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STRUCTURAL AWARENESS IN COMPLEX PRODUCT DESIGN – THE MULTIPLE-DOMAIN MATRIX

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1 INTRODUCTION

Complexity in product development represents a challenge that can be outlined by the following statements: In spite of well-known approaches on avoiding, reducing, and controlling complexity in product development, a steady increase of complexity can be assumed for the past and predicted for the future. Structures that result from the connectivity of elements represent an important tool for accessing complexity in product development. And if complexity can be controlled, it does not necessarily imply negative aspects but can provide competitive advantages in product development.
Concerning the management of complexity in product development this paper introduces an approach that focuses on the constellations formed by existing linkages in objects. This provides far-reaching possibilities for analysis, control, and optimization of complex products and services in a holistic context, while the amount of data remains manageable. The analysis implies exploring the connectivity of an object in order to identify content, and thus to interpret and better understand the considered object. Controlling complexity means interacting with the elements of an object in order to understand consequences resulting from implemented actions. And optimization implies adapting the connectivity of an object in order to better suit its desired functionalities. The holistic context means to consider all relevant aspects of a complex object. In the following, the objectives and the technical realization of the approach will be presented.

2 OBJECTIVES OF STRUCTURE-BASED COMPLEXITY MANAGEMENT

The presented approach on complexity management is based on the finding that on the one hand each technical product, as well as the processes of its creation, can be accessed by its structure (the term "structure" is understood as the network formed by dependencies between system elements and represents a basic attribute of each system). On the other hand, the structure generation itself emerges without being controlled (passive structure synthesis) and often does not apply to the requirements of the product or process. However, the structure determines the attributes and behavior of products and processes. Some of their characteristics can even be defined in the structural composition only, e.g. the robustness to component changes [1]. Cyclic dependency chains between components can cause self-energizing or self-impeding effects and hierarchical substructures can produce avalanche effects; and the creation of clusters can indicate possibilities of modularization [2]. Known approaches of complexity management focus either on isolated aspects (e.g. optimizing variant numbers from a production view), or address a comprehensive modeling approach implemented at an abstract level of detail. This dilemma between the considerations of extracts and global views that are difficult to manage can be solved by applying a structure-based approach comprising the following objectives:
Determination of relevant domains: It is important to determine all relevant aspects, as improper simplification or the extraction of single aspects can hinder the re-transfer of the outcome to the initial problem. In contrast, all irrelevant aspects must be excluded from considerations.
Selection of relevant system views: Complex systems comprise a multitude of aspects and dependency types that allow for many system views; users must be able to select the relevant ones.
Analysis of dependency structures: Dependency structures must be analyzed concerning the existence of characteristic structural attributes that allow for suggesting the system behavior.
Structure manual: A structure manual points out relevant system elements and structure constellations. This helps estimate the potentials and risks of component changes.
Identification of suitable structural designs: The established structural optimization approaches (e.g. modularization, design for product robustness) must be amended and provided at a generic level for application to user-defined systems.

3 THE MULTIPLE-DOMAIN MATRIX

For the interaction with complex systems, many different visualization techniques and computational approaches exist; however, matrix-based methods have been commonly used in product development. Starting from the modeling of relations within one domain by use of the Design Structure Matrix (DSM), the mapping between different domains by Domain Mapping Matrices (DMMs) has acquired a multitude of development methods. Furthermore, some multi-domain approaches are mentioned in the literature that combine several DSMs or DMMs and allow for more comprehensive system consideration [3] [4]. However, a lack of appropriate analysis methods exists.

