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STRUCTURAL COMPLEXITY MANAGEMENT USING DOMAIN-SPANNING STRUCTURAL CRITERIA

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1. Introduction

Manufacturing technical products implies complex design processes as well as complex product architectures. While there are many facets to evaluate such processes and architectures, one perspective is to characterize products and their design processes by their underlying structures. In order to handle and manage such structures, various methods e.g. from systems engineering can be used. With the introduction of the *Design Structure Matrix* (DSM)-Methodology in the 80ies, more and more scientists developed algorithms and discovered structural criteria.

However, comparing and evaluating the criteria of a complex structure makes it necessary to interpret underlying patterns, different structural criteria and then evaluate their impacts. To do so, structural complexity management provides different analysis criteria for comparing and assessing the system's underlying structures. Concerning the DSM-Methodology, there are many structural criteria, which help in describing patterns included in single domains. However, there is no systematically approach in order to interpret structural criteria with entities related to more than one domain.

This paper closes this gap by interpreting domain-spanning structural criteria and complements the existing possibilities to evaluate system's underlying structures, i.e. the particular interaction of a system's elements and their interdependencies.

The paper is structured as follows: After defining relevant terms in section 2, a short review of the current research in structural complexity management is presented in section 3. Section 4 presents an approach for using structural meanings considering "components" and "employee". Therefore, the structure of a race car and its design processes is analysed. Finally, the paper proposes an outlook how structural meanings should be used.

2. Definitions

2.1 System

A system is created by entities (elements) and their interdependencies (relationships) forming a system's structure. Such a structure possesses individual properties, which contribute to fulfil the system's purpose [Boardman 2005]. Systems are delimitated by a system border and connected to their surroundings by inputs and outputs. Changes of system's parts can be characterized by dynamical effects, which lead to a specific system's behaviour. However, in this paper variations over time are not considered.

2.2 Domain

Domains represent the classification of elements, which create the system. Examples of domains are "components" or "documents".

2.3 Relationship type

The relationship type describes the meaning of a dependency. Different relationship types can even exist between the same elements and between the same domains [Maurer 2007]. Examples of relationship types are "change impact" or "waiting for".

2.4 Structure

"Structure" is understood as the network formed by dependencies (edges) between a system's entities (nodes). It furthermore relates to the semantics of this network; the structure of a system therefore always contributes – in its constellation – to the purpose of the system. Structures and their subsets can be analyzed by means of computational approaches, primarily provided by the graph theory and related sciences [Maurer 2007].

2.5 Structural criteria

A structural criterion is understood as a particular constellation of nodes and edges, i.e. it is formed by a particular pattern considering nodes and edges [Maurer 2007]. The criterion gains its meaning by the way the pattern is related to the actual system it is part of, i.e. it must serve a special purpose in the context of the overall system [Boardman 2006]. A structural criterion only possesses significance in the context of the system it is describing.

2.6 Structural meaning

Structural meanings relate structural criteria to their respective effects impacting the modelled system. The effects are, amongst other factors, dependent on the modelled domain, the relationship type describing the dependencies between the corresponding entities (see figure 1).

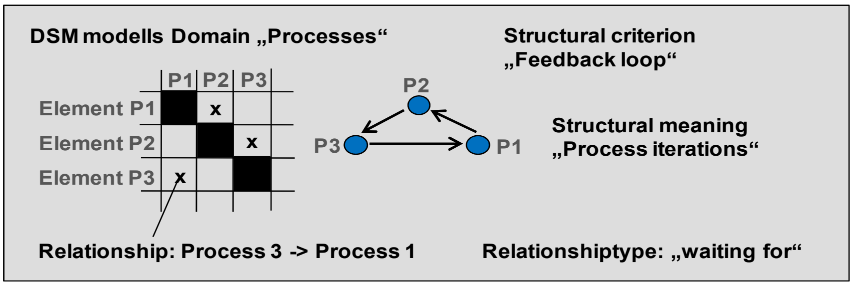

Figure 1. Definition of structural meanings

3. Structural complexity management

To manage a structure efficiently, different methodologies prevail: Most commonly, matrix based methodologies such as the *Design Structure Matrix* (DSM), *Domain Mapping Matrix* (DMM), and *Multiple Domain Matrices* (MDM) are commonly applied, and the underlying theory provides for ample means of analysis. Furthermore, network theory is available, describing how the structure of random systems in nature, which have evolved over time, can be described. Ultimately, graph theory provides for a formal, mathematically founded framework grasping complex interdependencies.

