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Cumulative Dissertation

ENVIRONMENTAL SYSTEM-OF-SYSTEMS ENGINEERING FOR INTEGRATED NEXUS DESIGN
-
DEVELOPING PARTICIPATORY APPROACHES TO DESIGN DECISION MAKING PROCESSES IN COMPLEX HUMAN-NATURE-TECHNOLOGY SYSTEMS

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Preface

Pro-active participatory design of social, environmental and technical systems is required to decrease resource exploitation and that damage which humanity inflicts on our planet. Whereas the earth actually does not depend on humanity, we depend on the available natural resources to sustain our livelihoods. The design of our environment has always been an elementary part of human life. Nowadays, we take many objects which influence our daily lives for granted: Technology such as computers, smartphones and fitness trackers; social services and platforms such as medical support services and personal coaching programs, but also natural services such as ecosystem services which provide clean drinking water, fertile soil and recreational areas, just to name a few. However, what modern society seems to underestimate are the negative effects of our actions on the foundation of the above-mentioned functions and services upon which we build our livelihoods.

This doctoral dissertation provides theoretical, conceptual and methodological insights on the role of participatory design for sustainable development on a regional and national scale to support decision making in environmental System-of-Systems (SoS). The term "participatory design for sustainable development" describes the development of sustainable system functions the design of which is based on human perceptions of the actual system users. This bottom-up approach to system design is needed because our modern economy tends to support just a small proportion of people and organizations which have a large influence on society. In addition, many people do not sufficiently reflect on how best to use available resources and services. If a specific technology or service is also advantageous for others, is often not a criterion for using or buying it. Therefore, we may find ourselves in a situation of doing something or acting in a way which may have short-term benefits for us but is not in any way valuable for others. To participate in activities with other actors and questioning current behavior and actions of ourselves and our peers, may help to shape our environment in a more sustainable way. Today, we live in a world of many opportunities; we live in a "full world".

Acknowledgements

First, I would like to sincerely thank Professor Claudia Pahl-Wostl for her guidance, support, patience, and for the many hours we have spent discussing the ideas in and milestones of this thesis. In 2015 Professor Pahl-Wostl asked me if I would like to pursue a PhD under her professorship. This was a great honor for me. Working together with her and her team has always been a demanding and instructive undertaking which taught me many things, and not only about research and science. As a doctoral candidate, I am also grateful for the high degree of freedom which I had during the past few years.

Second, I would like to thank Professor Stefanie Engel for her warm and sincere support. Being part of her research group has been a very fruitful experience. Thank you for supporting me in so many ways, for providing me with the right amount of realism and practicability, for having confidence in me, and last but not least, for teaching me how to say “no”.

In the last few years, I made the acquaintance of so many intelligent and congenial colleagues, many of whom have become friends, and I would like to say “Thank you” to all of you. It has been a great time in Osnabrueck. I would especially like to thank Johannes for everything from Pinocchio to the inspirational walking sessions in the forest and a legendary conference; Caroline, for your friendship, your companionship and trust in me; Christian, for motivating me to “boldly go where no one has gone before”; Juan-Felipe, for the best office colleague one could imagine; And Elke and Eva, for making everything possible behind the scenes.

Last but not least, I am grateful for having such supportive friends and family. Thank you for all the positive and motivational words and your support over the past few years.

Fabian Heitmann, October 2020

Abstract

In this thesis, a conceptual framework and related methodological approaches for complex system design are developed and tested. The approaches are based on insights from the fields of Systems Engineering (SE) and System-of-Systems Engineering (SoSE), as well as Natural Resources Management (NRM) (Figure 1). The focus of this thesis is on: 1) the development of the System-of-Systems Design Framework "FRESCO", 2) the development of a methodological framework for participatory system design, 3) the application of the framework in two case studies, and 4) the development of an evaluation scheme to qualitatively measure the effectiveness of the methodological framework. The overall objectives of this doctoral dissertation are to highlight synergies between SE and NRM and to develop a methodological framework for designing decision-making processes in a human-nature-technology context.

The complexity of coupled and complex adaptive systems (CAS) such as the Water-Energy-Food Nexus (WEF Nexus) and sustainability strategies, influences the design of decision-making processes and strategy building. Integrated process design which is promoted by the developed frameworks can assist in such tasks on an urban, regional, and national level.

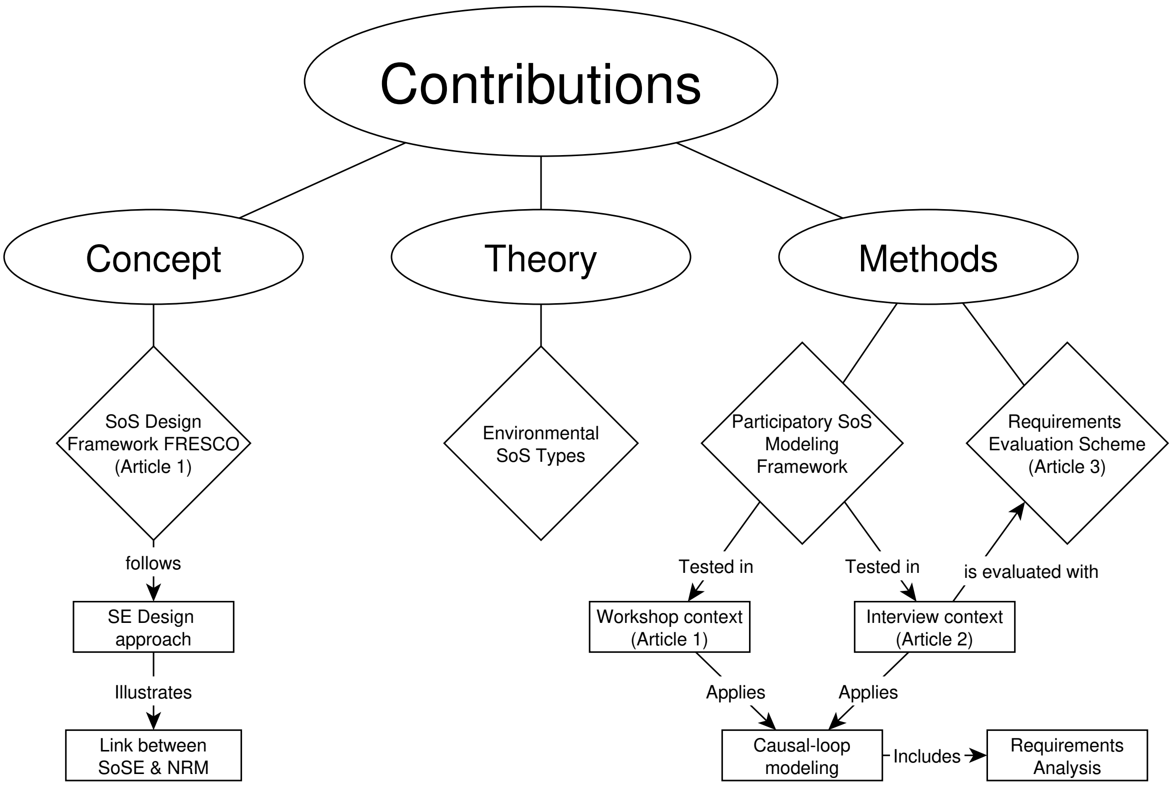

Figure 1 Graphical abstract summarizing the results of this thesis related to conceptual, theoretical and methodological insights.

Figures

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Boxes

Tables

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Abbreviations

[BEK]	**B**erliner **E**nergie- und **K**limaschutzprogramm Berlin Energy and Climate Protection Programme
[BLE]	**B**undesanstalt für **L**andwirtschaft und **E**rnährung Federal Office of Agriculture and Food
[CAS]	**C**omplex **A**daptive **S**ystem
[CONOPS]	**Con**cept **of** **Op**eration**s**
[FRESCO]	**F**unctions, **R**equirements, **E**valuation, **S**tructures, **C**onstraints and **O**utputs
[LSN]	**L**andesamt für **S**tatistik **N**iedersachen State Office for Statistics of the Federal State of Lower Saxony
[NRM]	**N**atural **R**esources **M**anagement
[SDS]	**S**trategy for **S**ustainable **D**evelopment
[SE]	**S**ystems **E**ngineering
[SEBoK]	**S**ystems **E**ngineering **B**ody **of** **K**nowledge
[SES]	**S**ocial **E**cological **S**ystem
[SoS]	**S**ystem-**of**-**S**ystems
[SoSE]	**S**ystem-**of**-**S**ystems **E**ngineering
[WEF Nexus]	**W**ater-**E**nergy-**F**ood Nexus

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Summary

This doctoral dissertation introduces a concept and methods for a participatory Systems Engineering (SE) design process to provide solutions to complex environmental resource management problems. The approaches presented originate from the field of SE and are usually applied for process optimization, systems development and technical project management in general. Underlying systems for design originally are software applications and technical infrastructure such as surveillance systems, civil aerospace technology, and large- and small-scale power grids (Anderies and Janssen, 2016; Crowder et al., 2016; Eusgeld et al., 2011). Therefore, SE is mainly using technocratic terms and narratives to describe design processes and tasks. Most recently, this scope has been broadened and SE approaches are also tested, for example, for water management projects (Hipel et al., 2008a, 2008b; Hipel and Ben-Haim, 1999) as well as the analysis and design of combined Water-Energy-Food Systems (Garcia and You, 2016; Lubega and Farid, 2016, 2013). However, technological elements of these systems are mostly being designed with the use of engineering approaches. But learning how available engineering tools perform in combined human-nature-technology systems, also requires the application of these tools on systems which include social and environmental elements. This has been done in the context of this doctoral dissertation. The large toolbox available through SE and the ability to deal with complex system design make SE particularly worth considering for the sustainable design of coupled human-nature-technology systems. Three research gaps are addressed in this thesis: ***First***, a system design framework for complex human-nature-technology systems is missing. However, such a framework is necessary to apply SE methods to human-nature-technology systems in a reasonable way. This gap is closed by developing such a framework and testing it in two case studies. ***Second***, methodological guidance for applying requirements analysis from the engineering literature is missing in social and systems science for sustainability and sustainable development applications. Even though participatory modeling (PM) already provides an approach to understanding system dynamics and structures by directly including system users in the research process of such systems and to support sustainability (Gray et al., 2017; Nabavi et al., 2017; Vennix, 1996), no structured and standardized procedure exists which could guide a more comprehensive design process to solve complex resource management problems. ***Third***, no evaluation scheme exists which could provide a control mechanism for measuring the coherence of the outcomes of the developed procedures. Evaluation schemes for PM approaches exist in general (Hassenforder et al., 2015; Hovmand et al., 2013), but not in a level of detail which would meet the requirements of a detailed system design process where coherent, correct, complete, traceable, testable and feasible requirements have to be formulated and modeled.

The interdisciplinary character of the underlying research benefited greatly from collaboration with other doctoral candidates and colleagues in the interdisciplinary Institute of Environmental System Research at Osnabrueck University, Germany. In 2017, the framework ("FRESCO") for the analysis of coupled and complex adaptive systems has been developed. Applications of the framework to a regional WEF Nexus case study and in the context of the German strategy for sustainable development (SDS) (i.e. the national directive of the EU Agenda2030) have been finished in late 2018. In addition, a three-week research stay in the System-of-Systems lab at the Julie Ann Wrigley Institute of Sustainability of the Arizona State University (ASU) in September 2018 specifically informed the engineering part of this thesis. The third article (chapter 5) is a result of this collaboration.

Research Questions & Objectives

Based on the research gaps, one overall and three sub-research questions are defined in this doctoral thesis and are described on this section.

To what degree does Systems Engineering contribute to the solution-oriented design of complex human-nature-technology systems?

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i. *RQ1: What elements does a conceptual design framework from systems engineering need to include in order for it to be applied for Water-Energy-Food Nexus design?*

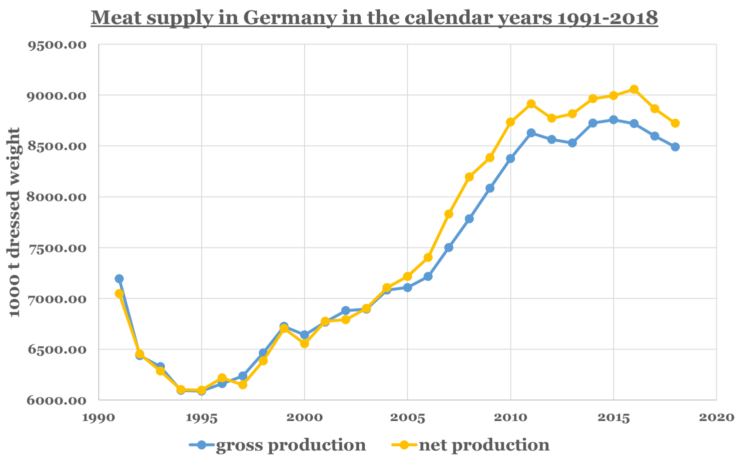

Figure 2 Meat supply in Germany (1991-2018)

The WEF Nexus exemplifies the complex relationships between Water, Energy and Food systems by conceptualizing trade-offs and synergies among the inherent sectoral resource management objectives. The area of Lower Saxony, Germany where the first case study of this thesis has been carried out, is an area of high intensity farming, and one example for such a Nexus. Lower Saxony has only 15.5% of the available land use area of Germany, but produces 21.2% of beef meat, 31.3% of pork meat, 37.6% of laying hens and 65.4% of chicken meat for Germany. The number of large-scale farms significantly increased in the last six decades (Table 1). At the same time, meat demand increased by 37.84% in 2017 compared to 1997[1]. This led to an increase in the meat supply in Germany (Figure 2), higher animal density, more monoculture, and in consequence to more diffuse entries in water bodies. European and national agricultural policies changed the use of fertilizer and agricultural practices in general. Also, EU and national energy policies motivated farmers to produce more bio-energy through subsidies. Reinforcing feedback effects of biogas production on the proportion of monocultures and mass production of animals occurred. All in all, the negative effects on the natural environment increased which caused environmentalists, civil society and science to change their agendas and focus on these inter-sectoral effects of Water, Energy, and Food systems. Because integrated solutions to the above-mentioned problems are hard to identify and to implement, a participatory design approach has been developed to guide decision making of involved actors at a conceptual level.

Table 1 Enterprise size structure in Lower Saxony

Enterprise size structure in Lower Saxony

Number of enterprises	1960	1971	1983	1994	1999	2003	2007	2010	2013	2016
1-2	31,9	20,0	14,1	9,3						
2-5	45,5	27,7	17,5	11,0	9,1	7,9	5,6			
5-10	41,5	23,3	13,9	9,1	7,2	6,3	5,3	4,9	4,6	4,8
10-20	53,5	37,1	20,1	11,1	9,3	8,0	6,8	6,1	5,4	5,3
20-50	34,6	43,5	37,7	23,8	17,1	13,1	10,9	9,5	8,5	7,9
50-100	5,2	7,3	11,7	15,0	14,6	13,5	12,3	11,4	10,7	9,4
100 and more	0,8	1,1	1,8	4,0	5,3	6,4				
100-200							5,8	5,9	6,1	6,2
200 and more							1,3	1,6	1,8	2,1
total	213,1	159,9	116,7	83,3	62,6	55,1	48,0	39,4	37,2	35,7

*Number of enterprises in thds.
Agricultural enterprises by utilised agricultural area size class
Source: Landesamt für Statistik Niedersachsen (LSN), agricultural structure surveys and agricultural censuses

ii. *RQ2: To which extent can the FRESCO framework support the development of a requirements-based sustainability strategy?*

To answer this research question, several tasks have been carried out: (1) Review of the current sustainability landscape in Germany, which includes the review of existing goals on the national level, strategy documents on the national, federal state and urban levels, identification of the interfaces between these strategies, review of indicator reports, and clarification of current projects of relevant actors; (2) identification of case studies; (3) development of a requirements-based and participatory system design approach for strategy analysis and development; and (4) a test of this system design approach.

