SUPPORT OF THE DESIGN AND OPTIMIZATION OF COMPLEX PRODUCTS

U. Lindemann, M. Maurer

Technische Universität München
Department of Mechanical Engineering
e-mail: udo.lindemann@pe.mw.tum.de

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Abstract: *This paper addresses the weak capability of human beings to tackle complex matters without specific help. We will present a tool that allows designers – and others too – to recognize critical dependencies and their structure.*

1. Complexity

Different definitions of complexity are available in literature. In our understanding the complexity of a system is depending on:

- the kind and the variety of its elements, their number and the inhomogeneity of their distribution,
- the kind and the variety of its dependencies between the elements and the system environment, their number and the in-homogeneity their distribution,
- the number of different conditions and the dynamic behaviour of the system.

Why does complexity cause problems? A number of scientists have analysed the capabilities of human beings to tackle complexity. For example Dörner [1] did a large number of experiments concerning this topic. His findings include the following faulty actions:

- missing preceding analysis,
- missing consideration of distant as well as side effect,
- missing consideration of the kind of process behaviour,
- lack of insight concerning conflict of aims
- lack of reflection,
- missing consideration of implicit problems.

Similar results can be found in the reports of Reason [2] and Rasmussen [3]. The key problems may be characterized by attention (because of information overload), perception (concerned to interpretation of available information), memory (not being available in a reasonable way within the given situation) and logical reasoning (failing because of complexity). Frankenberger and Badke-Schaub [4] have shown that experience is misleading decisions in about 40% of all situations in product development. Because of all these findings we have tried to tackle this problem since a number of years. Based on systems engineering methods Steinmeier [5] tried to model a passenger car with its parts as well as all important system properties and the dependencies. The plan was to add the processes of development to this model too. The complexity of this model could not be handled at all. The number of dependencies grew up to more than 150000, the windscreen was linked to more than 70 other objects.

A new approach started with the research of Ambrosy [6], Aßmann [7] and Pulm [8]. They started to build an integrated product model including requirements, functions, parts as well as processes. Including the question of individualized products new methods were required.

As former trials of automation of design and development processes had only limited success we started to think about adapted possibilities to support designers handling complexity.

One specific and important kind of complexity is the structural complexity. Questions arising concerning this sub-topic are the modularisation of products, the management and the impact of technical changes, the identification of weak areas, the awareness of the type of structure etc.

Conventional methods and tools used for product and process modeling are only partly suitable for the interaction with objects like complex products or processes, as additional element and inter-dependency types, as well as uncertain and fuzzy information, cause increased complexity [9].

We will focus on the topic of structural complexity and the demand of supporting designers to handle this kind of complexity. A software tool for the modeling, structuring, and analysis of complex product spectrum structures, by means of graph theory and visualization in matrix and graph depiction will be presented and discussed in conjunction with its application. We will describe in the following useful methods, their implementation in the software tool, and realized functionalities. Two case studies will facilitate the understanding of practical applications.

2. Software tool to support handling structural complexity

Fundamentally, different methods for the consideration of product structures are available [10, 11, 12]. A commonly applied approach is the use of matrices systematized in the Design Structure Matrix (DSM) [13]. Another possibility is given by structure representation in graphs [14], which at present is mainly used for static implementations. All representations display only a specific part of information contained in the fundamental mathematical network description. In addition, handling and adaptation of comprehensive structure networks is rather difficult in commonly used applications.

