DESIGNING CONSISTENT STRUCTURAL ANALYSIS SCENARIOS

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ABSTRACT
Companies face challenges due to rising complexity through shorter market lifecycles, manifold costumer requirements, additional solutions options and discipline-spanning cooperation. Efficient tools for analyzing and assessing solutions and processes are necessary during the development. Structural considerations are an established approach, which can be used in early phases of the innovation process. Manifold structural analysis criteria such as cycles and clusters are applicable in complexity management. The criteria are interconnected. Their interrelations cause redundant analyses. Developers must choose appropriate criteria combinations to gain significant results efficiently. Researchers have to develop consistent, non-redundant structural analysis scenarios. In this paper we present a model of the interrelations of structural analysis criteria. We propose a procedure for the development of structural analysis scenarios and show its application in one case study. Researchers get a tool for the systematic creation of structural analysis scenarios. Industrial applicators get efficient tools for structural complexity management.

Keywords: Structural complexity management, graph theory, structural analysis, design structure matrix, multiple-domain matrix

1 INTRODUCTION
Companies face challenges due to rising external complexity in engineering design. Reasons are shorter product life cycles, manifold costumer requirements, more solution options due to technological advances and combinations of products and services. Companies react by offering more products and introducing discipline-spanning collaboration. This increases internal complexity. If complexity is not managed successfully it leads to longer development times, cost overruns and wrong decisions with highly detrimental and long-term consequences [1-3].
Structural considerations are an established approach to manage complexity. One of the most used methods in engineering design is the design structure matrix (DSM) [4]. It has been applied to products, organizations, processes and parameters [5]. Its analytical capabilities have been supplemented by graph theory [1] and network analysis [6]. Its modeling capabilities have supplemented by the domain mapping matrix [7] and the multiple-domain matrix [1]. Maurer has proposed a structural approach to deal with complexity in technical systems [1,2].
Manifold structural analysis criteria have been proposed in complex systems research. They are from graph theory [8], network analysis [9], matrix theory [2] and motif analysis [10]. The criteria comprise properties of entire structures like planarity or connectedness, subsets of structures like cycles or clusters, metrics like degree or relational density and visualizations like matrices, graphs or portfolios. Maurer [1] and Kreimeyer [3] have proposed collections of structural criteria. Especially, the introduction of motif analysis has led to an almost infinite variety of structural criteria. The need for careful selection of analysis criteria arises. Developers must choose appropriate criteria combinations to gain significant results efficiently. Kreimeyer sets up a collection of about 50 metrics to evaluate engineering design processes which he models from six viewpoints. Kreimeyer has used an approach based on the goal-question-matrix to guide applicators in choosing the right criterion [3]. His approach neglects the internal dependencies of the criteria. Therefore, many criteria are redundant in at least one view. However, they are consistent as the complete set of metrics has been thoroughly discussed in workshops. This approach to consistency checks is rather tedious and still produces redundant criteria. A more efficient approach is needed which produces non-redundant analysis scenarios.
Researchers have to develop consistent, non-redundant structural analysis scenarios. The scenarios describe how and for which purpose structural criteria are applied. They may comprise multiple steps

of refinement of the analysis results. They tell applicators which criteria can be used at the same time to produce non-redundant results.
Following research questions are addressed in this paper:

- How can consistent structural analysis scenarios be developed?
- How do structural criteria interdepend?
- Which criteria are unique in terms of significance?
- Which criteria refine others?

In this paper we present a model of the interrelations of structural analysis criteria. We propose a procedure for the development of structural analysis scenarios and show its application in one case study. We show how the model can be used for systematic consistency checks and for deriving non-redundant analysis scenarios. Figure 1 shows the context of this work in structural complexity management. The focus is structural analysis. We do not address the applicability of structural criteria (see [11] for a detailed treatise). We focus on the combination of structural analysis criteria.