[1] Source: Statistisches Bundesamt, Thünen-Institut, BLE (423)

iii. *RQ3: What is the added value of a detailed system design process for existing sustainability strategy documents?*

According to von Borries (2016), design which is constraining opportunities for action, is surrender. Therefore, when applying a new methodological design approach, its actual value for system design should be evaluated. An evaluation method for a requirements analysis in complex human-nature-technology systems is still missing. To close this gap, an evaluation scheme for requirements-based design solutions has been developed. The scheme uses data from PM interviews from the second case study of this dissertation and compares the data with already existing strategy documents on the same geographical scale. The evaluation scheme reveals the added value of the actor requirements by analyzing to what degree the requirements add information to the strategy document. In addition, the coherence of the actor requirements with what is in the documents is tested. This can reveal knowledge gaps and contribute to a more precise and grounded discussion of possible future pathways for strategy implementation.

Results

> ***Main result I:***
> *A System-of-Systems Design framework "FRESCO" has been developed and tested to guide the structured design of and to support decision making in environmental System-of-Systems.*

Box 1 Main result I

A conceptual design framework from SE which can support decision making in environmental SoS needs to include a systems thinking perspective which can be applied together with the users/actors of the system. To support decision-making processes in these systems, requirements-based and solution-oriented causal models can be developed. These models reveal the relationships between the requirements which are needed to achieve a specific overall objective. To understand and model such relationships is a key factor to understanding also complex systems with diverse actor objectives. In order to also be applicable in Water-Energy-Food Nexus design, such a framework should be able to connect ecosystem functions with the actions which are implied by the functional requirements of the actors. The FRESCO framework includes these elements and is presented in more detail in the first research article of this doctoral thesis (Chapter 3).

Main result II:
A methodological framework has been developed and tested to apply requirements analysis in participatory settings in the context of multi-level-governance in human-nature-technology systems.

Box 2 Main result II

The development of a methodological design approach in the context of multi-level-governance in human-nature-technology systems closes the gap of a missing requirements analysis approach for strategy development. Its participatory elements help to engage scientific experts and non-scientific stakeholders in the design process of Nexus systems. A series of mainly non-scientific expert interviews on the German sustainable development strategy has been conducted. Several urban actors from the cities of Hamburg and Berlin in Germany were asked to support the development of requirements-based causal-loop models to study the conceptual and detailed design of long-term strategy identification and development processes. The methodological framework and the exploratory case study are presented in chapter 4.

Main result III:
A requirements evaluation scheme has been developed and tested to assess the additional value of requirements analysis with causal-loop diagrams for detailed strategy design.

Box 3 Main result III

An evaluation scheme has been developed in collaboration with the System-of-Systems laboratory of Arizona State University, USA. The scheme reveals information gaps in strategy documents. It illustrates a procedure to qualitatively compare available expert knowledge from causal-loop diagrams with strategy documents to inform the re-development of these strategies. The evaluation scheme is presented in chapter 5.

Main result IV:
A new classification of environmental System-of-Systems has been developed:
SoS-Type 1*, where the overall objective is designed, and* ***SoS-Type 2****, where the subsystems are designed to align to an overall objective.*

Box 4 Main result IV

During the development of the FRESCO framework, two possible types of environmental SoS have been identified: Type 1, which defines a SoS without an overall objective (e.g., the WEF Nexus), and Type 2, where, in principle, an overall objective exists but is interpreted differently for different sub-systems. These SoS types refer to what is called virtual and acknowledged SoS in the engineering literature. The thesis also reveals their existence in human-nature-technology systems.

"There is a real need for a greater sense of global responsibility based on a sense of the oneness of humanity", The Dalai Lama, Excerpt from a letter to the COP24 Climate Conference, November 20th 2018

1. Introduction

We are living in a dynamic and drastically changing world. Humanity faces complex environmental resource management challenges such as droughts, floods, storms and other extreme weather and climate phenomena to a yet unknown degree of intensity (Able and Munich Re, 2017; Emanuel, 2005). The underlying dynamics of these phenomena are highly heterogenic and complex because diverse factors at the micro-level interact and lead to an often uncertain or unpredicted outcome at the macro-scale. This is referred to as emergent behavior. Therefore, the underlying system dynamics have to be understood from various perspectives and through a range of concepts and lenses; For example, one micro-effect might be technologically induced whereas another effect might have a social or natural origin. Emergent behavior is defined as a phenomenon "arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems" (Goldstein, 1999). These structures develop on the macro level of a system through interaction of the elements of these structures on the micro level. A large number of theories have emerged upon which disciplines try to frame environmental resource management problems as emergent system behavior and provide guiding frameworks for contributing to the global scientific debate on sustainability. Depending on the degree of the system's complexity and the diversity of interests of stakeholders in these systems, various theories and methodologies can be used to understand a system. For example, chaos theory, general systems theory, the concept of Complex Adaptive Systems (CAS), the system dynamics approach, and Systems Engineering (SE) may be used for complex systems with uniform stakeholder positions, whereas System-of-Systems Engineering (SoSE) is used in the case of complex systems with stakeholders who have conflicting goals (Mahmood, 2016).

However, a successful debate on how to sustain the resources which we need to survive, not only depends on a deep understanding of complex system dynamics but also on approaches which can design decision making processes and integrated solutions in environmental System-of-Systems (SoS) to successfully take action. Therefore, this thesis including its constituent research articles provide new insights into the concept of design thinking and system design in the field of Natural Resources Management (NRM) and social science by: 1) developing a conceptual design framework which makes SE methods, i.e. requirements analysis, functional analysis and process planning, available in NRM; 2) by developing a methodological framework for applying requirements analysis in scientific expert workshops;

3) by developing a methodological structure for applying requirements analysis in Participatory Modeling (PM) with causal-loop diagrams; and 4) by designing and testing an evaluation scheme for such causal-loop diagrams.

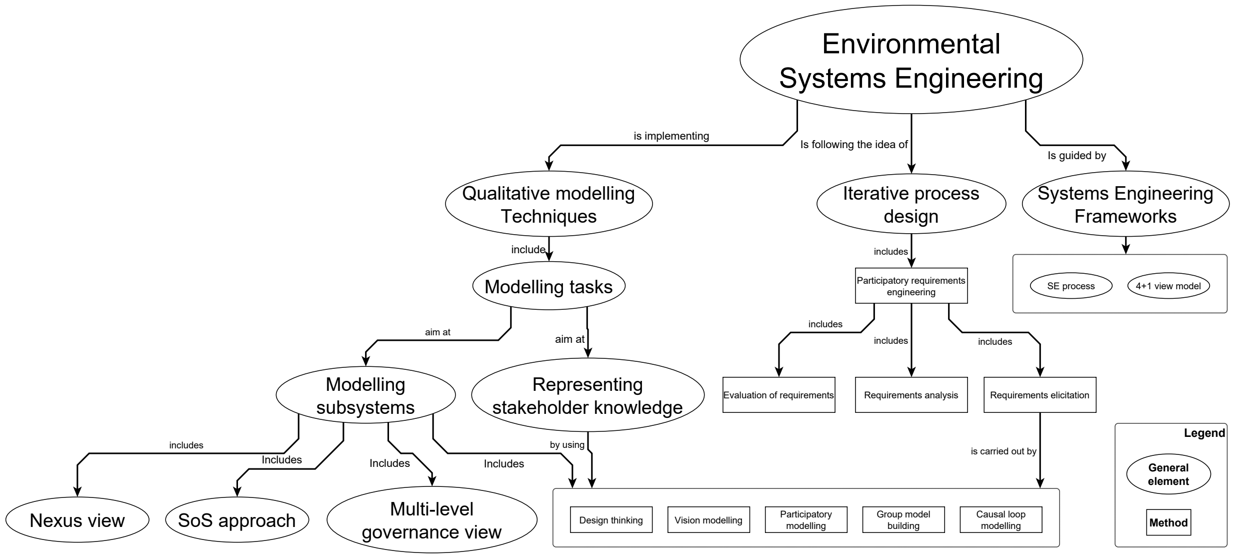

Figure 3 How Systems Engineering is used in this thesis

The theoretical underpinning for this doctoral thesis is the combination of two research streams: SE and NRM. NRM refers to the sustainable use of natural resources and their functions and services they provide for human life. Over the last few years, SE has developed from an exclusively technologically-oriented field to a wider variety of disciplines. However, SE still mainly focuses on technological systems design. In this thesis, methods from SE are combined with NRM and redeveloped to apply them also in a human-nature-technological systems context. How this is done is illustrated in Figure 3. For example, until now, methodological guidance for applying requirements analysis from the engineering literature has been missing in social –and nature environmental science. Even though PM already provides an approach for understanding system dynamics and structures by directly including system users into the research process of such systems to promote sustainability (Gray et al., 2017; Nabavi et al., 2017; Vennix, 1996), no structured and standardized procedure exists which could guide a comprehensive design process. Conceptual approaches bridging the gap between SoSE and nature environmental management on local, regional and global levels are not a novelty (Hipel, 2012; Hipel et al., 2010, 2008c, 2008b), but a framework to apply the process-oriented nature of SoSE in Nexus design is still missing.

A conceptual design framework, "FRESCO" (**F**unctions, **R**equirements, **E**valuation, **S**tructures, **C**onstraints and **O**utputs), is developed by combining various streams of literature from SE and SoSE. The structure of the framework is based on the standard iterative system design process which has been applied in a large number of cases and contexts in the industry in the last few decades (Crowder et al., 2016). In chapter 3, the development process for the framework and the framework itself are presented in detail.

The methodological system design framework for application in scientific expert workshops is based on experience from PM exercises and workshop design methods. It combines several approaches such as vision modeling, requirements analysis and group-model building to develop a qualitative model for framing an underlying problem and designing possible solution strategies. In May 2018, the framework was tested with eight scientific experts from Osnabrueck University on a case of water pollution caused by diffuse nitrate emissions in surface water bodies in the state of Lower Saxony in northwestern Germany. In chapter 3, the framework and the application to this specific case are illustrated.

The elicitation of requirements as one way to design actor-oriented, feasible and practice-oriented solutions applied in a PM context requires, on one hand, a standard procedure for conducting actor interviews or workshops, and, on the other, a high degree of freedom for participants to provide diverse and unbiased knowledge to inform the modeling process. How these requirements are reflected and included in the methodological framework is described in chapters 3 and 4.

Causal-loop diagrams or models are one method for conducting such a PM exercise. These models show a high degree of uncertainty with respect to the correctness of the inherent causal-relationships and their interpretation. Therefore, evaluating these models is an important part of the modeling process. In chapter 5, an evaluation scheme for such models is presented. The scheme has been tested in an exploratory case study with practitioners. This case study and its results are presented in chapter 4.

To conclude, complex environmental resource management problems are often caused by interaction of many different and heterogeneous elements. These may be social, technical or natural elements. For example, social elements could be diverse actors with many different opinions, expertise and objectives, technical elements could be machines, structures or technical elements in general interacting with each other, and natural elements can be ecosystems, animals or natural processes such as water filtration. A design approach which is capable of including all this diverse information into decision making processes has been missing. Therefore, a SE-based iterative system design process has been adopted for the application to complex human-nature-technology systems. This includes the development of a requirements engineering approach which can provide helpful guidance to understand and guide strategy design for sustainable development. This perspective on requirements engineering beyond technical systems design describes a system design with respect to new types of requirements which also can be applied to sustainable strategy design. Finally, an evaluation scheme to assess the effectiveness of requirements engineering for this type of strategy design has been developed and tested. These approaches are represented by the three constituent research articles which are summarized briefly.

1.1 Articles related to the dissertation

1.1.1. Requirements Based Design of Environmental System-of-Systems: Development and Application of a Nexus Design Framework

Social, technological and environmental systems have become increasingly interconnected. Integrated problems arising between embedded water, energy and food systems require political and strategic cooperation between the actors involved at multiple governance levels. A holistic design approach is needed to guide inherent decision-making processes. In this article, a normative decision-making framework based on SoSE is developed. It demonstrates how the framework can help to foster the cross-sectoral design of solutions to these interlinked water, energy, and food issues. Actors involved in the case study demonstrated a strong interest in collaborating across sectors and participating in the transition to cross-sectoral and sustainable resources management practices. However, experts from science and praxis face a high degree of uncertainty when they design solutions to cope with existing regional problems. As almost all regions of the world are highly integrated in national and global markets, future research could focus on conducting larger research projects which link design approaches to inter-regional, national and international levels. The methodological approach illustrates how such a project could be structured on a regional level and identifies the processes that are important to consider.

The case study presented in this article deals with the problem of water pollution from agricultural activities from diffuse sources in Lower Saxony, Germany. Nitrate and phosphorus are the two primary by-products of intensive agriculture in the region. Political discussions on how to the address the issue have been numerous over the last two decades. Although the problem is now widely discussed in society and also in the agricultural sector, no effective measures have been implemented to fundamentally change the situation. To provide a more solution-oriented approach to understanding the complexity of the underlying problem and to design innovative strategies to cope with these regional problems, a Nexus design framework is presented. The framework is tested in an exploratory expert workshop in a scientific context. This includes the application of participatory modeling and group model-building methods to derive a concept of operations, requirements and functions as an underlying basis for a more sophisticated and detailed systems design. Experts have been asked to derive requirements and functions in a group model-building setting and to develop a conceptual model of the case study region. To also demonstrate the practical applicability, the outcome of the workshop was complemented by comparing the data to the results of individual stakeholder interviews with experts from praxis.

1.1.2. Integrated and participatory design of sustainable development strategies on multiple governance levels

An increasing number of strategies for sustainable development (SDS) are being developed for municipalities and countries. The design of such strategies is inherently complex. This is a result of the intricate relationships between various SDS on different levels, and a large number of requirements that need to be addressed in strategy implementation. A particular challenge is the integration of strategies across different governance levels (e.g., city, federal and national levels). Methodologies are currently lacking that systematically design SDS which take the full complexity of the dependencies of the strategies into account. In this article, a participatory requirements analyses approach is proposed to support strategy building across governance levels. Experience from SE has shown that requirements are the basis for designing systems or strategies. In this article, requirements are elicited by applying a participatory modeling approach with causal-loop diagrams in an individual interview setting. To illustrate this methodology, the design approach developed is tested in an exploratory case study in which the interdependencies between SDS at the city level (i.e., the cities of Berlin and Hamburg) and the German national SDS are highlighted. The design process reveals critical factors which are needed for the overall success of the strategies. The resulting causal models reveal that, despite coordination activities to achieve regional objectives that are intended to fulfil national targets, trade-offs exist between the strategies with regard to the underlying conditions for their implementation (e.g. national law, federal state law). In addition, the level of detail of requirements to achieve certain objectives at the national level and across sectors is too general. This hinders the emergence of system wide co-benefits of potential solution strategies. Requirements analysis can highlight interdependencies, such as trade-offs and synergies between strategies at multiple governance levels and, based upon this, can support a more coherent strategy design.

1.1.3. Evaluating the effects of alternative system designs in multi-actor environmental System-of-Systems

The design of strategies for sustainable development is becoming increasingly complex. The complex nature of multi-level governance systems where SDS are often embedded, is one of many reasons for this complexity. In addition, expert knowledge, which is needed for guiding strategy development, is scattered across governance levels and not always represented in strategy documents. Therefore, to follow a joint pathway for implementing SDS, actors need to agree on certain key requirements. These key requirements are important for coping with the main challenges of implementing each strategy. In this paper, data on a PM task from several expert interviews is used. The data includes key requirements for CO2-emission reduction in Germany and the city of Berlin, which is used for comparison with statements made in the corresponding strategy documents. This includes a comprehensive qualitative text analysis with MAXQDA and the application of an evaluation scheme developed as part of the research design. This novel approach helps to 1) specify important interfaces between governance levels in strategy design, and 2) reveal knowledge gaps in strategy documents. By comparing the statements of the interviews with the strategies, the approach helps to evaluate the effectiveness behind the PM approach. To measure the added value of the interview data for these strategy documents, an evaluation scheme has been developed. The scheme helps to measure the degree of detailed expert knowledge inherent in such documents compared to expert interviews which are formalized as causal-loop diagrams. The analysis reveals that detailed information on requirements is missing in the German SDS, whereas in the Berlin Energy and Climate Protection Program (BEK) the interviews provide additional knowledge on relationships between objectives, actors and interfaces.