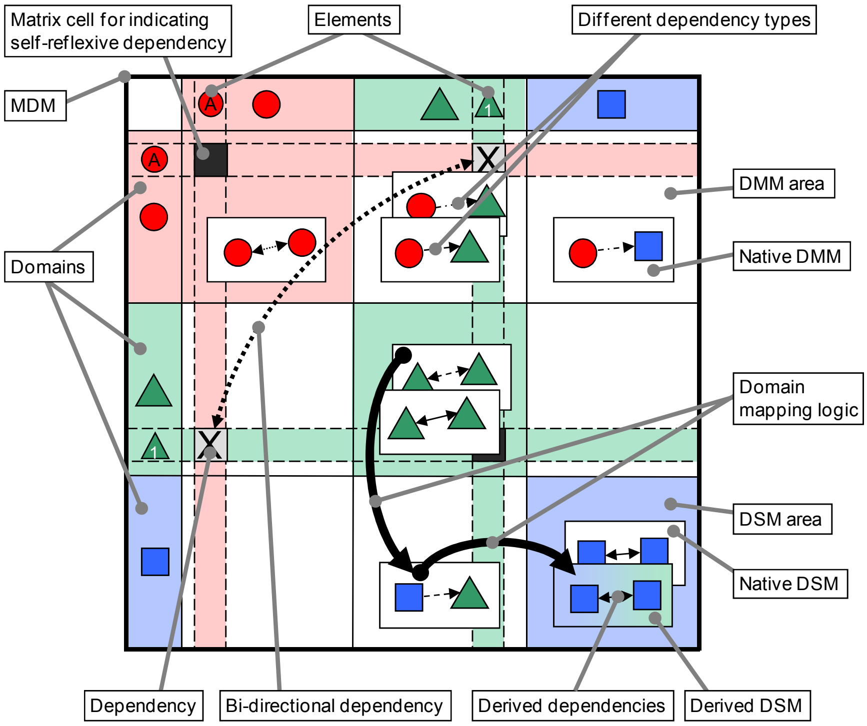

Figure 1. Construction of a Multiple Domain Matrix

In Figure 1, an integrative matrix combination of DSMs and DMMs, which will be denoted as Multiple-Domain Matrix (MDM). The MDM possesses all features of a common DSM; in fact, it represents a DSM on a higher level of abstraction.

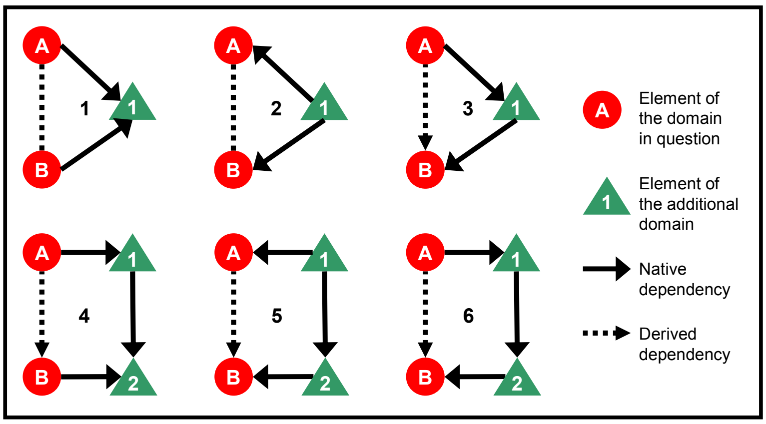

Figure 2. Computational logics for deriving DSMs from other DSMs and DMMs

The MDM allows for the systematic modeling of networks comprising different domains and dependency types. Although MDM models are not restricted to isolated views of single domain and dependency types, DSM-like analysis can still be performed, as subsets of homogeneous content are represented separately in the implied subsets. The MDM is generally not a two-dimensional matrix system, as different matrices can exist for the same DSM or DMM subset. This means that two different dependency types are depicted that exist within the same combination of domains in parallel.

The decisive advantage of a MDM is the possibility for deriving DSMs based on information from other DSMs and DMMs. Six computational logics exist, if dependencies possess a direction (Figure 2). Obtainable insight to complex systems will be shown in the presentation.

4 USING GRAPH THEORY FOR ENHANCED DSM ANALYSIS

Once DSMs have been determined analysis methods can be applied in order to obtain structural characterizations. Most of the available algorithms refer directly to the matrix representation, i.e. structural characteristics are pointed out by realignment of element orders in matrices, e.g. [5]. A common base for the description of all DSM analyses is given by the graph theory. Its consequent application on DSM-conform structures does not only allow for more efficient and improved application of known methods (e.g. triangularization), but also provides a many further analysis methods. A collection of these methods will be shown in the presentation.

5 THE STRUCTURE MANUAL AND SUITABLE STRUCTURAL DESIGN

A structure manual comprises of selected information about the occurrence of basic analysis criteria for further interpretation. Results of methodical analyses are systematically presented and facilitate the planning and tracing of system adaptations as well as their resulting impact. These methodical analyses are the feed-forward-analysis, the impact checklist, mine seeking, the structural ABC-analysis, and the trace-back-analysis. The provision of visualized networks that clarify domain-spanning dependencies and occurring structural characteristics can help developers to better understand a system, especially effects beyond their own scope of responsibility. As well, the structure manual can indicate opportunities and restrictions for product adaptations.

