ON THE APPLICABILITY OF STRUCTURAL CRITERIA IN COMPLEXITY MANAGEMENT

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ABSTRACT

Companies face challenges due to increasing complexity through shorter product life cycles, manifold costumer requirements, more solution options and discipline-spanning collaboration. During the development of complex systems efficient tools for analysis and for assessment of solutions are necessary. A common approach is structural analysis, which can be applied in early development phases. System structures are analyzed with structural criteria such as cycles and clusters. Manifold criteria have been introduced in graph theory and applied in complexity management. In industrial applications suitable criteria have to be chosen. In research the significance of the criteria has to be shown. Based on an extensive literature review we show applications of structural criteria in complexity management. We derive requirements onto structural criteria from the applications. We show methods to prove the applicability of the criteria. Researchers get tools for proving and assessing the significance of structural analyses. More effective analyses can be developed. The quality of technical solutions increases and manifold solutions can be developed.

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 their 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 been supplemented by the domain mapping matrix (DMM) [7] and the multiple-domain matrix (MDM) [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.

Following research questions are addressed in this paper:

- What are applications of structural analysis criteria in complexity management?
- Which requirements of structural analysis criteria arise from the applications?
- How can structural analysis criteria be tested for compliance with the requirements?

The scope of this paper is application of structural analysis criteria in engineering design. We include applications in concept design, process management, project management and organization management but are not limited to them. We exclude applications in production, manufacturing and logistics. We focus on criteria, which can be applied to structural models, which do not comprise node

or edge parameters like weights, costs or probabilities. We also exclude criteria based on labeled graphs.
The paper is structured as follows. First, we describe our research approach for the literature survey (section 2). We present an overview of applications for structural criteria in complexity management (section 3). We show requirements arising from the applications and present methods for testing criteria for compliance (section 4). We discuss the results and derive questions for future research (section 5). Finally, we conclude this paper by proposing future research and supporting activities (section 6).

2 METHODOLOGY FOR LITERATURE REVIEW

We follow, like Krishnan and Ulrich [11] and Browning and Ramasesh [12], a loosely structured approach to survey the literature relating to complexity management within the defined scope. We focus on works that identify themselves with the term complexity management or complex system. However, because many papers address similar issues without this term, we also surveyed some non-complexity-specific literature in areas such as project management, and systems engineering, where these fit our scope. First, we created a superset of papers related to structural complexity management through following steps:

1. We searched the tables of contents of the DSM knowledge area of DSMweb [13] from 2001 to 2010, which contains journal articles, books, book chapters, reports, theses and conference proceedings. DSMweb provides access to proceedings of International DSM Conference from 2004 to 2010.
2. We searched the tables of contents of ten major journals from 2006 to 2010: ASME Journal of Mechanical Design, Design Studies, European Journal of Operational Research, IEEE Transactions on Engineering Management, Journal of Engineering Design, Journal of Operations Management, Management Science, Operations Research, Research in Engineering Design, and Systems Engineering. These journals span the engineering design, management science, and operations management areas.
3. We conducted a general search of the literature based on key words, looking also at the broader literature on software engineering, engineering processes, and engineering management.
4. We used the reference lists from highly cited papers.

These steps resulted in a master list of about 300 papers, from which we derived a working list of about 80 papers by filtering out ones that were:

1. outside our scope
2. not in archival publications
3. devoted to software tools, vendors or algorithms
4. presenting case studies without developing new methods

In this paper we present the qualitative results of the survey. Therefore, we omit all quantitative results in the remaining paper.

3 APPLICATIONS OF STRUCTURAL CRITERIA

In this section we present the applications. Table 1 shows the nine applications, which we derived from literature. Each application is assigned to a phase of structural complexity management process as proposed by Maurer [1]. We found applications in four of five phases: data acquisition/modeling, deduction indirect dependencies, structural analysis and discussion of practices. We describe each application by giving an estimation of its commonality, naming its aim and describing the purpose of the structural criteria. For each application we present selected references describing the application or contributing by proofing the significance of a structural criterion.

