

Increasing the reproducibility of structural modelling

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Information management and documentation is a major challenge for the modelling of complex systems. It is difficult for others than the modellers themselves to decide if the structural model at hand is sufficient in quality, scope and underlying information for the desired purpose, as it is usually not possible to reproduce the modelling purpose. Reproducibility in modelling in general is hard to achieve, as the modelling process depends on several individual influencing factors. Existing literature on reproducibility in modelling reveals that the creation process of the model as such, as well as the information over the creation process are both essential for the reproducibility of the generated model. We identify three areas of support in order to increase the reproducibility of structural modelling. We provide a framework for increasing the reproducibility of structural modelling. A documentation template to capture the information generated within the modelling activities is suggested. As a result the framework highlights the importance of documentation for modellers and ensures that all the required information is captured. The application and success evaluation shows the benefit of the framework by increasing the reproducibility of structural modelling and that it also offers opportunities for better information management in general.

Keywords: reproducibility; modelling quality, structural modelling; documentation; information management

1. Introduction and Research Method

1.1 *Motivation and Problem Description*

The engineering design community constantly faces challenges due to the increasing complexity of processes and systems. Based on an explorative study, (Rouse 2007) states that these challenges are related to:

- the intentions with which one addresses the system,
- the characteristics of the representation that appropriately accounts for the system's boundaries, architecture, interconnections and information flows,

- the multiple representations of a system, which are all simplifications,
- the context, multiple stakeholders and objectives associated with the system's or process's development, deployment and operation,
- the learning and adaptation exhibited during the system's evolution.

Reasons for increasing complexity include e.g. shorter product life cycles, manifold customer requirements, multifunctional products or combinations of products and services (Biedermann and Lindemann 2011). Also interactions within and between several domains are a challenging part of large multidisciplinary and networked systems (Diepold et al. 2010). In order to handle and manage this complexity, various methods, mostly from the field of systems engineering, are applied. Structural considerations, such as dependency modelling by Design Structure Matrices, Domain Mapping Matrices or Multiple Domain Matrices, are established approaches to manage complexity.

One methodology for structural modelling in engineering design is the Structural Complexity Management (StCM) methodology. In accordance with the StCM methodology (Maurer 2007) we define the term "structural modelling" as the modelling of the network formed by dependencies between system elements which represent a basic attribute of each system. Structures can thereby be characterized by the specific compilation of implied linkages between system elements and can be divided into subsets (Maurer 2007). StCM offers generic methods for modelling and analysing the underlying structure of complex systems (Lindemann, Maurer, and Braun 2009). The analyses are computed in a so-called Multiple Domain Matrix (MDM) and are used to increase system understanding and as an initial point for the specific optimization of the focused system (Lindemann and Maurer 2007).

Even though the StCM offers a methodology for structural modelling, information management and documentation remain a major challenge for the modelling of complex systems. In particular a lack of reproducibility of the modelling process has been identified as a major drawback to modellers. This can be observed in a survey conducted at the DSM Conference 2010 (Wynn et al. 2010). This lack of reproducibility of the modelling process leads to models where it is difficult to assess the quality of the underlying information. Currently only the model as the result of the structural modelling process is documented, but no further information on the creation process of the model is captured. This makes it difficult for others than the modellers themselves to decide if the structural model at hand is sufficient in quality, scope and underlying information for the desired purpose, as it is not possible for them to reproduce the modelling process. Thus, it is difficult for others to understand how and why certain suggestions and decisions were made.

1.2 Research Objective and Desired Support

The objective of this work is to deal with the lack of reproducibility in structural modelling. To solve this revealed need for reproducibility, we provide a framework for increasing the reproducibility of structural modelling, based on 3 areas of support:

- the modelling process to be conducted,
- the information to be captured, and
- the context factors to be documented.

1.3 Content

This paper is structured as follows: After an introduction to structural modelling and the StCM methodology, we identify what makes reproducibility within structural modelling so hard to establish. Furthermore, we define reproducibility in the context of this work

and provide a literature review on reproducibility in existing modelling frameworks. Based on these insights, we describe the three identified areas of support. Consequently, we introduce our proposed framework as well as a template for documenting the information generated by the modelling process. The framework is evaluated by two experimental setups to prove its applicability and also that it successfully supports the reproducibility of the modelling process.

1.4 Research Methodology

Within this work the Design Research Methodology (DRM) has been used (Blessing and Chakrabarti 2009). In accordance to the DRM, research clarification is presented after an initial problem description, based on an extensive descriptive study I. As part of the prescriptive study, a solution is developed, and the final descriptive study II is presented along with its application and evaluation.

The first section introduces a lack of reproducibility as the initial problem description and clarifies the research as to how structural modelling has to be supported to increase its reproducibility. The resulting research tasks are:

- to clarify reproducibility in structural modelling and to identify the cause for the lack of reproducibility in structural modelling,
- to develop a framework which supports reproducibility in structural modelling, and
- to evaluate the applicability and support of this framework.

In order to fulfil the first research task, in section 2, the theoretical background of structural modelling, existing definitions of reproducibility, as well as the topic of reproducibility within existing modelling frameworks are reviewed. At the end of this section the necessary support is derived from literature and the identified three areas of

support to increase the reproducibility of structural modelling are clarified and further distinguished.

Based on this clarification, the developed framework is presented as a prescriptive study within section 3.

An application evaluation as well as a success evaluation according to (Blessing and Chakrabarti 2009) are conducted to present and review the applicability and benefits of the framework as part of the descriptive study II within section 4. The application evaluation aims to identify whether the developed framework and documentation templates can be used by anyone other than the authors of this paper for the task for which they are intended. To verify the positive effect of the developed support, the success evaluation aims to identify whether the framework and the documentation templates have the expected impact on the structural modelling procedure. Here the focus is on the utility of the developed support.

