

A TOOL FOR MODELLING FLEXIBLE PRODUCT STRUCTURES - MOFLEPS

Maik Maurer, Nils-Olaf Boesch, Guo Sheng, Boian Tzonev

Keywords: Product structure, product spectrum, product configuration, matrix illustration

1 Introduction

Manufacturers can obtain new possibilities regarding product strategy and customer orientation, if they focus on extensive product spectra instead of a single, distinct product. In contrast to models of invariant products, a product spectrum comprehends forecasted degrees of freedom, possibilities of implementation and descriptions of the solution space. Thus, the product spectrum specifies the potential from product view and implies further element and interdependency types; in contrast to common product models. The systematic creation, adaptation, and optimization of product spectra can result in competitive advantages, since new products can be realized shortly in high quality by means of existing knowledge. Conventional methods and tools used for product modeling are only partly suitable for the interaction with product spectra, because additional element and interdependency types, as well as uncertain and fuzzy information, cause increased complexity [1]. Herein, we present 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.

2 Basic design of the software tool

Fundamentally, different methods for the consideration of product structures are available [2, 3, 4]. A commonly applied approach is the use of matrices systematized in the Design Structure Matrix (DSM) [5]. Another possibility is given by structure representation in graphs [6], 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.

We present a new software tool called MOFLEPS (modeling flexible product structures), which bases 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 is the fundamental control module of the software tool. All data operations and providing general settings are enabled by it. Furthermore, users can choose the application of global algorithms and filters in this control module.

