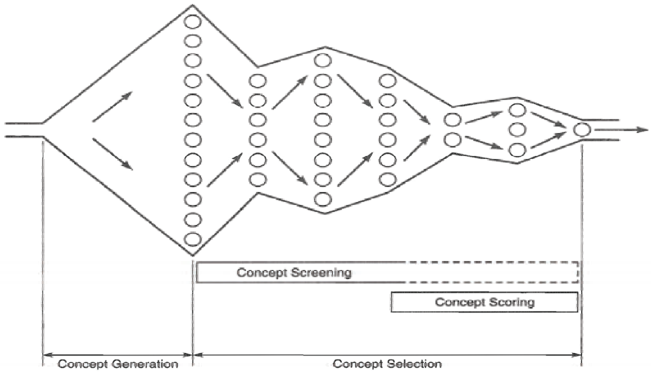

Figure 1: Conceptual design phase [14]

Therefore in the following concept selection phase this high number of solutions and fragments has to be reduced to a much smaller and manageable one for further treatment. This evaluation process is necessary because in most cases there are not enough resources (time and individuals) available to evaluate all theoretical solution on a detailed level [8]. The concept selection phase is an iterative process of screening, evaluating and eliminating solutions. The main challenge of this task is to handle complexity resulting out of the large number of generated solutions. There are two conflicting influences on the evaluation and selection process. On one hand it should be carried out with a minimum of resources, on the other hand it has to be ensured that no promising concept is eliminated and truly the best solution is selected at the end.

There are different methods to handle complexity and reduce the large number of theoretical concepts to manageable number (a good overview is given in [8 and 14]). A well introduced and promising approach is the use of representative solutions. These representatives summarize a group of concepts under a significant expression of superordinate concept. In case of large solution fields the problem with this method is that due to the high complexity the designer is not able to identify a group of representatives that cover all generated solutions. He has no idea how many representatives are necessary to describe the complete solution field best and which abstraction level is adequate. Therefore a method is needed which systematically identifies proper representative solutions and also reduce complexity during the concept selection phase. Thereby it has to be ensured that no promising concept is eliminated without being made aware to the designer.

Besides the methods given in [8, 14] there are other approaches to manage structural complexity in engineering design. One of these approaches is the Design Structure Matrix (DSM) [10]. In a DSM the elements of a system are arranged in the rows and columns [10, 5]. The interdependencies among two elements are marked in the corresponding field. In case of undirected connections the matrix is completely symmetrical. The matrix representation allows for a detailed analysis of the interdependencies and structures among the elements in a regarded domain. It is also possible to identify dependencies what were not visible before. These methods for analyzing can be used to identify subsystems or critical elements in the complex structure.

There are a lot of methods and algorithms available to analyzed theses matrices. An often used method is the cluster analysis. It allows for an automated identification of strongly interconnected elements inside the system [9, 5]. Dependent on the kind of the examined dependencies the subgroups are similar in a specific way. This approach can be uses to identify in some way related elements in the solution field. A possible representation of a DSM is the use of force directed graphs. They allow for a graphical analysis of the structure and help the designer to visualize the computed results [5], e.g. the computed clusters can be marked in the complete system structure.

The DSM method is well known today and used in different tasks like process management, variant management, mechatronic development and so on [3, 5]. There are also approaches to use DSM for the support of the conceptual design [e.g. 4] by identifying valid combinations of the generated solutions. A shortcoming of this approach is that it only works well when the abstraction level is not to low and the (partial-)solutions can be allocated clearly to a certain subfunction.