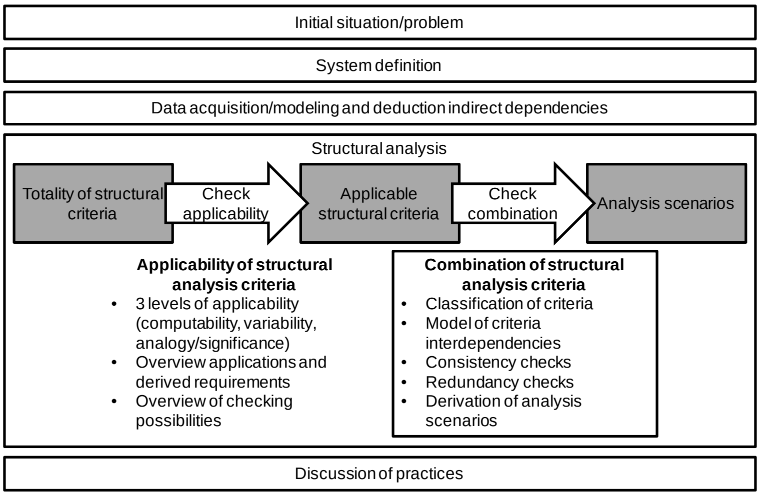


Figure 1: Integration of this work into the general structural complexity management process (based on [1]*)*

The paper is structural as follows. In the next section we present a collection of structural criteria and their interdependencies. In section 3 we describe a procedure to design consistent structural analysis scenarios. In section 4 a case study dealing with networked requirements is presented. In section 5 and 6 the results are discussed and conclusions for structural complexity management are drawn.

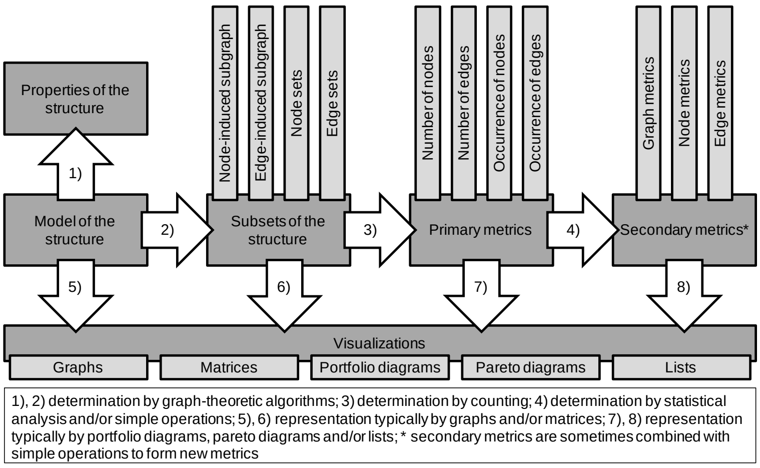


Figure 2: Classes of structural criteria, their definition processes and their representations (partially based on [3]*)*

2 STRUCTURAL CRITERIA AND THEIR RELATIONS

In this section we present the model of the relations among structural criteria. First, we introduce the taxonomy of the criteria. Then, we present the meta-model of the relations. Finally, we present the model itself.

2.1 Taxonomy of structural criteria

Figure 2 shows the classes of the structural criteria. We follow loosely the taxonomies proposed in [1] and [3]. The root criterion is the model of the system structure. Properties and subsets are derived by graph-theoretic algorithms. The subsets subdivide into node- and edge-induced subgraphs and node and edge sets. Subgraphs are partial graphs of the complete structure. They differ in the carrier of information. In edge-induced subgraphs knowing the edges suffices to reconstruct the whole subgraph including its nodes. The node and edge sets do not include edges or nodes respectively. The primary metrics are derived from the subsets by counting the nodes or edges in the subset or by counting how often a node or edge occurs in a type of subset. The secondary metrics are combinations of primary metrics. One way to derive them is to compute mean or extreme values of primary metrics. Another way to derive them is combination by algebraic operations. The criteria are visualized by matrices, graphs, diagrams and lists. In the remaining paper we omit visualizations.