6 CONCLUSIONS

The here presented approach meets both major shortcomings of existing methods in complexity management – the lack of promising and generic instruments for analysis, control and optimization of complex system structures on the one hand, and the applicability on comprehensive and domain-spanning problems on the other. The approach is founded on established matrix-based methods and provides therefore the derived Multiple-Domain Matrix as core of a systematic methodology. Available analysis methods and strategies have been transferred to the integrative fundament of graph theory and systematically complemented. Building on that, practical procedures for the analysis, control, and optimization of complex system structures have been generated.

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[5] Kusiak, A. *Engineering Design – Products, Processes and Systems*, San Diego: Academic Press 1999.

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Structural awareness in complex product design – The Multiple-Domain Matrix

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Overview

- The challenge of complexity in product development
- Requirements on effective complexity management
- The Multiple-Domain Matrix
  - Systematic concept
  - Deduction of system views
- Management of multiple-domain environments

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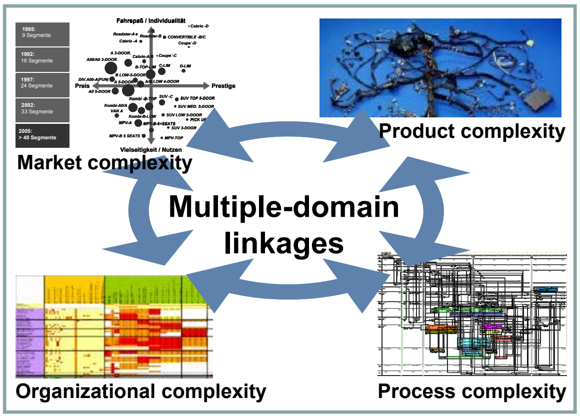
Facts about complexity in product development

- Steady increase of complexity
- All artefacts comprise structures describing the linkages between elements
- Structure generation emerges without being controlled
- The structure determines the attributes and behavior
- Structures often do not apply to the initial requirements

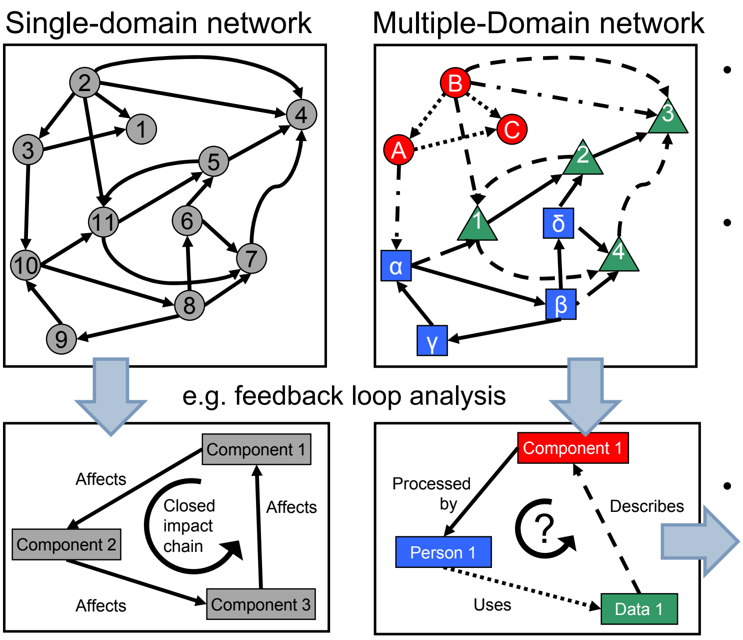


If complexity can be controlled, it does not necessarily imply negative aspects but provides competitive advantages

Objectives of the structure-based complexity management

- Known approaches
  - implement comprehensive modeling on an abstract level of detail
  - or focus on isolated aspects
- Objectives of the structure-based approach
  - **Determination of relevant domains**
    → Which aspects must be considered?
  - **Selection of relevant system views**
    → Which information is required?
  - **Analysis of dependency structures**
    → What can be concluded from constellations?
  - **Structure manual**
    → What to do and expect when interacting in complex systems?
  - **Identification of suitable structural designs**
    → Does the structural design suit for the product's intention?