Furthermore there are methods in the fields of learning theory and knowledge management which deal with the comprehensible representation of knowledge which can also be very complex. Besides the well introduced common MindMaps there are different other representations. One of these representations is the "Concept Map" [6] and approaches like "Concept Mapping" [11] are based on it. There is a large application field for these methods in education, diagnostics of learning difficulties as well as the planning and evaluation of projects [6, 11].
The basic idea behind these approaches is the learning assimilation theory by Ausubel [1]. The fundamental idea in his cognitive psychology is that learning takes place by the assimilation of new concepts and propositions into an existing concept and propositional framework held by the learner [1, 7]. This knowledge structure as held by the learner is also referred to as the individual's cognitive structure [7]. So the knowledge of a person is described as a cross-linked and strongly connected system of ideas [7]. A concept in this context is "a perceived regularity in events or objects, or records of events or objects, designated by a label" [6]. Ausubel also makes a distinction between meaningful and rote learning. Meaningful learning thereby describes a process in which new content can be connected to existing knowledge. This kind of learning leads to well organized relevant knowledge structure and is therefore more effective than rote learning [1].

One possibility to support meaningful learning is the use of concept maps [6]. The basic idea of the assimilation theory is the linking of new information or concepts to existent knowledge. This structure is similar to the cognitive structure or the human memory where terms are linked through relations. Concept maps are a graphical tool for organizing and representing knowledge. [7] They include concepts and relationships between concepts which are indicated by a connecting line. To specify the relationship between two concepts expressions written on the connecting line can be used. An example concept map is shown in figure 2 left. A characteristic of concept maps is that concepts are represented in a hierarchical fashion with the most general at the top of the maps and specific, less general concepts are arranged hierarchically below. There is also the possibility to include cross-links which are relationships or links between concepts in different segments or domains. Adding examples or objects can be uses to clarify the meaning of a given concept [7].

The idea underlying concept maps is also used for the evaluation and planning of projects and has therefore been adjusted and extended. The resulting method of "Concept Mapping" [11] is a type of structured conceptualization which can be used by groups to develop a conceptual framework which can guide evaluation and planning. The approach consists of six steps (preparation, generation, structuring, representation, interpretation and utilization). By applying the method the participants develop a global understanding of the project and identify with the results. For the identification of representatives the interesting steps are structuring, representation and interpretation of the generated ideas [11].
During the structuring phase a "total similarity matrix" is generated to identify relationships among the elements. Therefore a set of binary similarity matrices is generated in a first step. Every user has to sort all generated ideas "in a way that makes sense to him" [11]. There are some basic rules e.g. that not all ideas can belong to one pile. Afterwards the results of each user are put into a similarity matrix. In this matrix a "1" is entered if two corresponding concepts were sorted in the same pile. In all other cases the entry is "0". To combine the results of all participants the total similarity is created by adding all binary matrices together. In the resulting matrix a high number in a field indicates a strong relationship between two elements and that they are similar in some way [11].
For the analysis and representation of the matrix the same methods like in complexity management (multidimensional scaling [2], clustering [5, 9]) are used. A comprehensive visualization of identified clusters is the use of a cluster map (see figure 2 middle). This map is a two-dimensional representation of the total similarity matrix where the distances of the points correspond to the similarity of the different ideas. Afterwards the graphical representation can be used to identify clusters (close groups of points) or the results of a computed cluster analysis can be visualized. The representation in a cluster map is very similar to the graphical representation of a Design Structure Matrix [11].
For the interpretation of the results all clusters are written down in a structured list. Afterwards the participants have to define describing names for all of the clusters and can discuss them. Thereby it is still possible to regroup the single ideas if necessary. The names of all clusters can also be added to the cluster map to visualize the results (named cluster map, figure 2 right). These names or describing

terms of the clusters can be interpreted as superordinate concepts or connecting concepts of the ideas. For this reason it seems to be very promising to use the approach for the identification of representative solutions during the conceptual design phase.
The concept mapping approach also contains different methods for a detailed planning and an evaluation of projects but these are not of any interest for the presented approach.