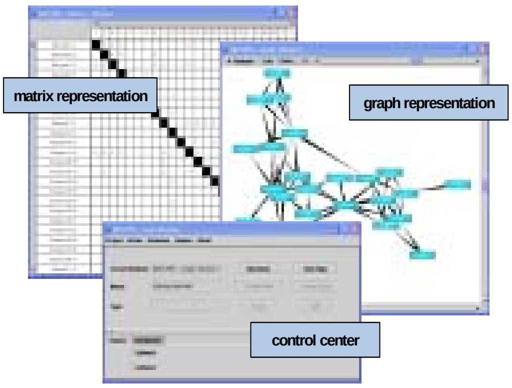

Fig.1. *Main modules of the software tool MOFLEPS*

We have developed a new software tool called MOFLEPS (modeling flexible product structures), which is based on parallel representation of product structures in matrix **and** graph form. The user has freedom of choice of a representation model for interaction with the network structure. The three main modules of the tool are displayed in figure 1, containing exemplary content. The matrix module is oriented at established applications of the DSM and operates with adjacency matrices. In these matrices, the elements are symmetrically applied to both axes, and dependencies between elements are described in the resulting matrix fields. The graph module contains a strength-based directed graph. Generally, elements push off each other, and existing dependencies between them realize their mutual contraction. This depiction possesses the great advantage of automated network arrangement, which permits users to intuitively tear conclusions. For example, strongly interconnected network elements are arranged centrally located in the graph, whereas elements possessing only few dependencies are pushed to the borders. The control center (figure 2) is the fundamental control module of the software tool. All data operations and general settings are enabled by it. Furthermore, users can choose the application of global algorithms and filters in this control module.

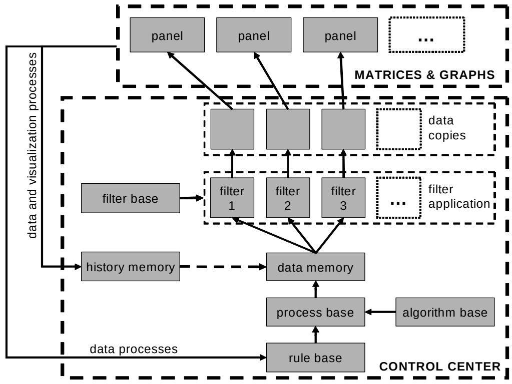

Fig.2. *Schematic design of the software tool*

Numerous functionalities have been implemented for practical software tool application. The suitability for product structure analysis is shown in a case study in chapter 5. First, the realized possibilities of structure interaction are presented in order to provide a better overview. Each function is applied to one of the main modules. The matrix as well as the graph module allows the operation of arbitrary quantities of entities.

2.1. Functionalities of the matrix description

Matrix depiction is an established method for common product structure planning [12, 13]. Therefore, the matrix panel of MOFLEPS is widely oriented at known conventions, and implements the theory of DSM with user oriented ergonomics. In contrast to common matrix tools, the presented matrix is characterized by easy drag-and-drop functionality. Elements (nodes) can be relocated on the vertical or horizontal axis by means of mouse movements. The corresponding line or column is simultaneously displaced on the second axis. Possibilities of structure adaptation (adding and deleting of nodes and edges) can be executed by context menu options. Filter functions can be found in these menus as well. Figure 3 shows the sequential sorting of a product structure by means of the triangularization filter.

Based on the unsorted product structure as much edges as possible are aligned at one side of the

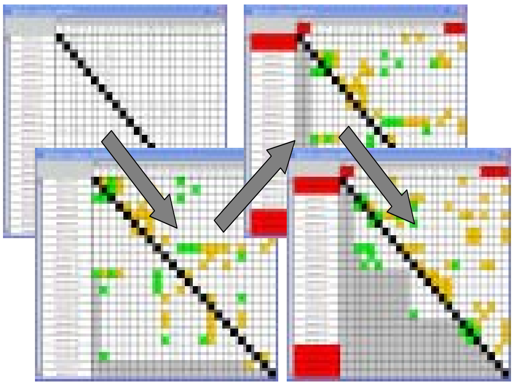

Fig.3. *Functionality of triangularization filter in matrix representation*

matrix diagonal. Now, elements that form feedback loops are located at the opposite side (in this case lower side) of the diagonal. If feedback loops are to be avoided in the considered product structure (e.g. because of self-energizing effects), the decisive elements become accessible.

