1 INTRODUCTION
During the conceptual design phase the basic working principle or concept of a product is defined [1]. The selection of a specific concept is a very important step in the development process because this decision has multiple effects on the following phases and the final product. In this early stage the field of solutions should be as wide as possible. To achieve this and to handle complexity at the same time it is common to use the method of factorization [1]. A complex system is divided into separate manageable sub-problems which can be solved individually. The consistent combination of partial solutions leads to the overall solution (concept). Thereby a high number of theoretical concepts can be created out of a small number of sub-problems and solutions. This high number has to be reduced so that the selection of an optimal concept is possible. The presented approach provides a systematic assistance in the selection of an overall concept by consequently eliminating inconsistent solutions and identifying promising combinations.

2 BASIS AND RELATED RESEARCH
A well introduced method to order and systemize the allocated partial solutions is the usage of a one dimensional ordering scheme. In this morphological matrix developed by Zwicky [2] the sub-functions are allocated in the first column and the associated partial solutions are arranged in the belonging row. The combination of one partial solution out of every row leads to the overall principle solution or product concept. The number of theoretical possible concepts which can be generated is the multiplication of each number of partial solutions in each row (e.g. 4 sub-problems with each 3 partial solutions result in 88 alternative concepts). In most cases no resources are available for checking up and evaluating all these theoretical overall concepts. Therefore methods are needed which allow to reduce this high number of alternatives significantly. To fulfill this task a compatibility matrix [3] in which inconsistencies among two different partial solutions are marked can be used. Through this inconsistent concepts with non compatible partial solutions can be identified and eliminated from further considerations. A different method which also visualizes the possible concepts is the usage of tree structures [3]. In these trees of alternatives all possible combinations of solutions are carried out systematically. In case of an incompatibility among two solutions the according branch is aborted. The remaining complete branches represent the possible and consistent overall concepts.

In general both approaches represent interdependencies among different partial solutions. Networks like this consisting of only one type of domain, in this case partial-solutions, can be described by a design structure matrix (DSM) [4]. A comparable approach has been presented in the field of variant management for analyzing product ranges [5]. The focus there lies on the identification of clusters of different variants and it gives impulses for setting up suitable design modules.

3 IDENTIFICATION OF CONSISTENT CONCEPTS BY USING THE DSM
Transferred to the systematic combination and selection of concepts in early phases a matrix is needed which represents all possible connections between the partial solutions. Therefore the “classic” compatibility matrix is transformed into a compatibility design structure matrix or “consistency matrix” in which all compatible combinations of elements are marked (see figure 1). This matrix can easily be created by inverting every element of a given compatibility matrix. Compared to the classic one the new compatibility DSM can be seen as an inverted or negative image. Regarding the practical application the designer can still mark incompatible combinations because this number is much lower in most cases. Afterwards the inverted matrix can be calculated automatically.
Since the connections of the elements are undirected, the compatibility DSM is completely symmetrical and it is only necessary to fill in one half (like in the original one). Furthermore only combinations from different lines of the morphological scheme have to be considered because it is only allowed to select one partial solution for each sub-function [2].

With this representation it is possible to identify consistent overall concepts by performing a cluster analysis. A consistent and complete concept correlates with a completely interlinked cluster. Thereby the size of the cluster has to meet the number of partial functions (rows in the morphological scheme). This is due to the fact that all elements contained in a solution have to be compatible to each other and that every partial problem has to be fulfilled. To validate this assumption the identified clusters were compared to a manually created tree of alternatives. The results confirmed that structure and number of the completely interlinked clusters are identical to the complete branches.

Smaller completely interlinked clusters can be seen as a partial solution for the overall problem. This is especially interesting if the sub-functions are arranged in a specific order that represents their importance. Elements which are not contained in any completely interlinked cluster are eliminated from further considerations. In that way the number of theoretical solutions can be reduced significantly. The identification of clusters can be done by a computational algorithm so that the user is completely exempted from all combination activities.

The structure and interdependencies of the partial solutions can also be represented by strength based graphs [4]. In these graphs partial solutions which are contained in many different overall solutions are arranged in the middle. Solutions with fewer connections or those which are not contained in any completely interlinked cluster can be found on the border of the structure (cf. [5]).

4 EXTENDING THE MATRIX TO GAIN A RANKING ORDER

The simple identification of consistent solutions and elimination of unfitting partial solutions is only the first step during the process of concept selection. In general the remaining number is still too large to be analyzed and evaluated during embodiment design. Considering the importance of this step the identification of an overall concept which meets the requirements best is needed [1].