Concept Map Cluster Map Named Cluster Map

Figure 2: Different representations of concepts [7, 13, 11]

To sum it all up the analysis of the engineering design process showed the necessity to support concept selection during the conceptual design phase and to provide the reduction of the high number of solutions. One main challenge is to deal with the high complexity. There are some methods to support this task but there is an additional need for assistance, e.g. using representative concepts is not practical with large solution fields. Thus there is a need for a systematic approach which allows for a most simple and compact description of the complete solution field and thereby ensures that the “best fitting“ solution can be selected at the end.
Further examinations showed that in complexity management, education theory and project planning are a lot of methods available that deal with the identification of relations, interconnections and structures of elements in a system. These methods can be used to show similarities among elements and thereby retrieve superodinate concepts for these relations.
The presented approach combines and transfers these methods to the identification of representatives by applying the concept mapping approach and structural analysis methods to a generated solution space. A major advantage of the used methods is that they are able to deal with different levels of abstraction and that there is no necessity for a detailed description or quantification of the connections.

4 IDENTIFICATION OF REPRESENTATIVE SOLUTIONS

In this work the identification of representative solutions is used to handle complexity of the concept selection and thereby support the concept selection phase. This method allows for a compressed view of the complete generated solution field by identifying superordinate principles of the generated solutions. According to [11] designers can also identify with the results because they are able to follow the complete generation process. The presented approach also ensures that the complete solution field is represented by the selected representative. This is especially in case of large solution fields when the designer has no idea of the basic solutions principles and is not yet able to achieve an overview.

4.1 Identification of similarities among the concepts

The basic idea of identifying representative solutions is to analyze and identify similarities between the generated solutions. The term “similarity” is often use used in philosophy, geometry (forms) and statistic (multivariate analysis, multidimensional scaling [2]). In this work it only refers to the basic working principle of two solutions. So the similarity is only defined in a qualitative way and thereby depending on the designer’s point of view. In the following this qualitative definition is used:
“Two (partial-) solutions are marked similar if the basic working principle or the underlying idea of both solutions is similar.” This is a very weak and subjective definition, but it is sufficient for the actual task (compare to the sorting of ideas in concept mapping).
According to the assimilation theory [1] and the concept mapping techniques [11] the structured and depicted representation of the solutions helps the designer during an evaluation and planning process. Therefore the implicit knowledge contained in the generated solutions and fragments has to be

structured and visualized in a comprehensible manner. This is another reason for the usage of representative solutions during the design process.
The procedure for the identification of representatives in engineering design is quite similar to the procedure in concept mapping [11] or the decomposition of systems [14]. The solutions are summarized in groups with the same basic ideas or working principles. Afterwards these groups are analyzed to identify superior aspects that are representative for the complete group. So it can also be interpreted as an inversion of this classification tree where the superior classes are not known. This view corresponds to the principles of concept maps [6], too. The difference to the classic use of representatives is that in the beginning of the process this superodinate principles are not knows to the designer. Furthermore the approach is able to deal with different levels of abstraction of the generated solutions and fragments. The approach shown in [4] works well in case of a high and homogenous level of abstraction. In case of very uncertain solutions it is not possible to classify them into a combination scheme and an application is not practicable. Finally the approach ensures that the complete solution field is represented and thereby the best solution can be identified.

The first step for the identification of representative solutions is the setting up of a binary similarity matrix in which all pair-wise similarities between the solutions are marked. This matrix contains all generated solutions in the rows and columns and the size meets the number of generated solutions. Following the ideas of concept mapping [11] the participant only has to insert a “1” in case of an identified similarity into the belonging field. In all other cases “0“ is inserted or the field is left blank. There is no documentation or distinction in what way the solutions are similar or how similar they are. This similarity matrix can be seen as a Design Structure Matrix (DSM) because it represents interdependencies among the domain of the generated solutions [10].
A generic and simplified similarity matrix is shown in figure 3. It consists of 8 solutions (A to H) that are arranged in a similarity matrix. An “X” in the matrix marks two solutions as similar. The matrix is completely symmetrical [11] so it is only necessary to fill in one half. The entries on the diagonal are also not important because a single concept is always similar to itself.