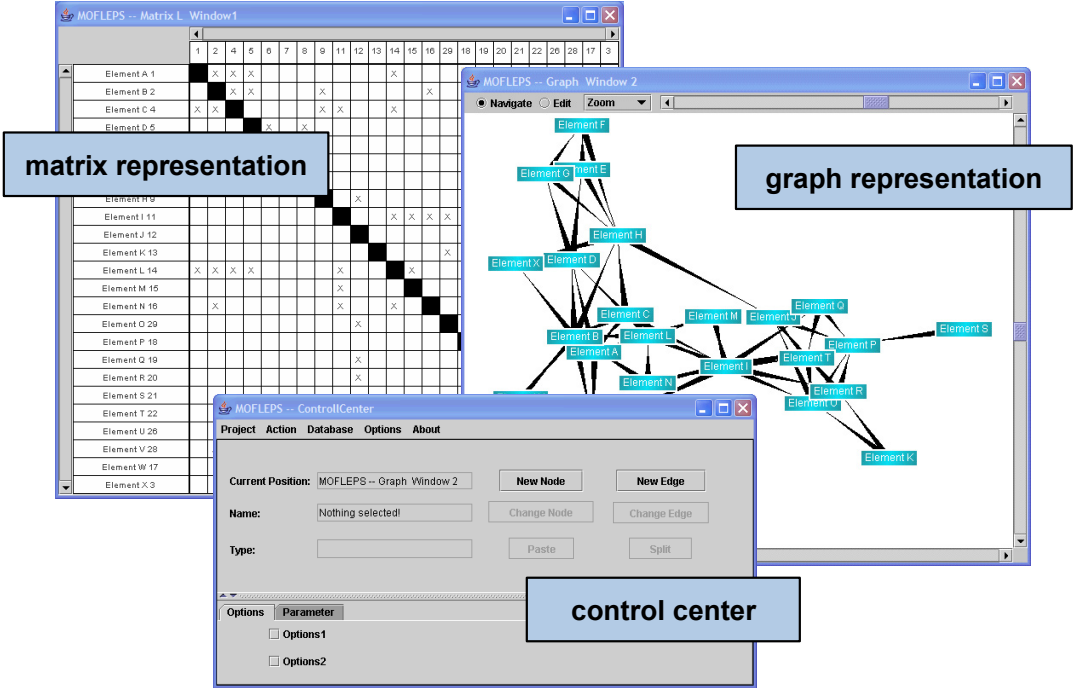


Figure 1. Main modules of the software tool MoflePS

The general design of the software tool with its main components is schematically displayed in figure 2. The rule base is an essential part, as it determines the valid application of operations to the actually concerned network structure. In particular, the rule base serves for validation of combined algorithms. The algorithm base consists of a collection of implemented algorithms and is also realized as an independent software module. Thus, it becomes possible to integrate further algorithms at any time without large efforts or adaptations in other modules. The process base integrates input from the rule base as well as available methods from the algorithm base, and generates valid operations, which are subsequently applied to the data memory. In this data memory, the fundamental structure data of the network is saved. If this data is processed, filters can be applied independently to them. The implemented filters are located (similar to algorithms) in an own module in order to permit simple enhancement. In general, algorithms differ from filters as they adapt data; filters only select relevant structure information. The results of filter applications are copies of original data sets, which are visualized independently in different output panels. Matrix and graph visualization are available for such panels without limits in applied panel quantity. If users process adaptations in one specific output panel, resulting information is transferred to the history memory as well as to the rule base. The history memory provides undo-functionality, in case users want to cancel processed adaptations. If adaptations reach the rule base, the validity is determined by use of available rules. In case of positive rating, a new operation with global impact to the structure network is generated in the process base. After passing the applied filters again, ultimately adapted data is displayed in all active panels. This tool design guarantees consistent information independent from the actual process status or panel interactions.

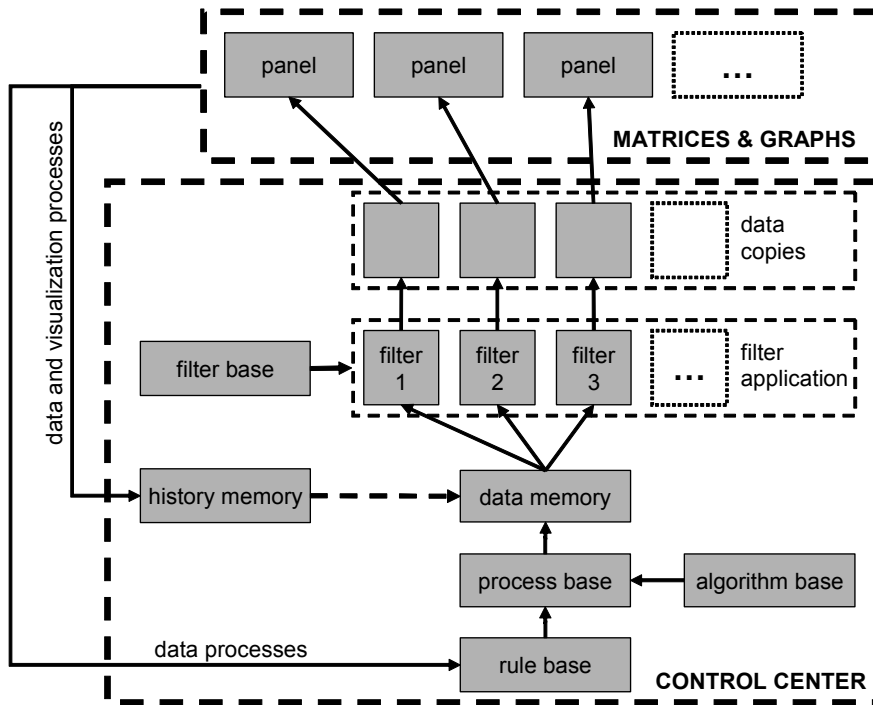


Figure 2. Schematic design of the software tool

In general, adaptations can also be processed in one local output panel without impact to global network data. This can be useful, e.g. for considerations on specific test scenarios. In this case, adaptations are not transferred to the rule base, and impact on further panels will not occur. However, adaptations get lost in case of panel shut down.

3 Available functionalities of the software tool

Numerous functionalities have been implemented for practical software tool application. The suitability for product structure analysis is shown in the case study in chapter 4. First, the realized possibilities of structure interaction are presented in order to provide a better overview. Each functionality is applied to one of the main modules. The matrix as well as the graph module allows the operation of arbitrary quantities of entities.

3.1 Functionalities of the Control Center

The control center provides general file operations, for instance load, save, and import functions. As these functions are commonly known and do not constitute special characteristics of the presented tool, they will not be considered further. 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 available for selection in the control center module

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

Implemented algorithms base on known approaches of graph theory [7] 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, which an requires effective selection of relevant information. Such a process is exemplarily shown in figure 3; the screenshot at the right side displays the result of algorithmic search for feedback loops (cycles) in a product structure. 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 second screenshot in figure 3 (left side) displays the result of a spanning tree search. As explained before, first search results are listed in the control center and identified elements can be selected for subsequent visualization. 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 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 [8, 9] 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 [10], which identifies temporal or process oriented arrangements of elements. This information content can only be represented in matrix panels.