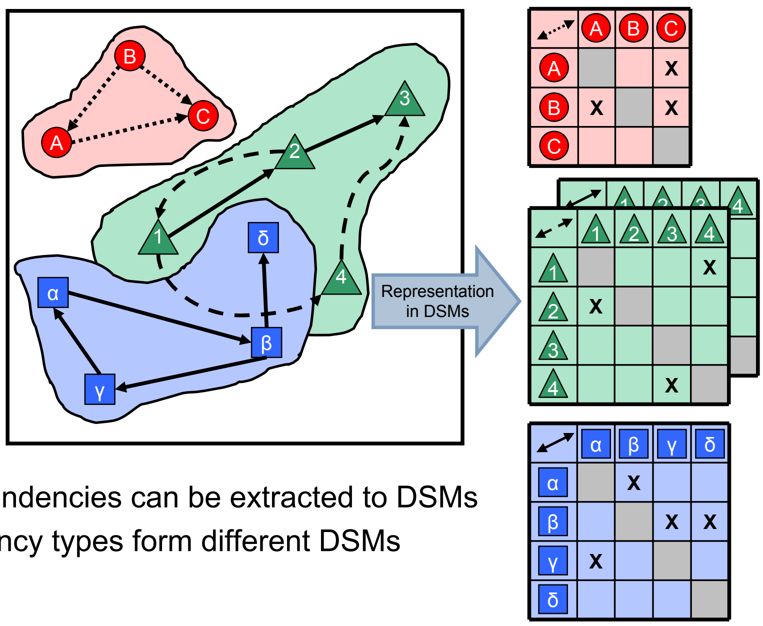
The need for systematic multiple-domain modeling



- Most problems require consideration of multiple domains and dependency types
- People often mix different domains in one network

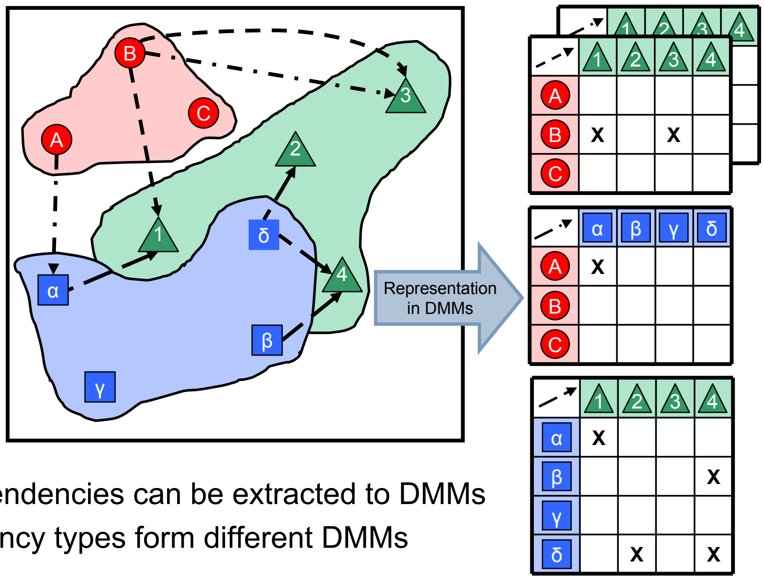
- So far, most analyses can not be applied for multiple-domain networks

Systematic subdividing of multiple-domain networks: DSMs



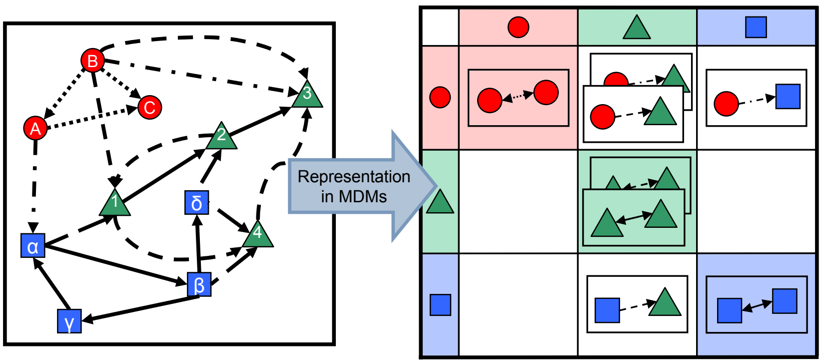
- Intra-domain dependencies can be extracted to DSMs
- Different dependency types form different DSMs

Systematic subdividing of multiple-domain networks: DMMs



- Inter-domain dependencies can be extracted to DMMs
- Different dependency types form different DMMs