2. Literature Review

2.1. Background

Structural Complexity Management is a methodology for coping with complexity in the context of product design. It has its origins in the work of (Steward 1981) who proposed the Design Structure Matrix (DSM) to analyse the structure of system design processes.

The DSM is a square-matrix used to represent elements of a system and their interactions (Eppinger and Browning 2012). DSM can be applied in the development of complex, engineering systems and is primarily used in the area of engineering management in a multitude of different applications – for a recent overview on the various methods and applications see (Eppinger and Browning 2012; Browning 2001). The DSM represents a certain view on the system's architecture by showing the

structure of elements of a single domain (e.g. components of a product, process steps within a process, team communication within an organisation). The elements and relations of two domains can be represented in a Domain Mapping Matrix (DMM) (Danilovic and Browning 2004; Danilovic and Browning 2007). For example, in a DMM, functions can be mapped to components of a product.

The combination of several domains within one matrix is called Multiple Domain Matrix (MDM) (Maurer 2007). On the diagonal of this MDM, DSMs represent relations between elements of the same domain and on the other fields DMMs represent relations between elements of two domains.

Lindemann et al. propose the Structural Complexity Management (StCM) methodology for modelling and analysing complex systems by using a MDM as model (Lindemann, Maurer, and Braun 2009). StCM provides a five-step procedure that supports users in system definition, information acquisition, deduction of indirect dependencies, structure analysis, and the application on the product design. Here StCM allows the analysis of a complex system according to its structure. Algorithms for calculating indirect dependencies from direct dependencies are used to generate different views on the system. Both matrix-based as well as graph-based analysis algorithms are applied for the identification of structural criteria that reveal insights about the complex system.

In general, the structure of a system comprises of the elements and their relations (Checkland 1981). Structure is closely related to the architecture of a system as “the system architecture is the structure of a system – embodied in its elements, their relationships to each other (and to the system’s environment), and the principles guiding its design and evolution – that gives rise to its functions and behaviours.” (Eppinger and Browning 2012). Structure can also be illustrated as a network of graphs. (Newman

2003) defines a network as a “set of items, which we will call vertices or sometimes nodes, with connections between them, called edges”.

Information acquisition and information transfer play an important role in structural modelling processes. Different steps have to be performed by different persons to model the structure of a complex system. According to the StCM methodology, the model is built within the first three steps: system definition, information acquisition and deduction of indirect dependencies. To mark the importance of information generation and transfer, the explicit step of information acquisition was inserted in the methodology. This information is the basis for the generation of the structure of the model and the key point of structural modelling (Kasperek, Kohn, and Maurer 2013). Specific challenges that occur within these first three phases and especially in the phase of information acquisition are:

- The solution of complex problems requires the involvement of interdisciplinary stakeholders (Renger, Kolfshoten, and De Vreede 2008).
- One single expert doesn't usually have the competency for both building the model (methodological expertise) and the required knowledge of the system (context expertise) (Mostashari 2011).
- Persons have to interact and exchange information. For example, one person builds the structure model and a second person analyses the model on the basis of the work done by the first person.
- During structural modelling, existing information has to be interpreted (as it has to be represented in the language of models, i.e. the MDM) and new information has to be generated (analysis result, deduction of indirect dependencies). Often the existing information can be interpreted in different ways. Depending on the

specific interpretation of the modeller the model will differ and therefore the analysis results may also differ from the model.

Even though approaches for most of these specific challenges exist in literature, authors state that the reproducibility of the StCM modelling process has to be increased (Kasperek, Kohn, and Maurer 2013). In addition, a survey at the DSM Conference 2010 revealed that the reproducibility of the modelling process remains a major challenge for modelling dependencies in general (Wynn et al. 2010). This can be seen by the aspects the participant rated high when responding to the question: How important is it to improve this aspect of dependency modelling? The most important aspects were:

- Methods to elicit knowledge from experts,
- Methods to assess the accuracy of models,
- Methods to check the consistency of models,
- Methods to validate the analysis results,
- Methods to account for uncertainty.

The results of this survey show that existing methodologies for dependency modelling, i.e. structural modelling, have not reached a sufficient state of conformance with the modellers' demands so far. Within this work, the authors would like to comply with the modellers' demand for increased reproducibility of structural modelling.

2.2. *Reproducibility – Definition*

In scientific research, reproducibility is one of the core aspects of high scientific standard (Stodden 2009) in various scientific disciplines. When evaluating a study or a model, scientists must ask themselves “how reproducible are the findings ?” (Dingman 1969).

A lack of reproducibility of scientific results would lead to meaningless interpretation and analysis (Downing 2004; Spitas 2011). Reproducibility (repeatability) of experimental results is an essential requirement (Wiebe and Pizzi 2007) of scientific results. (Donoho et al. 2009) shows the effects of bad reproducibility by identifying that without reproducibility it is impossible to verify most of the results that computational scientists present at conferences and in papers.

Reproducibility is interpreted differently across disciplines, see (Anda, Sjøberg, and Mockus 2009) for a review.

According to the same authors, reproducibility is often closely related to the definitions of repeatability and replicability. In an encyclopaedia of the philosophy of science (Tetens 1995), reproducibility is defined as the repeatability of the process of establishing a fact, or of the conditions under which the same fact can be observed. Reproducibility in natural science is often related to the repeatability of experimental conditions and results. (5725-1 1994) defines conditions of reproducibility as conditions under which test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment.

Based on a statement, given by (Anda, Sjøberg, and Mockus 2009), on the reproducibility of software engineering projects and products, the following statement can be deducted for structural modelling projects of complex systems: As complex systems are, by definition, not trivially small or simple, it is unlikely that models of complex systems are completely reproducible in all respects. Every modelling project has its own unique requirements and is carried out by a unique modelling team. Here (Anda, Sjøberg, and Mockus 2009) state that the team is unique in the sense that, even if the same team were to conduct several identical projects, their experience would increase from one project to the next. Consequently, we draw the conclusion that it is

not usually possible to study the reproducibility of complete modelling projects of complex systems.

