Complexity Metrics in Engineering Design

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Managing the Structure of Design Processes

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To Monica

FOREWORD BY THE AUTHORS

To manage and improve engineering design processes in a methodical and systematic manner, an important issue that needs tackling is their analysis, interpretation and goal-oriented improvement. Although approaches for managing complex processes exist, a systematical, method-based analysis and improvement is still highly difficult.

To support the systematic and holistic analysis and improvement of an engineering design process, this book presents a measurement system that makes use of complexity metrics to embody various patterns of the interplay of a process' entities (e.g. tasks, documents, organizational units, etc.). These metrics are used to draw inferences about the process' behavior (e.g. timeliness, need for communication, forming of opinions, etc.). This way, knowledge about a process can be extracted from existing process models, or new process models can be structured systematically by addressing desirable patterns. This supports management in reducing the risks in process planning through better understanding how the structure of a process impacts the behavior of a process. Generating such a means of process analysis and management provides a major contribution both for academia and industry, especially for the improvement of large and complex engineering design processes. The metrics embody the foundations of network theory and the management of structural complexity to generate a practice-oriented application.

The metrics are supported by a meta-model for process modeling. The meta-model uses multiple-domain matrices, integrating existing process models across common domains and relationship types. The modeling method is enhanced with additional constructs of modeling that act as a bridging between existing dependency models and established process models.

Furthermore, the analysis approach is operationalized by a framework to select the metrics in accordance with the goals of the process analysis. To this end, the metrics are classified and allocated to the common goals of process analysis with regard to the structure of a process, producing eight different guidelines. To enable a flexible application, a modular set-up consisting of three steps is chosen: As a starting point, the strategic level is addressed using common goals of process analysis. Then, these goals are concretized by typical questions that can be posed in their context. Finally, these questions are answered using the metrics and parts of the meta-model.

The overall approach is detailed using three case studies from automotive development; on the one hand, the modeling and goal-oriented analysis of the body-in-white design of a premium class mid-size sedan is shown and, on the other hand, the detailed analysis and extraction of possible weak spots within the concept design, programming, and testing of electronic control units for an SUV is regarded. A third case study on general automotive design is used to illustrate all individual metrics. Results from the case studies point e.g. to particularly robust parts of the process, to critical structural bottle-necks, to the core drivers for iterations or rework, and, more generally, to potential weak spots in the overall structure of a process.

The book is based on a rigorous scientific approach to illustrate the origin of the presented results as well as the limits of their applicability. At the same time, much attention was put to illustrating all details in their industrial relevance to bridge the scientific approach and its industrial application.

Therefore, the book provides both academia and industry with new insights, above all a comprehensive collection of complexity metrics and their interpretation towards common problems in process management. It expands literature in structural complexity management into this field without limitation to its significance to other areas of application, as e.g. the design and management of complex product architectures.

At the same time, the research in this book was motivated to come "full circle", i.e. it was created in a way that both the modeling scheme, the analysis approach and the overall guidance about how both modeling and analysis work together were integrated in a more general framework. This endeavor thus guides the overall outline of the book. Nevertheless, none of these constituents to the solution are designed to be exclusive, so that, for example, the complexity metrics can also be based on models other than the multiple-domain matrices that are used here.

Munich, March 2011

Dr.-Ing. Matthias Kreimeyer

Prof. Dr.-Ing. Udo Lindemann

THE RELEVANCE OF COMPLEXITY METRICS

Industry and scientific research require methods to support management of complex engineering development processes in a way that recognises and exploits the characteristics of their structural complexity. In particular, there is a pressing need to find ways to exploit the structural knowledge represented in process models in support of process management.

This research addresses this need through development of a systematic and scientifically rigorous yet practical approach to modelling and analysing processes. The approach is clearly demonstrated by application to different case studies of automotive design. It thereby presents a significant contribution to practitioners wishing to understand and improve their complex processes. It also fills a major gap in the scientific literature by further developing and systematising the emerging area of structural complexity management in engineering design.

The empirical background of this research highlights the complexity of engineering design and clearly outlines the problem that, even when models of the activities, information flows, resources etc. are available, such models are sufficiently complex that problem areas cannot be identified by inspection. The concept of structural analysis serves here as a promising means to address this by identifying potential ‘problem areas’ within a complex process.