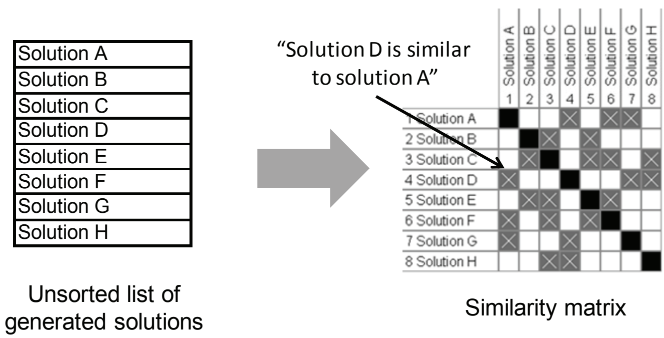

Figure 3: Setting up the similarity matrix

There are two different ways for the generation of setting up the similarity matrix. The first way bases on the description of concept mapping given in [11]. In this scenario every involved (or maybe not) designer sets up his own binary similarity matrix. Afterwards the “total similarity matrix” is computed by simply adding all generated matrices or using their average. The resulting matrix is used for all following analysis. This allows for a more detailed analysis of the clusters and the interdependencies among the solutions. The simple making of one similarity matrix is very depending on the view of the designer.
The second and probably more practical way for applying of the method is the use of only one single binary similarity matrix. This proceeding is much less time consuming than the generation of several matrices. Furthermore it is possible to split up the matrix so that every designer only fills in a limited sub matrix. The complete matrix is afterward generated by putting all sub matrices together.
On the first view it seems that the usage of only one binary matrix produces poorer results compared to a total similarity matrix. The generated results depend much more on the subjective views of the designer and nobody can ensure that different designers even have the same idea about similarity. A

detailed view on this proceeding shows that it is possible to use only one matrix without losing much quality of the results. The first reason is that similarity is only measured in a very weak and qualitative way. So the entries in a total similarity matrix are not categorical better. The second and essential reason is that during the on gonging process the results of the cluster analysis are checked manually in a team. The similarity matrix is only used to get a first impression for possible clusters.
At this point it should also be mentioned that a major advantage of the pair-wise comparing of solutions is that the user can concentrate on the evaluation. He does not have to keep in mind which other solutions were created and what are the possible connections to the rest of the solution field.

4.2 Concept clustering

The next step is the clustering of the solutions in the similarity matrix. The clustering can be done by computer programs that use special cluster algorithms (e.g. spectral clustering [15]) or by hand in case of not too large matrices. As a result the number of clusters should be reduced to a manageable number. The decision how many clusters have to be identified depends on the available resources and time. It is suggested that a maximum of 10 to 15 clusters is a suitable number for the subsequent steps.