In this paper, also loosely based on (Anda, Sjøberg, and Mockus 2009), we consider structural modelling as reproducible for a given purpose, if the structural model that results from the structural modelling process is sufficiently similar to an original structural model of the same system, which was modelled by another person or team.

2.3. Reproducibility in Existing Modelling Frameworks

Reproducibility is not only a challenge for structural modelling. Reproducibility in modelling in general is hard to achieve, as the modelling process and the model as its result depend on several individual influencing factors: Two business architects, without a common method, tend to develop different models of the same real world. Individual assumptions used by the modellers can be another factor that can lead to different models even of the same system (Halfon 1983). In addition, general objections and aversions against reproducibility exist (Donoho et al. 2009), as people do not see the general benefit. (Donoho et al. 2009) discuss several objections (time effort, missing individual benefit, complexity issues, etc.) and show that most of them are wrong.

Different approaches exist in several fields that try to emphasize and ensure reproducibility within processes and modelling frameworks. Table 1 shows and compares the aspects addressed by frameworks for increasing reproducibility in modelling and the provided support in each framework. The frameworks focus on the documentation of modelling processes, the sharing of data and the models, a shared environment for modelling and use of the models and the documentation of context factors. Each framework provides individual support for some of these aspects.

(EFCOG 2010) identifies documenting the questions to be addressed by the research as vital for common understanding, reproducibility and an assurance that the correct questions are being asked.

The Yale Law School Roundtable emphasize the need for data and code sharing in different fields as geoscience, neuroscience, bioinformatics, applied mathematics, psychology and computer science (Yale Law School Roundtable on Data and Code Sharing 2010). They provide recommendations for scientists, funding agencies, and journal editors, in the form of steps that scientists can take to generate reproducible results.

(Howe 2012) identifies cloud computing as a possibility for achieving reproducibility in science, and provides reasons on how cloud computing can improve reproducibility, as well as describing the remaining challenges. By cloud computing, shared and collaborative environments can lower the costs of modelling and improve data sharing and the reuse of models. (LeVeque, Mitchell, and Stodden 2012) investigate reproducibility in computational research and identify obstacles involved in creating reproducible computational research as well as some efforts and approaches to overcome them. The growing amount of available data, examples of reproducibility and tools and best practices for reproducibility are identified as major themes in this field. They state that context information about the modelling process has to be captured.

Model repositories are used to enforce the reproducibility of models in science – for example model repositories in Systems Biology (<http://systems-biology.org/resources/model-repositories/>), the BioModels Database (<http://www.ebi.ac.uk/biomodels-main/>) and Reproducible Research Planet (<http://www.rrplanet.com/>). Reproducibility is enforced by fixed annotations of submitted models by linking model components with terms from controlled

vocabularies and entries in data resources (<http://www.ebi.ac.uk/biomodels-main/annotation>). Reproducible Research Compendiums (RRC) serve as a container for the different elements of a result (e.g. all documents, code or data of the research) that are necessary for others to understand and reproduce the research (Gentleman and Temple Lang 2004).

(Vitek and Kalibera 2011) also emphasize the importance of documentation in order to achieve reproducibility. They demand the development of minimal standards for documenting the experimental conditions and reporting the results. (Kolic 2009) proposes steps and documentation of the parameters in order to enable a more repeatable, reproducible, and valid test method for characterizing lumbar support in automotive seating.

Table 1. Summary of existing frameworks for increasing reproducibility and the addressed aspects therein

Literature	Aspects addressed by the framework				Provided / demanded support
	Documentation of processes	Data/Model sharing	Shared environment	Documentation of context factors	
EFCOG, 2010	X				Quality guidelines
Round Table, 2010		X		x	Recommendation for process steps
Howe, 2012		x	X		Cloud computing
leVeque, Mitchell, Stodden, 2012		X			Model repository
Gentleman & Temple Lang, 2004		X	X		Reproducible Research Compendiums (RRC)
Vitek & Kalibera, 2011	X			x	Minimal standards for documentation

Kolich, 2009	x				Recommendation for processes
Zaychik & Regli, 2003	x			x	Collection of context factors

The reproducibility of results is often closely related to the quality of decision making and the traceability of decisions. In engineering design, many different decisions have to be made (Krishnan and Ulrich 2001). In order to evaluate the quality of decisions, the reasons behind them have to be traceable (Ayağ and Özdemir 2007). The traceability of decisions is influenced by the complexity of the considered documentation, the available documentation, the informal knowledge acquired through experience, and the accessibility both to documentation and knowledge (Cimitile, Lanubile, and Visaggio 1992).

(Zaychik and Regli 2003) identify context factors as important for reproducibility (context=collection of circumstances or conditions) this also includes influences on the modelling process. Also, they capture communication and context factors in the software project lifecycle to enable context-aware e-mail collaboration among software developers. They define context factors as the collection of circumstances or conditions under which the considered process occurs.

In engineering design practice, reproducibility is hard to achieve. (Busby 1999) identified the aversion of most designers to writing and reporting. Due to the immanent time pressure in engineering design, documentation is often labelled as 'non-value-adding activity' as it does little for the current project (Busby 1999). This aversion against documentation poses a great challenge for the reproducibility of structural modelling in practice. Therefore, a balance of the amount of documentation and the gained benefit of reproducibility always has to be borne in mind. (Yale Law School Roundtable on Data and Code Sharing 2010) propose that the extent and volume of

documentation should be commensurate with the risks associated with the consequences of not having documentation.

2.4. *Identified areas of support for increasing the reproducibility of structural modelling*

By looking at the existing work on reproducibility in modelling, it can be seen that the creation process of the model as such, as well as the information on the creation process are both essential for the reproducibility of the generated model.