Steering and controlling of the data acquisition/modeling – This is a rather uncommon application. The aim is to plan the modeling process and to put most of the effort to critical parts of the system model. Improved planning increases the efficiency of the modeling process. The structural criteria are used to identify parts of the model, which are likely to be erroneous, or to estimate the impact of potential errors. Biedermann et al. have proposed a measurement system to improve data acquisition workshops [14].

Model checking for consistency and plausibility – This is a rather uncommon application. The aim is to test the model for errors and to correct them. This increases the model quality. The structural criteria are used to test the model for characteristic properties. Braha and Bar-Yam contribute by identifying characteristic degree distributions of design processes [15]. Shaja and Sudhakar contribute by showing that structural characteristics of components are specific for the type of product [16].

Determining of formulas for deducing indirect dependencies – This is a rather uncommon application. The aim is to derive structural models from models, which are already existing or easier to create. This increases the efficiency of the modeling process. The structural criteria are applied to the meta-model of complex system. Biedermann and Lindemann propose a method to identify computations of DSMs using cycles [17]. Mocko et al. use paths to identify computations of DMMs and DSMs [18].

Table 1: Applications of structural criteria in the structural complexity management approach (partially based on [1]*)*

Phase in the structural complexity management process	**Applications**
Data acquisition/modeling	Steering and controlling of the data acquisition/modeling
	Model checking for consistency and plausibility
Deduction indirect dependencies	Determining of formulas for deducing indirect dependencies
Structural analysis	Identification of prominent elements, which determine the system behavior and properties
	Identification of system partition, which allows for efficient handling
	Comparison of system architectures
	Deduction of an optimal substructure
	Deduction of consistent system specifications
Discussion of practices	Steering of searches for error causes/Estimation the impact of changes and planning of changes

Identification of prominent elements, which determine the system behavior and properties – This is one of the most common applications. The aim is to identify system elements, which are important to the system behavior and its properties. This improves the handling of the system and leads to optimized systems. The structural criteria are used to rate the elements. Sosa et al. use network metrics to estimate the component modularity in product networks [19]. Kreimeyer uses structural metrics to evaluate engineering design processes [3]. Batallas and Yassine use social network metrics to identify key players in product development networks [21]. Gokpinar et al. estimate the likelihood of quality problems with structural metrics of the product architecture network [22]. Kurtoglu and Tumer use failure paths to remove potential failures and to design capabilities to detect and mitigate failures [23]. Lee et al. use structural metrics to measure the importance of parts and modules for change impacts and propagation [24]. Zakarian et al. use matrix metrics to identify elements, which are relevant for product robustness [25]. Sosa et al. use metrics to estimate quality in software architectures [26].

Identification of system partition, which allows for efficient handling – This is the most common application. The aim is to find a partition of the system. This improves the handling of the system and leads to optimized systems. The two major methods are clustering and partitioning. The structural criteria are used to identify clusters or system partitions or to evaluate the resulting partition. Chen et al. use system partitioning for rapid redesign [27]. Pektas and Pultar use structural properties of parameter networks to determine the optimal decision sequence [28]. Bustnay and Ben-Asher use graph theoretical properties to identify independent subsets of a system [29]. Seol et al. combine clustering and partitioning to derive process modules [30]. Gershenson et al. give an overview of modularity measures [31]. Kusiak and Wang use cycles and strong components for process planning [32]. Yassine gives an overview of structure-based objective functions for partitioning and clustering [33]. Browning surveys partitioning methods and their applications [5].