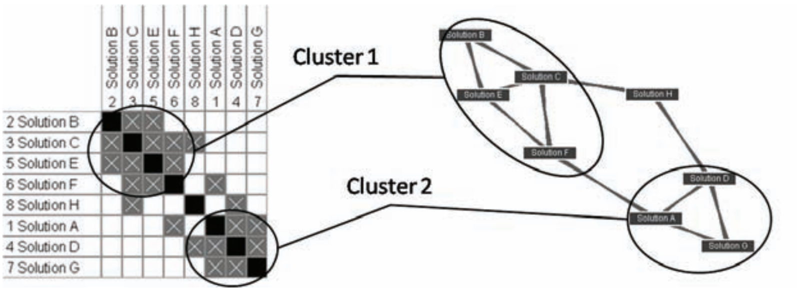

Figure 4: Cluster analysis and graphical representation

The result of a cluster analysis is shown in figure 4. It shows a completely interlinked cluster in the lower right corner consisting of three solutions (A, D, G). Another cluster consisting of four solutions (B, C, E, F) can be identified in the upper right corner. It is not completely interlinked because the connection D - F is missing. The remaining solution H is not clearly allocated to one of the clusters. Therefore a more detailed analysis is necessary whether the solution represents a third class of solutions or belongs to one of the others.
On the right of figure 4 the graphical representation of the matrix in form of a force directed graph is shown [5]. In this generic example it is very easy to identify the two clusters in the graph. A more complicate graph taken out of an actual research project is shown in figure 6. There is almost no possibility to identify cluster just by manually analyzing the graph. But the representation can be used during the following steps to verify the identified clusters and visualize the results.

4.3 Interpretation of the identified clusters

The last step is the analysis and interpretation of the clustered solutions. This task should be performed in a team were the participants can discuss the results. It leads to the identification of superordinate principles and through this the identification of representative solutions. Therefore all clusters have to be analyzed concerning the similarity of the contained concepts. The designer has to check whether the generated clusters make sense to him or not. If a group of solutions make sense the superordinate principle has to be identified that describes the complete cluster best. In case that some clusters are not homogenous enough or single solution seems to belong not to the rest of the group they can be regrouped into another cluster. It also has to be checked whether these concepts belong to a new cluster or whether one cluster has to be split up. As a result there should be a manageable number of clusters with their belonging superordinate principles which make sense for all participants.
The last step is the identification and naming of representatives. These representative solutions can be new generic solutions or one fitting solution out of the cluster. In figure 5 the step of identifying representative solutions is shown. For the two clusters 1 and 2 (figure 4) new representative solutions have been created. The solution H does not belong to any of the groups, so it represents a third "group" of solutions.

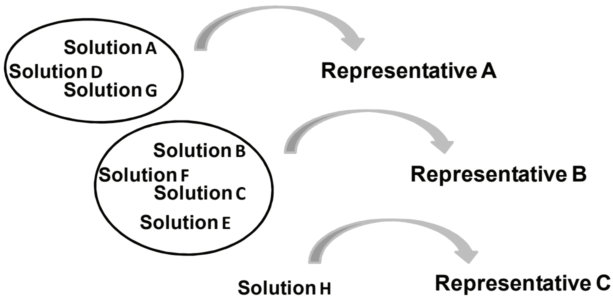

Figure 5: Identification of representative solutions

It is possible to repeat the method on different levels of abstraction. If in a first step the number of solutions cannot be reduced to an acceptable level it is possible to find superior concepts on a higher level as well. Afterwards a preselection can be performed and the unsuitable solutions are eliminated. Thereby the number of solutions to be evaluated can be reduced systematically. After the elimination of single representatives the remaining clusters are split up and the contained solutions can be analyzed in more detail. The method can also be used to initiate the generating of new solutions. In case of a "cluster" containing only one solution or in case of a very small but promising one this information can be used to create more solutions based on this basic idea or to generate variants of this solution.

A closer look on the described approach might provoke the impression that the results are very random and not very reliable. All steps (except the cluster analysis) of the method are strongly influenced by the designer's subjective point of view. This question concerning validity and reliability of concept mapping (where this method is based on) is discussed in [12]. Thereby 20 concept mapping projects were analyzed. The result was that the creation of a concept map has both aspects (science and art). But it is also proved that the method is valid and reliable in a scientific sense. [12]

5 EXAMPLE APPLICATION

The presented approach for the identification of representative concepts has been carried out during the conceptual design phase of an improved production machine in the textile sector. The development focuses on a specific subsystem of the machine which should overcome actual limitations. Due to the fact that it is a very central system there are many connections to other subsystems that have to be taken in considerations. Additionally for a long time there has been no improvement of the basic working principle of the systems so that there is a need for new and innovative solutions. The following example shows how the identification of representative concepts was used to handle complexity during the concept selection phase and allows for the selection of promising solutions for a detailed analysis.