Network and graph theory are closely interconnected. Hence, it is not easy to separate them. Whereas network theory focuses on the global features of any network, graph theory addresses structural features that originate from the interaction of single nodes and edges of a network structure. Graph theory is often traced back to Euler's works (e.g. [Gross 2005]), while network theory can be dated back to the research of Erdös (1959).

Research on matrix based complexity management has come a long way. Originating from a process focus with the first published formulation of a DSM [Steward 1981], a whole community has developed around this research. The DSM is able to model and analyze dependencies of one single type within one single domain. Browning (2001) classifies four types of DSMs to model different

types of problems: component-, team, activity-, and parameter-based DSMs. However, many other classifications exist (e.g. in Maurer (2007)) nowadays.
There are numerous algorithms to analyze the overall structure of the relationships within a DSM; starting from the original algorithms for tearing, banding and partitioning [Kusiak 1999], [Steward 1965] to a still non-exhaustive list provided by Maurer (2007).
The authors of Danilovic (2007) have extended DSM to DMM, i.e. Domain Mapping Matrices. The goal was to enable matrix methodology to include not just one domain at a time but to allow for the mapping between two domains, as previously postulated e.g. by Yassine (2003). Maurer (2007) has taken this approach further to model whole systems consisting of multiple domains, each having multiple elements, connected by various relationship types. He refers to this approach as Multiple Domain Matrix (MDM). He provides a number of ways to analyze the system's structure across multiple domains, condensing each single analysis into one DSM that represents multiple domains at a time. That way, he is able to apply algorithms for DSM analysis meaningfully across several domains, i.e. across a whole system. As especially the last DSM conferences have shown, matrix-based approaches integrating multiple views "domains" become more and more accepted to manage several perspectives onto a system, especially when it comes to large structures (e.g. >1000 elements per DSM).

3.1 Classification of structural criteria

Almost all of the approaches of structural complexity management look into what criteria qualities can be found in a structure, from the level of a global structure down to the integration of individual nodes. Structural criteria relates to the pattern of nodes and edges. Figure 2 orders the structural criteria, as provided by Maurer (2007), by the evaluation of the number of edges and nodes that form a structure. In fact, most of the criteria can be traced back to a few basic elements [Kortler 2009, Kreimeyer 2010] (e.g. a hierarchy is a special kind of path taking attainability into account).

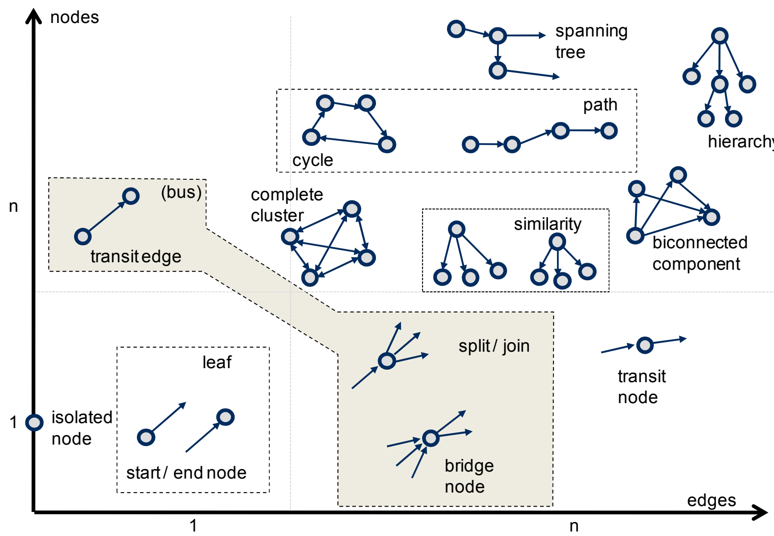

Figure 2. Basic structural criteria [Kortler 2009, Kreimeyer 2010]