Based on this insight, we can identify three areas of support in order to increase the reproducibility of structural modelling:

The modelling process: As e.g. (Yale Law School Roundtable on Data and Code Sharing 2010) claimed, there is a need for more data. Even though a methodology for the StCM modelling process exists, the guidance through the detailed steps of the modelling process should be increased, as the existing three steps (system definition, information acquisition and deduction of indirect dependencies) are too generic to explicitly specify all necessary activities. In addition, considering e.g. the work of (Dingman 1969; EFCOG 2010), it has to be questioned whether all necessary activities for reproducible structural modelling are incorporated in the StCM modelling process.

The capturing of information generated within the particular modelling steps: For the existing three steps of the StCM modelling process, the MDM is the only location where the generated data can be stored (Lindemann, Maurer, and Braun 2009). As the capturing and documentation of information about the particular modelling activities is identified as major aspect of reproducibility by various authors, we claim that this area needs further support. An important aspect that has to be considered for this area is that the literature review identified an aversion against documentation by most of the modellers.

The documentation of context factors on the modelling process: Because e.g. (Zaychik and Regli 2003) identified context factors as being important for reproducibility, these factors also should be documented. Context factors can be seen as factors that influence the generation of the information within the particular modelling steps.

3. Framework for increasing reproducibility in structural modelling

Based on the three identified areas of support, a framework to increase the reproducibility of structural modelling is introduced. First, the enhanced version of the first three steps of the classic StCM methodology, which are the steps in which the actual MDM model is generated, including additional modelling steps and activities, is presented. This is followed by a description of which information generated in the particular modelling steps the authors see as necessary for the reproduction of the modelling process. Here we also focus on context factors of structural modelling. In the last part of this section, we provide a documentation template for documenting the necessary information for increasing the reproducibility of structural modelling according to our framework.

3.1. *Enhancement of the classic StCM modelling process*

Figure 1 illustrates the proposed modelling process for increased reproducibility within structural modelling. Within this illustration, the modelling phase of the StCM methodology with its classic steps of system definition, information acquisition and deduction of indirect dependencies is addressed, further detailed, and enhanced. The step structure analysis and product design application are not discussed in the modelling process for increased reproducibility, as they focus on the analysis of the structure. The existing classic structural modelling process (system definition, information acquisition

and deduction of indirect dependencies) is summarized in the step modelling. Therefore two additional steps of problem definition and model purpose and conceptual preparation of modelling are added before the main Modelling step. The step of model validation is added at the end.

The proposed modelling process consists of four modelling steps which are comprised in two comprehensive steps. The first comprehensive step is the step Basics on StCM modelling which addresses the fact that the modellers should have basic knowledge of the StCM methodology and modelling in general before conducting the modelling activity to ensure high quality modelling.

Another procedure which runs parallel to the four central modelling steps is Parallel activities. This procedure is proposed as not all activities within the modelling process can be assigned to sequential steps, but also may generate important information for the reproducibility of the modelling process. For instance, project controlling as one of these parallel activities may reveal mistakes within previous steps that significantly influence the further modelling process. Most of these parallel activities can be considered as project management.

3.1.1. Problem definition and model purpose

Classically, the StCM modelling process starts with the step of system definition. The result of this step is the so-called meta model. The meta model represents the modeller's view of the most important entities and interactions for the description of the considered system (Kortler and Lindemann 2011). Here the domains of the MDM and their dependencies are defined.

In this first step, even though an in-depth look into the system, the problem definition and the potential sources of information was conducted, no further information on the considered system than the meta model is documented. This loss of

information makes it difficult for others to reproduce the modelling process, as the link between the originating system and the meta model is very thin. According to (Stachowiak 1973), information about the original system is very important to understand the generated model and its functionality.

Therefore, we suggest inserting additional modelling steps at the beginning of the modelling process. As (Stachowiak 1973) states, the modelling process should start with the definition of the problem to be solved and the model purpose.

3.1.2. Conceptual preparation of modelling

After the problem definition and the description of the model purpose, the modelling activity can be conceptually prepared. This additional step “conceptual preparation of modelling” has two main subjects: Potential areas of consideration have to be identified as well as potentially available sources of information or knowledge. The object is to obtain an overview of the considered system.

The preceding step conceptual preparation of modelling shall therefore provide the basis for the following, classically first, modelling step of system definition. To create an overview of the considered original system and available data increases the likeliness that the structural model is, according to the authors’ definition of reproducibility, sufficiently similar to other structural models which are generated by the same modelling framework.

3.1.3. Modelling

This step includes the classic activities in the context of structural modelling: system definition, information acquisition and deduction of indirect dependencies as suggested by (Maurer 2007).

3.1.4. Model validation

In addition to the incorporation of steps at the beginning of the modelling process, we also suggest the inclusion of a further step of model validation at the end of the modelling process. (Moody 2005) states that a validation of models is of substantial importance for later use of the models when assessing their quality. Table 2 describes the modelling steps incorporated in this framework.

Table 2. Modelling steps of the framework for increasing the reproducibility of structural modelling.