Comparison of system architectures – This is a common application. The aim is to determine the best system architecture. This improves the quality of the final solution. The structural criteria are used to estimate properties of the system or to compare the system structures. Hofstetter et al. compare structural system models to identify opportunities for commonality [34]. Ameri et al. use network metrics to quantify the design complexity [35]. Gokpinar et al. compare product architecture networks and communication networks to quantify the coordination deficits [22]. MacCormack et al. compare software architectures based structural modularity metrics to evaluate the effect of the mode of organization [36]. Summers and Shah use graph metrics to measure the complexity of design problems and to estimate the effort necessary to solve design problems [37]. Hölttä-Otto and de Weck develop two modularity metrics to characterize systems [38]. Shaja and Sudhakar use structural component characteristics to classify complex products [16]. Browning and Yassine use relational density of project activity networks to choose the appropriate priority rule for resource allocation [39].
Deduction of an optimal substructure – This is an uncommon application. It is a standard application in operations research and management. The structural model describes a network including all potential solutions. The model is often supplemented by parameters like costs. We omit examples, which require weighted network model as they are out of the scope of this paper. The aim is to identify the best solution. This increases the effectiveness and quality of the final solution. The structural criteria are used to identify the substructure or to evaluate the substructure. Cappelli et al. use trees to identify the optimal disassembly sequence [40].
Deduction of consistent system specifications – This is a rather uncommon application. The structural model describes a network including all potential solutions. The aim is to identify all consistent solutions. This increases the effectiveness of the result and the efficiency of the development process. The structural criteria are used to identify system specifications. Braun and Deubzer use cliques in variant management [41]. Hellenbrand and Lindemann use cliques to identify consistent concepts of aircrafts [42]. Gorbea et al. use cliques to identify consistent requirement sets and consistent concepts of hybrid electrical vehicles [43].
Steering of searches for error causes/Estimation the impact of changes and planning of changes – This is an uncommon application. The aim is to support engineers in decision making by highlighting the decision's consequences and in finding root problems by guiding the search. This improves the system handling. In operations research search strategies are commonly applied. Here, we focus on semi-automated search. The structural criteria are used to guide the search by focusing on important elements. Maurer describes the use of active and passive degree in feed-forward analysis and mine seeking [1].

4 APPLICABILITY REQUIREMENTS

In this section we describe the requirement arising from the applications. We show how they are handled in literature and how they are tested.

4.1 Computability

The basic requirement is computability of the criteria based on the structural model. It comprises two sub-requirements. First, the criterion must be defined for the type of structure and an algorithm to compute them must be known and implemented. Criteria can be defined for undirected structures only (e.g. blocks) or for directed structures only (e.g. active degree). Directed structures can be transformed into undirected ones to allow for applying all structural criteria. Transforming undirected to directed structures is not feasible as the results do not reflect the directedness. Second, the criteria must be computable in a given time. The computation time depends on the complexity of the structure, the complexity of the algorithm, the implementation of the algorithm and the computer hardware. The available computation time depends on the project and the analyzing engineer.
There are many tools available for structural analysis [44,45]. The issue of implementation hardly arises. The computation time is not limiting the application of structural criteria in engineering design due to advances in computer hardware and algorithmic graph theory. In the papers describing applications in engineering design the computability of structural criteria is not addressed unless many models are involved [46]. In network theory much larger structures are analyzed and computation time is still an issue [9]. There is no specific testing method for this requirement. It is usually tested by self-assessment.

4.2 Distribution and variety requirements

The distribution and variety requirements refer to the forms, which structural criteria may have. In contrast to the computability they depend on the application and the type of structure. Distribution and variety depend on each other. Low variety correlates with uniform distribution and vice versa. Table 2 shows the applications and the derived requirements. The fulfillment of the requirement depends on the system, on the type of structure and the structural model. Three applications pose no requirement onto the distribution and variety of structural criteria: Determining of formulas for deducing indirect dependencies, deduction of an optimal substructure and deduction of consistent system specifications.

Table 2: Distribution requirements depending on the application of structural criteria

Application	Distribution requirement
Steering and controlling of the data acquisition/modeling	Unequal distribution within the system.
Model checking for consistency and plausibility	Uniform distribution across systems.
Determining of formulas for deducing indirect dependencies	None
Identification of prominent elements, which determine the system behavior and properties	Unequal distribution within the system.
Identification of system partition, which allows for efficient handling	Unequal distribution within the system.
Comparison of system architectures	Unequal distribution across systems.
Deduction of an optimal substructure	None.
Deduction of consistent system specifications	None.
Steering of searches for error causes/ Estimation the impact of changes and planning of changes	Unequal distribution within the system.

Unequal distribution within the system – This is the most common requirement as it applies to four applications – the two most common among them. The criteria must occur in many varieties with unequal frequencies. The rarest and the most extreme forms of the criteria (e.g. the highest criticality) characterize elements, which have outstanding importance for the system. The requirement can be tested within one system model. To prove the general applicability several models have to be tested. In literature this requirement is mostly not explicitly addressed. It is implicitly expected to be fulfilled. Criteria, which do not fulfill the requirement, are generally omitted.