Therefore the presented compatibility-DSM is extended by weighting factors (see fig. 2). These factors represent a positive or negative influence between two solutions. Instead of just checking the (in)compatibility, the degree of positive or negative influence between two concepts is inserted in the matrix. Two partial solutions which have mutual positive influence or work perfectly together receive a high value, poor combinations receive low factors. The evaluation of all pair wise combinations of partial solutions has to be carried out by the designer. Therefore different evaluation methods can be used (cf. [6], [7]). In this context adequate evaluation criteria and a fitting value function (e.g. linear or logarithmical) have to be defined. It is also important that the level of information of all partial solutions is almost identical. Otherwise the results are not reliable and promising concepts may be eliminated accidentally [1], [7].

To support the selection of a concept a ranking order can be calculated from the given weighting factors. The quality of a concept is represented by the sum of all the weights in a completely interlinked cluster. Concepts with a high value contain positive evaluated combinations of partial
solutions; concepts with a lower sum include poor or average combinations. Based on this a ranking of consistent overall concepts can be derived easily. This way of calculating a ranking out of the weights is possible because all considered clusters consist of the same number of elements and connections. Not completely interlinked or smaller clusters were eliminated in the first step. The generation of the ranking based on the extended compatibility matrix can be done completely automatically. The designer can concentrate on generating and evaluating the partial solutions.

<table>
<thead>
<tr>
<th>A1</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>C1</th>
<th>C2</th>
<th>D1</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.1</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>B1</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>B2</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>B3</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>C1</td>
<td>0.3</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>C2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>D1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.** Extended compatibility matrix and derived ranking of concepts

### 5 CONCLUSION AND OUTLOOK

The exposed approach shows that design structure matrices can be used to support the selection of an overall product concept during early design phases. It offers a structured and computer supported proceeding to derive a ranking order of consistent concepts from a given number of (partial)solutions. It allows for dealing with large numbers of theoretical alternative solutions and relieves the identification of one or more promising concept(s).

The next step will be the application of the approach in different research projects. Up to now there was only an example application with a relative small morphological matrix. The results approved the working of the approach with real data. In the future it will be applied to much bigger matrices. Thereby it has to be analyzed which combination of evaluation methods, assessing values and value functions for the weights leads to an optimal result. Another open issue is the implementation of tools to support setting up and interpreting the used matrices. Furthermore the approach can be transferred to other domains such as the identification of capable consistent scenarios in scenario technique. An application for the selection of working structures seems promising as well.

### REFERENCES


Contact: David Hellenbrand
Technische Universität München
Institute of Product Development
Boltzmannstr. 15
85748 Garching, Germany
Phone: +49 89 289 15126
e-mail: david.hellenbrand@pe.mw.tum.de
www.pe.mw.tum.de
Using the DSM to Support the Selection of Product Concepts

David Hellenbrand, Udo Lindemann
Technische Universität München
Institute of Product Development
Germany

Index

• Introduction and Motivation
• Basis and Related Research
• Approach and Objectives
• Identification of consistent concepts
• Extended compatibility matrix
• Example application
• Future work
• Conclusions
MANAGE COMPLEX SYSTEMS

FOLLOW THE FLOW OF INFORMATION!

Introduction: Conceptual Design

Conceptual Design phase:
- Main result: Definition of product concept
- Method of factorization often used to achieve manageable system
- Problem divided into sub problems
- Creation of a large field of partial solutions
- Often usage of a morphological matrix to get an overview of the complete solution field
- Decision has multiple effects on complete following development process

Problem/Task

- partial problems
- partial solutions
- Product concept

<table>
<thead>
<tr>
<th>Partial functions</th>
<th>Partial solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_A</td>
<td>A_1   A_2</td>
</tr>
<tr>
<td>T_B</td>
<td>B_1   B_2 B_3</td>
</tr>
<tr>
<td>T_C</td>
<td>C_1   C_2 C_3 C_4</td>
</tr>
<tr>
<td>T_D</td>
<td>D_1   D_2</td>
</tr>
</tbody>
</table>

Handling a high number of alternative concepts

- In a morphological matrix new concepts are generated by combination of different partial solutions
- A small number of functions and solutions leads to high number of theoretical concepts
- Many of these theoretical concepts are unfeasible
- Revision of all combinations is much too extensive