No. of step	Name of step / procedure	Description
0	Basics of StCM	The knowledge about structural modelling and the framework for reproducible structural modelling itself, form the basis for the application of the suggested framework and are illustrated with a triangle above the other modelling steps.
1	Problem statement and model purpose	The actual framework begins with the definition of the particular problem statement and model purpose: Within this step the problem statement and model purpose shall be adjusted iteratively until they both fit together. Here the problem definition represents the actual problem that shall be solved by the structural model. Typical questions to be answered are: What is the context of the problem? Why is the problem relevant in this context? It is also necessary to define the model purpose, as this is the actual description of how the model shall contribute to solve the stated problem.
2	Conceptual preparation	The modelling has to be conceptually prepared. This includes two steps: Potential areas of consideration have to be identified as well as potentially available sources of information or knowledge. Here, no concrete decisions are made. The object of these two steps is to obtain an overview of the considered system. For each problem, a certain aperture of reality is relevant. These apertures shall be collected within the step of identifying potential areas of consideration before the actual modelling. With the step potentially available sources of information or knowledge, the goal is the same on an availability of information level: What information may be available about the system? Where is the information stored? Within the mind of experts or within databases?
3	Modelling	With this step, the classic StCM modelling steps of system definition, information acquisition and deduction of indirect dependencies are addressed.
4	Model validation	After the modelling process itself is finished, the obtained result has to be validated. Within the proposed framework, we incorporate two particular steps of model validation: The particular step of model validation and verification. Within the step of model validation and verification, the model has to be validated to see if it serves the originally aspired model purpose as defined at the early stage, and also verified to see if the implementation is flawless.
P	Parallel modelling activities	Not all modelling activities can be performed as sequential steps. Therefore these on-going activities have to be documented in addition to the previously-described sequential modelling steps.

3.2. Detailed modelling activities for the enhanced modelling process within the framework

For the existing three steps of the structural modelling process - system definition, information acquisition and deduction of indirect dependencies, the only location for storage of the generated data is within the MDM. Here domains of the system can be appointed and elements can be assigned to them. In addition, interdependencies between the domains can be depicted and these interdependencies can be also depicted on a more detailed level between the particular elements by relations.

Within the current StCM methodology, no additional information has to be stored by the modellers. Information about why particular domains were chosen, or which sources of information were used is currently not available. This kind of information is necessary to increase the reproducibility of the structural modelling process, because:

- Important decisions made during the modelling process are necessary to understand the model as well as to assess the quality of the model.
- Parts of the model, such as the meaning of domains and dependencies, may not be understandable without further information.
- Information about the background of the modelling activity such as resources and time frame are necessary to assess the model.

Important decisions during the modelling process have to be documented, as well as the reasons why these decisions were made. This means that all steps in which decisions that influence the modelling process are taken have to be made explicit and documented. Therefore the modelling process as illustrated in Figure 1 has to be further detailed and subdivided into particular modelling activities. The modelling activities are

defined by decisions to be made within the structural modelling process. The particular modelling activities for each modelling step are shown in Figure 2.

Table 3 provides an overview of the suggested particular modelling activities. The small postit notes assigned in Figure 2 are a preview on the assignment of modelling activities to categories as explained in sub-section 3.4.

Table 3. Overview of the individual steps of the framework for reproducible structural modelling

No. of step	Name of step / procedure	Notes
0. 1	Basics of StCM	To successfully use the framework for increasing the reproducibility of structural modelling, the modelers have to be aware of the main basics of this methodology.
1.1	Definition of problem statement	The concrete problems that need to be solved by the pending StCM activity have to be stated.
1.2	Definition of model purpose	The purpose of the model also has to be stated for precise modelling. The model purpose offers a higher level of abstraction than the problem statement.
1.3	Analysis of solvability of problem statements by model purpose	The solvability of the particular problem statement by the purpose of the model has to be questioned. In this step, one has to question whether the desired models actually have the potential to decrease the inner variance. Otherwise, the system boundaries may have to be adjusted: for instance supply-chain components also ought to be included.
1.4	Project planning	Project planning includes the assignment of resources and responsibilities to work packages within the modelling task, as well as the use of classic tools for project planning such as GANTT charts.
2.1	Identification of potential areas of consideration	For each problem statement, a certain aperture of reality is relevant. These apertures have to be collected within this step in advance of the actual modelling
2.2	Identification of potentially available sources of information or knowledge	With this step the goal is to identify: What information may be available on the system? Where is the information stored? Within the mind of experts or within databases?
3.1 and 3.2	Definition of areas of consideration and definition and assessment of quality of potential sources of information	When beginning of the actual modelling, two steps have to be conducted simultaneously due to their high interconnectivity. A certain level of detail has to be chosen for the model. This step is only possible through the mapping of the potential sources of information on areas of consideration and through an assessment of the quality of these potential sources.
3.3	Definition of domains	As the boundary of the considered system is defined and the sources of information are determined, the domains of the multiple domain matrix have to be defined. Domains are fundamental parts of the meta model of the MDM. They enable the grouping of single elements according to their meaning. The definition of domains step includes the documentation of all necessary information for the comprehension of the domains.

3.4	Definition of interdependencies	Interdependencies are, besides the domains, the second part of the meta model of the MDM. Interdependencies describe the meaning of a relation between two domains. They have to be obtained directly or indirectly by computation.
3.5	Choice of information acquisition technique	After the definition of the meta model, a technique for the acquisition of information has to be chosen, as the correct acquisition technique is dependent on the situation and the project context. Common techniques used are: surveys, databases, workshops, etc.
3.6	Determination of elements	With the chosen information acquisition technique, elements have to be determined. An element is an instance of a domain and may be connected to other elements by relations.
3.7	Determination of relations	Relations are instances of interdependencies as defined in the meta model and have to be determined. A directly determined relation describes the dependency between two elements that has not been computed.
3.8	Deduction of indirect dependencies	Dependencies can be also deduced indirectly by computation. Consequently these indirect relations describe relations resulting from deduced indirect interdependencies. The interpretation of indirect dependencies determines the meaning of a relation.
4.1	Model validation and verification	The model has to be validated if the model serves the original model purpose, and verified if the model implementation is flawless.
4.2	Estimation of the degree of reproducibility	In addition to the model validation and verification, the degree of reproducibility of the modelling activity should be estimated. This can be conducted for example through an assessment of the quality of the generated documentation.
P1	Project monitoring and management	To uphold the quality of the modelling process, supplementary steps of project monitoring and management have to be conducted. If any deviation is identified, the cause and effect of this deviation (e.g. change of project aim) have to be documented.
P1.1	Mapping of compliance with model purpose	The project's progress has to be mapped. This includes the comparison of the achieved modelling results with the initial modelling purpose and, if required, an alignment of the modelling results with the purpose.
P1.2	Mapping of achievability of model purpose	New insights on the considered system can necessitate a change within the model purpose. Therefore the achievability of the modelling purpose has to be mapped.
P2	Management of conflicts and disagreement	The management of conflicts and disagreement can be seen as another supplementary step. Conflicts and disagreement may occur at any project at any time and need to be managed. They are not necessarily negative, but they should be resolved and the solution should be documented. Here, the focus lies on conflicts and disagreement within the single steps of the framework for reproducible structural modelling.