Structural criteria make use of phenomena, which are described in graph theory. Table 1 illustrates the available basic phenomena in graph theory, based on Gross (2005). Although there is no complete one-on-one relationship between phenomena and structural criteria, the table regroups what phenomenon a structural criterion focuses on [Kortler 2009, Kreimeyer 2010]. For each, the table shows whether the mathematical phenomenon has an application in engineering design or not. As can be seen, most of the phenomena are used for engineering application already. On the one hand, future work can be concentrated on forming further structural criteria using known phenomena. On the other hand, known structural criteria can be ordered to structural meanings (interpretation of structural criteria) according to the domains of the modelled elements.

Table 1. Phenomena in graph theory ordered to their application in structural criteria

Graph theory	Structural criteria available
Cliques, Subgraph	Strongly Connected Components (√)
Walks	Cycles (√) Paths (√) Distance (√)
Trees	Leafs (√) Roots (√) Spanning Trees (√) Knots(√)
Adjacency and Degree	Neighbourhood (√) Bridges(√) Degree (Activity…) (√) Independence (×) Connectivity (Attainability,…) (√)
Genus	Planarity (√) Thickness (√)
Weighted graphs and networks	Weighted Nodes (√) Weighted Edges (√) Minimum Spanning Tree(√) Shortest Path (√)
Colouring	Chromatic Number (√×) K-Colouring (×) Colour-Classes (×)
Multipartite Graphs	Disjunctive sets (×) N-Partite Graphs (√)
Eigen values	Eigen spectra (×)

3.2 Interpretation of structural criteria describing the domain "components"

In [Maurer 2007], several structural criteria are identified and interpreted considering propagation changes between the elements regarding the modelled domain "components". Therefore, Maurer (2007) divided structural criteria depicted in figure 2 into 2 groups: Structural criteria describing the meaning of nodes and edges and structural criteria describing the meaning of subsets. For each of these groups Maurer (2007) discovered the structural criteria's meanings considering the development of a race car. The author presented how structural meanings ease structural complexity management by suggesting several interpretations of structural criteria. According to a subset of components forming a cluster[1], a structural meaning may point out the subset's suitability for declaring a module.

4. Interpreting structural criteria describing design processes

Based on that, Maurer (2007) allows for interpreting structural criteria considering components. Applying these analysis criteria in particularly allow for identifying effects caused by changes in one or more of the considered components. However, manufacturing technical products and their design processes typically include further domains which may cause changes in components.

4.1 Interpreting domain-spanning structural criteria

Today, there are more and more domains impacting the manufacturing of technical products. These domains and the dependencies between their elements form the context, which impacts the meaning of structural criteria. Whereas interpreting the meaning of structural criteria describing patterns of elements, which belong to the same domain, is useful. The evaluation of structural criteria describing elements of strictly connected domains may be reasonable. In particular structural criteria describing

[1] Subset contains a large number of internal interdependencies compared to external ones.

patterns of elements connecting domains with high impacts at each other should be investigated in order to capture chains of effects on the whole.

For this purpose, the authors examined several development processes within the scope of a collaborative research centre at the Technische Universität München (SFB 768). This research centre consisting of 14 subprojects engages problems, which emerge during the innovation process. The authors' subprojects address the modelling and analysing of discipline-spanning structural criteria and their impacts on product development processes. To do so, the authors analysed the development processes of a race car and validated their findings examining further development processes in the scope of the SFB768.