In the following chapter, the key concepts of this doctoral thesis, 1) *SE* as a concept which provides a structure for designing technological systems, and 2) *Environmental SoSE* as a multidisciplinary approach which focusses on the understanding, analysis, modeling, and design of interconnected, diverse and dynamic human-nature-technology systems are presented. Subsequently, the role of a systems engineer is described and specified by the tasks which have been implemented for this research project. These tasks are *Requirements analysis* and *Participatory Stakeholder Modeling* which have been carried out in individual and group settings. After that, the *Nexus Thinking* concept is presented as a holistic approach which focusses on understanding and managing interdependencies between water, energy and food systems with the aim of overcoming sectoral fragmentation and sustainability deficits. Chapter 3, 4, and 5 include the central research articles of this thesis. The results are presented in chapter 6. These are discussed in chapter 7. Limitations of the approaches used are described in chapter 8. The thesis closes with some thoughts on future research opportunities.

2. Systems Engineering

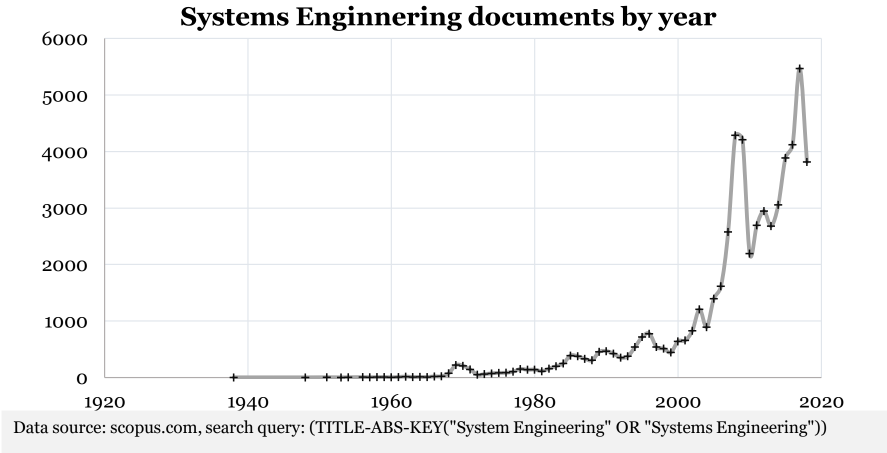

Figure 4 Systems Engineering publications per year, 1938-2018

Systems Engineering is a technology-oriented field with methods applied mainly in the context of process and software engineering. However, SE has evolved over the last 50 to 60 years into a multidisciplinary domain which provides a diverse set of engineering approaches and methods for multiple application-contexts (Crowder et al., 2016). SE was originally perceived as an approach which “seeks to optimize the overall functionality of a system, utilizing weighted objectives and trade-offs in order to achieve overall system compatibility and functionality”, (Crowder et al., 2016). SE “focuses on holistically and concurrently discovering and understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, deploying, sustaining and evolving solutions while considering the complete problem, from system concept exploration through system disposal” (BKCASE Editorial Board, 2015, p. 1).

The field of SE was developed in the early 1950s. After NASA began its first Apollo program, a variety of heterogeneous subprojects under this program, technical subsystems, as well as functions and processes that were all needed for the implementation of the program, had to be coordinated to successfully achieve the overall program objective. During the next 20 years, the rising complexity of engineering systems led to more sophisticated SE methods. The simultaneous development of object-oriented modeling methods led to the development of even more complex system designs (Crowder et al., 2016).

Nowadays, SE includes many approaches which have also spread into different fields, such as computer science, mathematics, and physics, as well as social science, business and management, and environmental science. Figure 5 shows the range of fields but also indicates that only 1% of all SE documents are published in the field of environmental science.

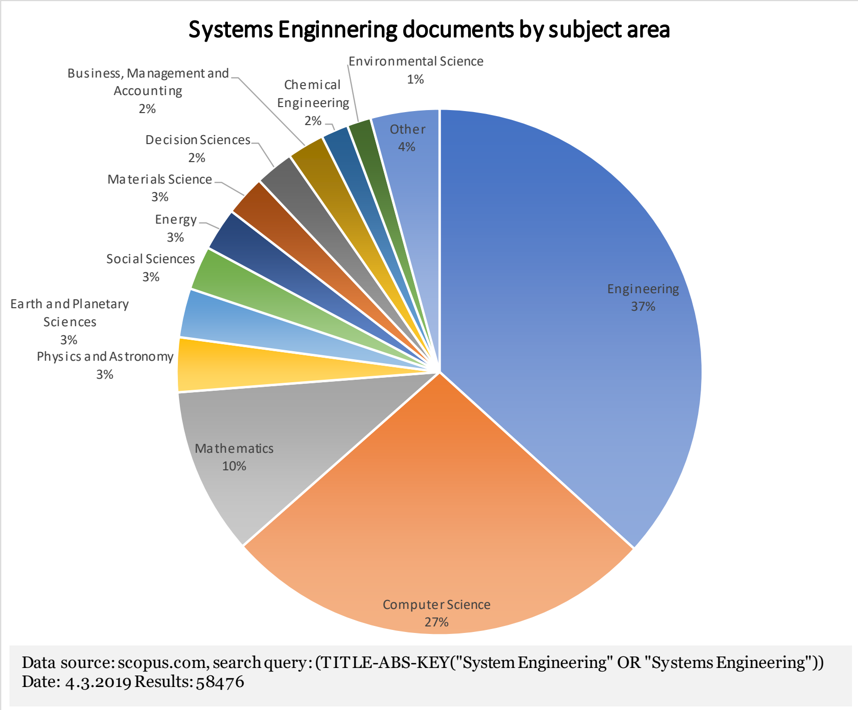

Figure 5 Systems Engineering publications by subject area (1938-2018)

The diversity of SE methods and applications available results from various multi-level use case scenarios for which SE is being used, for example overall system design, software engineering, test engineering, safety engineering and cognitive SE. Several methodological frameworks exist for each of these applications. Depending on the overall objective, these frameworks can either be combined or applied in isolation. Examples of SE frameworks which have informed the development of the FRESCO framework are the Zachman framework (Zachman, 1987), the DoDAF framework (Department of Defense Deputy Chief Information Officer, 2011; Mittal, 2006; Piaszczyk, 2011), the MODAF framework ("MOD Architecture Framework," 2012), the 4+1 view model (Kruchten, 1995), and the standard SE process (Crowder et al., 2016).

In this thesis, SE is generally understood as a concept for guiding the design of complex systems (Kossiakoff et al., 2011). SE focusses on (1) holistic modeling of systems; (2) understanding and modeling actor/user needs and their embedded/operational environment; (3) guiding conceptual and detailed system design; and (4) the multidisciplinary character of the modeling process. These characteristics are what makes SE as a theory particularly interesting for complex system design in a NRM context. A holistic system view is one of the core ideas underpinning systems thinking (i.e. "the conceptual patterns of how we think systemically", (Cabrera et al., 2008, p. 301)). Depending on how we view a system, different actor needs and perspectives can be taken into account to solve problems in a system on a conceptual level. At a higher level of detail, methods such as participatory stakeholder modeling (chapter 2.3.2) (or requirements analysis, as it is called in engineering literature) can be helpful in developing even more detailed system models.

However, conceptual and detailed system design may only be applied, if we have sufficient information about the system under investigation (e.g., information on complexity, structure and dynamics), which refers to the term "system science" (Cabrera et al., 2008). Lastly, the multidisciplinary character of the modeling process in the engineering literature proposes that different perspectives in systems thinking are taken into account. These perspectives may only be taken into consideration, if the system is being analyzed from the viewpoint of different scientific fields. The latter can often be found in institutes and study programs that are oriented towards system science. In addition, SE has overlaps with project management tools and approaches. The structure of the design process is very important in SE. More specifically, the combination of SE and project management is one innovative aspect for understanding and shaping interactions in human-nature-technology systems which is also highlighted in this doctoral thesis (chapter 2.3). The actual management and structure of the analysis on the meta-level of system design can help to standardize modeling approaches and to make them more transparent to non-scientific actors. This is particularly important for building trust for policy -and decision-makers (Ostrom and Walker, 2003a).

All in all, the above mentioned characteristics of SE and its overlaps with systems thinking and systems science concepts, give the impression that SE could inform NRM on both conceptual and methodological levels. The hypothesis also assumes that the detailed and structured way that SE frameworks are built help to inform methods such as PM and make them more effective if applied with actors across research domains (SE, SoSE and NRM). However, narratives from the engineering field are often not consistent with those of resources management. How to address these difficulties is described in Chapter 3.

2.1. Systems Engineering Frameworks and their role in this thesis

A number of SE frameworks exist, which are widely applied in the industrial, military and technology sectors. SE frameworks are categorized into various types. Two examples for architecture and process management frameworks are presented here which inform the development of the "FRESCO" framework: The 4+1 view model and the basic SE process. Architecture frameworks usually support to guide the system development or analysis process for the structure, i.e. the architecture of the overall system, whereas process management frameworks generally guide the system design or analysis process by defining processes, i.e. the management, of the overall system (Crowder et al., 2016, chap. 4.1; Kruchten, 1995). With the term "framework", the definition of Binder et al. (2013) is used, who define a framework as the provision of "a set of assumptions, concepts, values and practices that constitute the way of viewing the specific reality." (2013, p. 2).

In contrast to other engineering frameworks, the 4+1 View Model (Kruchten, 1995) defines several "views" of the designed system. These views describe the system from the user or actor point of view and describe the "logic", "development", "processes", "physics", and "scenarios" of the system (Kruchten, 1995). For developing the FRESCO framework, a *logical view* approach was implemented by including the elicitation process of functional requirements in the system design process. The causal relationships between these requirements are exemplified by causal-loop-models which can be developed either in a single interview or group settings. The *development view* in the 4+1 view model framework usually refers to software management and programming tasks. It is defined as "the static organization of the software in its development environment", (Kruchten, 1995, p. 2). Because the objective of the FRESCO framework is to design parts of governance systems such as policies and processes, the development view is interpreted as the organization of the design process and how it is structured. It therefore describes what methods are used, in what order and how the design processes are steered towards achieving the overall design goal. The *process view* refers to the system dynamics and structure of the underlying system. It "captures the concurrency and synchronization aspects of the design", (Kruchten, 1995, p. 1). Processes are defined as the sequence of activities which together fulfil a specific purpose and form, together with a structure and a function. Processes can be included in causal diagrams as links but can also be described by single variables. Actual processes of an already existing system are captured in the Concept of Operations (CONOPS) step of the FRESCO framework, whereas processes can also be part of the newly developed system design model. Therefore, processes can be described by using requirements or constraints at the same time. The *physical view* is included in the requirements elicitation and functional analysis steps of the FRESCO framework. In the SE literature, it "describes the mapping(s) of the software onto the hardware and reflects its distributed aspect." (Kruchten, 1995, p. 1). In the NRM field, the physical view is interpreted as the description of all physical objects which are part of the implementation of the system design. This may be actors, technical systems or environmental systems such as recreational areas which are affected by the implementation. As with processes, the physical view is included in the causal models which are developed during the application of FRESCO. The *scenario view* refers to a later step in engineering frameworks. It deals with formulating or implementing use case scenarios where the functional system design can be tested. It can include if-then formulations or a first "proof-of-concept". Evaluating the system architecture is one important step in preparing the draft design for a later implementation phase. Evaluating the requirements that have been derived can help to support scenario development tasks, because this analysis reveals the added value of the proposed design. Comparing scenarios with requirements and evaluating different types of requirements to assess their added value for already existing systems (e.g., strategy documents), is described in chapter 5.

In this doctoral thesis, the conceptual design of governance systems and the requirements elicitation are specifically highlighted as application areas for FRESCO. The framework has been tested in a research context as well as in practice. Although all system views as described by Kruchten (1995) are described by FRESCO, the actual physical design and implementation are not addressed in this thesis. This has two reasons: 1) the role of a researcher in system design while applying FRESCO in a research context is interpreted as an “analytical” or “communicative” role, and the actual decision for the system design to be developed is taken by the participating experts; (2) the role of a person while applying FRESCO in practice, e.g., for guiding a process that is convened by a ministry, is interpreted as a moderator or facilitator role. The actual decision is taken by the political decision-makers who may be part of the design process.

In addition to the 4+1 view model, the standard engineering process framework guides the development of the proposed FRESCO framework. It provides a structure for understanding, analyzing and designing systems, and, at the same time, suggests several tasks for each step. For the purpose of developing FRESCO, the framework has been reviewed and steps have been checked for their applicability in a human-nature-technology context. For each element of the basic systems engineering process, as shown in Figure 6, a representative concept, method or approach has been sought in the field of NRM. Some elements of the SE process are not defined in NRM. Therefore, identifying a corresponding element throughout the whole process framework was not possible. However, several elements could also be identified in the NRM literature. To better understand the SE concepts presented, the language used in the original SE literature has been partly adopted which is more consistent with NRM-oriented terminology. For example, “Trade Studies” in the SE process is interpreted as cost analysis (for the design process and for the implementation of the system design model); Customer, technical and quality directives are interpreted as types of actor requirements (see chapter 3). Figure 6 illustrates the aspects of the standard SE process that are considered within the scope of this thesis.

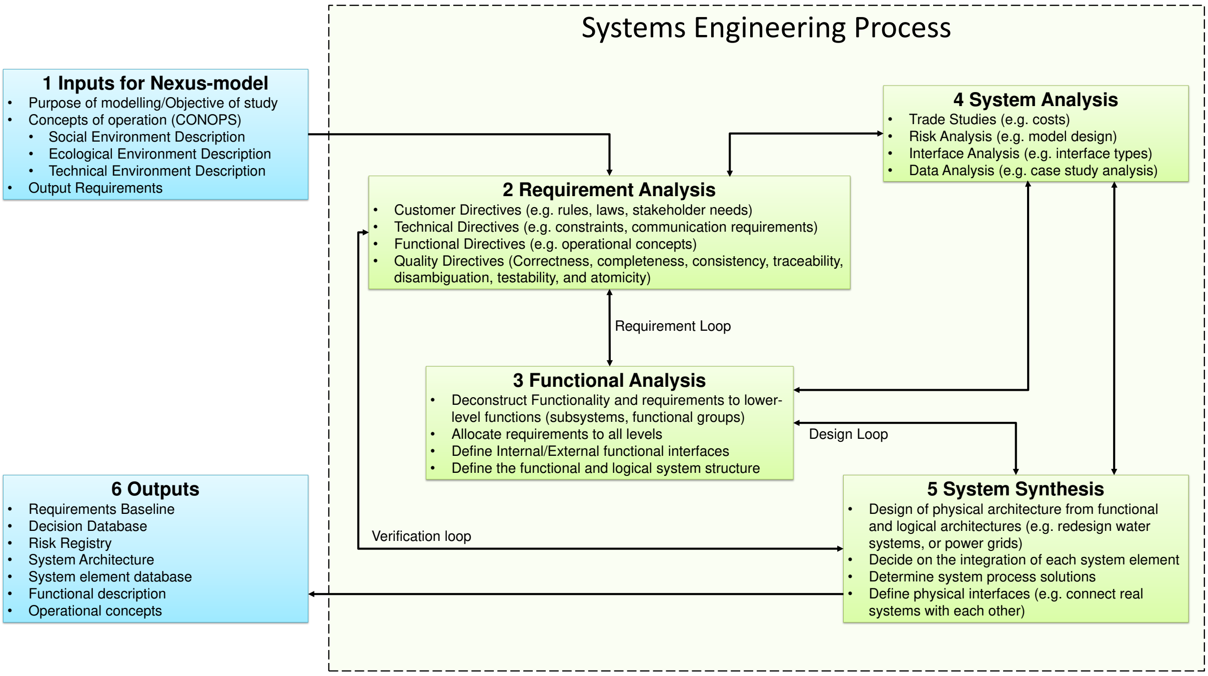

Figure 6 Basic Systems Engineering process, adapted from Crowder et al. (2016)

2.2. Environmental System-of-Systems Engineering

SoSE is a special type of SE that aims at designing SoS or parts of it. In the engineering domain, SoS is commonly defined as a collective system with autonomous and diverse subsystems, which are connected dynamically with each other and have their own goals contributing to the overall goal of the SoS (Baldwin et al., 2015a). Historically, SoSE did not include the non-technological interrelationships which are inherent for example in complex adaptive human-nature-technology systems. Therefore, we build upon the SoS definition of Hipel (Hipel et al., 2010, 2008c), and add a social and environmental perspective to the SoSE approach. We define an environmental SoS as a complex adaptive human-nature-technology system which is usually managed among multiple subsystems and has an overall SoS objective. The engineering of such systems is defined as environmental SoSE.