3.3. Context factors influencing the reproducibility of structural modelling

(Cimitile, Lanubile, and Visaggio 1992) and others especially emphasize the influences of context factors on the decision-making process. Therefore, in addition to the information generated within the modelling steps, we document context factors on the modelling activities within our framework where necessary.

Context factors are factors that influence the generation of the information documented in the documentation template. These influences on particular modelling activities, causing the decisions taken, are often necessary to understand the modelling process.

A lot of context factors on modelling processes can be found in literature. For example, (Renger, Kolfshoten, and De Vreede 2008) state that context factors such as group factors (e.g. size and composition), task (e.g. session time, model goal) and interventions (e.g. roles and modelling approach) influence the outcome of the modelling process. As for example (Clevenger, Haymaker, and Ehrich 2012) state that documentation effort should be not excessive, we have clustered these factors into three categories for documentation:

- Involved persons
- Team aspects
- Surrounding conditions

Involved persons: Within this category, the modellers can annotate, if according to their point of view, factors like the motivation of the participants played an important role within the generation of the particular information. Other possible factors could be special skills of the participants or cultural aspects.

First evaluation studies have shown that modellers suffer with the unspecific nature of this category. Therefore we have divided this category into elementary competences, expertise, modelling experience, and motivation. For each of these sub categories, modellers have the possibility to annotate context factors.

Team aspects: If the modellers think that team aspects such as role allocation, responsibilities, or team sources played an important factor, they can describe them

within this category. For instance, it could be possible that particular persons that may have the required information, but do not dare to say because the line manager is in the same round.

Surrounding conditions: In this sub category, modellers can annotate other factors that might have influenced the modelling activity significantly, such as the time of the day, room conditions, or time pressure.

Not all categories are equally important for each modelling activity, and it is not necessary to generally document all three categories of context factors. The authors suggest rating the importance of the particular factor on the modelling activity on a scale from 1 (not a great influence) to 3 (highly influential). As a guide, all influencing factors rated as highly influential (3) should be documented. It has to be noted that modellers might not correctly assess the level of importance of the context factors. Their participation in the modelling process biases their perspective. Nevertheless, this rating can give an insight into the occurrence of context factors during the modelling process. Their perspective may be useful for others and also be beneficial for the modellers themselves by having to reflect upon the modelling activity.

3.4. Documentation templates

The generated information is manifold, and a procedure for saving this information is needed. This reveals the question where and how this information should be documented. Therefore, we propose documentation templates for each modelling activity to capture the generated information.

Within this documentation template, the information to be captured is assigned to a modelling activity and described. This is followed by a detailed description of how the information shall be documented for each particular activity and a description of how the authors define the information to be documented.

This is followed by a field where the modellers can enter the requested information.

Within this template, all the information required to reproduce the particular activity should be stored. Consequently, this document also captures information about the context factors on the modelling activity: In the last part of the template, the categories of the context factors are listed with the possibility of rating the influence. The modeller could be asked the question “Was the generation of the information within this modelling activity influenced by these context factors?” The possibility to enter a description for each particular context factor that influenced the activity should be provided.

In the end, one documentation template should be filled out for each particular modelling activity. As the modelling process consists of numerous modelling activities, a high amount of documentation templates will be generated.

As these documents are designed for the reproduction of the modelling process by persons not involved in the modelling process, the documents are ordered in a different way than the sequential modelling steps, respectively activities. The categories for the order of the documents, as identified by a precedent series of interviews with structural modelling experts, are given below. The question for the interviews was: “Which categories interest you for understanding and reproducing a structural modelling process?”:

- A - Problem description
- B - Project, conflict and change management
- C - Meta model
- D- Sources of information
- E- Elements and relations

- F - Model validation

4. Evaluation and discussion of the modelling framework

Section 3 introduced a framework for increasing the reproducibility of structural modelling to enhance information generation and transfer. The steps and activities of the framework were discussed in detail, context factors were defined and a documentation template was presented. This section evaluates the applicability of the framework and its benefit in increasing the reproducibility of structural modelling.

To evaluate the applicability of the framework, it was applied in two different use cases: A group of mechanical engineering master students applied the framework within a one-week student project on systems engineering. To further prove its industrial applicability, the framework was also applied in an industrial value management project (Section 4.1). Based on a proven applicability (Section 4.2), the framework was evaluated for its benefit in increasing the reproducibility of structural modelling by a case study conducted with an expert focus group on structural modelling consisting of post doctorates and PhD candidates with industrial background (Section 4.3). The results of the evaluation on the success of the modelling framework are discussed in section 4.4.

4.1. Evaluation of the applicability of the modelling framework

In the systems engineering project, a group of 10 mechanical engineering master students used the StCM methodology and several other methods in the field of systems engineering to decompose, understand and redesign a complex industrial system. Here DSM and MDM models were used. The students applied the framework and documentation templates throughout the modelling process. After the week they were interviewed to give feedback on the framework and the documentation templates. In

general, the master students were able to apply the framework without further support by the authors, except an illustration of the framework and the documentation templates for each modelling activity including a description of the particular modelling activities.

The applicability of the framework was also evaluated in an industrial use case. The case was taken from a value engineering project for an engine. For the analysis of the component and function relationships, an MDM model was designed. The structural modelling process of the MDM model was carried out with the modelling framework. It was executed by an experienced StCM modeller.