4.2 Structural meanings of patterns including "components" and "employee"

Considering design processes, there are several strictly connected domains. Manufacturing technical products always include components forming the product and employee responsible for the design processes creating these components. Hence, this paper proposes structural criteria describing patterns including these 2 domains. A DSM_C modelling the dependencies between components as well as a DMM_{E-C} modelling the connections between components and responsible employee are used to derive a DSM_E describing the connections between employees. Two employees are connected if they are responsible for the same component. Structural meanings describing structural criteria modelled in DSM_C, DMM_{E-C} and DSM_E are depicted in table 2 and table 3. The structural criteria are separated in 2 groups: Structural criteria describing nodes (table 2) and structural criteria describing subsets (table 3). The naming of these structural criteria is based on structural criteria proposed by Maurer (2007), but sometimes adapted if useful. If necessary, there is a distinction between structural criteria describing nodes belonging to domain "employee" or to the domain "components" (depicted in table 2).

Table 2. Structural meaning of nodes (domains: component and employee)

Structural criterion	Explanation	Structural meaning
Interrelation Sum (employee)	Quantity of connected components	Employee with high interrelation sum provide numerous impacts to components
Interrelation Sum (component)	Quantity of connected employee	Components with high interrelation sum lead to numerous indirect dependencies between employee
Intrarelation Sum (component)	Quantity of connected components	Component A with a high intrarelation sum receives numerous impacts from further components. Changes in one or more connected components may lead to changes in component A
Intrarelation Sum (employee)	Quantity of indirect connected employee via components	Employees with a high intrarelation sum need sufficient time for communication in order to arrange the terms of working with their common components
Inter/Intra Measure (employee)	Division of interrelation sum by intrarelation sum	The lower the inter/intra measure is, the more independent is an employee from other employee
Inter/Intra Measure (component)	Division of interrelation sum by intrarelation sum	No special meaning
Inter Articulation Node (employee)	Only employee responsible for components	This employee is responsible for all of the components manufactured in the respective company
Inter Articulation Node (component)	Only component manufactured in the respective company	Companies manufacturing only one component. This component represents the core competence of the company
Inter Attainability (employee)	Employee is not connected to a component	An unconnected employee A (not attainable) is not connected to any component; hence, changes to any component will not impact employee A

Inter Attainability (component)	Component is not connected to a modelled employee	An unconnected component A (not attainable) is not connected to any employee; hence, the unconnected component is not manufactured in the respective company – it may be a bought in component
Domain Bridge Node (employee)	Employee who is not connected to other employee, but connected to multiple components	No special meaning (directed relationship)
Domain Bridge Node (component)	Component which is not connected to other component, but connected to multiple employee	Bridge nodes create indirect dependencies between employees (DSM_E). Hence, indirect connected employee need to arrange the terms of working with their common components
Domain Transit node (component)	Component which is connected to other components and to one employee.	Changing component A may cause changes of further components, because it's native interdependencies
Domain Transit node (employee)	Employee who is connected to other employee and to one component	No special meaning (directed relationship)
Multiple Mapping Node – (component)	Component possessing a multitude of connections to other components and to employees.	Multiple Mapping components creating indirect dependencies between various employee and provide several changes to connected components
Inter Criticality (component)	Multiplication of interrelation sum and intrarelation sum	The inter criticality shows a component's degree of integration to change impacts in the system. A high value refers to possible domain-spanning impacts
Monogamic Node	Component A is an isolated node according to components. Employee A is an isolated node according to employee. Component A and employee A are connected.	The connected nodes represent autonomous subsystems. There is possibility for outsourcing

Table 3. Structural meaning of subsets (domains: component and employee)

Structural criterion	Explanation	Structural meaning
Cluster	Subset contains a large number of internal edges compared to external ones	Components of a cluster are suitable for declaring a module [Maurer 2007], responsible for this module are connected employee of a cluster. In order to support the development process, the employee of a cluster should be placed in one office or in offices standing nearby for assisting communication.
Strongly connected part	All employees and components are mutually connected by a edge path	As described above (cluster)
Domain Distance (employee)	Specifies the minimal number of edges between two employees. Whereas employee A is not connected to any component, employee B is connected to one or more components.	According to problems with interfaces between components, the domain distance value specifies whether an employee is an appropriate employee in order to highlight interface problems or not. The higher the domain distance's value is, the less information about components and their interfaces an employee can provide
Domain Locality (component)	Subset that includes a component A and all connected employees	All employees are connected via component A. Hence, communication between all considered employee need to be assured