5.1 Initial situation

During a previous creative concept generation phase a high number of about 150 (partial-) solutions were created. The first step to reduce this number was the appliance of simple evaluation methods for a preselection. During this evaluation, all concepts which are much too uncertain or which do not meet the requirements were eliminated. Thereby the number of solutions could be reduced to 79. Since this number of concepts was still too high for a detailed evaluation it had to be reduced to a much smaller one. In the first attempt the developers tried to classify the remaining concepts into a combination table to get an overview of the generated solution field. It pointed out that no created arrangement led to a satisfying result. This was mainly due to the fact that the regarded solutions were on different levels of abstraction. Furthermore they partly fulfilled only one or sometimes more sub functions. So the idea came up to identify the basic working principles underlying the generated solutions. This should allow reducing the number of solutions to be evaluated significantly. Afterwards the remaining concepts can be specified for a detailed evaluation.

5.2 Setting up the similarity matrix

The remaining 79 solutions were arranged in a Design Structure Matrix (DSM). This matrix should visualize the structure of the solution field and thereby help to identify basic working principles and representative solutions. Afterwards the similarity of all entries in the matrix was compared pair wise. There was no distinction in which way the solutions were similar and no documentation how similar they were. The designers only got the advice that the solutions should be similar in the underlying basic principle. If in the view of the designer two solutions are similar in any way, a “1” was inserted in the particular corresponding field. Other rules were not created.

Due to the fact that the matrix is completely symmetrical and the entries on the diagonal are not relevant, there are still about 3000 decisions to be made. To save time and resources the creation of the similarity matrix has spitted up among the four involved designers. Every designer had to fill in a certain number of complete rows.

For further support of this task a simple Excel-Macro has been implemented. It shows the names of two regarded concepts and offers the opportunity to insert “1” or “0”. After filling in the answer it jumps to the next field in the matrix. This little tool helps to fasten up the process of filling in the similarity matrix significantly. It also ensures that the designer can concentrate on the pair-wise evaluation and dos not have to think about the matrix and the methodology behind. So it can also be used by individuals with little or no experience in working with large matrices. Last but not least a third advantage of the tool is that it ensures that all entries are made at the correct place.

Following the filling in of the sub matrices the complete similarity matrix was created. The generated binary similarity matrix and the graphical representation are shown in figure 6.

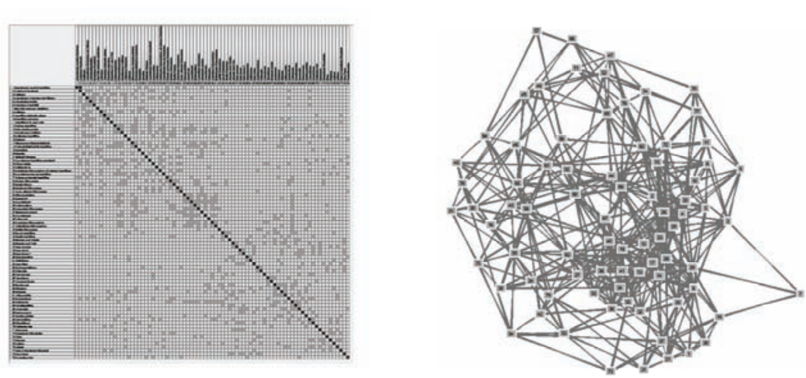

Figure 6: Generated similarity matrix and belonging graph

A first attempted of a graphical analysis (Figure 6 right) did not allow for a simple identification of clusters. So the next step was to find a practical and resource-friendly way to identify and visualize structures in the solution field.

5.3 Clustering of concepts

The clustering analysis was performed by a team of 6 designers. Most of the team members had no experience with the clustering methods. Due to the high time pressure and that there was no suitable software at hand the decision was made to carry out the analysis manually. This also allows for a better understanding of (intermediate) results. Furthermore the necessary plausibility analysis could be integrating in the generation of the clusters.