The term “System-of-Systems” was to the best of our knowledge first introduced by Ackoff (1971). Subsequently, the SoS approach was further developed by Jackson (1990) & Jackson and Keys (1984), who built their work to a large extent on complexity theory described by Simon et al. (1962). The SoS approach was then further expanded by Maier (1998) who defines principles for the classification of SoS. The SoS literature proposes these principles, also called “Maier’s criteria”, as elemental parts upon which the concept of SoS and SoSE is based. According to Maier (1998), these criteria are: (i) “Operational & Managerial independence”, i.e. the subsystems can and do maintain their functions independently of other subsystems, (ii) “Geographical distribution”, i.e. the subsystem elements are strongly coupled through spatial proximity, but the subsystems are only loosely coupled, (iii) "Emergent behavior", i.e., the development of new emerging properties through interconnectivity of subsystems, and (iv) "Evolutionary Development", i.e., objectives, functions and processes in the SoS can change continuously. These criteria classify a system as a SoS (Maier, 1998). However, the discussion will show that Maier's criteria do not necessarily apply for SoS in a socio-ecological systems context.[2]

Whereas SE and SoSE were originally developed to optimize process development, product design of technical systems and complex and dynamic projects, SoSE also offers "strategic and operational methods to carry out creative problem-solving on our most pressing global problems, which involve multiple participants in interconnected complex systems." (Hipel et al., 2010, p. 7).

The SoS literature focuses mainly on managing technical infrastructure (Eusgeld et al., 2011; Mostafavi et al., 2011). Complexities and uncertainties (DeLaurentis and Ayyalasomayajula, 2009; Mostafavi et al., 2011), as well as coupled technical-human systems are often described without explicit links to environmental issues (Anders et al., 2015; Keating et al., 2008; Mittal, 2006; Mittal et al., 2008). A technical overview of the role of SoS model applications in SoSE is provided by Mittal et al. (2008), whereas Keating et al. (2008) give a broader overview of applications of the SoS approach. In the latter, only one chapter points to an explicit link to environmental issues (Hipel et al., 2008c). Also, more recent publications such as a special issue on SoS in IEEE-Reliability Society do not emphasize linkages to natural resources (Hansen et al., 2016). One of the most influential authors who explicitly relates SoS to environmental themes is Keith Hipel who proposes SoS as an approach to inform integrated water resources management and to enhance food security (Hipel et al., 2010, 2008b). Further information about environmental issues and their linkages to SoS can be found in Hadian and Madani (2015), Hipel et al. (2008a), Lehmann et al. (2015), Yaeger et al. (2014) and Anderies and Janssen (2016). Applications of the SoSE concept include but are not limited to: model development of the whole or parts of a SoS; breaking down constituent subsystems inside a SoS; understanding specific processes and functions inside a SoS; or a combination of those. A policy-oriented approach on SoSE is taken by Agusdinata and Delaurentis (2011) who is analyzing the extent to which alternative policy solutions constitute fairness among involved policy actors (Heitmann et al., 2019b).

[2] For more information on this aspect, see (Austrup, 2017).

Table 2 System-of-System types based on Dahmann et al. (2009)

Type	SoS Engineering interpretation	WEF Nexus interpretation
Virtual	There is no specified central management entity. The subsystems maintain complete control (e.g., market structure).	The subsystems/sectors (Water, Energy, Food) are interconnected subsystems and cannot maintain complete control of themselves.
Directed	The SoS is a centrally managed system, to ensure it functions, whereas the functions of the system components are subordinate to the overall SoS-function (e.g., military systems).	A top-down regulated system would fit under this type of SoS. Policies could aim for controlling all sectors of the WEF Nexus. In the case of Germany this approach would fail because of the federal political system. In addition, some functions within each sector (e.g., water provisioning in the water sector) are essential to maintain functions in other sectors (e.g., providing irrigation water for food crops).
Acknowledged	The subsystems fulfil a high-level objective which is often achieved through the sharing of resources. Nevertheless, subsystems keep their own identity and goals. Changes in the system are dependent on collaboration between them (e.g., Ruhr Regional Association).	This type of SoS could be seen as reflecting a normative view of the WEF Nexus. As all Nexus sectors share resources (technical and natural), coordination or collaboration is needed to design a sustainable WEF Nexus. This could be formulated as a "high-level objective".
Collaborative	Not all subsystems necessarily have the same purpose. Cooperation between the subsystems and actors provides the mechanism for maintaining the SoS functions (e.g., the internet).	The Nexus itself is governed by each of the sectoral goals. The achievement of these goals (e.g. water security) provides the mechanisms for maintaining each sectoral function. Therefore, the overall functions in the Nexus are not maintained through single actors, but political institutions (e.g., policy coordination across the individual sectors).

Engineering a SoS first requires a correct framing of the underlying system. The SE literature refers to this as defining the SoS type. According to Dahmann et al. (2009), four SoS-types can be defined in a technical environment: Virtual, directed, acknowledged and collaborative. Each type describes how the overall SoS is managed: an acknowledged SoS is managed by a central control instance whereas the subsystems maintain their own control: directed SoS do not maintain their own control; collaborative SoS are managed by collaboration among the subsystems; virtual SoS are managed neither by collaboration nor central control. Table 2 illustrates the existing SoS types and provides examples for their application in the WEF Nexus domain. The graphical representation of the four SoS types is illustrated in Figure 7. The arrows indicate the direction of control. In the case of a directed SoS type, the central governance system has control over the subsystem's functions. However, the subsystems maintain connection with each other. An acknowledged SoS type illustrates a bi-directional relationship between the central control instance and the subsystems. The governance system controls the subsystems, but the subsystems also influence the governance system.

This may be the case with WEF-Nexus governance, where higher governance levels (e.g., the national or EU level) are influenced by regional requirements or urban policies constraining high-level policy making. A virtual SoS-type describes a SoS which has no central control or management instance, similar to a collaborative SoS-type which also has no central control mechanism but is managed by collaboration among the constituent subsystems.

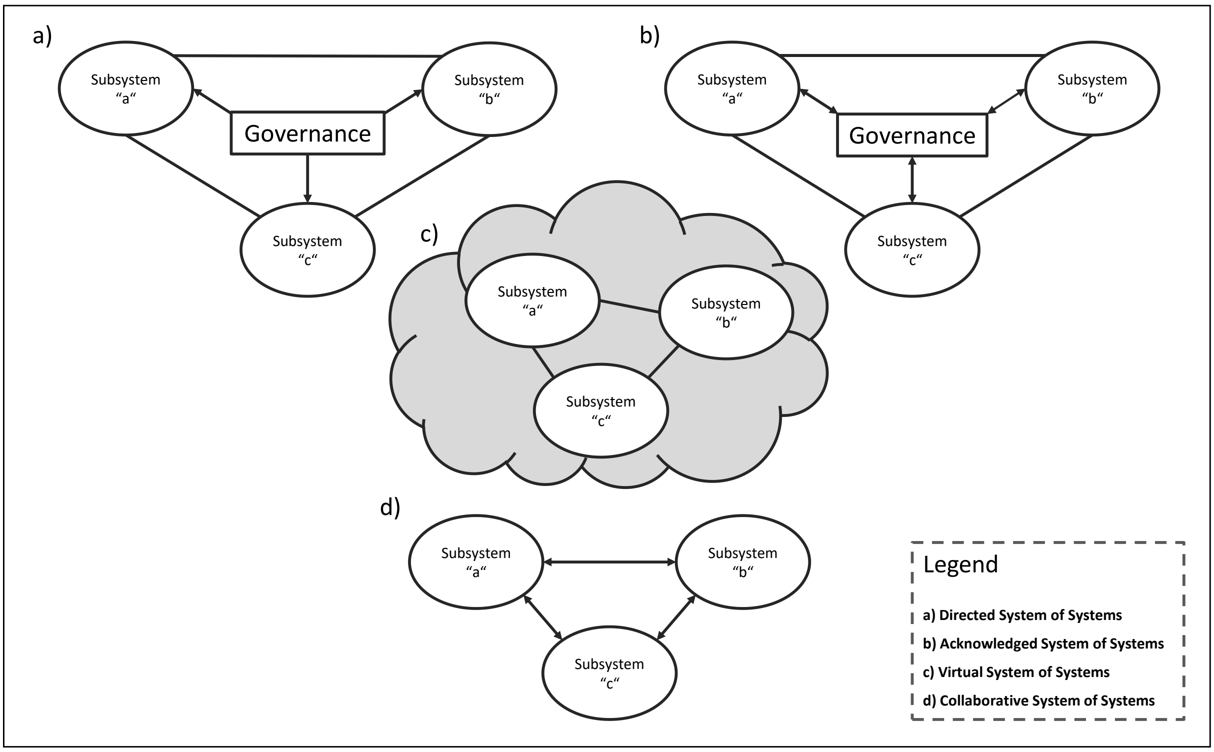

Figure 7 System of System Types (Lane 2013)

2.3. The Role of a Systems Engineer

Generally spoken, the role of a systems engineer is to ensure that the overall goals of the system design process are achieved. This task includes several specific roles and steps to follow, which are described in detail in the systems engineering body of knowledge (SEBoK) (BKCASE Editorial Board, 2015). The environment in which the systems engineer is working has various aspects. According to the description of BKCASE Editorial Board (2015, fig. 1), the systems engineer elicits the needs of the customers, specifies what the development team does, and supports the process of the system to be designed. This includes SE tasks, systems implementation as well as project management tasks. Therefore, a systems engineer should focus on the whole system being designed and not take isolated decisions which are only based on information of parts of the overall system (Kossiakoff et al., 2011). However, in human-nature-technology system design, where several stakeholders are in charge of implementing the system design as decision-makers, the systems engineer as a project manager rather takes a role as a moderator or mediator in the design process. Within science, the scope of a systems engineer as a manager of a research project can be different to their role in a design process in practice because the system design depends on external and practical expertise on the system which may be beyond the scope of a scientific expert. For example, if a researcher develops a solution-oriented conceptual system model to guide decision making for practitioners, the researcher may be fully in charge of the theoretical or hypothetical system model, but important requirements or functions making this model effective in practice may only be elicited with the help of other external experts and system users, i.e. practitioners. This example illustrates that the specific tasks of a systems engineer depend on the actual system to be designed and on the context in which it is to be applied. In addition, depending on the size of the project, several system engineers could also form a team to divide the workload.

With respect to the overlap of SE and project management, Kossiakoff et al. (2011) describe "Task definitions (task allocation and program reviews), Risk management (risk assessment and risk mitigation), and customer interaction (management and technical)" as shared roles of a systems engineer and a project manager (2011, p. 112). To better understand the role of a systems engineer in the SE domain, it is also important to take into account the fact that SE itself involves several "knowledge areas" such as resilience engineering, safety engineering, environmental engineering, and others (BKCASE Editorial Board, 2015). These knowledge areas illustrate the different types of information which are important for the process of "engineering" a system. They also further specify the role of the systems engineer, as each knowledge area contains important concepts to follow in the design process. Knowledge areas which have been incorporated in the definition of the role of a systems engineer in this thesis, are defined in Table 3.

Table 3 Knowledge areas of Systems Engineering

Knowledge area	Definition
Resilience engineering	To design resilient systems (also see Box 10), four design attributes may be applied: capacity (the ability to resist an external shock), flexibility (the ability of a system to reorganize), tolerance (the ability of a system to maintain its functions in a mitigated manner), and cohesion (the ability of a system to be operated in case of a shock) (BKCASE Editorial Board, 2015, p. 891ff).
Safety engineering	The purpose of safety engineering is to minimize negative impacts on a system or reduce the risk of these impacts happening (BKCASE Editorial Board, 2015, p. 875ff).
Environmental engineering	Environmental engineering includes the system design to fulfill requirements of its environment. According to BKCASE Editorial Board (2015), these requirements are related to legal, budget, and schedule requirements, as well as product sustainability (Lockton et al., 2017, 2008; Stasinopoulos et al., 2009) and sustainable construction (Maydl, 2004; Meryman and Silman, 2004).

The role of the systems engineer has been simulated to carry out both case studies presented in this thesis including: (1) the WEF Nexus in the region of Osnabrueck, Germany, and (2) the SoS-based strategy design of parts of the German SDS, in relation to the urban sustainable development strategies of the cities of Berlin and Hamburg. The case studies include various types of common outcomes of a SE process which are described according to Kossiakoff et al. (2011) in Table 4. The "problem definition" for the first case study is a result of the analysis of a causal-loop model which has been developed in a University study program together with graduate students (see chapter 3). The problem definition for the second case study is a result of a political discourse on the effectiveness of the current German SDS (see chapter 4). The "CONOPS" outcome is explained in both chapter 3 and chapter 4. The "context diagrams", "requirements", "user needs", "concept of operations" and "system functions" have been developed in the form of causal-loop diagrams or tables either in individual or group interview settings (chapter 2.3.2). The corresponding results are also described in chapter 3 for the first case study, and in chapter 4 for the second case study. Intermediate results of the workshop which has been conducted for the first case study (i.e. requirements, functions and visions), are illustrated in Table A 4 to Table A 7 (appendix). "User needs", "use cases", "system/product effectiveness", "verification and validation" have been part of the discussions with the participating actors in both the workshop and in the individual interview settings. The "user/owner identification" refers to the correct translation of the actor's mental model into a causal-loop model which implies that the actor who takes part in the design process can identify herself/himself within the causal model developed (see also chapter 2.3.2).

The “candidate concept” refers to this mental model of an actor which is captured by a causal model. “Traceability” is a process to ensure that requirements can be traced back to their source. It should be applied throughout the entire modeling process (Heitmann et al., 2019b).

Table 4 System Engineering activities and related documents (Kossiakoff et al. 2011)

Context diagrams	**Opportunity assessments**	Prototype integration
Problem definition	**Candidate concepts**	Prototype test and evaluation
User/owner identification	Risk analysis/management plan	Production/operations plan
User needs	**Systems functions**	Operational tests
Concept of operations	Physical allocation	**Verification and validation**
Scenarios	Component interfaces	Field support/maintenance
Use cases	**Traceability**	**System/product effectiveness**
Requirements	Trade studies	Upgrade/revise
Technology readiness	Component development & test	Disposal/reuse

Taking into account the roles mentioned above, knowledge areas and tasks of a systems engineer, it becomes clear that a systems engineer is one of the key stakeholders in a system design process (Kossiakoff et al., 2011). The systems engineer not only designs but also manages the process of design as a project manager. This implies the need for a deep knowledge of the system of interest, but also administrative skills. Working together with other actors and involving them into the system design process is one of the key tasks of a systems engineer in managing a successful project. Therefore, eliciting and analyzing requirements together with other actors, are the most important tasks while engineering a system.