Table 1 shows the taxonomy of structural criteria we use in this paper. It is not exhaustive but easily extensible. We focus on criteria originating in graph theory and network theory. The taxonomy does not contain most of the metrics discussed in [3] as many of them require parameterized or labeled graphs. It does not contain criteria introduced by motif analysis. The definitions of the criteria are available in [1-3,8]

Table 1: Taxonomy of structural criteria (partially based on [1] and [3])

Main category	Sub-category	Structural criteria and references
Sub-sets	Node sets	independent set, vertex cover, adjacency set, active adjacency set, passive adjacency set, reachable set ,active reachable set, passive reachable set, separating set
	Edge sets	feedback arc set, edge cover, incidence set, active incidence set, passive incidence set, cut set
	Node-induced subgraphs	connected component, strong component, k-connected component, block, clique, biclique, start node, end node, leaf node, transit node, articulation node, isolated node
	Edge-induced subgraphs	open sequence, closed sequence, path, shortest path, cycle, triangle, elementary cycles, tree, spanning tree, bridge edge
Primary metrics	Number of nodes	Order, order of clique, order of separating set, order of independent set, order of vertex cover, degree, active degree, passive degree, reachability, active reachability, passive reachability
	Number of edges	Size, size of cut set, size of edge cover, distance, path length, cycle length
	Occurrence of nodes	No. of cycles per node, no. of cliques per node, no. of triangles per node, no of shortest paths per node
	Occurrence of edges	number of cycles per edge, number of cliques per edge
Secondary metrics	Graph metrics	average path length, average degree, relational density, diameter, girth, cyclomatic number, vertex connectivity, edge connectivity, independence number, clique number, vertex covering number, edge covering number, degree distribution
	Node metrics	degree centrality, betweenness centrality, closeness centrality, snowball factor ,forerun factor, clustering coefficient, activity, criticality
	Edge metrics	Karatkevich number

2.2 Taxonomy of relations among structural criteria

The types of relationship were derived from the description of the criteria and the model shown in figure 2. We differentiate three types: inheritance, composition and derivation. Inheritance and composition only occur among subsets and the structural model. Inheritance means that one criterion is the parent of the other. The child criterion has all properties of the parent and may have additional constraints and properties. Our model allows for multiple parents. Composition means that one criterion is a subset of the other. The part criterion partially defines the properties of the composition criterion. The part criterion has more constraints. Our model allows for multiple parents. Derivation occurs between subsets and primary metrics, between primary and secondary metrics and among secondary metrics. Derivation means that one criterion is used to compute the other. Our model allows for multiple derivation paths but not for their distinction. Table 2 shows the taxonomy of relations among structural criteria.

Table 2: Taxonomy of relations among structural criteria

Relation	Definition	Example
Inheritance	One criterion is a more specific kind of the other	Each triangle is a clique consisting of three nodes.
Composition	One criterion is a subset of the other.	Each cycle is part of one strong component.
Derivation	One criterion is used to derive or compute the other.	The degree is derived from the incidence set of a node.

The taxonomy is incomplete as it omits relations which result from the type of model and the application context. This includes coexistence, correlation and exclusion relations.

2.3 Model of structural criteria and their relations

Figure 3 and figure 4 show the complete model of interdependencies among the criteria listed in table 1. Figure 3 shows the inheritance relations. Figure 4 shows the composition and derivation relations. The figures show the direct relations. We omit indirect relations for the sake of simplicity. The inheritance and composition relations are transitive. For example isolated nodes inherit all properties of leaf nodes, block and k-connected components.