Aggregation of the Multiple-Domain Matrix



- A MDM is a DSM on a more abstract level of detail
- A MDM comprises DSMs and DMMs
- Different dependency types can be modeled (3D-matrix)
- DSM and DMM subsets can result from native or computed data
- **The MDM provides the methodical basis for domain-spanning system analysis and optimization**

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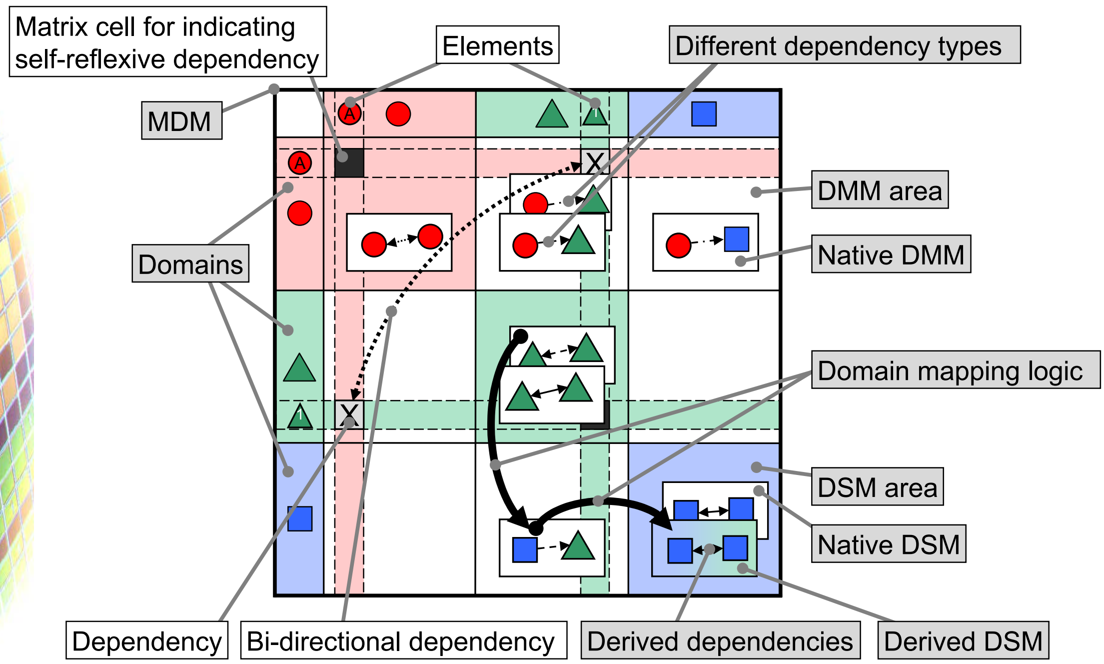
Composition of the Multiple-Domain Matrix



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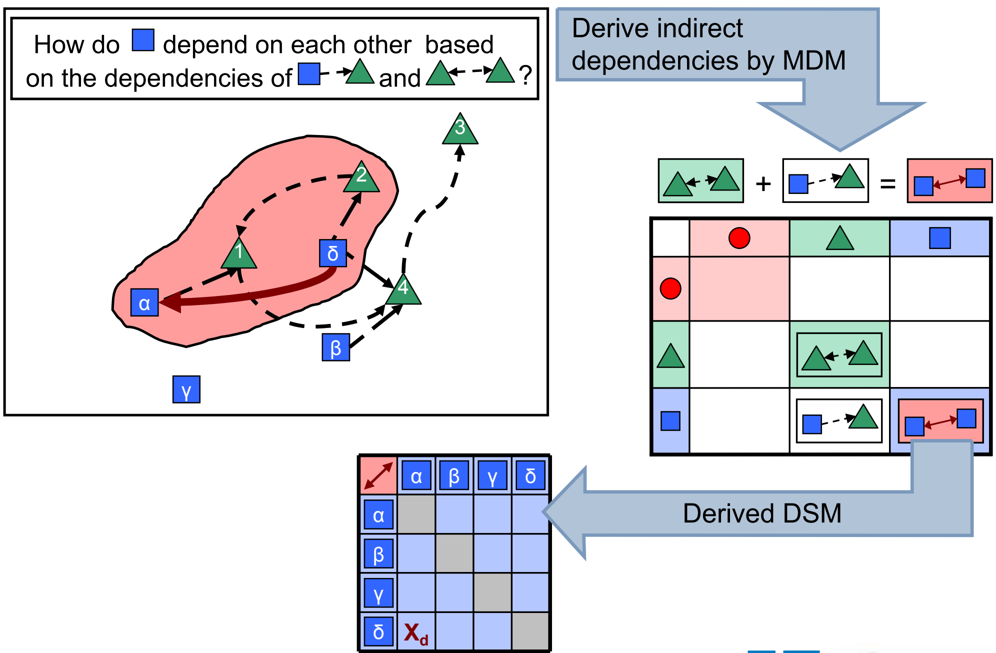
Deduction of DSMs from multiple-domain contexts