2.3.1. Requirements Analysis

Requirements are defined in this study as factors to be fulfilled by an actor as part of an individual task in her/his working environment (based on Department of Defense Systems Management College, 2001). Therefore, to limit the risk that the design process fails, it is important to capture requirements and constraints during the whole design process (Heitmann et al., 2019b). This happens by formulating conceptual and detailed requirements in the form of documentation, interview protocols or, as it is described in this thesis, with causal-loop diagrams. Requirements can also be connected with functional models to describe a more detailed picture of what the designed system should do. In order to form a valid basis for the implementation of requirements-based models, several “test”-criteria for requirements evaluation exist. Compared to other design approaches and modeling methods, these criteria are one innovative aspect of SE for NRM. The criteria, or good practices of SE, can be used to ensure that the design process follows requirements which are correct, complete, consistent, traceable, unambiguous, testable, and atomic (Crowder et al., 2016) (see also Table 5).

Table 5 Requirements Quality Attributes according to Crowder et al. (2016) In Heitmann et al. (2019b)

Correctness			Disambiguation	Testability	Atomicity
Completeness	**Consistency**	**Traceability**			
No information is undefined. No information is missing from the requirement.	No requirements are allowed to be in conflict with each other, e.g., if requirement "a" enables "b", requirement "c" cannot imply that "a" does not enable "b".	The relationships between the requirements have to be clearly formulated and documented. This is of particular importance for the understanding and management of the objectives.	"An unambiguous requirement contains facts, and is written without negative language or compound statements. The disambiguated requirement does not contain opinions and is not subject to interpretation" (Crowder et al., 2016, p. 110)	The systems engineer has to be able to demonstrate, test, inspect, and analyze the correct implementation of the requirements.	A requirement should not contain connections to other requirements. It has to be the smallest element possible, e.g., "cultivation of bioenergy plants" should be divided into "cultivation" and "bioenergy plants".

If external actors are involved in the design process, collecting information on requirements together with them can help to identify trade-offs and synergies inside a system, to reveal limitations of physical design solutions, and to build up a basis for future stakeholder discussions. Requirements can be clustered into different categories such as functional requirements and constraints. In the first case study of this thesis, nine requirement types are defined: economic, financial, institutional, interface, legislative, process, social, structural and technological), whereas in the second case study, six types of requirements are defined to capture the complexity of the underlying system: economic, financial, general, policy, social, and technical requirements (chapter 4). In both cases, the actual actors who participated in the case studies defined these requirement types.

Requirements can be derived from human needs. These needs can be directly expressed to the modeler in individual interview settings or group-model building sessions. Strengths of individual interviews for eliciting requirements are for example (1) the opportunity to have a more focused and in-depth discussion on the topic and related requirements, and (2) to have an unbiased mental model of the actors' perceptions of the problem perspective. Eliciting requirements in a group setting requires a greater amount of preparation and also moderation during the modeling process. If the goal is to develop a requirements model which consists of many individual mental models, a group setting may lead to a faster result. However, as illustrated in Inam et al. (2015), an overall model of requirements for a larger and/or complex system can also be achieved by a combination of individual models. Nevertheless, in all cases the requirements elicitation process follows the same iterative standard procedure (Figure 8). Strengths and weaknesses as well as a detailed description of both approaches, i.e. the group model building workshop and PM with causal diagrams to derive requirements, are described in the following sections.

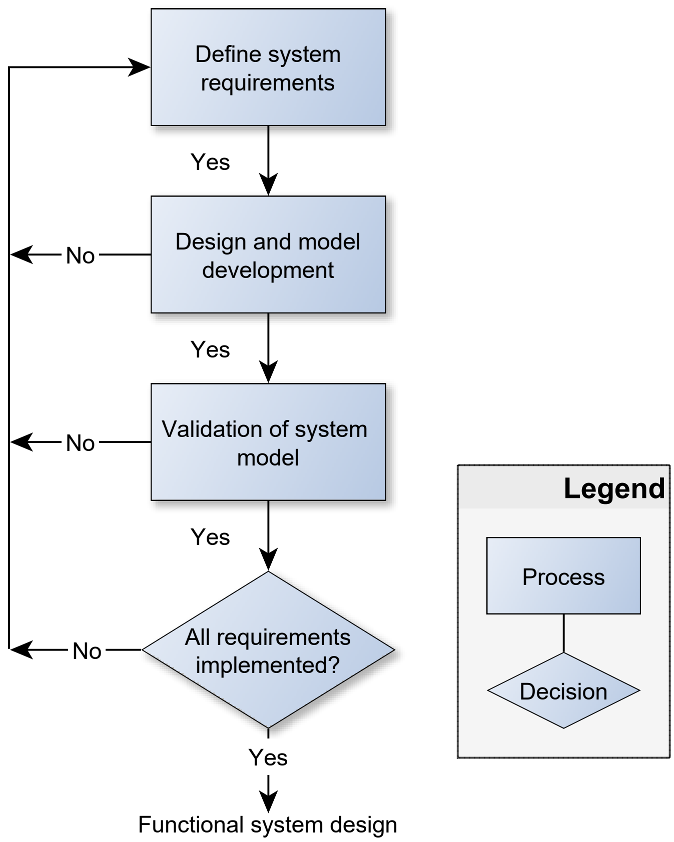

Figure 8 Requirements Engineering adapted from Blanchard and Blyler (2016, p. 57)

2.3.2. Participatory Stakeholder Modeling

Participatory modeling (PM) is increasingly becoming an approach to include various actors in a system modeling process. These actors can be stakeholders of the modeled system such as political decision makers or civil society, actors with expert knowledge on the system, such as practitioners or scientists, and, depending on the scale of the modeling process, business managers and employees of companies. Several PM methods exist with different scopes and objectives such as “group model building”, “community modeling”, “mediated modeling” and “shared vision planning” (Gray et al., 2017). PM is seen to support decision-making by providing knowledge on social environmental systems where uncertainties with respect to the interactions of system elements are often high (Kopainsky et al., 2017). PM can also help to inform theories on decision making which lack an understanding of causal relationships by developing a system model (Schlüter et al., 2017).

According to Stave (2010), participation in systems modeling means to collectively model an underlying system or parts of it, for example an integrated problem inside a complex system. A high degree of participation exists if actors are included in the framing of the underlying problem or modeling objective, modeling the system, and use the model for further steps such as the development of tools to inform political decision makers or implementing solutions for the problem that has been modeled. A lower level of participation may refer to a system model which is used to inform actors on causal relationships within a system (see also Figure 11). Because participatory processes have the potential to enhance cooperation among actors, PM can also help to build trust and reputation over time (Ostrom, 1998).

One powerful strength of participatory processes is the ability to enhance social learning (Scholz et al., 2014). Social learning can occur if different mental models of the participating actors are discussed in a group setting. Individuals or the group as a whole can derive new insights from these mental models and relate the outcome of the design process to these models. According to Scholz et al. (2014), a mental model is defined as the “personal internal representation of the surrounding world [of each participant]” (p. 577). If several actors are collectively engaged in a model process, this is called a group model process. In such a setting, shared mental models can be combined and represent a shared understanding of a problem perspective. Although mental models are considered as unstable and inconsistent, mental models are (1) helpful for understanding dynamics and structures of systems (Kopainsky et al., 2017; Stave, 2010), and (2) often form the baseline for system design processes carried out by system engineers (Crowder et al., 2016; Jones et al. (2011); Scholz et al., 2014). In this thesis, the concept of mental models is primarily used as an approach to understand complex interactions and relationships between different types of system functions. Because in system design processes, requirements are the interpretation of user needs and functions. The implementation of these requirements, mental models, also illustrate the interactions between requirements inherent in participatory processes which use mental models.

Supporting learning processes as part of a design process for complex human-nature-technology systems is important to consider, especially if stakeholders involved in the system design are included in the design process. On the one hand, learning influences the outcome of the process positively because new insights can be directly included in the system design model. On the other hand, learning can also lead to a system design which does not fit the design which was originally intended by the system engineer. This could, for example, be the case in a political process, where a decision should be steered towards a desired outcome, and group dynamics during the design process lead to a solution which is not primarily perceived as an optimal solution. Nevertheless, as in complex human-nature-technology systems such as the WEF Nexus or the German sustainability landscape no single optimal solution exists, learning processes in participatory processes can lead to an actor-oriented solution than a directed solution.

Many other factors influence participatory processes: The different relationships among the participants, sufficient moderation and mediation during the process, cultural aspects, the level of participation, trust and the structure of the process are only a few important aspects to consider when conducting a participatory process. Several tools and handbooks exist which can help organize and evaluate such processes. Hassenforder et al. (2015) suggest a framework for the comparison of participatory processes (COPP) to analyze the effectiveness of participatory processes and their elements. A framework with a similar objective can be found in March (2013), who defines additional evaluation criteria such as the "level of influence", "public supervision of the results" and "learning of agents" in evaluation workshops, document analysis, discussion groups and questionnaires (2013, p. 19). How to plan, structure and conduct multi-stakeholder consultations as well as a number of best practice examples and a report on lessons learned from a EU project on participation can be found in Ridder et al. (2005). A comprehensive collection of PM can also be found in Gray et al. (2017).

From the design perspective, PM is an interesting approach for engaging actors in system design. System design first requires a specific definition of the design objective. Such an objective could be a vision, a specific need or the solution to a specific problem. Particularly in socio-ecological systems modeling, the identification of various viewpoints of the actors involved can help to build common ground among those who are involved in decision making and implementation of targeted measures or policy instruments. PM has already been used in the context of sustainable systems design. For example, PM with causal-loop diagrams can be used to bring together researchers and ecological activists. By deriving key feedback processes in social, ecological and economic systems and by identifying leverage points for systemic interventions in such systems, it is possible to reveal insights into the consequences of a given proposal and explore "what-if?" questions and future pathways on a macro level (Videira et al., 2014).

Another example where PM with causal-loop diagrams can generate knowledge which can help in dealing with sustainability problems, is the application of PM to sustainable consumption patterns. However, motivating people to consume more sustainably is difficult. For example, several factors such as market dynamics exist which prevent the development of a sustainable food system. Sedlacko et al. (2014) assess, how PM can help to cope with this complex problem and how insights can be used to formulate policies for sustainable consumption.

However, the derived models, or mental maps, need to be based on a large number of individual mental models to be representative enough to inform the design of policies which have an effect on consumers. Therefore, it is suggested that PM be combined with other methods such as visioning workshops or multi-criteria-analysis (Videira et al., 2017). When conducting vision modeling workshops, the visions derived and discussed also need to be evaluated with respect to their degree of sustainability. This means that the effect of the visions at different governance levels on several functions, such as ecosystem services, needs to be assessed. Halbe and Adamowski (2019) present a methodological framework for vision design and assessment (VDA) to achieve that task.

In this dissertation, two exploratory case studies are presented, in which some of the above-mentioned insights from PM with causal-loop diagrams are adopted and applied. The first case study applies PM in a group setting with the overall objective to formulate a conceptual macro-model of the WEF Nexus in the Osnabrueck region in Lower Saxony, Germany. This macro-model includes eight individual mental models of scientific experts who participated in a two-day group model building workshop, and illustrates the starting point of a comprehensive type 1 SoS design process which refers to the design of an acknowledged SoS (see also Figure 7). A similar approach has already been applied by Martinez et al. (2018) who developed a PM approach to identify the main interlinkages within a WEF Nexus in Andalusia, and developed a system dynamic model at a later stage. The innovative aspect of the study presented in this thesis is the application of SoSE approaches and methods on a WEF Nexus case in a workshop setting. According to Lopes and Videira (2015), PM is used to support conceptualization of feedback processes and functions to accomplish a shared problem framing. The workshop design is formulated according to the script template by Hovmand et al. (2013). The workshop design as well as the methodological approach are described in chapter 3. The script template can be found in Appendix 1, Table A1 and already includes lessons learned from the conducted workshop series. The second case study applies PM with causal-loop diagrams in a number of individual expert interviews with the objective to illustrate knowledge and strategic pathways of several SDS in Germany. This application shows the importance of system design as an iterative approach in a type 2 SoS which refers to a directed SoS (Figure 7). This exploratory case study is described in Chapter 4.

Causal-loop diagrams are used in both case studies to model requirements and functions. Causal-loop diagrams are the formalization of individual mental models of actors. They can be used to model the relationships between several different variable types. The literature does not specify the type of variables inherent in such models. However, based on the different design phases and the different possible elements in causal models, it makes sense to define when to use which type of causal model in a design process. Therefore, four different types of causal-loop diagrams are defined in this thesis: (1) unspecified causal-loop diagrams (i.e. nodes and edges are not specified); (2) requirements causal-loop diagrams (i.e. nodes are defined as requirements); (3) functional causal-loop diagrams (nodes are defined as functions, processes or structures); and (4) mixed causal-loop diagrams (i.e. mixed requirements and functional diagram). Depending on the stage of the design process (CONOPS, requirements analysis, functional analysis, test, implementation, or support), different types of diagrams can provide different insights into the design process. In addition, each diagram type can be applied at different levels of system design (conceptual or detailed). This is illustrated in Figure 9.

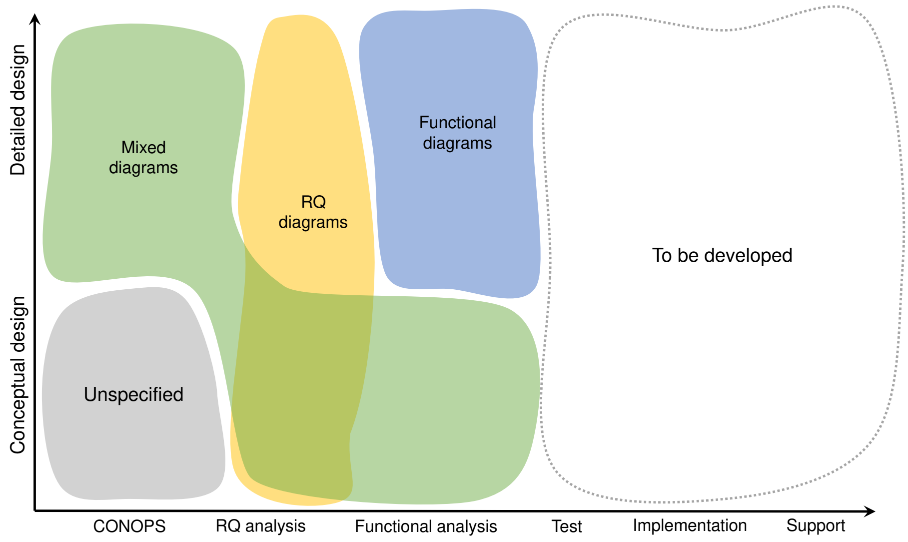

Figure 9 Strengths of causal-loop diagrams for system design phase and level

Variables in causal-loop diagrams are formalized as "nodes". The nodes are connected through "edges". Each edge represents a logical connection between two elements (Vennix, 1996). A causal relationship can be either positive or negative (Figure 10). A positive causal relationship indicates a positive influence of variable A on variable B, a negative causal relationship indicates a negative influence on Variable B. Combining two or more causal relationships creates a causal chain, i.e. a feedback-loop. Feedback-loops can reinforce themselves if the number of negative causal relationships in one feedback-loop equals an even number. In other cases, the loop balances itself out. This means that a reinforcing feedback-loop has an overall self-enforcement effect, whereas a balancing feedback-loop has an overall balancing effect on itself.