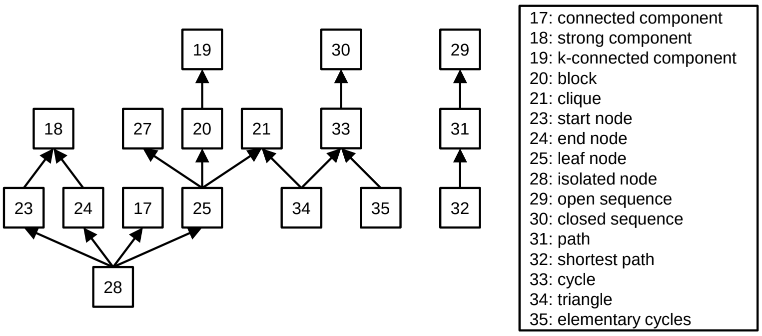


Figure 3: Network of the inheritance relations of the structural criteria

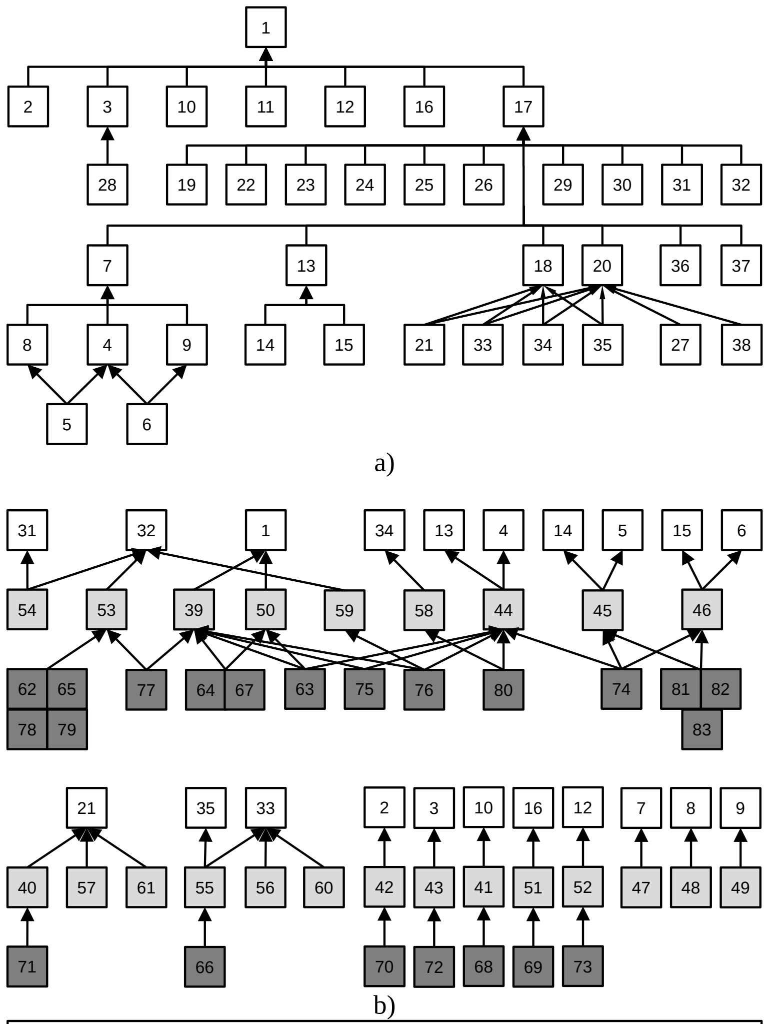
The four inheritance relations of the isolated nodes result from the rigorous interpretation of the criteria definitions. In practice they do not play a prominent role. The exposed position of the connected components in the composition network results from the fact, that most subset definitions require connected graphs as reference system. The prominent positions of degree and order in the derivation network result from the wide application as reference and/or norming metric.

3 DESIGN OF STRUCTURAL ANALYSIS SCENARIOS

In this section we present the theoretical foundations of our approach and a procedure to create structural analysis scenarios.