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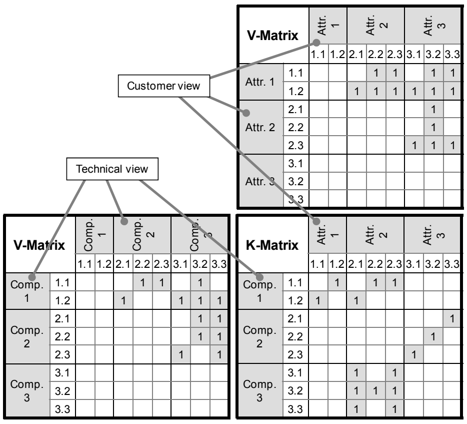
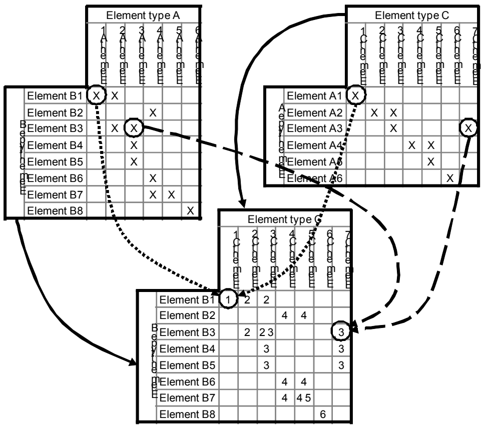
Special use cases of the MDM application

K&V-matrix



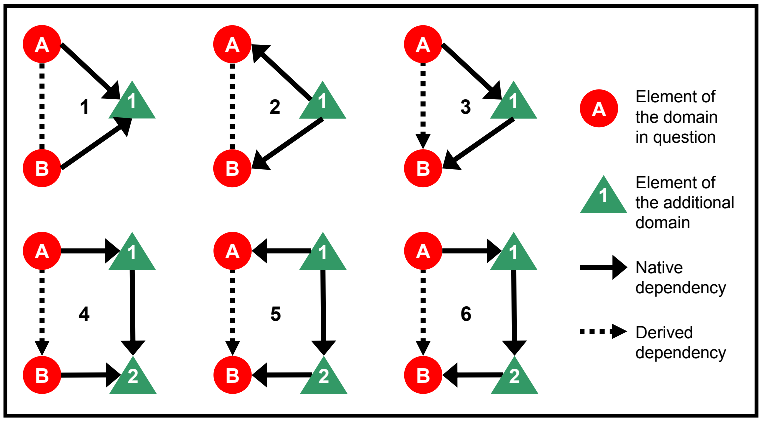
Deduction of a DSM by
1 DSM & 1 DMM
(*Bongulielmi et al. 2001*)