Uniform distribution across systems – This requirement applies to criteria for the uncommon application of model checking. The criteria must occur at low variety in all systems of the same type. There is some literature on characteristic properties of complex systems in general. There is hardly any literature on the characteristics of structures, which occur in engineering design. The fulfillment of the requirement can be tested by analyzing a significant proportion of all systems of the same type. The test also depends on the meta-model and the modeling process.

Unequal distribution across systems – This requirement applies to structural criteria for the common application of architecture comparison. The criteria must occur in high variety across systems of the same type. The distribution of the criteria must significantly differ among the systems. The requirement can be tested by comparing a few system models. In the literature this requirement is hardly addressed. It is expected to be fulfilled. Criteria not fulfilling the requirement are generally not presented.

4.3 Significance and relevance requirements

These requirements are the most important. The fulfillment of the two other groups of requirements is necessary but not sufficient for a criterion to be applicable. The requirement is fulfilled if the criterion allows for describing or estimating a system property, which is relevant for the application. If the purpose is reduction of development time the criterion must e.g. correlate with the process duration. If the purpose is increasing product quality the criterion must e.g. correlate with error frequencies. The requirement is addressed in about half of the papers. We found four methods in literature, which have been applied to test and proof the fulfillment: analogy, comparison, simulation and statistical analysis. We describe each method by presenting its rationale, an example and its major challenges and limitations.

Analogy of the criterion and a known phenomenon – This approach builds an analogy between the criterion and a known phenomenon. The implications, properties and effects of the phenomenon are transferred to the criterion. The significance and relevance of the criterion is correlated with the phenomenon's properties. Kusiak and Wang [32] use this approach to develop a structure-based sequencing method. They show an analogy between iterations and cycles in the activity network. Iterations are repetitions of activities and tasks. Cycles are close sequences of information flows among activities. Iterations tend to increase the process duration and the planning uncertainty. Cycles inherit these properties. Efficient dealing with cycles allows for better handling of iterations. Removal of cycles lowers the risk of iterations. The analogy approach does not allow for quantified structural analyses as only tendencies but not quantified parameters are inherited.

System structure comparison – In this approach exemplary structures are created, which possess extreme structural properties. They are expected to represent ideal systems with pure characteristics without trade-offs as they occur in real engineering systems. The structures are compared to real systems. The differences can be quantified to measure the real system's properties in relation to the ideal systems. Hölttä-Otto and de Weck [38] use this approach to measure the degree of modularity of engineering systems and products. They define three exemplary (or canonical in their terms) structures: integral, bus-modular and modular. They compare these with real system structures. They also compare pairs of systems with the same functionality but different technological constraints. Highly-constraint systems tend to be more integrally modularized. Hölttä-Otto and de Weck also include random structures to show that real engineering have significantly different structural characteristics. Comparing real structures to randomly created ones is a common research approach in network theory [9]. The approach allows for semi-quantified result. They are limited to measuring the differences to the exemplary structures. They cannot measure system properties directly as the properties of the exemplary structures are not quantified. The main challenges are to find appropriate reference structures, and to reliably determine the real structures.

Simulation – In this approach simulation models are derived from structural models. The simulation results are compared to structural criteria. The significance and relevance of criteria are shown by correlating them with significant and relevant simulation results. Browning and Yassine [39] use this approach to evaluate priority rules for resource allocation in multi-project environments. They show that relational density of activity networks is one of three criteria to choose appropriate priority rules. They achieved this result by synthesizing and simulating 12,320 project set-ups. The variations and means of the simulation results were analyzed. The analyses showed a significant correlation between relational density and the appropriate choice of priority rules. The simulation approach allows for quantified structural analyses. The main challenge is to create simulation models, which cover the complete parameter space. Both, the space of the potential structures and the space of the simulation models have to be explored.