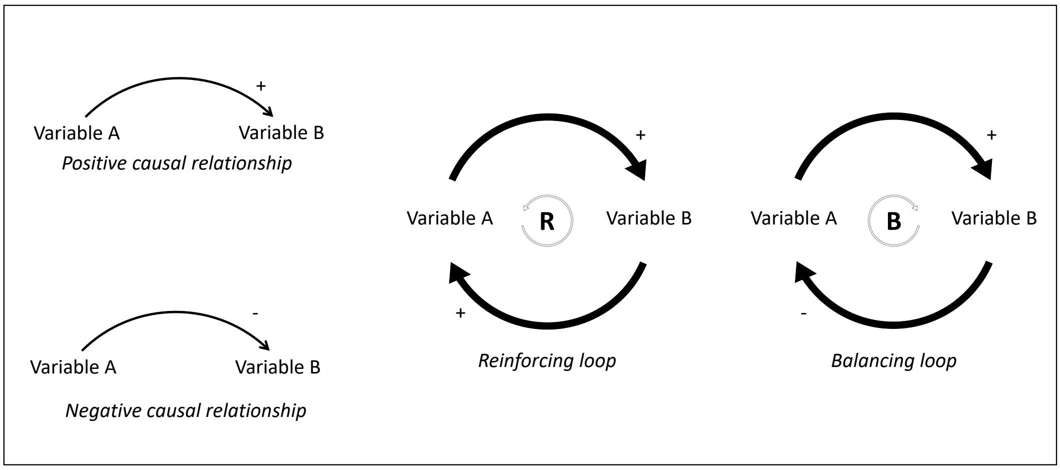

Figure 10 Notation of causal-loop diagrams (Videira et al. 2017)

As described, the principle of causal-loop diagrams can be applied in real life situations if the structure or dynamic of a system has to be understood and analyzed. Depending on the degree of complexity, the resulting diagrams can become very complex. To deal with this complexity, different network statistics can be applied to “filter” the diagram and to identify the most important variables. The application of the causal-loop modeling approach on the German SDS in chapter 4 shows some suggestions how to achieve this task. Depending on the available equipment for and the objective of the causal-loop model approach, it is suggested to develop such models in personal interviews via pen and paper. This ensures flexibility during the interview and builds trust for the interview partner because the recorded nodes and edges can be erased and changed at all times. If available, another option is to use a white board to save ink and paper. Online interviews can be developed by a browser-based online app such as “Participate” by Simon Hötten[3] and the “Mental Modeler”[4]. Both apps allow the interactive drawing of causal diagrams over a flash-enabled web-browser in real time. Considering the option of simultaneously developing such a causal-model with online tools, the implementation of a computer-based platform in a group-model building setting is conceivable.

In a participatory process, stakeholders can be involved at different levels from information provision, to consultation, empowerment and control (Arnstein, 1969). These levels of participation can be exemplified with the “ladder of participation” (Figure 11). A low level of participation does not necessarily mean a suboptimal participatory process. Usually, eight or nine participation levels are defined in the ladder of participation. For simplification purposes, these levels can be grouped into four or five basic categories:

“Non-participation”, “preliminary stages of participation”, “participation”, and “beyond participation”, sometimes also referred to as “Communication”, “listening”, “consulting”, “engaging”, and “partnering” (Corporate Consultation Secretariat, 2000; Sterne and Zagon, 1997). Depending on the intention of the participation process, each step can make sense. Examples of how group participation processes applying system design elements are structured, and what roles the levels of participation play, are provided in chapter 2.3.3, as well as in Table A1 and Table A2.

[3] https://participate.hoetten.org/ [25.03.2019]
[4] http://www.mentalmodeler.org/#home [08.04.2019]

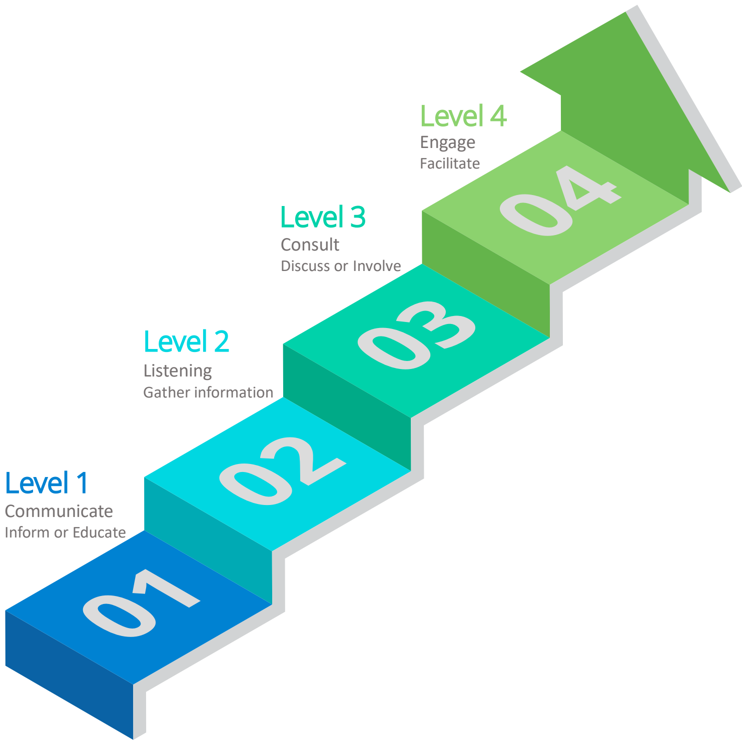

Figure 11 Ladder of Participation adapted from Arnstein (1969)[5]

Based on experience, some general criteria for deciding when to involve participants on what level of participation in a system design context are summarized in Table 6. Following these criteria, the level of participation for case study 1 is level 3 – consultation, because participating actors in the design workshop and in the preparatory interviews that were conducted are potentially affected by the outcome of the process (new information gathered, new perspectives gained due to interaction and discussion with scientific experts and practitioners from other research fields). In addition, participants had an interest in the system under investigation, either because of current or planned field studies (scientific experts) or because they are directly embedded in the system (e.g. farmers and water managers from the region). The level of participation for case study 2 varies between level 2 and 4 depending on the activity undertaken.

Some of the interviewed actors are experts from practice and are more or less actively engaged in the decision-making processes related to the envisaged system design (e.g. public administration member in charge of coordination tasks, scientific advisory board member, political decision makers, author of the strategy under investigation itself, or a consulting organization with direct relationships to and a mandate from political decision makers). For these actors, participation level 4 – engagement has been chosen. Other actors (i.e. scientific experts) have been part of the process in a consulting position because they may have an

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[5] Parts of the figure are designed by “Katemangostar / Freepik”

interest in the system design but no direct power to change or influence it. Level 2 – listening has been applied with one actor who was willing to provide information to the process but was engaged in other work. However, information on the system design provided by this actor was crucial for modeling the detailed system design level for the strategy design at the urban level in the city of Hamburg.

Table 6 Criteria for stakeholder engagement in a design process adapted from Corporate Consultation Secretariat (2000)

Level 1 (Communicate)	- The decision for a system design has already been taken - Stakeholders need to be informed about the completed system design - Changes to a specific system design are not possible - A system design has already been fixed but needs to be accepted by the target group - A preparatory level 1 involvement could be used to start a broader participation process
Level 2 (Listening)	- Information from actors is needed to develop the conceptual or detailed system design ideas (e.g. conceptual model, strategy design or policy) - The aim of the participation process is to inform and discuss, and the outcome of the process is not intended to change the system design - Participants have an interest in the system design
Level 3 (Consult)	- A dialog between the systems engineer (or the engineering team) and actors/stakeholders is needed, for example to enhance cooperation or collaboration. - Actors in the participation process are potentially affected by the discussed system design - Participants have an interest in the system design and are maybe affected by the outcome of the process - Participants may have the power to influence existing systems (e.g. policies) through the system design
Level 4 (Engage)	- Participants are empowered to actively design or re-design systems (e.g. policies or political processes in general) - The systems engineer and the participants agree that the outcome of the process will be implemented in the actual system design concept

o conclude, participatory stakeholder modeling can be carried out through individual semi-structured PM interviews with the use of causal-loop diagrams or by conducting group model-building workshops. In the latter, social learning among the participants may be envisaged.

It depends on the overall objective of the design process which modeling method is most effective. Actors involved can be included at several levels of participation in the system design tasks.

2.3.3. Conducting a system design workshop

In the context of the first research article for this doctoral thesis (chapter 3), simplified system models have been developed together with participating actors in a group model-building workshop. The general content-specific aim of the workshop was to (1) understand linkages among inherent subsystems with different functions in the water, energy and food domains (see Box 5 for an explanation of group model building), and (2) to identify possible integrated solutions to address existing trade-offs between these subsystems. The actor-oriented system view which was applied in the study aimed to enable decision makers to design or re-design systems specifically targeted to the requirements and expectations of the system users (actors) (Crowder et al., 2016, p. 2). The results from the workshop serve as a data base for subsequent analyses, in which the focus lies on the mapping of trans-sectoral requirements as well as the derivation of important system functions and processes.

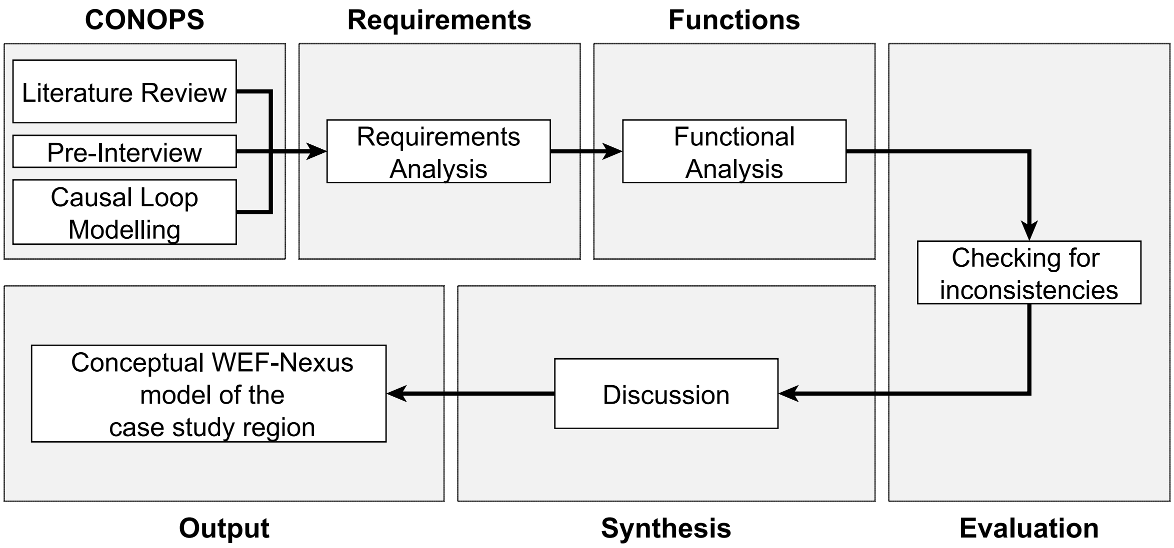

Figure 12 Nexus Framework application in a group model building workshop (Heitmann et al., 2019b)

Figure 12 illustrates the approach carried out in this study, whereas Table 7 describes the setting of the workshop and how SE elements have been included in the workshop. A comprehensive script for carrying out this workshop which is adapted from the script template of Hovmand et al. (2013) and Lopes and Videira (2015) can be found in the appendix (Table A 1). Additional information which was provided to the participants, can also be found in the appendix (Document A 1).

Table 7 Description of the Nexus Design Workshop

Workshop setting	
Aim of the workshop	(1) To apply the framework "FRESCO" developed within the scope of a dissertation in a scientific context together with experts and to reflect critically on it (2) To promote collaboration between the participating experts within the framework of the university's strategy process, UOS 2020, and the university's so-called profile lines, with the option of publishing one or more scientific strategy articles in the long term.
Topic	(1) Development of a structured overview of the WEF Nexus in Lower Saxony, Germany with the help of the framework developed (2) Development of available knowledge about multi-layered policy processes, sectoral interfaces and requirements for future changes in the region such as technological innovations or legal framework conditions as well as the resulting functions.
Participants	5 Professors; 1 Post-doctoral researcher; 2 doctoral candidates
Facilitation	Fabian Heitmann
Organization	Fabian Heitmann
Representation of Systems Engineering elements	
Overall SoS goal	Goal setting variables
CONOPS	Decision baseline for all participants/decision support; Underlying facts, preparatory interview and status quo
Requirements	Necessary elements of the transformative pathway towards achieving a vision
Function	Implementation of requirements for the concept map (Figure A 2)
Outcome	A conceptual mixed requirements diagram is generated by the participants to build up a shared understanding of the problem perspective and solution strategies. The diagram consists of visions for transformations in the regional WEF sectors, lists of functional and non-functional requirements, and functional groups which are embedded in causal models.

Regarding the level of stakeholder participation in this system design process, all steps excluding the preparatory literature review and pre-interviews have been conducted together with the participants. However, a conclusion drawn from these experiences, is that it is advisable to clarify the role of the participating actors prior to the workshop. Depending on the field of expertise of the participants (e.g. scientific experts or practitioners), different levels of participation for the actors can be anticipated. In the scientific expert workshop (chapter 3), the main level of participation was “consultation”. Stakeholders have been asked to share their individual knowledge in the process, develop a common simplified conceptual system model based on several different types of requirements, develop functional groups, and discuss possible relationships between those groups.

The outcome of the workshop has served as a baseline for a common scientific publication on the regional problem of water nitrification which is mainly caused by high manure production from the agricultural sector. However, because the actual implementation of such system designs mainly depends on political decision makers, and the participants do not have the power to also implement the modeled system designs, no higher level of participation is possible in comparable workshop settings. However, the design approach presented could also be applied with actors who are in charge of such decision-making processes. This would ultimately allow participants not only to design solutions but also pathways for the implementation of such solutions which could be discussed afterwards in a broader political debate.

As a preparatory step for the workshop, insights from 14 individual stakeholder interviews conducted in 2015 on the topic of bioenergy production in the region have been reviewed. These interviews provide information on the problem domain which was the focus of the workshop. The interviews were conducted in the context of a seminar in the study program, "Environmental Systems and Resources Management," at Osnabrueck University in Germany. During the seminar, groundwater quality was identified as the most important variable among the participating stakeholders. Therefore, this variable was also suggested as a key topic for the subsequent stakeholder workshop.

As additional preparation for the workshop, one scientific expert had been asked to participate in a preparatory individual PM exercise. The pre-interview helped to better understand the underlying functions and the status quo in the region. Such a preparatory step supported better organization and moderation of the subsequent two-day group model-building workshop with scientific experts which has been organized to test the application of the systems engineering approaches presented in this thesis.

The combined insights from the pre-interview, the individual stakeholder interviews and the workshop captured important concepts related to the status quo and provided a more precise picture of requirements and functions needed for a sustainability transformation in the case study region. In particular, simplified system models which have been developed together with participating actors in the workshop, helped to understand linkages among regional WEF Nexus subsystems with different functions in the water, energy and food domains.

What is Group Model Building?

Group model building is defined as a modeling process which involves the simultaneous modeling of a system or its elements with two or more participants, where direct communication among the participants is possible.

In general, group model building can be used to develop system dynamics models which are directly based on the perceptions of the participants (Vennix, 1996). *Additional objectives of a group modeling process include, but are not limited to, the alignment of individual mental models, achieving group agreements, and accomplishing a group commitment to a decision that has already been taken* (Vennix et al., 1997).

As in other participatory approaches, group model building can create new knowledge or understanding of a problem perspective, and thus support social learning in the group (Inam et al., 2015; Scholz et al., 2014; Stave, 2010).

SE methods are usually not part of a group model-building process where facilitating (social) learning, building trust and a common ground among actors and helping them to understand the system structure and behavior are most important (Stave, 2010; Vennix et al., 1997). Because particularly requirements are important for a successful system design process (Carr, 2000), requirements analysis is integrated into the group model building process which is presented in this thesis.

Box 5 What is Group Model Building?

Together with the workshop participants, an actor-oriented system perspective has developed. Such an approach can enable decision makers to design or re-design systems specifically targeted to the requirements and expectations of the system users (actors) (Crowder et al., 2016, p. 2).