Connectivity maps

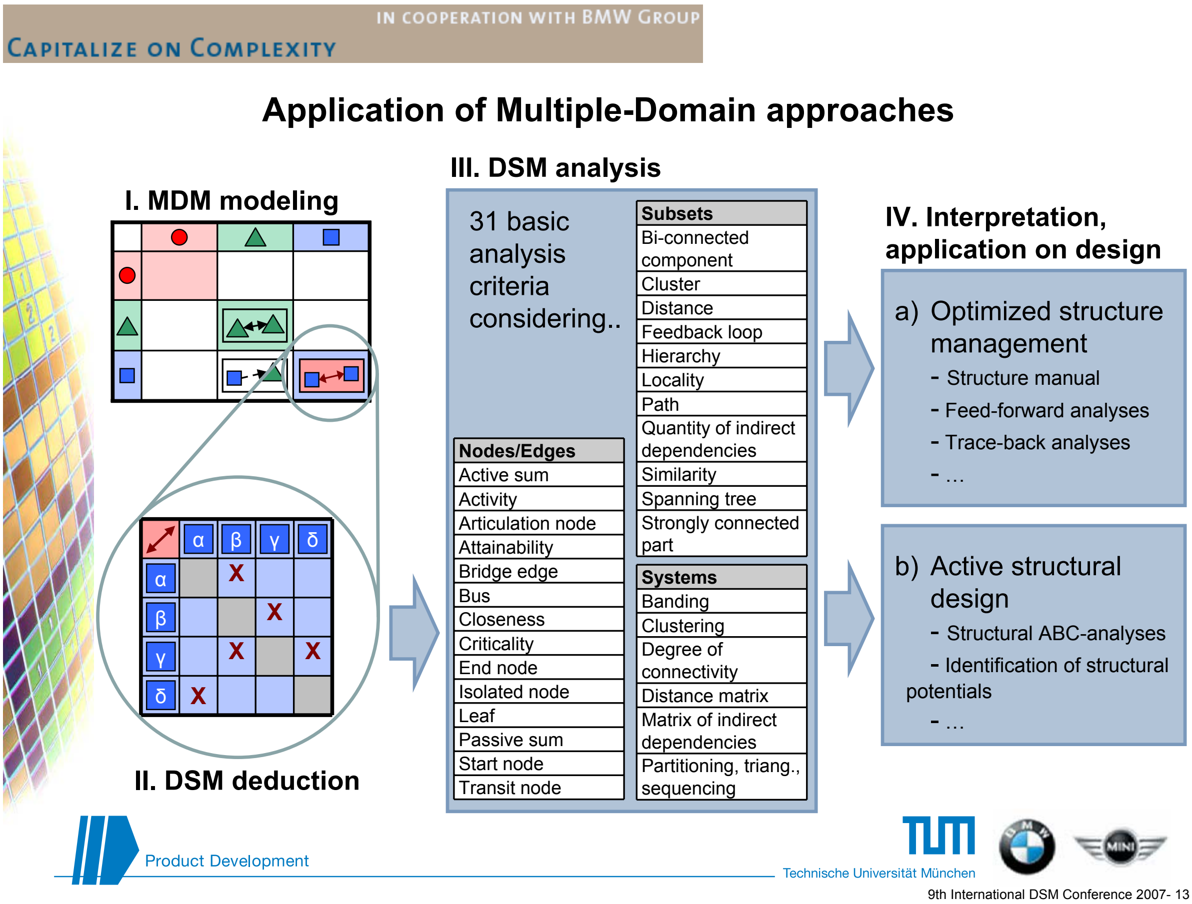


Deduction of a DMM by
2 DMMs
(*Yassine et al. 2003*)

Systematics for deriving DSMs using one auxiliary domain



- Computations based on matrix multiplications
- Non-directed and bi-directional relations would extend the quantity of computational use cases
- Additional domains can be considered by sequential application of the systematics