2.2. Functionalities of the graph description

Graph depiction is already using applied methods of structure analysis for visualizing product structures [14]. Especially the easy information perception in comprehensive network structures is a decisive advantage. However, graph visualizations used so far are limited to static views and element arrangements do not possess any significance. The visualization used in MOFLEPS is a strength-based graph [15] with automated arrangement of nodes by mutual pushing and contracting due to linking edges. An exemplary visualization of a network structure is shown in figure 4.

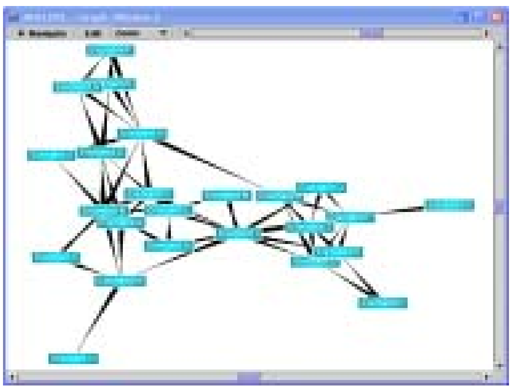

Fig. 4. *Automatic strength based graph representation*

The advantage of identifying relevant structure attributes can be easily seen. Highly interrelated nodes, which represent core elements of the structure, are centrally located, whereas slightly integrated nodes are automatically pushed to the network border. The arrangement of nodes in this depiction can only be unambiguous in (rather simple) use cases. In all other cases one possible balanced positioning is reached due to pushing and pulling strength. The depiction is continuously adapting to actual constraints. Thus, structure adaptations result immediately in new positioning.

The functionality of constricting concerned network areas to relevant surroundings supports users in structure consideration, especially when interacting with comprehensive product structures. Thus, MOFLEPS provides the possibility to constrict the visualized scope to nodes, which are within reach of a selected node by linking edges in a certain quantity of steps (which can be freely determined by users).

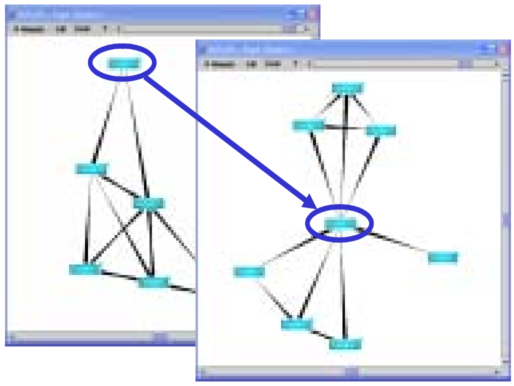

Fig.5. *Limiting the representation to the direct element surrounding*

Figure 5 shows as an example the possibility to navigate in comprehensive product structures. The left screenshot depicts a structure area constricted to the nodes, which are directly interrelated to the selected one (in one step). If the user chooses the highlighted object at the upper border of this area, the visualization in the right screenshot appears immediately. The selected node is centered and directly connected nodes in its surrounding are displayed.

3. Input data

3.1. Generate Input data

First of all the level of abstraction and the object area that is to be analyzed have to be defined. A specialist will be able to define the dependencies to be treated within less than a day, if the number of elements is not higher than about 25. In case of different opinions and knowledge input sources a moderated workshop will supply the required input data. In such a case, intelligent procedures exist to shrink down the quantity of dependencies that must be considered.

Usually spread sheet software is used for documentation and as an input file. However, the

MOFLEPS software provides an easy to handle input support including a documentation possibility.

3.2. Use existing input data

Quite often the required information already exists in different documents. The building structure of a known product may be one example; the organizational structure of a company with its sub-suppliers can be another one.

Before starting to generate required input data, one should look for possibilities to use what is already available.