The workshop results, i.e. visions for transformations in the regional WEF sectors, lists of functional and non-functional requirements, functional groups, and causal models which include all this information, served as a data base for subsequent analyses, in which the focus lies on the mapping of trans-sectoral requirements as well as derivation of important system functions and processes. First, each participant was asked to describe in written form at least two visions which are most important to consider based on their individual scientific expertise. Next, requirements were formulated which are needed to design the transformative pathway from the current system state to the desired outcome which has been formulated in the vision modeling exercise. Afterwards, participants connected the derived requirements with each other and developed functional groups which include these requirements. This included the definition of key functions and sub-functions for the final WEF Nexus model. The requirements identified in the preceding modeling step have been used to define the specific purpose and description of each function. The requirements and functions developed were discussed in several discussion rounds with respect to their effect and importance for the regional WEF Nexus. To steer this process, parts of the vision modeling approach have been used as a supporting element. More specifically, the formulation of possible future visions by each participant on moderator cards, the moderated discussion of these visions, and the formulation of possible transformative pathways towards achieving these visions have been organized and implemented by the workshop moderator to guide participants step-by-step through the modeling process. As described by Iwaniec et al. (2014), the aim of a vision modeling process is to express the structure and function of a future system design in a system model and finally to guide the system towards an desired state. From a SE viewpoint, the formulated visions in the workshop are the representation of CONOPS. They explain how the desired system should be operated. The structure and model of the system design are represented by the links of the elicited requirements and by the functional causal models which has been collectively developed by the participants. In addition, the group discussed if these models are consistent with the requirements and functions which has been already defined. Although a comprehensive vision modeling exercise usually includes more steps such as applying quality criteria for the formulated visions (Wiek and Iwaniec, 2014), the focus in the workshop design that was presented is on developing a common ground among the participants and aligning the different viewpoints of the participants who had diverse backgrounds and knowledge. The outcome of the workshop, a preliminary and conceptual WEF Nexus model, illustrates how requirements and functions can be modeled with SE methods and concepts in a group model-building workshop (Figure A 3)

2.4. Nexus Thinking for Systems Engineering

“Nexus” is defined as complex relationships between actors or actor groups, institutions, requirements, functions, subsystems and other elements which are considered to be part of an overall SoS. In the literature, the term is used in many different ways. The WEF Nexus, as a more specific Nexus type, describes the problem of a lack of coordination and cooperation between water, energy, and food sectors despite strong interdependencies between these sectors (Heitmann et al., 2019b; Pahl-Wostl, 2017). The WEF Nexus concept refers to a growing research field that fosters cross-sectoral analysis of water, energy, and food issues to overcome sectoral fragmentation and the resulting sustainability deficits (Pahl-Wostl, 2015). Whereas the WEF Nexus concept has already been applied in several case studies and with different methodologies, “there is no fixed concept of Nexus, and the Nexus is internationally interpreted as a process to link ideas and actions of different stakeholders under different sectors and levels for achieving sustainable development”, (Endo et al., 2015, p. 3).

Because the relationships in Nexus systems are highly important to understand the overall behavior of a system on a macro level, the WEF Nexus represents a promising approach for overcoming the failure of governance to deal with complex and interconnected resource management challenges.

The WEF Nexus concept focusses on understanding and managing interdependencies between water, energy and food with the aim of overcoming sectoral fragmentation and sustainability deficits. Therefore, the local and global importance of cooperation between actors in WEF-Nexus governance can be exemplified by the environmental effects of large-scale livestock farming where cooperation is essential to prevent resource overuse and negative environmental impacts.

At this point of the thesis, the question remains why the WEF Nexus or the Nexus concept in general should be considered as a SoS, and why Nexus thinking is worth considering in SE design processes. Thus, in Nexus systems, the relationships between the Nexus sectors (e.g. water, energy and food) need to be defined. In addition, cross-sectoral interdependencies have to be identified to develop effective solution strategies, for example if trade-offs exist. These processes are part of many SE frameworks. Requirements are elicited and their linkages analyzed (Heitmann et al., 2019b). Functions are derived from these requirements which then defines the overall outcome of the system that has been designed on a macro scale, as well as the interactions between the individual subsystems. A Nexus perspective of complex systems, i.e. the analysis of complex relationships between elements in systems or subsystems in SoS, can help to better understand the structure and dynamics of such systems. In SE, understanding how a system should be designed (i.e. the design objective), the structure and dynamics of a system and, as explained above, what is required to achieve this design (i.e. requirements and functions) are described as crucial steps for a successful system design process (Crowder et al., 2016). With respect to WEF Nexus systems, it can be concluded that, according to the definition of a SoS, a WEF Nexus system can also be considered a SoS: Although, functional and operational independence as parts of the SoS definition cannot be applied to the WEF Nexus (the WEF-Nexus sectors are not maintained or operated in isolation, and the functions of one sector may depend on the functions of other sectors), the WEF Nexus is usually considered as a complex adaptive system. Therefore, other SoS criteria, i.e. emergent behavior and evolutionary development, also hold true for the WEF Nexus. A more comprehensive comparison of the WEF Nexus and SoS definitions and criteria can be found in Austrup (2017). Because of the overlap of the Nexus concept with the SoS framing, this thesis discusses the advantages of SE and SoSE for analyzing requirements and functions in Nexus systems such as the WEF Nexus and the Nexus of SDS in Germany. The research articles presented in the following sections demonstrate that SoSE can contribute to an analysis that identifies, facilitates and guides the implementation of systemic approaches and solutions with the aim of addressing Nexus challenges.

The research approach presented which includes the analysis of processes, functional designs, and their requirements and constraints in two case studies, is intended to motivate scientists to acquire an engineering perspective on coupled human-nature-technology systems. This perspective could also lead to the development of new innovative technologies. These technologies can be understood as embedded systems in a larger socio-environmental context and are ideally designed to increase sustainability on the overall SoS level. In addition, SE is presented in this thesis as an approach which can be used to guide, inform and design political processes such as decision-making processes in a governance system. The following sections illustrate these areas of application and present some novel methodological approaches which have been developed to manage the transition between SE, SoSE and WEF-Nexus governance, as well as SE, SoSE and sustainable stakeholder-based strategy design.

3. Article 1 – Requirements Based Design of Environmental System-of-Systems: Development and Application of a Nexus Design Framework

Published as:

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The first research article which is related to this thesis, presents the developed FRESCO framework and tests its applicability on the case of nitrate pollution of water bodies in Lower Saxony, Germany. The area is dominated by intensive agriculture and is one example for missing inter-sectoral coordination of sustainability goals in a Nexus system. The situation is characterized by trade-offs between energy production through energy crops, profit optimization of food production by intensive agriculture, and the provisioning of drinking water for domestic use (Pahl-Wostl, 2017). Whereas the food and bio-energy industry often benefit from intensive agricultural practices, institutional restrictions with the aim to minimize the nitrate load on ground water and on the same time a high demand for meat consumption, makes decision-making for farmers but also for other actors challenging. Trade-offs between these interlinked objectives are often unavoidable but they may be reduced by enhancing cooperation between the sectors, or taken into account in pursuit of an overarching goal.

Article 1

Requirements Based Design of Environmental System of Systems: Development and Application of a Nexus Design Framework

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Abstract: Social, technological, and environmental systems have become increasingly interconnected. Integrated problems arising between embedded water, energy, and food systems, require political and strategic cooperation between the actors involved at multiple governance levels. A holistic design approach is needed to guide the inherent decision-making processes. In this article, we developed a normative decision-making framework based on System of Systems Engineering (SoSE) and demonstrated how it can help to foster the cross-sectoral design of solutions to these interlinked water, energy, and food issues. The actors involved in our case study demonstrated a strong interest in collaborating across sectors and participating in the transition to cross-sectoral and sustainable resource management practices. However, experts from science and practice face a high degree of uncertainty when they design solutions to cope with the existing regional problems. As almost all regions of the world are highly integrated in national and global markets, future research might consider conducting larger research projects that also link the design approaches to inter-regional, national, and international levels. Our methodological approach illustrates how such a project could be structured on a regional level and identifies the processes that are important to consider.

Keywords: water–energy–food; nexus; system of systems; complex systems; framework; systems design; requirements analysis; participatory modeling

1. Introduction

The Water–Energy–Food (WEF) Nexus represents a promising approach for overcoming governance failures in dealing with complex and interconnected resource management challenges (Pahl-Wostl, 2017). The WEF Nexus concept focusses on understanding and managing interdependencies between water, energy, and food systems with the aim of overcoming sectoral fragmentation and sustainability deficits. Therefore, the local and global importance of cooperation between the actors in the WEF Nexus governance can be demonstrated by the environmental effects of large-scale livestock farming where cooperation is essential to prevent resource overuse and negative environmental impacts (Pahl-Wostl, 2016).

On a regional level, the case of nitrate pollution of water bodies, in areas dominated by intensive agriculture in Germany, is one example of missing inter-sectoral coordination of sustainability goals in a Nexus system.

The situation is characterized by trade-offs between energy production from biofuel-crops, profit optimization in food production through intensive agriculture, and the provisioning of drinking water for domestic use (Pahl-Wostl, 2017). While the food and bio-energy industry often benefit from intensive agricultural practices, institutional restrictions with the aim of minimizing the nitrate load on groundwater and meeting the high demand for meat at the same time, makes decision making for farmers challenging. Trade-offs between these interlinked objectives are often unavoidable but they could be balanced by enhancing cooperation between the sectors, or, at least, taking it into account in pursuit of an overarching goal (Pahl-Wostl, 2015).

To understand these and other relationships between the nexus sectors of water, energy and food, and to come up with effective strategies to address the trade-offs, cross-sectoral interdependencies have to be identified. Several WEF Nexus frameworks have been developed, which focus on the different parts of the WEF Nexus, such as climate change , natural infrastructure (Ozment et al., 2015), sustainable development goals (Weitz et al., 2014), sustainable development and food security (FAO, 2014), landscape investment and risk management (Bizikova et al., 2013) and general conceptual frameworks (El Costa, 2015). These frameworks have proven to be successful in analyzing the overarching structure of the underlying systems, as well as understanding the processes and the actor relationships within each WEF Nexus case, from different perspectives and on different scales (Bizikova et al., 2013). However, most frameworks do not focus on the different levels of detail in system design, which is particularly important for developing practical solutions to the integrated WEF Nexus problems and for taking action to strengthen sustainability in the WEF Nexus. Thus, what is missing from the actual nexus frameworks is a design-driven approach for nexus assessments.

As described above, decision-making in human–nature–technology systems such as the WEF Nexus is very complex, because actions in one part of the system often show emergent behavior at the overall system of systems level (Sivapalan and Blöschl, 2015). In addition, uncertainties among the actors who lack information on other sectors (Agusdinata, 2006), ambiguities caused by various narratives in the different sectors (Dewulf et al., 2005), complex relationships within and between sectors, and heterogeneous requirements and constraints of the actors to take action, make decision-making in this nexus even more complicated. Therefore, we argue that these decision-making problems might be solved by applying a design perspective on the WEF Nexus. Designing the process of decision-making, i.e., providing helpful guidance on how to gain information, and how this information can be structured and modeled, might help to reduce and manage uncertainties in the WEF Nexus governance.

The concept of the WEF Nexus has been developed to contribute to a deeper understanding of the appropriateness of governance structures to address interdependencies in complex human–nature–technology systems. It focusses on “the interface and interactions between sectors instead of being defined from an inwards directed sectoral perspective” (Pahl-Wostl, 2017, p. 3). Therefore, the nexus-perspective could support “a reframing of the problem perspective and could support more balanced negotiations of interests between sectors and engage diverse actors” (Pahl-Wostl, 2015, p. 275f).

Although cooperation between actors is a bottleneck in taking action in the WEF Nexus, no design framework currently exists that provides a structure for the decision-making processes in the WEF Nexus and which takes the complexity of these cross-sectoral interactions into account. Therefore, in this paper we discuss the advantages of Systems Engineering (SE) and System of Systems Engineering

(SoSE) for analyzing the requirements and functions in nexus systems such as the WEF Nexus. We argue that the combination of SE and SoSE approaches, which largely focus on the process management and system design, help to address the complexity arising within the application of the nexus concept. To achieve this, we provide a structural design approach for the decision-making processes in environmental System of Systems (SoS). On a methodological level, there have already been attempts to connect SE approaches and the WEF Nexus perspective (Garcia and You, 2016; Lubega and Farid, 2016, 2013). However, these studies often focus on the analysis of technical elements of the WEF Nexus. Our framework broadens the focus and emphasizes the design of human–nature–environment subsystems, which are often interlinked within the WEF Nexus. The framework illustrates essential conceptual approaches that should be incorporated into the design of decision-making processes, across nexus sectors. Incorporating the different viewpoints of the actors within each of the subsystems of water, energy, and food, is particularly important when designing a specific measure or strategy. By using the term, "framework", we refer to Binder et al. (2013), who defines a framework as the provision of "a set of assumptions, concepts, values and practices that constitute the way of viewing the specific reality" (2013, p. 2). We illustrated the potential of our framework by applying it in an exploratory case study dealing with nitrate pollution of water bodies in Lower Saxony, Germany. We first conducted an expert workshop in a scientific context and asked experts in a group model-building setting to define requirements and functions for the development of a conceptual model of the case study region. To demonstrate the practical applicability of this model, we verified the outcomes of the workshop by comparing the data to the results of individual stakeholder interviews with practitioners.

The article is structured in six sections. Following the introduction, we provide a short theoretical background on the WEF Nexus perspective. We subsequently discuss the applicability of SE and SoSE in the field of natural resource management, and highlight the overlaps between requirements and functions, as they are described in the SE literature and the WEF Nexus perspective. The derivation of requirements and functions was integrated into (1) a participatory modeling exercise, and (2) a two-day group model-building workshop. The latter included the development of an overarching vision of the regional WEF Nexus to address uncertainties in strategy planning caused by complexity and ambiguity, and the formulation of alternative system designs that could enable practitioners and decision makers to design more sustainable and effective strategies. In Section 3, we present our Nexus SoS Design Framework—Functions, Requirements, Evaluation, Structures, Constraints, and Outputs (FRESCO). In Section 4, we illustrate the application of our framework by describing its application in the exploratory expert workshop. Finally, we conclude that our framework can help to better understand the complex relationships of the WEF Nexus, by focusing on the requirements and functions of different governance levels represented in the WEF Nexus concept.

2. Theoretical Background

2.1. The WEF Nexus

The WEF Nexus can be used to define the problem of lack of coordination and cooperation mechanisms between the water, energy, and food sectors, despite the strong interdependencies between these sectors (Pahl-Wostl, 2017). The approach refers to a growing research field that fosters cross-sectoral analysis of water, energy, and food issues to overcome sectoral fragmentation and the resulting sustainability deficits. The term "Nexus" itself is used in many different ways. Although the WEF Nexus concept has already been applied in several case studies and with different methodologies, "there is no fixed concept of Nexus, and the Nexus is internationally interpreted as a process to link ideas and actions of different stakeholders under different sectors and levels for achieving sustainable development" (Endo et al., 2015, p. 3). Therefore, it can be understood as a systems thinking concept (Cabrera et al., 2008). We define "Nexus" as complex relationships between the actors or actor groups, institutions, requirements, functions, subsystems or other elements, which are considered to be part of the overall SoS. Examples of Nexus systems are subsystems (Water, Energy, and Food), governance levels (household level, community, municipal, sub-state, regional, state, interstate, macro-regional, national, binational, and multinational) or complex relations within social systems (e.g., network structures). One innovative and important aspect of the Nexus concept is the focus on multi-centric perspectives and the interdependencies between sub-systems (De Strasser et al., 2016). Hence, the analysis of the overall system structure through a multidisciplinary problem-oriented assessment, forms the bottom line of the Nexus approach. Consequently, the WEF Nexus is defined as the complex relationships between Water, Energy, and Food Systems.

Since 2011, the Nexus approach has become increasingly prominent, starting with the "Bonn 2011 Conference: The Water, Energy and Food Security Nexus Solutions for the Green Economy" and gained attention worldwide. Several frameworks have been developed, each trying to encompass the core idea of the concept, having an integrated approach to achieve water, energy, and food security (Bizikova et al., 2013; Federal Ministry for the Environment Nature Conservation and Nuclear Safety et al., 2011; Hoff, 2011). What makes the understanding of the WEF Nexus complex, are the different functions, processes and their feedbacks in each subsystem (Water, Energy, and Food) as well as different governance levels, which have different legislation, organizations and underlying rules for resource management. It is not only these complex heterogeneous elements but also the different concepts for understanding social, ecological, and technical subsystems that make it difficult to understand a WEF Nexus system (Bizikova et al., 2013). As described by Bhaduri et al. (2015), "security in food, energy and water is interwoven with human, economic and environmental sustainability" (2015, p. 723). Therefore, in our view, WEF Nexus research should ideally apply multidisciplinary methods to assess water, energy, and food-related issues from an inter-sectoral perspective, in order to identify systemic solutions to complex resource management problems. However, in practice, the individual goals of the three sectors still lead to suboptimal outcomes for resource management on a macro scale.