In the beginning all completely interlinked clusters in the matrix were identified automatically (the used software allowed for that). In the following the rows of the matrix were rearranged in a way that all completely interlinked clusters were grouped together and thereby the clusters are visible. The actual task clustering started with the largest complete cluster. Afterwards all remaining concepts were analyzed and added to a proper cluster. Through this approach the team was able to identify ten clusters of similar solutions. The results of the clustering and the rearranged matrix with some identified clusters marked are shown in figure 7.

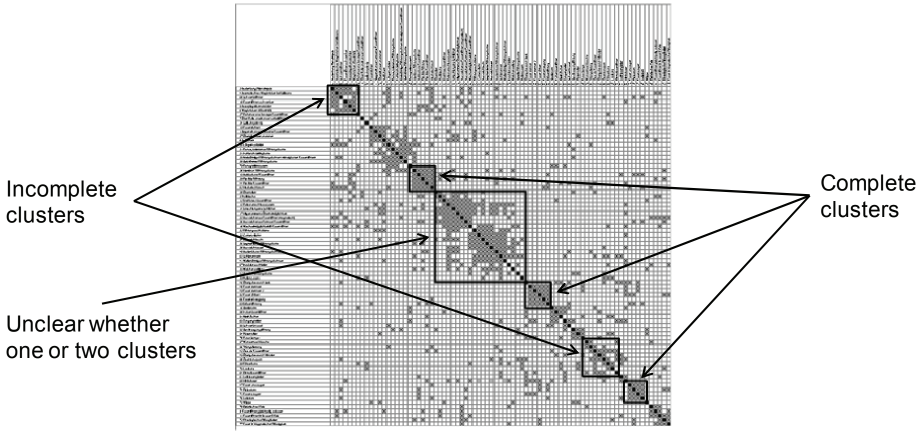

Figure 7: Results of the cluster analysis

The results of the analysis showed that some completely interlinked clusters and some with connections missing could be identified in the solution field. An interesting cluster was found in the middle of the matrix. In the case of this structure further analysis is necessary to decide whether it is a single cluster or consists of two substructures.
In the following it had to be analyzed if the identified clusters are really representative for a special group of solutions and if it is possible to determine the underlying working principle.

5.4 Interpretation and identification of representative concepts

The last step was the interpretation of the results and the naming of representative solutions. Therefore the clusters were analyzed in detail. First it was checked if all clusters really made sense to the designers. The results showed that the generated clusters really made sense. By visualizing all solutions of one single cluster the team was able to recognize similarities among the solutions that were not visible before.
In the following the designers were also able to identify the superordinate working principle of the created clusters. So the team was able to name ten representative solutions for a more detailed specification and evaluation. It also showed up that most of the solutions that have not been allocated to any cluster could be classified as "unfeasible" or that the level of abstraction is much too uncertain to be taken into further considerations.

6 CONCLUSION AND OUTLOOK

The presented work shows that the usage of representative solutions is a proper approach to support the concept selection phase and deal with complexity at the same time. The identification of relations and structures within the solution field allows for a deeper understanding of the generated solutions and their underlying working principles. The visualization of these superordinate principles and their interdependencies provide additional value to the designer during the important phase conceptual design phase.
The introduced method for the identification of representative solutions to support the concept selection allows for a systematic generation of a manageable number of representatives. The approach is able to handle the high complexity of this phase which is due to the large number and the varying level of abstraction of the generated solutions. It helps to reduce the number of solutions systematically and thereby ensures that no promising solution is eliminated by accident. So it overcomes the main shortcoming of other approaches to support this task.
The practical use of the method and the operability in a real practical project were analyzed in an actual research project and the results are very promising. In this specific case the approach was able to give new impulses to the development process.