3.1 Implications of the relations among structural criteria for their significance

The relations shown in table 2 imply constraints for significances of the connected structural criteria. Figure 5 shows the rationale of the constraints. If one criterion is a subset of the other its significance must be more specific and contribute to the significance of the composition criterion. If one criterion is a child of the other its significance must be same but may contain more specific aspects. If one criterion is derived from the other its significance must be more general and may highlight partial aspects. Table 3 shows the implications for the three relations in our model.



1: graph
2: independent set
3: vertex cover
4: adjacency set
5: active adjacency set
6: passive adjacency set
7: reachable set
8: active reachable set
9: passive reachable set
10: separating set
11: feedback arc set
12: edge cover
13: incidence set
14: active incidence set
15: passive incidence set
16: cut set
17: connected component
18: strong component
19: k-connected component
20: block
21: clique
22: biclique
23: start node
24: end node
25: leaf node
26: transit node
27: articulation node
28: isolated node
29: open sequence
30: closed sequence
31: path
32: shortest path
33: cycle
34: triangle
35: elementary cycles
36: tree
37: spanning tree
38: bridge edge
39: order
40: order of clique
41: order of separating set
42: order of independend set
43: order of vertex cover
44: degree
45: active degree
46: passive degree
47: reachability
48: active reachability
49: passive reachability
50: size
51: size of cut set
52: size of edge cover
53: distance
54: path length
55: cycle length
56: no. of cycles per node
57: no. of cliques per node
58: no. of triangles per node
59: no. of shortest paths per node
60: no. of cycles per edge
61: no. of cliques per edge
62: average path length
63: average degree
64: relational density
65: diameter
66: girth
67: cyclomatic number
68: vertex connectivity
69: edge connectivity
70: independence number
71: clique number
72: vertex covering number
73: edge covering number
74: degree distribution
75: degree centrality
76: betweenness centrality
77: closeness centrality
78: snowball factor
79: forerun factor
80: clustering coefficient
81: activity
82: criticality
83: karatkevich number

Figure 4: Networks of the composition a) and derivation b) relations of the structural criteria

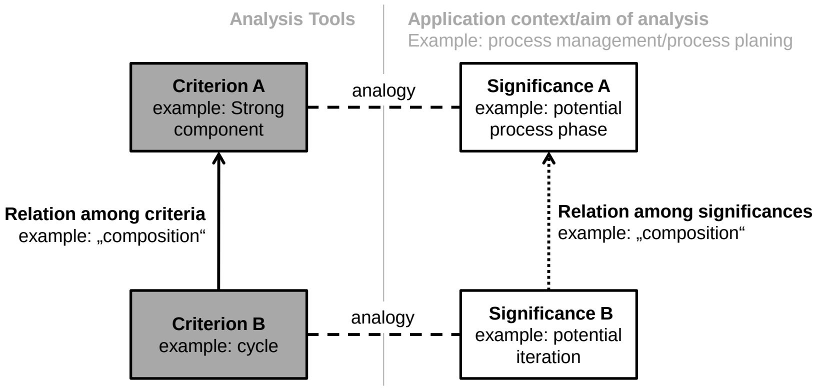


Figure 5: Applications of the network of structural criteria

Table 3: Implications of the relations among structural criteria

Relation	Implication
Inheritance	The child criterion has the same significance as its parent. As the child is more specific and fulfills more conditions its significance may be a special case of the parent's.
Composition	The significance of the composition criterion is an aggregation of the significance of its parts. The significances must not contradict each other. Part criteria of the same composition may not be related.
Derivation	The derived criterion is either a property of a subset of the network or an aggregation of metrics. Its significance is more general than the original criterion's or highlights the original's significance partially.