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Application of Multiple-Domain approaches
I. MDM modeling
II. DSM deduction
α
β
γ
δ
X
III. DSM analysis
31 basic analysis criteria considering..
Nodes/Edges
Active sum
Activity
Articulation node
Attainability
Bridge edge
Bus
Closeness
Criticality
End node
Isolated node
Leaf
Passive sum
Start node
Transit node
Subsets
Bi-connected component
Cluster
Distance
Feedback loop
Hierarchy
Locality
Path
Quantity of indirect dependencies
Similarity
Spanning tree
Strongly connected part
Systems
Banding
Clustering
Degree of connectivity
Distance matrix
Matrix of indirect dependencies
Partitioning, triang., sequencing
IV. Interpretation, application on design
a) Optimized structure management
- Structure manual
- Feed-forward analyses
- Trace-back analyses
- …
b) Active structural design
- Structural ABC-analyses
- Identification of structural potentials
- …
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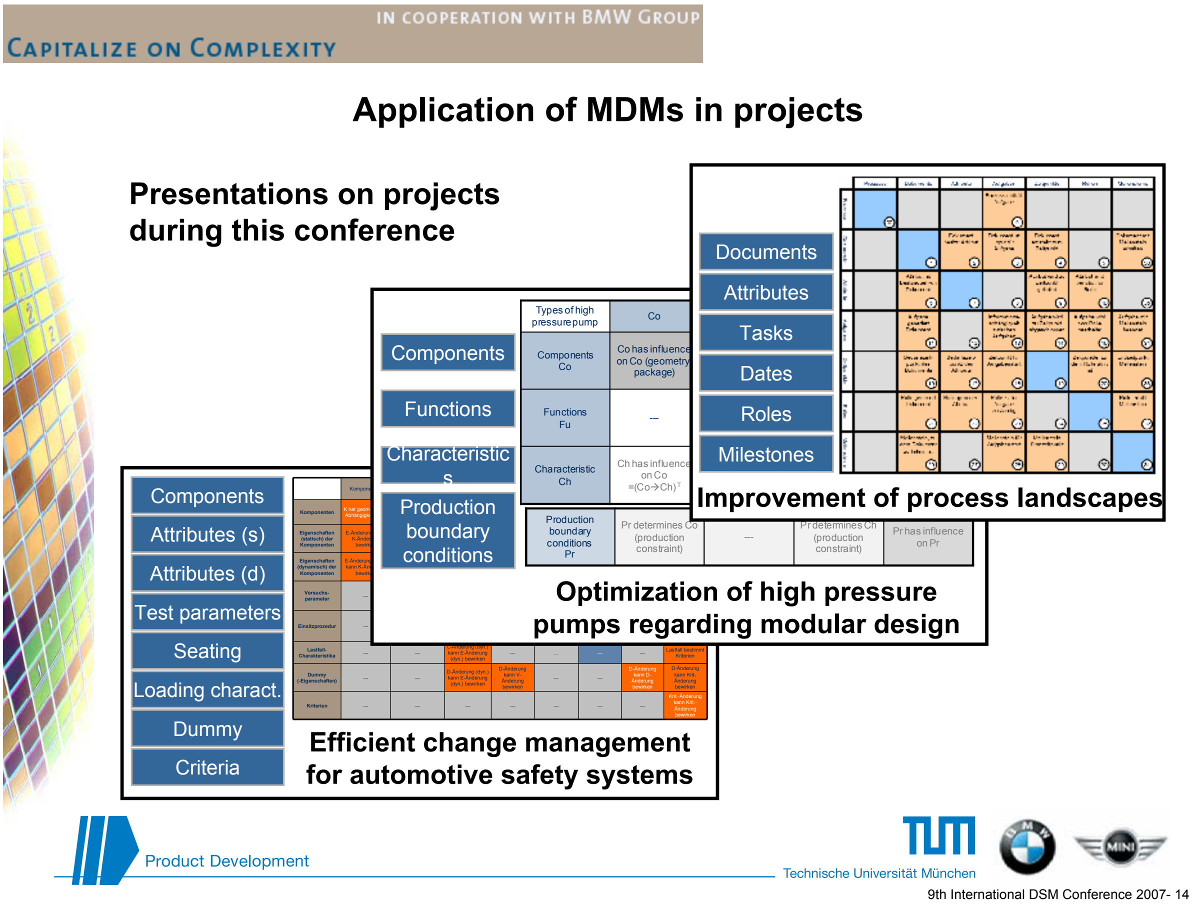

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Application of MDMs in projects
Presentations on projects during this conference
Documents
Attributes
Tasks
Dates
Roles
Milestones
Improvement of process landscapes
Components
Functions
Characteristics
Production boundary conditions
Types of high pressure pump
Co
Components Co
Co has influence on Co (geometry package)
Functions Fu
Characteristic Ch
Ch has influence on Co =(Co→Ch)ᵀ
Production boundary conditions Pr
Pr determines Co (production constraint)
Pr determines Ch (production constraint)
Pr has influence on Pr
Optimization of high pressure pumps regarding modular design
Components
Attributes (s)
Attributes (d)
Test parameters
Seating
Loading charact.
Dummy
Criteria
Efficient change management for automotive safety systems
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Conclusions & Outlook

- **The MDM is the basis of domain-spanning network analysis**
  - Focusing on relevant subsets allows for efficient acquisition
  - Deriving system views for analysis by DSM and graph theory
  - Consideration of domain-spanning effects and change propagation
- **Application of the MDM requires explicit system definition**
  - Relevant domains
  - Relevant dependency types
  - Specification of useful DSM computations
- **Future enhancements**
  - Quantification of elements and dependencies by attributes
  - Computational schemes for DMM deduction
  - Computational schemes for consideration of several domains
- **Software**
  - LOOMEO serves for MDM acquisition, analysis, and interpretation