Statistical analysis – In this approach the statistical relation between structural criteria and system properties is determined. If the results are statistically significant the structural criteria are significant as well. The relevance of the criteria depends on the relevance of the system properties. Sosa et al. [26] use this approach to show the connection between coupling in the component structure of software systems and the quality of the software system. They analyze the structures of 20 software systems (in 108 versions in total). For each version they compare the number of bugs and the number of resolved bugs with the coupling (e.g. in form of cycles) within the structure of the previous version. They show that high actual coupling (originating from the architecture) increases the number of bugs and that high intrinsic coupling (originating from the organization of the engineering project) decreases the capability to fix bugs. The statistical analysis approach allows for quantified results. The main challenges are to determine enough structures to be statistically significant, to reliably create the structural models, to determine the system properties independently of the structure and to avoid hidden parameter biases.

5 DISCUSSION

The results of the literature review comprise nine applications of structural criteria in complexity management, the requirements onto them and an overview of methods to test them.

We identified nine applications, which occur in four out of five phases in the structural complexity management approach. Five applications occur during structural analysis – the three most common among them. The applications in data acquisition (or modeling), deduction of indirect dependencies and discussion of practices are rather uncommon. This unequal distribution across the phases is a consequence of the primary focus of complexity management. Structural models are primarily a tool for system analysis. This is their original purpose [4]. Most of the subsequent research focused on it. Applications during modeling are uncommon; this is a result from the tendency in the literature to omit the model creation from the description and possibly consideration. A lack of support during modeling is mentioned by industrial appliers of structural analysis [47]. Researchers have recognized this lack as well. Participants of the 2010 International DSM Conference voted data acquisition the prime research topic in structural complexity management [48]. The rare application in discussion of practices can be explained by the focus of complexity management. Most applications support tasks during the planning and concept phases of product development. Module definition and initial project or process planning are typical task associated with complexity management. Applications in engineering day-to-day business have hardly been addressed.

We define three categories of requirements for the applicability of structural criteria: computability, distribution and variety, and relevance and significance. Computability and variety are mostly not discussed in the literature. They are expected to be fulfilled. Most papers only present criteria, which fulfill the requirements. In some cases (e.g. [16]) criteria are applied, which are not sensibly computable in the use case. As discussed in section 4.1 criteria for directed networks should not be applied to undirected networks. Most applications do not pose critical variety requirements onto the criteria. The notable exception is model checking, which requires low variety across systems of the same type. This application is uncommon. One reason is that structural models of many systems are needed to test the variety requirement. The third group of requirements comprises relevance and significance of the criteria. We present four methods to test these requirements and four exemplary applications (one for each method) in detail. The methods analogy and comparison test the criteria qualitatively. The methods simulation and statistical analyses test the criteria quantitatively. Most papers use qualitative methods. They can be applied at little expense as only one model is required. The quantitative methods require models of many systems to gain significant results. The methods allow for results, which can be used for optimization of systems. The rarity of quantitative results indicates a lack of models to test structural criteria.

6 CONCLUSION

The survey results show that there is a gap in applications in modeling and a gap in quantitative results based on structural criteria. According to the survey in [48] supporting the data acquisition is one of most pressing issues in complexity management research. The existing proposals (e.g. [14,17]) show promising results but need to be extended and validated. Optimizing systems based on their structural properties is a pressing issue as well. Optimization requires objective functions and quantitative measurements of the system. The few quantitative results (e.g. [26,39]) show that applying structural criteria allows for measuring relevant system properties. Yet, there are hardly any results available in literature. We derive two research questions from these results:

- How can structural modeling of complex systems be supported to become more efficient?
- How can researchers be supported in creating, testing and proofing quantitative structural analysis approaches?

We propose three measures to close the existing gaps and to answer the research questions:

- A collection of structural models of engineering systems, which serves as a reference set for testing structural criteria
- A collection of characteristic structural properties of engineering systems, which supports model checking and serves as a basis for example structure synthesis
- A tool for creating exemplary, characteristic and random structures, which serves as a base for simulation analyses of complex systems

Our results show that structural criteria are widely applied in complexity management. We show the requirements arising from the application and how they are dealt with in research. We support researchers in finding the right method to test their hypotheses. We support appliers to find the right criterion to analyze their systems. We show the limitations of the application and the research results. We propose measures to overcome the limitations. Thereby, the quality of the research results will rise. New and better tools to analyze complex systems will be developed and improve complex products and their development.

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