3.2 Procedure to design structural analysis scenarios

Based on the rationale shown in figure 5 we propose a procedure for designing consistent structural analysis scenarios. They depend on the analysis context and the structural model. The analysis context defines the scope and aim of the analysis. The structural model defines the types of elements and relations. Together, they impose requirements for the applicability of structural criteria (see [11] for a detailed treatise). The requirements reduce the totality of the criteria to applicable ones. By considering their interdependencies the applicable criteria can be reduced and structured to form analysis scenarios. For each combination of analysis context and structural model a new analysis scenario has to be designed. The proposed procedure is shown in figure 6.

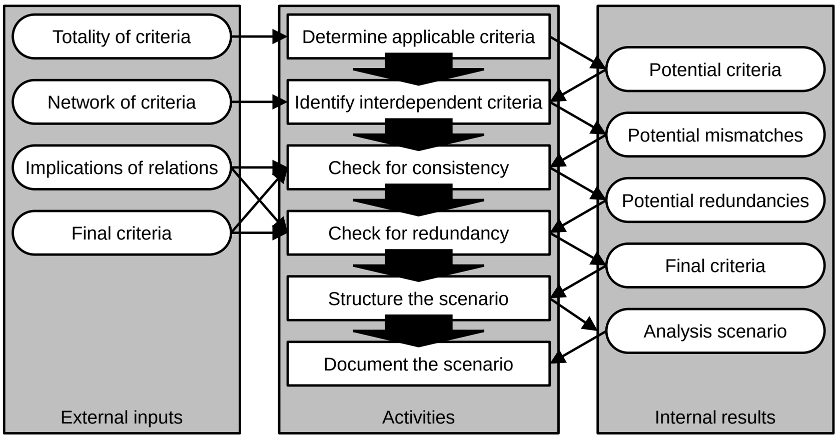


Figure 6: Procedure to define consistent, non-redundant structural analysis scenarios

Determine applicable criteria – As shown in [11] the criteria have to fulfill three criteria: computability, distribution and significance. Computability and distribution impose hardly any limitations. Significance is hard to test and quantify [11]. This step results in a list of potential criteria for the scenario.

Identify interdependent criteria – The interdependency model is reduced to the applicable criteria. All relations in the reduced model have to be for consistency and redundancy. This step results in list of pairs of criteria which represent potential inconsistencies and redundancies.
Check interdependent criteria for consistency – Based on the constraints in table 3 the pairs are tested for consistency. Usually, the significances should be consistent. If they are not the applicability of the connected criteria has to be retested. If a test is not possible one or both criteria have to be omitted. This step results in a list of consistent criteria and a list of potential redundancies.
Check interdependent criteria for redundancy – The remaining pairs are tested for redundancy. The criteria are redundant if they have the same significance. If a pair is redundant one of the criteria can be omitted. Usually the more specific criteria should be omitted to avoid unnecessary computations. This step results in the final list of criteria for the scenario.
Structure the criteria – The criteria are assigned to the analysis aims base on their significance. One criterion may be assigned to multiple aims. The criteria in each group are ordered to form incremental steps of analysis. The ordering can be done by partitioning [4] the criteria network. The most general or most aggregated criteria are placed first. More specific criteria are assigned to subsequent analysis steps as they allow for in depth analysis if necessary. This step results in an ordered scenario.
Document the scenario – The documentation contains a description of all criteria including their significance and computation and the structure of the criteria.
The presented approach is straight forward as it guides the discussion about consistency and redundancy towards the criteria which interdepend. One critical step is to determine the applicability of the criteria. We omit the discussion of applicability for the sake of brevity and refer to [11] for a thorough discussion. All subsequent use the model of criteria interdependencies for consistency checks, redundancy checks and structuring of the critera.

4 A STRUCTURAL ANALYSIS SCENARIO FOR NETWORKED REQUIREMENT MODELS

We use the results of Eben and Lindemann [12] in this case study.