Feedback loop (components)	Components with circularly arranged edges	Change impacts affect the originating component via further components in a feedback loop. Change impacts of the originating component are caused by one of the connected employee
Domain Similarity	Two employee are connected to a high quantity of identical components	New employees can be connected to the same components as an experienced employee in order to instruct new employees. Domain similarity can also be helpful for saving employee.
Domain Spanning tree	Subset connecting all employee and all components by a selection of existing edges	The minimum spanning tree indicates a subset where all employees are still responsible for at least one component, but components with more than one responsible employee are reduced. Usable if companies aim for reducing production without firing employee
Bi-connected component	Component where the elimination of one edge does not separate the structural coherence	Components are connected to more than one employee. Bi-connected components represent assumptions for using domain spanning tree and domain similarity

4.3 Using structural meanings

Table 2 and table 3 depict structural criteria and their associated structural meanings regarding components and employee responsible for manufacturing them. In order to identify the proposed substructures and nodes, visualisation tools can be helpful. After visualising the respective system's structure, the proposed meanings can be used to give suggestions as depicted in figure 3. All of the proposed structural criteria can easily be implemented in a supporting system. After implementing these structural criteria the system can automatically remember structural meanings for each subset and each node.

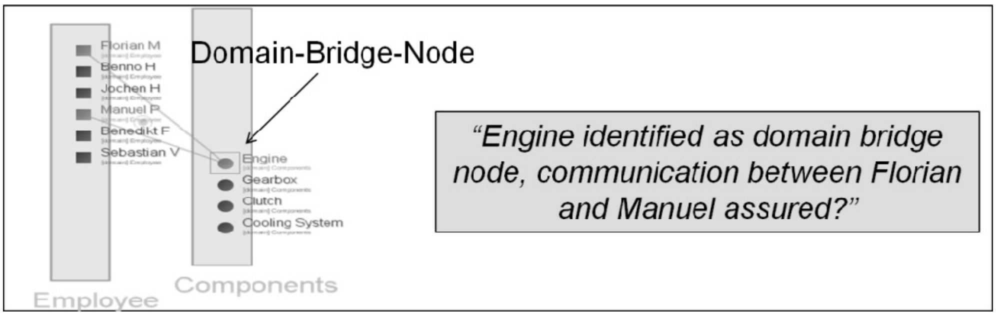

Figure 3. Example of suggestions derived by structural meanings

4.4 Findings and implications

The proposed structural meanings are to be part of a design supporting system. The aim of this system is helping in decision making about design questions considering the modelled system and particularly its underlying structure. Structural meanings considering employee and components can be extended by further domains concerning products and their design processes. Future work can be concentrated on examining further structural meanings considering further important domains. The findings can be sorted in an ordering scheme considering the relevant domains and relationship types impacting the meanings of structural criteria. Using this ordering scheme can be eased by implementing it in a software tool.

5. Conclusion

Structural awareness becomes more important regarding all important domains. Many approaches in structural complexity management observe structural criteria relating to pattern of edges and nodes. This work introduces the term "structural meaning". Structural meanings assign structural criteria in a respective context to a special meaning for the modelled system. Until today, subsets of edges and

nodes are evaluated and interpreted considering only one domain. This paper introduces the evaluation of structural criteria describing elements of strictly connected domains in order to capture chains of effects on the whole. Therefore, the structure of components considering a race car and responsible employee has been analysed. This work identified structural meanings referring to known structural criteria derived from phenomena in graph theory. In order to improve structural complexity management, the proposed structural meanings can be used for design supporting systems.
Future work can be focussed on discovering further structural meanings considering further domains. As dynamical system aspects (e.g. structural or relational changes) are gaining importance, incorporating them may be of particular interest. Moreover, all findings can be used in a software tool remembering the structural meaning.

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