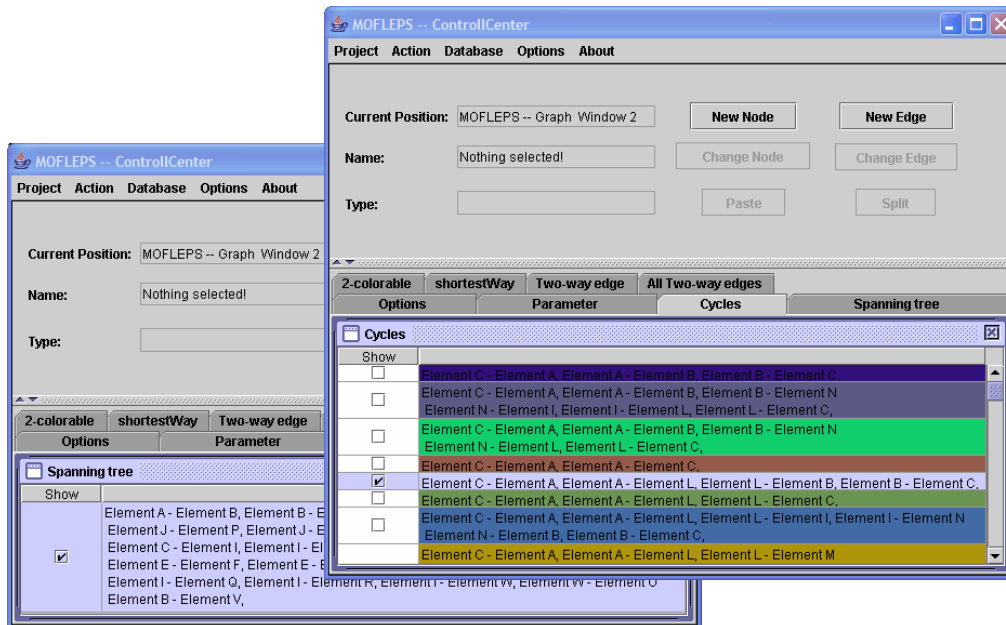


Figure 3. Filtered lists of feedback loops and spanning trees in the control center module

Start and end nodes, as well as bridges, are elements defined in graph theory [7]. 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.

3.2 Functionalities of the matrix description

Matrix depiction is an established method for common product structure planning [4, 5]. 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 4 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 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.