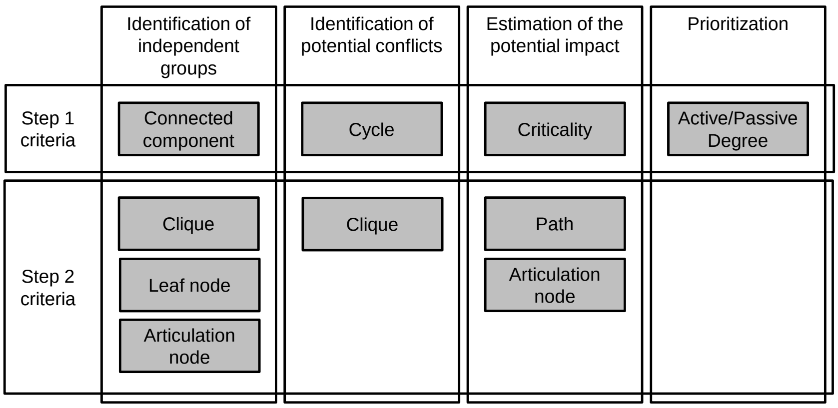


Figure 7: Structural analysis scenario for networked requirements

4.1 Applicable structural analysis criteria

Eben and Lindemann present a collection of 16 structural criteria to analyze requirement networks. The aims of the application are:

- Identification of independent groups of requirements
- Identification of potential conflicts among requirements
- Estimation of the potential impact of changing a requirement
- Prioritization of requirement

In the remaining section we omit all criteria which are not depended on other criteria for the sake of simplicity.

4.2 Interdependencies, consistency and redundancy

Table 4 shows the interdependencies of the criteria. Based on their significance the interdependencies are tested for consistency and redundancy. The test results are shown in table 4. All 13 pairs of criteria are consistent. One pair is redundant. Four pairs are partially redundant. The remaining eight pairs are non-redundant.

Table 4: Combined criteria in requirement models and their significance (based on [12]*)*

Criterion with significance	**Criterion with significance**	**Consistency Redundancy**
Composition relations – first column comprises second column		
Connected Component – A subset having no influence on other subsets. It can be regarded separately.	**Clique** – Requirements forming a clique may belong to the same class, and be highly interdependent.	Consistent, non-redundant
	Leaf node – The requirement is influenced by one other directly. Not necessarily the whole requirements structure is affected.	Consistent, partially redundant
	Articulation node - It links subsets of requirements. It may represent an interface or interaction in the system.	Consistent, partially redundant
	Path – Requirements connected via a path to a requirement can be affected by a change of the latter.	Consistent, non-redundant
	Cycle – Requirements connected in a cycle might form a conflict.	Consistent, non-redundant
	Tree – Requirements of a lower hierarchy level may inherit the priority of higher level ones.	Consistent, non-redundant
Inheritance relations – first column inherits from second column		
Isolated node – The requirement can be regarded on its own.	**Connected Component** – A subset having no influence on other subsets. It can be regarded separately.	Consistent, redundant
	Clique – Requirements forming a clique may belong to the same class, and be highly interdependent.	Consistent, non-redundant
	Articulation node - It links otherwise independent subsets of requirements. It may represent an interface or interaction in the system.	Consistent, non-redundant
Leaf node – The requirement is influenced by one other directly. Not necessarily the whole requirements structure is affected.	**Clique** – Requirements forming a clique may belong to the same class, and be highly interdependent.	Consistent, non-redundant
	Articulation node - It links subsets of requirements. It may represent an interface or interaction in the system.	Consistent, non-redundant
Derivation relations – first column is derived from second column		
Criticality – A requirement with a high criticality affects and is affected by a large number of other requirements. It should be given high priority	**Active degree** – Stands for the intensity of the requirement's influence on other requirements.	Consistent, partially redundant
	Passive degree – Passive requirements are affected by many others. It might be a source of uncertainty.	Consistent, partially redundant

4.3 Structural analysis scenario for networked requirements

Figure 7 shows the structural analysis scenario. It comprises four analysis aims, two steps and nine analysis criteria. The criterion isolated node was removed as it is redundant to connected components in the analysis context. Next, we describe each aim and the corresponding criteria in detail.