The main body of this research considers a comprehensive state of the art drawn from the fields of system theory, graph-theory, matrix-based methods for structural complexity management, network theory, process management and software engineering. Contributions from these disciplines are combined, using an established approach of system analysis, enhanced with a clear goal-orientation. The solution is therefore based on three constituents:

An enhanced method of process modelling is first introduced that encompasses a means of combining existing process models. This modelling scheme is, above all, constructed in a way that it serves as a means of making the use of complexity metrics compatible with existing models that, similarly, represent dependencies in a system.

Based thereon, 52 complexity metrics are explained to analyze a process. The metrics address the clear and pressing need for a rigorous approach to formalise and prepare the large volumes of data required for process analysis in many practical situations, as it is often the case with complex systems. At the same time, the abstract approach is illustrated with extensive tables to support the interpretation of any findings. Above all, however, the substantial set of 52 metrics should form a major resource for further research in structural complexity management for engineering design.

Third, both modeling and analysis approach are combined offering a goal-oriented conduction of process analysis. This completes the description of the new approach and convincingly supports the technical discussion of previous chapters by showing how the approach can be linked to the real challenges faced in industry.

Supported by three studies, the book clearly illustrates how the method of earlier chapters can be applied. The practical application of structural analysis to understand and improve complex processes is clearly demonstrated and critically reflected upon.

Cambridge, December 2010 Professor P. John Clarkson

Engineering Design Centre, University of Cambridge

BACKGROUND OF THIS RESEARCH

This work results from a series of research projects on the management of structural complexity at the Institute of Product Development at the Technische Universität München. Based on a rigorous research approach as a basis to the systematic obtainment of the results presented in this research, the authors' involvement in numerous research projects provides an experiential basis to design a methodology that fulfils all requirements.

The authors were, among other activities, involved in a major study to identify and conceptualize a possible reorganization of the development departments involved in the design and simulation of the body-in-white of a large German automotive manufacturer[1]. In fact, this project provided the motivation for the research presented in this research, as the initial study at the company showed that almost all problems were interconnected, and the systematic determination of improvement potential, while only "reorganizing" the existing structure, appeared as an almost insurmountable problem.

The authors were also involved in various projects to improve process management in engineering design. At a strategic level, a management framework based on common management models was developed in cooperation with a management consulting firm to better guide the development of automotive safety features [KREIMEYER et al. 2006d]. At the operational level, a project to set up guidelines to access the various committees inside a large automotive manufacturer was run to improve decision making; to do so, the overall structure of the various decision processes was analyzed to obtain specific routes through the various decision-making bodies. Another project was carried out to research the potential and implementation of architectural standards across all models of a premium class automotive manufacturer; here, the goal was to establish all necessary processes to implement the definition of sustainable architectural standards, derive individual models, maintain and update them, and integrate future technologies in a cost-efficient manner.

Part of the research presented in this research was done in collaboration with another large German automotive manufacturer [KÖNIG et al. 2008] [KREIMEYER et al. 2008d]. In combination with the data available from the reorganization project described above, these two comparable projects provided ample empirical data and relevant access to industry to guarantee an approach both pragmatic and relevant. A third set of empirical data was available publicly [Braha & Bar-Yam 2004].

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[1] For an overview see [DEUBZER et al. 2007]; a problem description is given in [KREIMEYER et al. 2005] and [KREIMEYER et al. 2007b]; the core concept is detailed in [HERFELD et al. 2006] and [KREIMEYER et al. 2006a] and completed in [KREIMEYER et al. 2007a].

At the same time, two large studies of engineering design were conducted. One study focused on the collaboration patterns in the "digital factory planning" in automotive companies and their ties to the engineering design and supply industry [KEIJZER et al. 2007]. A second study was carried out as a benchmark comparing the engineering divisions of three firms producing diesel engines of various sizes (400 to 100.000 horsepower). Both studies generated a broad picture of the necessities and particularities of engineering design.

Furthermore, the authors have been active for a long time in research on structural complexity management. As co-founders of the research group "Systems Engineering" at the Institute of Product Development[2], the authors repeatedly organized the International Dependency and Structure Modeling (DSM) Conference[3], which serves as an international platform for practitioners and researchers on structural complexity management. The authors were also co-foundera of the Special Interest Group "Managing Structural Complexity" within the Design Society, and still act as chairs of this Special Interest Group[4]. The authors also re-launched the web-portal www.DSMweb.org[5] to provide the international research community on structural complexity as well as interested practitioners with a comprehensive set of material, publications, and tutorials to facilitate the application of methods to manage structural complexity. At the same time, the authors were directly involved in re-launching the Special Interest Group on "Modeling and Management of Engineering Processes (MMEP)" within the Design Society[6].