The next steps are the application in different research projects with varying levels of abstraction to get more experiences with the method. This is important concerning the practical use as well as the reliability and validity of the approach. Thereby it has to be analyzed which effects the application of different matrices (single binary or total similarity matrix) have on the results. An interesting question is if the possible better results of the cluster analysis are able to compensate the required additional time for the generation of multiple matrices. It is also thinkable to identify attributes for the solutions to allow for a quantitative description of the similarity. By this it will also be possible to support the designer during the setting up of the similarity matrix by providing more detailed guidelines for his decisions.

To increase the practical use and the operability of the methods it is necessary to provide an adequate tool support. This also includes the integration and appliance of automated clustering algorithms which are able to identify not completely interlinked clusters. This will help to make the approach more practical because the manual clustering that this step takes lot of time. Some basic experiences with spectral clustering [15] were made but there is still more work to do.

Another point for further research is the integration of evaluation methods into the presented approach. As mentioned the concept mapping approach provides methods that allow for an integrated evaluation of the projects [see 11]. It has to be analyzed if these methods can be transferred to the selection of a product concept. This would lead to an integrated approach for the support of the concept selection phase which is able to deal with a high level of uncertainty and complexity.

REFERENCES

[1] Ausubel D. P. *Educational psychology - a cognitive view*, 1968 (Holt, Rinehart and Winston, New York)

[2] Borg I., Groenen P. *Modern Multidimensional Scaling: Theory and Applications*, 1997 (Springer New York)

[3] Browning T. R. *Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions*, IEEE Transactions on Engineering Management, 2001, 48(3)

[4] Hellenbrand D. and Lindemann U. *Using the DSM to support the selection of product concepts* in Proc. International Design Structure Matrix conference, DSM'08, Stockholm, November 2008

[5] Lindemann U. and Maurer M. *Structural Complexity Management*, 2008 (Springer, Berlin)

[6] Novak J. D. *Learning, creating and using knowledge: Concept maps as facilitative tools in schools and corporations*, 1998 (Lawrence Erlbaum Associates, Mahwah)

[7] Novak J. D. and Canas A. J. *The Theory Underlying Concepts Maps and How to Construct them*, Technical Report IHMC CmapTools 2006-01, Florida Institute for Human and machine Cognition, 2006

[8] Pahl G., Beitz W., Wallace K. (ed.) *Engineering Design*, 2007 (Springer, London)

[9] Pimmler T. U., Eppinger S. D. *Integration Analysis of Product Decomposition* in Proc. of the 1994 ASME Design Theory and Methodology Conference, ASME 94, September, Minneapolis, 1994

[10] Steward D. V. *The Design Structure System: A Method for Managing the Design of Complex Systems*. IEEE Transactions on Engineering Management, 1981, 28(3)

[11] Trochim W. M. K. *An introduction to Concept Mapping for Planning and Evaluation* in Trochim W. M. K. (guest ed.) Evaluation and Program Planning: A special issue of Evaluation and Planning, Vol. 12, No 1, 1989 (Pergamon Press, New York)

[12] Trochim W. M. K. *Concept Mapping: Soft sience or hard art?* in Trochim W. M. K. (guest ed.) Evaluation and Program Planning: A special issue of Evaluation and Planning, Vol. 12, No. 1, 1989 (Pergamon Press, New York)

[13] Trochim W. M. K. and Jackson K. Concept *Mapping as an Alternative Approach for the Analysis of Open-Ended Survey Responses*, Organizational Research Methods, Vol. 5, No. 4, 2002

[14] Ullrich K. T. and Eppinger S.D. *Product Design and Development*, 2004 (McGraw-Hill, Irwin)

[15] v. Luxburg U. *A Tutorial on Spectral Clustering* in Statistics and Computing Vol. 17, No. 4 December 2007 (Springer Netherlands), ISSN 0960-3174, p. 395-416

[16] Zwicky F. *Entdecken, Erfinden, Forschen im morphologischen Weltbild*, 1966 (Droemer Knaur, München)

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