4.2. Discussion of the applicability of the modelling framework

All of the master students of the systems engineering project group stated that the use of the framework caused a lot of knowledge to be gained for subsequent structural modelling activities, meaning that the process would be less challenging for further applications. They reached this conclusion based on their previous experience in the modelling of structural models and stated it at the interviews at the end of the project without any scale provided to the master students. A positive aspect mentioned by most students was the reflection of their own approach to model systems with the StCM methodology and the higher quality of the StCM model. In conclusion, the students agreed on the applicability of the framework and assumed an increased reproducibility of structural modelling using the framework. Although this is under the precondition that the modeller should have some basic knowledge and experience in StCM modelling and has already used the framework. The students also specified some challenges. The effort of filling in the documents was questioned, and difficulties in understanding parts of the documentation were discussed. These challenges are affected by the shortness of the time available to fill the documents due to the tough schedule for the project and the limited experience of the students in StCM modelling.

The industrial use case from the value engineering project also confirmed the applicability of the framework. The experience of the modeller in StCM modelling resulted in only minor challenges when filling in the documents. As an aside, not all requested information was populated in the documentation form as it wasn't acquired during the project, or modelling steps didn't occur, or problems hadn't been discussed. Therefore it is assumed that the necessary information to reproduce a particular structural model is individual and dependent on project-specific conditions. It may not be necessary to fill in every field of the documentation templates for each structural modelling activity.

4.3. Evaluation of the success of the framework for increasing the reproducibility of structural modelling

The success evaluation of the framework was carried out in a case study workshop. 12 post doctorates and PhD candidates of the institute of product development with expertise in modelling and especially StCM modelling were chosen as participants.

Use case, scenario and experimental setup: Results of an industry project dealing with an optimization problem in robot welding were used to build a scenario for the evaluation. In the original project, interdependencies between the welding sequence and welding distortion are analysed using StCM methodology. For the scenario, it is assumed that the responsible engineer in the project is leaving the company. An MDM of the welding process and the main results are already documented, but a simulation for the verification of the results is missing. A successor has to carry out this simulation. Therefore they have to understand the problem and the documents.

Every participant of the workshop assumes the role of the successor who has to understand the remaining documents. Every participant receives extensive data on the project documentation, for example a detailed MDM matrix of the problem, a

publication written about the results (Maisenbacher et al. 2012) or an overview of different analysis steps carried out in the MDM. In addition, the participants of the test group receive the filled documentation templates of the framework for the modelling process of the MDM, including the context factors as rated by the responsible engineer. The available time to understand the system was 2 hours for both groups. After this time the participants had to answer two kinds of surveys. In the first survey they were asked questions about the welding problem to show that they understood the project and its results. In the second survey, questions about the work, benefits and challenges with the documents were asked. A control group received the same questions and documents without the populated documentation templates. The objective of the proposed evaluation was to compare the reproducibility of the welding model with and without the modelling framework. Neither of both groups applied the framework, but assessed the reproducibility of the existing model. One group with the modelling framework and one group without the modelling framework. The main group had seven participants, whereas the control group had five participants. The answers given by the two groups were compared and analysed to evaluate the utility of the modelling framework. The questions of the second survey are given in Table 4.

Table 4. Questions of the second survey of the success evaluation concerning the benefits and challenges of the provided documents

General information
1) Age, gender, position
Questions concerning the expertise of the participants
2) How many DSMs, DMMs, or MDMs have you already modeled?
3) How long have you already worked in the field of structural modeling?
4) How do you rate your experience in structural modelling on a scale from 1 to 10?
Assessment of the reproducibility
5) Did you experience an increase in reproducibility with the information provided within this case study compared to the usual information on the modelling process?
6) Were you able to reproduce the modelling process based on the information provided? Evaluate the perceived reproducibility on a scale from 0 to 10
7) Which kind of information helped you the most to reproduce the modelling process?
8) Which kind of information did not help you to reproduce the modelling process?

<p>9) Which kind of information was destructive to reproduce the modelling process? 10) How many minutes did it take you to understand the system? 11) Was the information processed in an appropriate manner 12) If not, where do you see room for improvement?</p>
<p style="text-align: center;">Personal perception</p> <p>13) How did you proceed to reproduce the provided documents? 14) What was especially helpful concerning the provided documents? 15) Do you see any critical points concerning the provided documents? 16) Was the time spent for viewing the provided data proportionate to the knowledge gained? Rate on a scale from 1 to 10 17) Do you feel sufficiently informed by the available information for the upcoming phase of system analysis? 18) If not, why? 19) Do you think the effort in creating the provided documentation is worth concerning the benefit of the documentation? Rate on a scale from 1 to 10. 20) Do you think participating in this evaluation was beneficial for your daily work? 21) Would you have modelled the same MDM if you were faced with the same problem statement?</p>

The answers to the illustrated questions were used to conclude the following statements of this section. For each statement the originating questions are indicated in brackets. It was not possible to directly draw any statements from the questions that are not referred to in the text.

Expertise of the participants: The first questions in the survey about the usability of the framework ask about the knowledge the participants have of structure or StCM modelling (Q 2-4). On the question of how long they have been working in the field of systems engineering (Q 3), the average answer was between one and two years. On average, every participant has already modelled 10 to 20 DSM models (Q2) and estimates his own knowledge on structural modelling as six or seven out of ten, whereby ten is an absolute modelling expert (Q4). In the answers no significant differences between the main group and the control group were observed.

4.4. Discussion of the success of the modelling framework

Discussion of evaluation results with regard to comprehension of the model: To verify whether the participants had really understood the welding project and if their statements on their expertise are correct, the first survey with the questions concerning

the welding project was used. This survey asks detailed questions on the approach in the welding project, results and special characteristics of the project and therefore monitored the knowledge gain of the participants based on the available documents in regard to content. As an average eighty percent of the questions have been answered correctly, it can be assumed that the participants understood the project and the modelling process with the delivered information, and were able to give meaningful comments on the benefits and challenges in using the documentation forms.