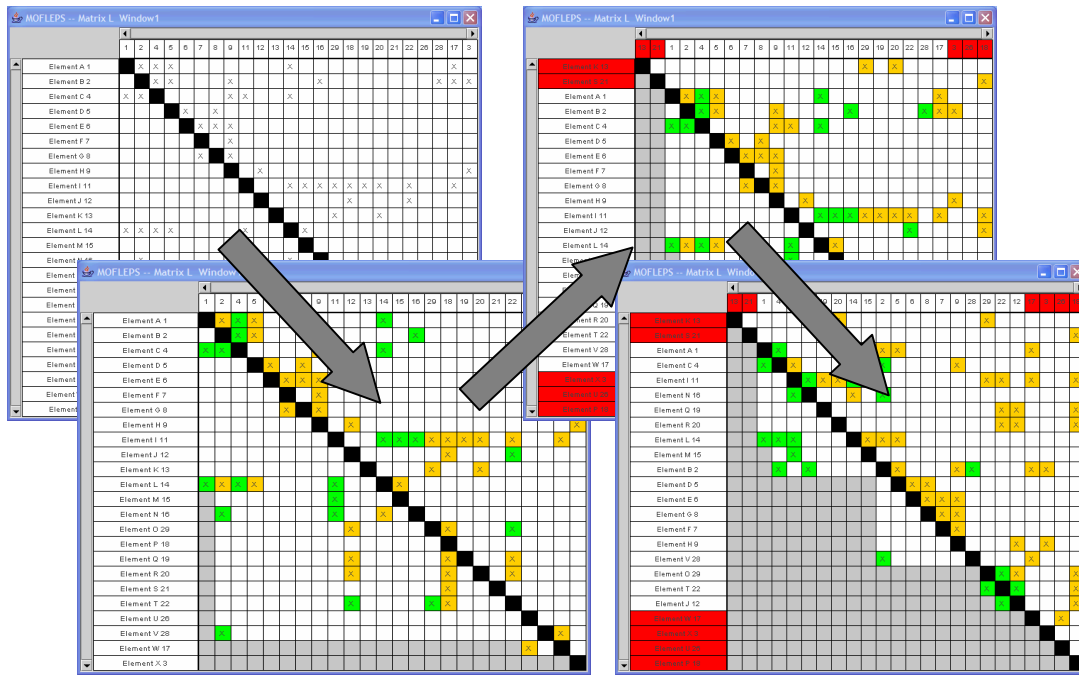


Figure 4. Functionality of triangularization filter in matrix representation

3.3 Functionalities of the graph description

Already applied methods of structure analysis use graph depiction for visualizing product structures [6]. Especially the easy information perception in comprehensive network structures is a decisive advantage. However, the 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 [11] 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 5.

In this picture 6, 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).

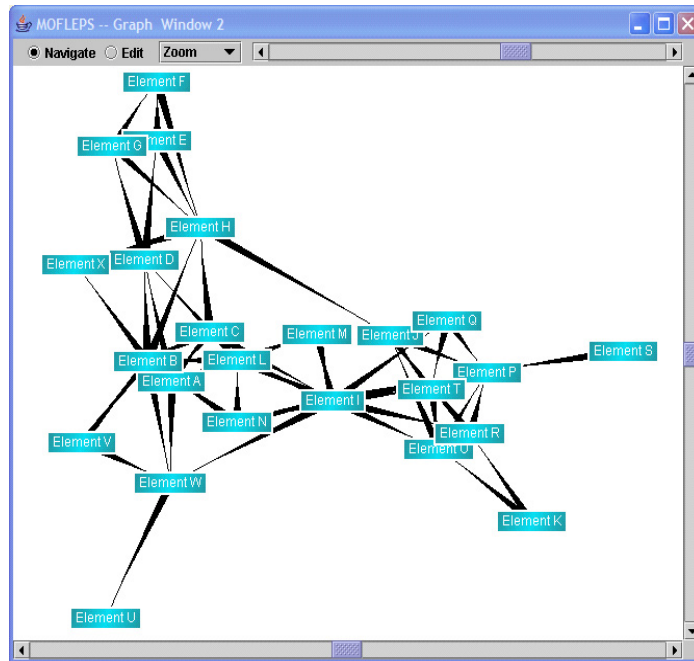


Figure 5. Automatic strength based graph representation

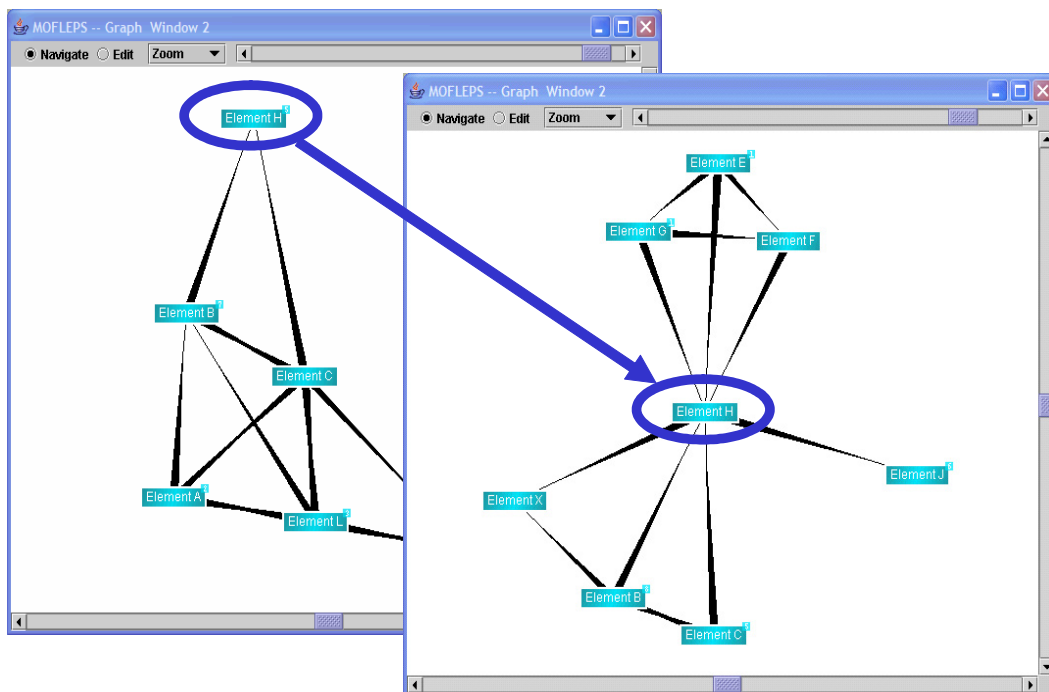


Figure 6. Limiting the representation to the direct element surrounding

Figure 6 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.