Identification of independent groups of requirements – The primary criterion is the connected component. It represents groups of requirements which are mutually independent. For more detailed analyses the scenario proposes three criteria: clique, leaf node and articulation node. Cliques represent highly-interconnected requirements which cannot be separated. Leaf nodes represent side requirements which are only loosely connected to the rest of the structure. Articulation nodes represent integrative requirements which have the potential for separating larger groups.

Identification of potential conflicts among requirements – The primary criterion is the cycle. It represents connected requirements which form a loop. For more detailed analyses the scenario proposes cliques. They represent highly-interconnected requirements which cannot be separated.

Estimation of the potential impact of changing a requirement – The primary criterion is criticality. It measures the local connectivity and impact of the requirements. For more detailed analyses the scenario proposes two criteria: path and articulation node. Paths represent modes of impact on the requirements. Articulation nodes represent integrative requirements which have the potential for separating larger groups.

Prioritization of requirement – The two primary criteria are active and passive degree. Active degree measures the intensity of the requirement's influence on other requirements. The passive measures the intensity of the influence on the requirement by other requirements. Passive requirements might be a source of uncertainty. The scenario proposes no criteria for more detailed analyses.

The original paper [12] gave a set of nine criteria for analyzing requirement networks. It showed the applicability of the criteria. In this case study we extended the original approach by checking the consistency and redundancy of the criteria. We showed that all criteria are consistent. One criterion is redundant and therefore removed from consideration. The final scenario comprises eight criteria. Two of them are applicable to two aims.

5 DISCUSSION OF THE RESULTS

We presented a model of the interdependencies of 83 structural criteria, a procedure to define consistent structural analysis scenarios and a case study. The criteria interdepend in three types of relations: inheritance, composition and derivation. Each relation imposes consistency constraints onto the criteria and their significance. The procedure comprises six steps and uses the model for systematic consistency and redundancy checks. The application of the procedure in the case study results in a two-step analysis scenario with only five out of ten applicable criteria in the first step. One applicable criterion was eliminated from the scenario as its significance is redundant. For three criteria subsequent criteria are available which support the refinement of the analyses. This supports incremental analysis approaches which allows for better planning and more efficient work.

Our approach to designing the analyses scenarios is more efficient and goal-oriented than previous guidance approaches such as the goal-question-matrix [3]. The GQM approach requires pairwise comparison of the criterion concerning their significances. In the case study this requires $(n^2-n)/2=(16^2-16)/2=120$ comparisons. In our approach only 13 comparisons are necessary. This corresponds to a time saving of about 90%. Moreover the new approach provides consistency requirements for each type of relation among the criteria. This leads to more savings compared to the GQM approach, where the requirements have to be worked out for each pair anew.

6 CONCLUSION

Our results allow for the first time the systematic creation of structural analysis scenarios under consideration of the inherent complexity of the analysis criteria and their interdependencies. They provide researchers with a tool for structuring and guiding their work. Industrial applicators get efficient tools for structural complexity management. The scenarios guide the planning and application of structural analysis criteria. They give an overview of the applicable, non-redundant criteria. They allow for efficient access to the criteria via the application context and aims. The handling of complex systems becomes more efficient.

Our results are not comprehensive. The network model neglects the existence of relations based on coexistence, correlation and exclusion. To include them is a task in future research. The taxonomy neglects criteria, which require parameterized or labeled graphs or were introduced by motif analysis. These need to be included to cover the complete spectrum of structural analysis criteria. However, there is no consensus in the research community, which criteria are developed. Through recent developments the amount of available criteria has reached the manageable limit. We think that our approach helps in focusing, guiding and structuring the work with structural analysis criteria.

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