On average, the participants required between forty minutes and one hour to understand the welding problem (Q10). In the answers on the questions concerning the welding problem itself, no significant difference between the main group and the control group was observed. This means that both groups understood the system over a roughly similar time. In addition, both groups rated the knowledge gained from the delivered documents as being highly positive (on average 7 out of 10) (Q16) and the added value in comparison to the effort still positively (on average 6.5 out of 10) (Q19).

Discussion of evaluation results with regard to documentation: One reason for the good and also rapid understanding of the welding problem and the good ranking of the documents is that the delivered information for both groups included a conference publication (Maisenbacher et al. 2012) and the presentation slides of the welding problem (Q7). These two documents summarized the approach and the main results in the welding projects so that the participants in the control group were also able to obtain a quick overview without having to have an in-depth look into all delivered documents. On the question of which document was the most helpful one for understanding the problem and reproducing the DSM (Q7), all participants of the control group named the publication. In contrast, five out of seven participants in the test group stated that the

filled documentation templates are the most helpful documents in the workshop. So in this group the documentation forms are rated higher than the publication documents.

Another fact which directly shows the benefits of the documentation framework appears through the answers to the question of in which order the documents were viewed to understand the welding project (Q13). Five out of seven participants in the test group went through all filled documentation templates first and afterwards through the proposed additional information referred in a certain documentation form. The control group conducted an overview of all information and then viewed the documents in different sequences. In this way, the documentation forms supported a structured sequence in capturing the information.

One advantage of the documentation form is, as stated by five participants from the test group, that the workshop, especially the documentation framework, increased awareness of the importance of documentation in modelling (Q20). A structured framework supports modellers in writing a complete documentation of a structural modelling project, and ensures that important information such as decisions is documented.

Discussion of evaluation results with regard to reproducibility: The results of the evaluation also prove the statement of (Anda, Sjøberg, and Mockus 2009): Even with the proposed framework, as the considered systems for the evaluation was not trivially small or simple, three of the seven participants with the framework stated in response to the specific question of whether they would be able to build an exact copy of the structural model themselves that they would not be able to do so (Q21). The other remaining four participants stated that they were not sure and thought that more information would be required. A similar structural model can, even with the framework, hardly be produced.

However, it can be concluded that the reproducibility of the structural modelling process as defined in this work as sufficiently similar to an existing model has been increased. For all of the questions Q 5, 6, 11 16, 17 the results for the group supplied by the framework were better than for the control group without the framework. A summary of the particular answers of the participants of both groups is illustrated in Figure 3.

The authors conclude that the framework not only provides support in increasing the reproducibility of the structural modelling process, as implied by Q5 and 6, but also facilitates the modellers in documenting the information in an appropriate way. The positive result of Q16 might indicate that this framework could be seen as benefit for modelling practitioners, as it seems to be a practical way of storing important information from a time-economic point of view.

However, the effort required for applying the modelling framework has to be proportionate to the benefit of having additional information. For the complete range of possible documentation, from a complete (simplistic) record of all modelling assumptions for example by screen captures all the way to no records, the benefit of having additional information changes.

With the framework for increasing the reproducibility of structural modelling the aim was to find a compromise on both scales: effort of documentation and benefit of the information documented. We agree with two participants of the test group that the framework can require a large amount of additional effort for the modeller, and it has therefore to be discussed whether such time-consuming documentation is required for all structural models (Q19). Further research is needed to determine how the addressed effort-to-benefit ratio for the framework can be accurately assessed. The authors are in agreement that for models where the probability of utilization by persons other than the

original modellers is low, it might not be worthwhile, but for models with a high probability of reutilization, an entire and structured documentation might be essential. Such documentation can be ensured by using our framework for increasing the reproducibility of structural modelling. One aspect that has not been addressed within the conducted evaluation is the preparation of the documentation templates: The success of the framework might be further increased by optimizing the information, form and layout of the documentation templates.

5. Conclusion

Within this paper, we provide a framework for increasing the reproducibility of structural modelling of complex systems. We identify what makes reproducibility so hard to establish within structural modelling. Furthermore, we define reproducibility in the context of this work and provide a literature review on reproducibility in existing modelling frameworks. Based on a definition of reproducibility and a literature review on reproducibility in existing modelling frameworks, we identify three areas of support:

- The modelling process
- The capturing of information generated within the particular modelling steps
- The documentation of context factors on the modelling process

Consequently, the classic structural modelling process is extended by additional modelling steps to increase the reproducibility. Detailed modelling activities are defined for the particular modelling steps. A documentation template to capture the information generated within these activities is suggested. In addition, we propose that context factors on the modelling activities should be documented within the documentation template. An application and a success evaluation are conducted to evaluate the applicability and the usefulness of the framework.

As a result, the framework highlights the importance of documentation for modellers, and ensures that all required information is captured. The information is stored in a structured sequence and is easier to reuse. Therefore it facilitates modellers in documenting the entire information in an appropriate manner. The evaluation shows that the presented framework not only serves to increase the reproducibility of structural modelling, but offers opportunities for better information management in general. In comparison to the current method of only capturing the information incorporated in the MDM, the framework offers various benefits. However, the industrial use of the framework requires additional work and effort.

For further research, we suggest the discussion of different scenarios and conditions for application of the framework. If the information on a modelling procedure is only required in part or not in detail, the framework might be reduced in scope. In contrast, if the information is required several times, a complete documentation as ensured by the framework is suggested. Furthermore, we suggest adapting the idea of this modelling framework for other fields of modelling, as a lack of a structured and thorough technique has also been identified by researches within other modelling disciplines.

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