3.4 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.

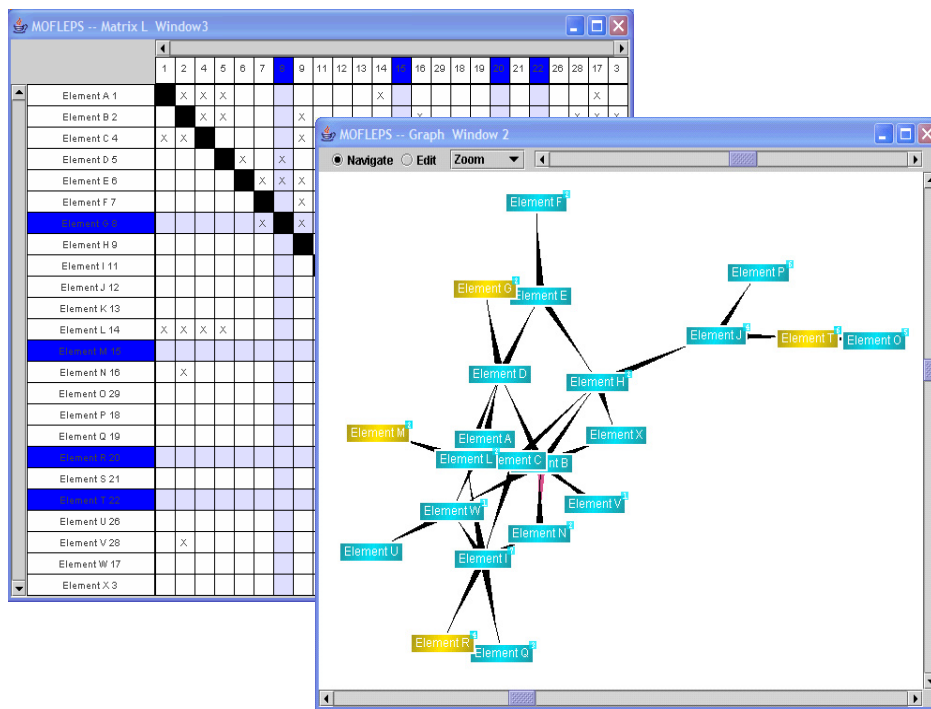


Figure 7. Parallel node selection in matrix and graph panel

Figure 7 shows 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 8 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.