4. Output Functionalities

4.1. Interaction between visual descriptions

As already mentioned before, matrix as well as graph visualization are applicable each for the depiction of specific, structural content. To provide an information representation as much extensive as possible, MOFLEPS offers the simultaneous visualization of structures in both views. Highlighting of nodes and edges performed in one output panel is transferred simultaneously to all other active panels. Structure adaptations are transferred to all panels in the same way, e.g. adding or deleting of edges or nodes.

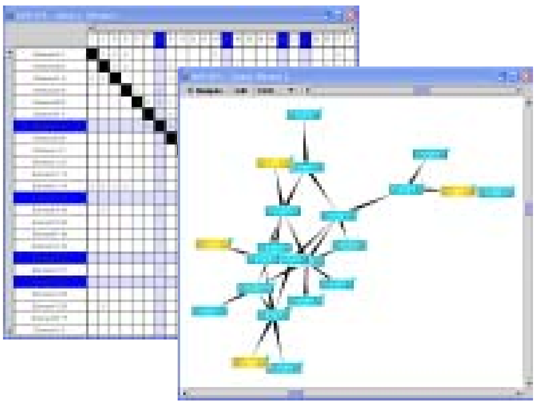

Fig.6. *Parallel node selection in matrix and graph panel*

Figure 6 shows a multi-select of nodes in both visualizations. It is irrelevant in which panel the selection is done, as the same fundamental data is accessed.

Figure 7 shows the visualization of a specific feedback loop, as identified by implemented search algorithms. This case highlights again the benefit of parallel matrix and graph depiction. Users can easier realize the connectivity of nodes in graph visualization. However, the matrix illustration can help, if specific dependencies must be analyzed. Yet, if cluster sub-structures must be identified (in order to build component modules), this would be only possible in a matrix panel.

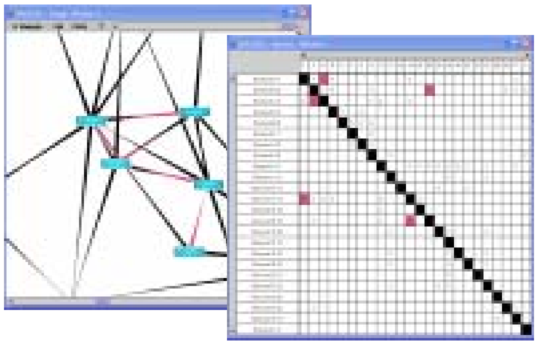

Fig.7. *Parallel depiction of a feedback loop in graph and matrix panels*

An important issue is the possibility to simulate any modification of the structure and check the impact on the system complexity. The results are requests to the engineering designers to try following the suggested modification of the system.

4.2. Evaluation support

In the control center module, users can select algorithms and filters, which are implemented (according to figure 2) in the algorithm and filter base. Algorithms are applied to the fundamental structure network data, and cause impact to all instances of output panels. Filters can (according to the description in the chapter above) be applied to specific panels operating with local data copies. Global filter application is rendered possible by selection in the control center module. Table 1 shows a collection of algorithms and filters available in MOFLEPS for general structure interaction.

Table 1**.** *Applicable functionalities for selection in the control center module*

Algorithms	**Filters**
Determination of…	Identification of…
Blocks	Clusters
Feedback loops	Hierarchies (matrix)
Distance matrices	Busses
Colorability	Triangularization
(Strongly) Connected components	Bridges
Hierarchies (graphs)	Start-/ End nodes
Spanning trees	Multi criteria alignment
Central embedding	Sub graphs

Implemented algorithms base on known approaches of graph theory [16] concerning the handling of structures consisting of nodes and edges. Especial algorithms for the determination of feedback loops and hierarchies have been specially adapted for the required demand in the presented approach. A case specific analysis can be processed by means of implemented algorithms, and must be followed by an interpretation of structural content.