Ultimately, much of this experience resulted in the successful application of the Collaborative Research Center SFB 768 on "Managing cycles in innovation processes–integrated development of product service systems based on technical products". Within this research center, the authors led the research group on "Development of models and processes" and supported both project A2 "Modellierung und Analyse disziplinen-übergreifender Zusammenhänge" ("Modeling and Analysis of trans-disciplinary Relationships") and B1 "Prozessplanung für die zyklengerechte Lösungsentwicklung" ("Process Planning for the Efficient Development of Product Service Systems").

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[2] see http://www.pe.mw.tum.de, viewed on 20 February 2009

[3] see http://www.dsm-conference.org, viewed on 20 February 2009

[4] see http://www.designsociety.org/index.php?menu=35&action=21, viewed on 20 February 2009

[5] see http://www.DSMweb.org, viewed on 20 February 2009

[6] see http://www-edc.eng.cam.ac.uk/mmep, viewed on 20 February 2009

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Lastly and mostly, I am deeply grateful to my parents, to Monica, and to my friends for supporting me all the while. Their patience and comprehension eave me the strength necessary for the finishing touch.

Munich, December 2010 Matthias Kreimeyer

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LIST OF ABBREVIATIONS

ARIS	Architecture of Integrated Information Systems
BSC	Balanced Scorecard
BPMN	Business Process Modeling Notation
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CFC	Control-Flow Complexity
DMM	Domain Mapping Matrix
DSM	Design Structure Matrix
EBB	Elementary Building Block
eEPC	Extended Event-driven Process Chain
EPC	Event-driven Process Chain
GQM	Goal-Question-Metric
HOQ	House of Quality
IDEF	Integrated Definition Method
IT	Information Technology
IUM	Business-Process Modeling (Integrierte Unternehmensmodellierung)
MCC	McCabe Complexity
MDM	Multiple-Domain Matrix
NVH	Noise Vibration Harshness: domain of simulation
oEPC	Object-oriented Event-driven Process Chain
OMEGA	Objektorientierte Methode für die Geschäftsprozessmodellierung und –analyse
PERT	Program Evaluation and Review Technique
PMM	Process Module Methodology
QFD	Quality Function Deployment
SADT	Structured Analysis and Design Technique
S-GQM	Structural Goal Question Metric
SMS	Structural Measurement System
SPA	Structural Process Architecture
UML	Unified Modeling Language
YAWL	Yet Another Workflow Language

LIST OF SOFTWARE TOOLS

ABAQUS	Solver for non-linear calculus by ABAQUS Inc.
ANIMATOR	Postprocessor by Dassault Systèmes
ANSA	Preprocessor by BETA CAE Systems S.A.
CATIA	Commercial CAD System by Dassault Systèmes
COVISE	COllaborative VIsualization and Simulation Environment: postprocessor for computational flow dynamics simulations by VirCinity GmbH
ENSIGHT	Computational flow dynamics postprocessor tool by CEI Corp.
EVA	EVAluator: Postprocessor software
FALANCS	Stress and strain simulation tool by LMS International
FEMFAT	Finite Element Method - FATigue: Fatigue simulation tool by Engineering Center Steyr GmbH & Co KG
GS Mesher	Surface and Solid Mesher by MacNeal-Schwendler Corporation
HYPERMESH	Preprocessor by Altair Engineering GmbH
ICEM	Parametric CAD surface modeler by ICEM Ltd.
LOOMEO	Software to support Multiple-Domain Matrices by Teseon GmbH
MEDINA	Pre- and postprocessor by T-Systems Enterprise Services GmbH
MS OFFICE	Office Product Range by Microsoft Corp.
NASTRAN	NAsa STRuctural Analysis: Solver by MacNeal-Schwendler Corporation
PAM CRASH / PAM VIEW	Solver and viewer for crash simulation by ESI Group
PATRAN	Pre- and postprocessor by MacNeal-Schwendler Corporation
PERMAS	Solver for linear calculus by Intes GmbH
POWERFLOW	Computational flow dynamics simulation tool by Exa Corp.
SFE Concept	CAD program with integrated preprocessor and mesher by SFE GmbH
STAR CD	Simulation tool for fluid flow, heat transfer and stress by CD-adapco