→ Identification of consistent and promising concepts

Embody Design
Basis and related research

- Different approaches to reduce the high number of alternatives
  - Adoption of the matrix
  - Integration of evaluation methods
- Common method: Compatibility matrix
- Inconsistencies are marked (geometric, energetic, …)
- Completely symmetrical
- Concentration on pair wise evaluation
- Difficult to manipulate results

Objectives and Approach

**Objectives**
- Support of concept selection in case of large matrices
- Handle a high number of theoretical concepts
- Automated identification of consistent and promising concepts
- Systematic and structured procedure
- Possibility of computerized tool support
- Comprehensible presentation of results

**Approach**
- Interdependencies among partial solutions can be represented in a DSM
- The compatibility matrix shows impossible combinations of solutions
- To recognize consistent combinations, all possible connections between the different elements have to be identified and represented in a DSM
- This matrix can be derived from a given compatibility matrix
- Consistent concepts can be identified by a cluster analysis
Adaption of compatibility matrix

- Classic compatibility matrix shows inconsistencies among solutions
- In the proposed compatibility DSM possible combinations are marked (“Consistency DSM”)
- Completely symmetrical
- Matrix can be derived out of classic representation automatically
- „Negative / inverted" image of the classic matrix

Identification of consistent concepts

Prerequisites of a consistent concept:
- All selected partial solutions have to be compatible to each other
- Every partial function has to be fulfilled

⇒ Consistent solutions are represented by completely interlinked clusters
⇒ Size of the cluster has to match the number of partial functions
Graphical Representation

- Strength based graph
- Easy identification of not used elements/solutions
- Highly compatible elements arranged in the center
- Identification of solutions contained in different concepts (overlapping of clusters)

Elements not contained in any completely interlinked cluster

Extended compatibility matrix

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>D1</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td></td>
<td></td>
<td>0.5</td>
<td>0.1</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>0.1</td>
<td>0.5</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td></td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.3</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c1</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>1.0</td>
<td></td>
<td>1.0</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**High weighting factor:**
Positive effects on each other

**Low weighting factor:**
Compatible, no or small positive influence

- Number of identified possible concepts still too high in most cases
- Reduction to a manageable number for further treatment

→ Identification of most promising concepts

→ Integration of weight factors which indicate positive effects among two partial solutions

→ Extended compatibility matrix
MANAGE COMPLEX SYSTEMS

FOLLOW THE FLOW OF INFORMATION!

Ranking of consistent concepts

- Weighting factors can be used to gain a ranking order
- All possible and complete concepts consist of the same number of elements and connections
- High weighting factor indicates positive influence

→ Sum of weighting factors is an indicator for the concept quality
→ Automated identification of promising concepts

Example application

- Cooperation between Product Development and Bauhaus Luftfahrt e.V.
- Aviation industry
- Early concept phase
- Embedded in project “HyLiner-R”
- Search for ESTOL configuration (Extreme Short Takeoff and Landing)
Created morphological matrix

- Four partial functions
- A total number of 24 partial solutions
- Number of theoretical concepts: 1120

Identification of consistent concepts

- Pair wise evaluation of all partial solutions
- Interdisciplinary team
- Unclear combinations are marked ("?"), but not taken into further considerations
Selection of two concepts

- Cluster analysis shows 59 consistent concepts
- Evaluation of the used technologies (expert interviews)
- Deduction of two basic concepts
  - Futuristic
  - Realistic

Future Work

- Application to different research projects
  - Development of mechatronic systems
  - Automotive industry
- Analysis of evaluation methods
  - Criteria for measurement of positive influence
  - Adequate weighting functions (linear, logarithmic, …)
  - Range of weighting factor
- Implementation of tool support
  - Assistance for setting up the (extended) compatibility matrix
  - Automated calculation of the ranking order
  - Comprehensible presentation of (intermediate) results
- Further analysis of the graphical representation
Conclusions

- During the conceptual design phase, a large number of alternative concepts has to be reduced to a manageable number.
- The well introduced classic compatibility matrix can be adopted to support this task even in case of large morphological matrices.
- In the presented approach a compatibility DSM ("Consistency DSM") is used to identify consistent concepts.
- This matrix is a “inverted/negative image” of the classic matrix.
- Graphical analysis in form of strength based graphs are possible.
- The extended compatibility matrix with weighting factors allows for the calculation of a ranking order of consistent concepts.
- First experiences with a small morphological matrix are very promising.
- Scenario technique and identification of working structures are also possible fields of application.