The application of general algorithms to product structures often provides extensive data amount, and requires effective selection of relevant information. An example is the determination of feedback loops, which can be intricate in comprehensive structures. The identified feedback loops are sequentially listed in the control center module, where users can extract relevant ones for closer consideration. Only selected feedback loops are visualized in output panels. The element selection from the previously generated result lists avoids the visualization of unmanageable complex information. Executed structure analyses show that already small product structures consisting of few elements possess numerous and even superposed substructures, e.g. feedback loops. If these would be visualized in graph or matrix panels without a preliminary selection step, it would be rather impossible for users to extract significant information.

Filters available in MOFLEPS are partly descended from the methodology which is used for DSM analysis. For example, clusters, hierarchies, and busses [17, 18] can be arranged in a matrix panel by optimized column and line alignment, in order to permit users to (visually) identify structure attributes. These filters are specially designed for matrix depiction and do not cause changes to graph panels, as the alignment of elements in matrices does not possess any corresponding information in graphs. The same holds true for filtering a triangularization [19], which identifies temporal or process oriented arrangements of elements. This information content can only be represented in matrix panels.

Start and end nodes, as well as bridges, are elements defined in graph theory [16]. A start node possesses only outgoing edges (dependencies) and is not influenced by other elements. End nodes describe the exact opposite. Bridges provide a connection between two sub graphs of a product structure, and are of major importance for closer consideration. The filter of central embedding is a specialty in application of strength-based graphs visualization. Due to automated arrangement of nodes (by mutual rejection as well as contraction by linking edges), the structural embedding of specific elements can be intuitively concluded by visual graph perception. Central elements, e.g. a skeletal structure of a machine, or an electrical control module, are centrally located in the graph structure due to their numerous linking to other components. Elements with few linking in the product (e.g. start and end nodes) are pushed to the borders.

5. Case study I

As a case study [21], the software tool MOFLEPS has been applied to the development of a combustion engine. The objective of a processed structure interaction was the better pre-estimation of possible impact resulting from adaptations on specific product parts. At the outset of the analysis, experts were well informed about technical correlations concerning their own field of responsibility, whereas far reaching dependencies remained mostly unconsidered. E.g., the impact from adaptations on mechanical engine parts to nearby components was known, but not the consequences in electronic controllers and their sub-systems. Furthermore, knowledge about change dependencies (impact on elements due to other element's adaptation) was only available implicitly. Because of this situation it was almost impossible to determine elements become critical for adaptation of the engine. Furthermore, probable consequences resulting from such measures were indefinable. In the following, a matrix containing the main components and their interdependencies was set up, supported by expert's knowledge.

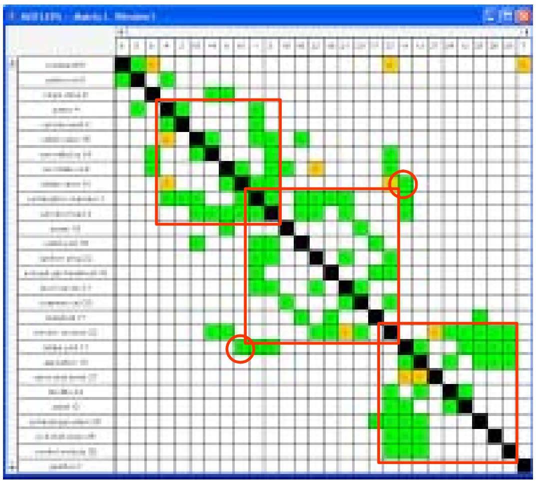

Fig.8. *Clustered matrix of a combustion engine*

Figure 8 shows the product structure in matrix depiction after the identification of the main clusters by search algorithms. The bridge elements 1 (combustion chamber) and 3 (cylinder head) are evident, connecting the first and the second cluster, as well as element 23 (electric module), which connects the second and third one (overlapping of clusters in figure 8). These bridges between the main modules were well known by the designers. However, further single dependencies (edges) could be identified, which are also acting as bridges and became only explicitly visible due to the application of the tool. Of major interest is the fact that only one single dependency realizes the linking between the first and the third cluster (bilateral linking between intake valve and intake port, encircled in figure 8). Possible impact between elements of both clusters must imperatively pass by this linking. This perception predestines this bridging structure element for closer design considerations. Depending on focused content (e.g. thermodynamics or stability), specific practical measures can be taken.