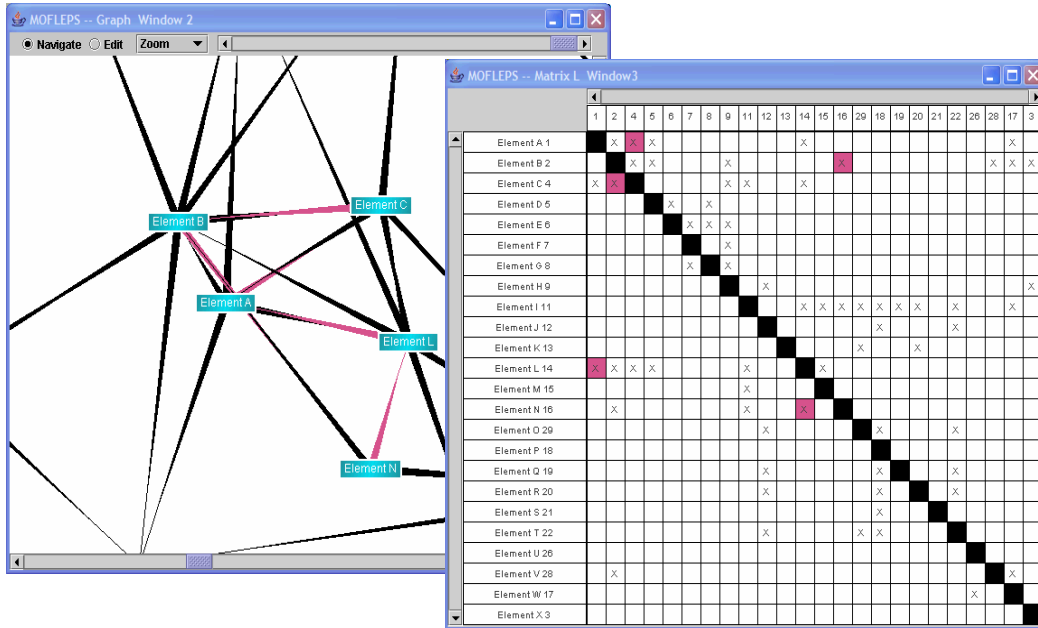


Figure 8. Parallel depiction of a feedback loop in graph and matrix panels

4 Case study

As a case study, 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. Figure 9 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. 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 9). 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.

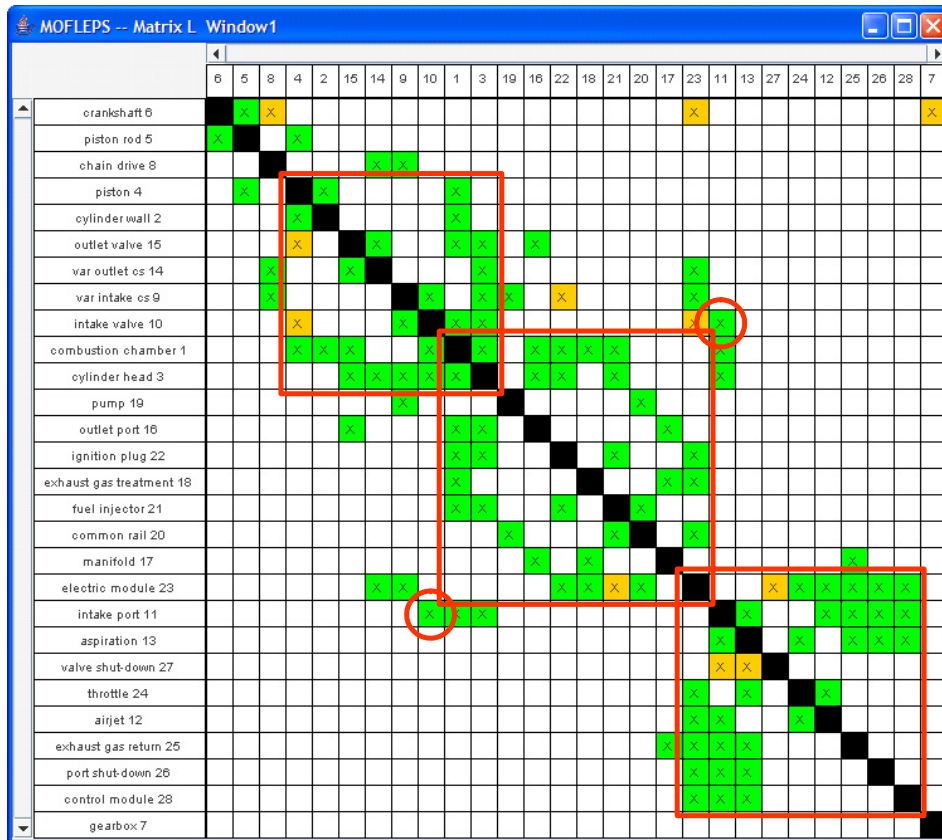


Figure 9. Clustered matrix of a combustion engine

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 element embedding visualized in the graph. This can be seen in the screenshots of figure 10. 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 10) 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.