By the use of graph visualization, the core elements of the combustion engine can be intuitively identified. These are the electric (control) module, the combustion chamber, the cylinder head, the intake port, and the aspiration. It is remarkable that the combustion chamber possesses almost exactly the same dependencies as the cylinder head. A probable consequence is that adaptations to one of both elements have to fulfill the constraints of both, as interrelated components are identical. Further relevant information can be obtained from specific

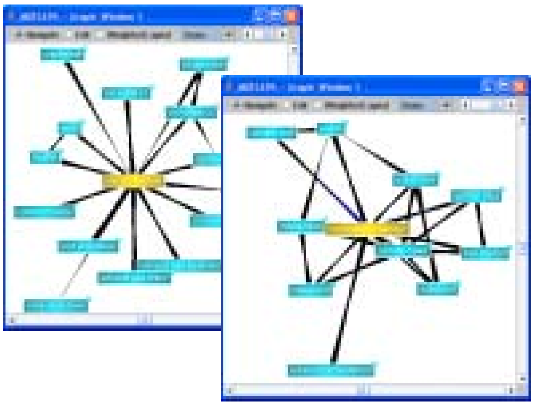

Fig.9. *Specific element embedding in the structure of a combustion engine*

element embedding visualized in the graph. This can be seen in the screenshots of figure 9. The interconnectivity in the surrounding of the electronic module is mostly star-shaped. It can be interpreted as a robust structure regarding possible product adaptations, because of impact bundling in one single element without feedback loops in its direct surrounding. In contrast to that, the surrounding of the combustion chamber (shown in the right screenshot of figure 9) is extremely interrelated by cross-linking edges. Thus, it can be expected that product adaptations to one element in the surrounding will lead to large impact and numerous unintended side-effects when adapting one single element. Probable measures to derive from this analysis could be to consider the combustion chamber and its directly related components as integrated module or black box and acquire its explicit interfaces to surrounding product components.

6. Case study II

This case study [22] will show a new possibility of using existing data as input as well as the handling of complex data sets using MOFLEPS.

The basic methodological approach of network portfolio analysis is the comparison of product portfolios of various competitors. The hypothesis is that the product portfolio of companies develops evolutionary. If a new product is successful on the market, it will remain within the portfolio. If it is not, it will be removed. By comparing the portfolios of a high variety of competing companies successful products can be identified, because they turn up more frequently than poor performing ones. Products, that often can be found at portfolios of direct competitors, might fit into the own product portfolio more likely from a technical and an economical view. One objective of the method is to identify these opportunities and add them to the own portfolio. Another objective of the method is identifying exotic products, which do not fit into the portfolio very well, and analysing whether these products are economically necessary or whether they can be dropped.

To find out, how often a certain product appears in different portfolios, one has to analyse the relationships between products and companies. If a company offers a product, it has a relationship with this product. If another company offers this product too, both companies have a relationship with each other via this product. Products have a relationship with each other if they are offered by the same company. This basic methodological approach is illustrated in figure 10.

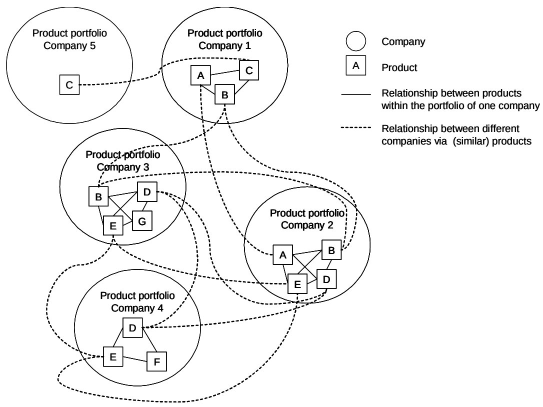

Fig.10. *Basic approach of network portfolio analysis*

Products, which already are offered by the own company, can serve as initial points of investigation (e.g. products A, B and C of company A in figure 10). Subsequently, all companies shall be identified that offer these products too (e.g. company 2 and 3 offer product B too). Now products are regarded which are offered by these other companies but not by the own one so far. On this way products are included into the investigation, which do not have a direct relationship to the original company (e.g. products D and E, which are offered by company 2). Again, other related companies shall be identified (e.g. company 4, which offers product D as well). If a variety of products and companies is regarded, a real network of products and companies can be revealed.

Analysis of portfolios and visualisation of the resulting network

Especially indirect relationships between objects can not be identified easily within the Design Structure Matrix. The more companies and products are regarded the more difficult it is to comprehend the entire network and the complexity of its manifold relationships. E.g., while the relationship between product 1 and 2 can be made out easily in the DSM in figure 11 (same column), the indirect relationship between product 1 and 3 is not obvious. This relationship can be recognised more easily in the illustration of the network in figure 11 on the right. Here, the same information is visualised as it is in the DSM on the left. Elements, that are products and companies, are represented by rectangles and ellipses (so called "nodes"). Relationships – the "x" in the matrix – are represented by arrows (so called "edges").

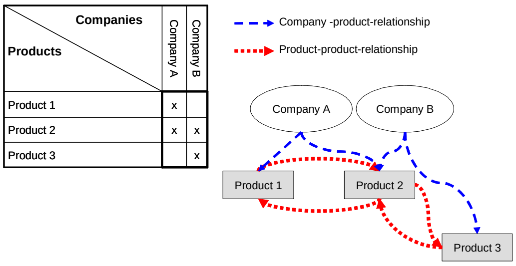

Fig.11. *Visualization of relationships within a Design Structure Matrix*

Strength based graphs now can be utilised for illustrating the semantic network between the portfolios of different companies. If a certain range of products is offered by several companies, these products get a higher weight and attract each other in the graph. This way product combinations can be identified easily which turn up in the portfolios again and again. They are clustered within the visualisation of the network. As well, rarely appearing product-product-combinations can be identified. These products are rather exotic and located at the fringe. From a strategic view the products, that are clustered together, should be added to the own portfolio. More exotic products might be dropped or should be developed strategically. Furthermore, companies with very similar portfolios have to be regarded as direct competitors.

The presented method was exemplarily applied at a company, which produces home and commercial electrical equipment. The objectives of the project were finding new opportunities for product diversification as well as identifying product lines which do not fit well into the existing portfolio. The product portfolio of the regarded company has grown historically and contained several completely different product lines. A company-product-matrix was established as described above. After only two iterations 112 other companies and over 220 products were added to the matrix.

In figure 12 the relationships between products and companies are illustrated as a graph view. Easily, all products within the portfolio (blue coloured) and the competing companies in each case can be identified. As well, two clusters can be distinguished which represent two different product lines. The first cluster on the left is established by products of the regarded company which seem to fit together especially well. The cluster on the right is made up of only one product which shows various relationships to competing companies. Possible strategic implications from that visualisation might be to drop the isolated product on the right or to add other, appropriate products, thus extending the product line strategically.