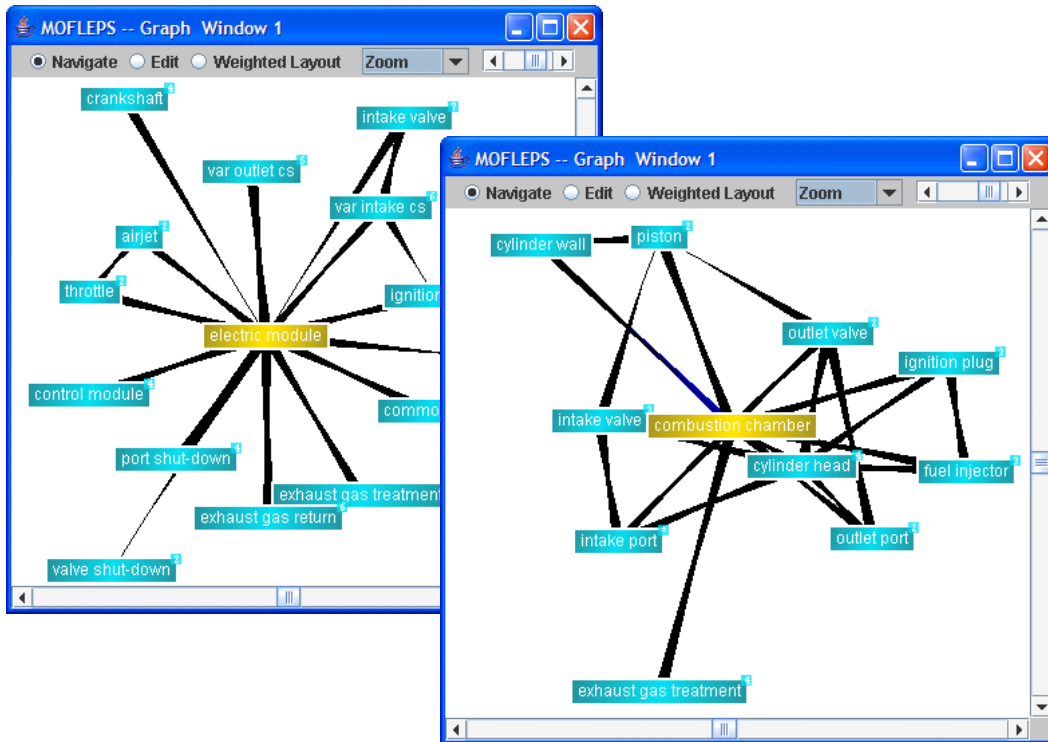


Figure 10. Specific element embedding in the structure of a combustion engine

5 Conclusions

The modeling of product spectra differs from those of conventional products in terms of a higher complexity of interdependencies. Furthermore, product spectra are designed on a more abstract level and contain undetermined quantities of possible variant specifications. Mathematical basics for the structure analysis are available, but have so far only been adopted for some special cases in modeling applications.

The software tool MOFLEPS has proved to be an appropriate support when interacting with product spectra, 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. A case study of modeling a combustion engine 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.

6 Acknowledgments

We would like to thank the DFG (Deutsche Forschungsgemeinschaft) for funding this project as part of the SFB 582, as well as our partners from the industry for good collaboration and extensive support.

References

- [1] Ericsson A.;Erixon G.: Controlling Design Variants – Modular Product Platforms. ASME Press: New York 1999.
- [2] Lindemann, U.; Pulm, U.: Enhanced Product Structuring and Evaluation of Product Properties for Mass Customization. In: HKUST; TUM (Eds.): MCP'01, World Congress on Mass Customization and Personalization, Hong Kong (China), 2001.
- [3] Stermann, J. D.: Business Dynamics - Systems Thinking and Modelling of a Complex World. New York: McGraw-Hill 2000.
- [4] Ulrich, K. T.; Eppinger, S. D.: Product Design and Development, Second ed., New York: McGraw-Hill 2000.
- [5] Steward, D. V: The Design Structure System: A Method for Managing the Design of Complex Systems. IEEE Transactions on Engineering Management, vol. 28, pp71-74, 1981.
- [6] Maurer, M.; Pulm, U.; Lindemann, U., “Utilization of Graph Constellations for the Development of Customizable Product Spectra”, Proceedings of the 4th International ICSC Symposium on Engineering of Intelligent Systems, Madeira, Portugal, February 2004, CD.
- [7] Gibbons, A.: Algorithmic Graph Theory. Cambridge: Cambridge University Press 1999
- [8] Kaufmann, L.; Rousseeuw, P.: Finding Groups in Data – An Introduction to Cluster Analysis. New York: Wiley-Interscience 1990.
- [9] Kusiak, A.: Engineering Design – Products, Processes and Systems. San Diego: Academic Press 1999.
- [10] Browning, T. R.: Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. IEEE Transactions on Engineering Management, Vol. 48, No. 3, August 2001.
- [11] Shapiro, A.: URL. <http://www.touchgraph.com>, Last access: 2005-02-28.

Maik Maurer
Institute of Product Development
Technische Universitaet Muenchen
Boltzmannstr. 15
D-85748 Garching
Germany
Tel: +49 (0)89 289 15155
Fax: +49 (0)89 289 15144
E-mail: maurer@pe.mw.tum.de