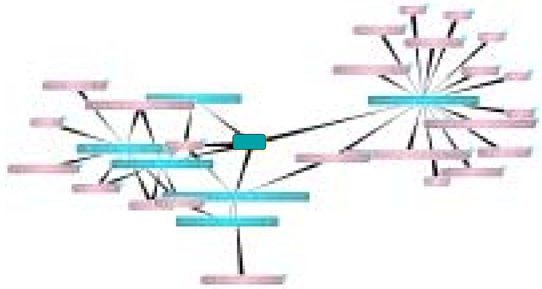

Fig.12. *Product-company-network (first level)*

If the products of the direct competing companies, and again related companies on the next level, are faded in as well, an extensive competition map can be spread. This network is illustrated in figure 13. Here, clusters of products and companies can be recognized even more clearly and in a broader view. Strongly related products are located in the centre while products of competing companies, which are only loosely or not related to own products, are located at the fringe. As well competition cluster of companies which have similar product portfolios can be identified. This visualisation of the competitors and their products helps companies to watch their competition environment. That way new competitors as well as shifts in the product portfolios of competing companies can be made out easily.

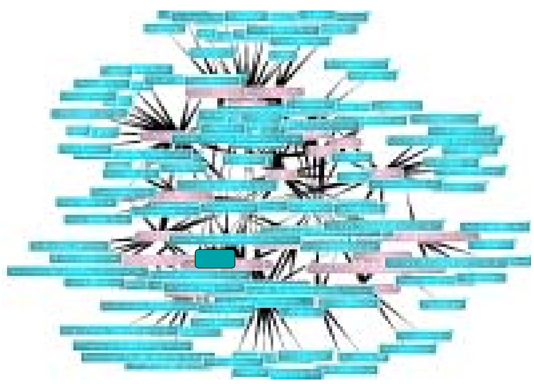

Fig.13. *Product-company-network (competition map on a deeper level)*

To find new opportunities for diversification of the existing portfolio, the product-product-relationships between the products have to be regarded. In figure 14 the relationships between an initial product – a high pressure cleaner – and other related products are shown exemplarily. Again clusters of strongly related products can be made out. E.g., vacuum cleaners, electrical heaters and electrical tools were identified as closely related products. These products might serve as promising starting points for a strategic diversification of the own portfolio. The development and market risk might be reduced because of the close relationship to already produced products.

By applying the method of network portfolio analysis in the presented project, new ideas for diversifying the existing product portfolio were found. As well, other strategic decisions were supported, e.g. to plunge certain products within the existing portfolio.

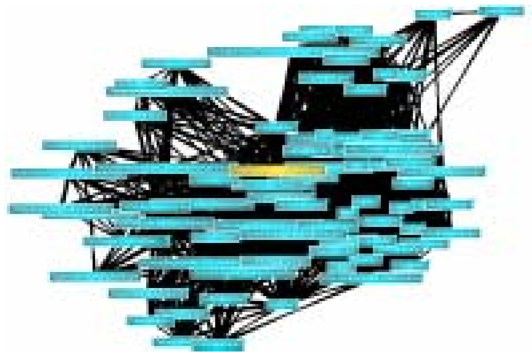

Fig.14. *Product-product-network*

Especially, the systematic analysis of competitors and their products, the intuitive visualisation of the complex relationships, and the consistency of the results were decisive. This led to a high acceptance of the method itself and the results at the project partner.

7. Conclusions

The modeling, visualizing, and analyzing of the structure of complex systems are important preconditions for controlling structural complexity.
The software tool MOFLEPS has proved to be an appropriate support when interacting with these complex systems, especially in the fields of analysis and adaptation. The applicable algorithms of the graph theory are helpful instruments for the identification of characteristics in complex networks, as well as for the comprehensive arrangement of structures. The implemented visualization both through graph and matrix depictions offers clearly extended possibilities of interaction, in contrast to product modeling tools considered in terms of invariant structures. Due to the two parts of the representation, which complement each other, very complex constellations can be imparted. The underlying design of the software tool allows simultaneous structure interactions and offers easy functional enhancement, especially concerning algorithms and filters. These can be implemented progressively in future work. The case studies of modeling a combustion engine as well as the analysis of the product market network highlighted the applicability of the tool and offered product designers possibilities to identify correlations unknown so far. This information permitted to acquire useful measures for further product design and optimization.

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