As illustrated by Pahl-Wostl (2017), the WEF Nexus could be used to enhance coordination among the actors by balancing the "negotiations of interests" between them (2017, p. 10). This can help to design individual sectoral goals and system structures, which lead to more sustainable and integrated solutions for the overall SoS. However, decision-making in the WEF Nexus is complex because of "fragmented approaches to planning and policy implementation (which) arise from competition among urban and rural local governments for central fiscal transfers, overlapping jurisdictional boundaries and inadequate management coordination among line departments and ministries" (Scott et al., 2015, p. 24). The "lack of synthesis of nexus knowledge", is consequently one of the most important gaps in nexus research (Bhaduri et al., 2015, p. 729), and reveals the fact that effective WEF Nexus analysis requires the collaboration of experts from diverse scientific disciplines (El Costa, 2015). However, a formalized concept which integrates the heterogeneous elements needed for an effective synthesis into a WEF Nexus analysis, is currently missing.

Nevertheless, WEF Nexus frameworks are not a novelty. While several of these frameworks exist, they often do not focus on the different levels of system design, which is particularly important for developing practical solutions to integrated WEF Nexus problems (Bizikova et al., 2013).

For example, the "IISD's Water–Energy–Food Security Analysis Framework", developed during the Bonn Nexus conference 2011, was supposed to promote the importance of the concept of security in nexus research and conceptualize WEF Nexus related concepts, such as the Ecosystems Service Concept (Bizikova et al., 2013; Millenium Ecosytem Assessment and MA, 2003). What remains missing is a high degree of specificity of the operationalization, in empirical terms.

To close this gap, we see, in particular, the potential in applying a design and process-oriented perspective in nexus systems. The objective of design in a WEF Nexus context could be, for example, the design of strategy-building processes, natural or technological functions, or the implementation of cooperation mechanisms or new governance structures.

The underlying goal of many WEF Nexus approaches is to induce transformative change in the system (Bizikova et al., 2013; El Costa, 2015). However, only if the functional relationships between the subsystems of water, energy, and food are understood, can cooperation between these subsystems be enhanced; insights on the different levels on a larger scale, also help. SoSE can contribute to closing this gap at a conceptual level. It guides the establishment of an "Effective Frame of Reference" (Crowder et al., 2016, p. 33ff), meaning an analysis that identifies, facilitates, and guides the implementation of systemic approaches and solutions with the aim to solve WEF Nexus challenges. More specifically, the analysis of processes, functional designs and their requirements and constraints, as well as how they all relate to each other, can contribute to the development of a more detailed representation of the WEF Nexus. While the nexus approach is deliberately conceptualized in a broad way, SoSE can support this concept with specific tools and methods that can be used to describe and manage a Nexus problem.

2.2. System of Systems Engineering and Natural Resources Management

SoSE is a special type of SE that aims at designing SoS or parts of it. In the engineering domain, SoS is commonly defined as a collective system with autonomous and diverse subsystems, which are dynamically connected with each other and have their own goals contributing to the overall goal of the SoS (Baldwin et al., 2015a). Historically, SoSE did not include the design of non-technological interrelationships that are inherent, for example, in complex adaptive human–nature–technology systems. Therefore, we built on the SoS definition of Hipel et al. (2010 & 2008c), and added a social and nature environmental perspective to the SoSE approach. We defined an environmental SoS as a complex adaptive human–nature–technology system that is usually governed by multiple subsystems and follows an overall SoS objective.

Originally, SE was perceived as an approach that "seeks to optimize the overall system functionality, utilizing weighted objectives and trade-offs in order to achieve overall system compatibility and functionality" (Crowder et al., 2016, p. 2). "It focuses on holistically and concurrently discovering and understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, deploying, sustaining and evolving solutions while considering the complete problem, from system concept exploration through system disposal" (BKCASE Editorial Board, 2015, p. 1). SE was developed around the 1950s. After the NASA began its first Apollo mission, a variety of heterogeneous subprojects under the Apollo program, technical subsystems, as well as functions and processes needed for the implementation of the program had to be coordinated, to successfully achieve the overall program objective. During the next 20 years, the rising complexity of engineering systems led to more sophisticated SE methods. The simultaneous development of object-oriented modeling methods led to the opportunity to handle even more complex system designs (Crowder et al., 2016).

The term "System of Systems" was to the best of our knowledge first mentioned by Ackoff (1971). After this, the SoS approach was further developed by Jackson (1990) & Jackson and Keys (1984), who built their work to a large extent on the complexity theory described by Simon et al. (1962). Afterwards, the SoS approach was further expanded by Maier (1998) who defines principles for the classification of SoS. The SoS Engineering literature proposes these principles, also called "Maier's criteria", as elemental parts on which the idea of SoS and SoSE is based. Following Maier (1998), these criteria are: (i) "operational and managerial independence", i.e., the subsystems can and do maintain their functions independently from other subsystems; (ii) "geographical distribution", i.e., the subsystem elements are strongly coupled through spatial proximity, but the subsystems are only loosely coupled; (iii) "emergent behavior", i.e., the development of new emerging properties through interconnectivity of subsystems; and (iv) "evolutionary development", i.e., objectives, functions, and processes in the SoS can change continuously. These criteria classify a system as a SoS (Maier, 1998). However, the discussion will show that Maier's criteria do not necessarily apply for SoS in a socio-ecological systems context.

Due to the formulation of different SoS types (i.e., virtual, collaborative, acknowledged, and directed SoS), SoSE supports, in comparison to other approaches, a standardized modeling method for representing diverse actor goals (Dahmann et al., 2009). (1) An acknowledged SoS has a common purpose, a common manager (e.g., a Meta-SoS agent to supervise the functions of the SoS), and common resources. Nevertheless, the individual subsystems keep their own identity and goals. Changes in the system are based on collaboration between the agents and the systems. (2) A collaborative SoS has no central entity. The cooperation between the key system and the actors provides the mechanism to maintain the SoS functions. (3) A directed SoS is a centrally managed system, to ensure the SoS functions, whereas the functions of the system components are inferior to the overall SoS function. (4) A virtual SoS has no central agreed purpose for the SoS (Dahmann et al., 2009; Maier, 1998). While, SE and SoSE were originally developed to optimize process development and product design of technical systems and complex and dynamic projects, SoSE also offers "strategic and operational methods to carry out creative problem-solving on our most pressing global problems, which involve multiple participants in interconnected complex systems" (Hipel et al., 2010, p. 7).

However, during a literature review, we identified a lack of SoS models and SoSE approaches, which relate to socio-ecological systems like the WEF Nexus. The SoS literature focuses mainly on managing technical infrastructures (Eusgeld et al., 2011; Mostafavi et al., 2011).

Complexities and uncertainties (DeLaurentis and Ayyalasomayajula, 2009; Mostafavi et al., 2011), as well as coupled technical-human systems are often described without explicit links to environmental issues (Anders et al., 2015; Keating et al., 2008; Mittal, 2006; Mittal et al., 2008). A technical overview about the role of SoS model applications in SoSE is provided by Mittal et al. (2008), whereas Keating et al. (2008) gives a broader overview about the applications of the SoS approach. In the latter, only one chapter points to an explicit link to environmental issues (Hipel et al., 2008c). Additionally, more recent publications such as a special issue on SoS in the IEEE–Reliability Society do not emphasize linkages to natural environment resources (Hansen et al., 2016). One of the most influential authors who explicitly relates SoS to environmental themes is Hipel, who proposes SoS as an approach to inform integrated water resource management and to enhance food security (Hipel et al., 2010, 2008b). Further information about environmental issues and their linkages to SoS can be found in Hadian and Madani (2015), Hipel et al. (2008a), Lehmann et al. (2015), Yaeger et al. (2014). Applications of the SoSE concept include, but are not limited to the model development of the whole or parts of a SoS; decomposing the constituent subsystems within a SoS; understanding specific processes and functions within a SoS; or a combination of those.

Frameworks from the engineering domain have mainly been developed for application in a technical context. These frameworks are generally goal-oriented, incorporating the needs of actors, and include design constraints, as well as economic factors like costs and risks. The Department of Defense Architecture Framework (DoDAF) or the similar Ministry of Defense Architecture Framework (MODAF) used by the British Defense industry, illustrate these principles (Department of Defense Deputy Chief Information Officer, 2011). These frameworks are classified as “Architecture Frameworks” and also guide a structured system design process. Other frameworks organize the system architecture into different viewpoints. One example for such a framework is the 4 + 1 architectural view model (Kruchten, 1995). It describes four views on a system (i.e., “Logical View”, “Development View”, “Process View”, and “Physical View”, which all support scenario development). We hope that those principles help to inspire people beyond the SE field and, therefore, propose a process-oriented SoS design framework for application in a resource management context.

A policy-oriented approach on SoSE is taken by Agusdinata and Delaurentis (2011), who analyzed the extent to which alternative policy-solutions constitute fairness among the involved policy actors. Meta-models also exist that describe the general aspects of complex systems and emphasize the importance of multi-view management of these systems (i.e., IEEE 1471 or ISO/IEC/IEEE 42010:2011).

To recap, conceptual approaches bridging the gap between SoSE and environmental management on local, regional, and global levels are not a novelty (Hipel, 2012; Hipel et al., 2010, 2008c, 2008b), but a framework to apply the process-oriented nature of SoSE in the nexus design is still missing.

We close this gap by proposing a SoS Nexus design framework that is tested in an exploratory expert workshop. This includes the application of participatory modeling and group model building methods to derive a concept of operations, requirements, and functions, as an underlying basis for a more sophisticated and detailed systems design. These SE tasks are usually not part of a group model building process where often facilitating (social) learning, building trust, and a common ground among the actors and helping them to understand the system structure and behavior, are most important (Stave, 2010; Vennix et al., 1997).

As requirements are particularly important for a successful system design process (Carr, 2000), we specifically focus on the elicitation of requirements and conclude on the practicability of this approach in a group model-building context.

In the following, we first present our conceptual basis and framework. In Section 4, we illustrate a first application of the framework on an exploratory case, in the context of the WEF Nexus.

3. The Nexus System of Systems Design Framework "FRESCO"

3.1. Introduction to the Framework

The "FRESCO" framework (Functions, Requirements, Evaluation, Structures, Constraints, and Outputs) is a general process design framework for application on environmental SoS. The framework is derived from SoSE concepts but uses narratives from the resource management domain. By following the process of the framework, the complexity of environmental SoS can be included into a system design task.

The main objective of FRESCO is to support the process design of decision-making strategies by including user-based requirements and functions into the decision-making process. One objective of engineered systems is to include a user-oriented system architecture and functions in the design of systems (Crowder et al., 2016). This is done, for example, to improve the usability or acceptance of the system for the system users. However, deciding for a specific system architecture can be very complex and requires additional tools and methods that help to reveal the actual effects of the system architecture on the overall SoS (Raz et al., 2018). Particularly in complex, natural environmental systems, i.e., environmental SoS, the actors still have to take decisions on the system design after the architecture or functions have been implemented. For example, the political actors have to decide for or against new policies, or experts from practice, such as farmers, have to decide within their decision-making space, to change their cropping behavior. This steady re-design of systems requires ongoing decisions on different governance-levels. These decision-making processes in natural resource management can face a high degree of uncertainty because of existing trade-offs, several consequences of the decision, optional alternatives which are maybe more feasible or because of different objectives from different actors (Gray et al., 2017). Knowing one's own role in the system and being able to understand the effects of the strategies used for other subsystems or for the whole SoS, should be natural for a decision maker (Hipel et al., 2010). Knowledge about the system and about the effects of a decision in terms of requirements and functions, might help understand and predict these effects. Therefore, we understand the decision-making problems that are inherent in natural environmental SoS as design problems, and provide a framework to guide this system design.

Our framework uses six concepts of the SE process and specifies their interdependencies, as well as inherent operations for application on human–nature–technology systems modeling. SE is understood as an iterative and feedback-driven approach (Crowder et al., 2016, p. 179). As a result, steps 2–5 of the framework should be applied iteratively. The outcomes of each step built up on each other, which implies a stringent step-by-step application of the framework. Figure 1 shows our framework. In the following, we will explain the key elements and linkages.

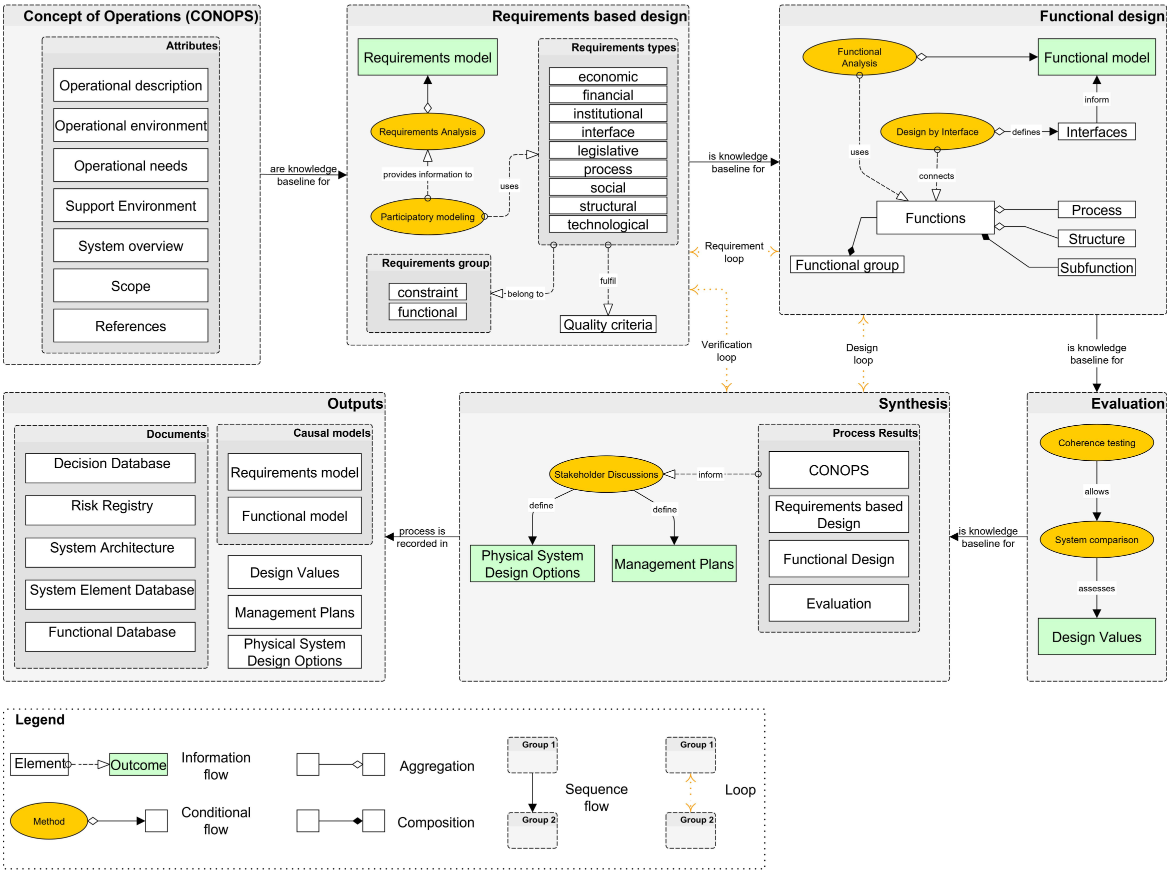

Figure 1. The Nexus System of Systems Design Framework.

3.2. Elements of the Framework

Concept of Operations (CONOPS)

We defined CONOPS by following the specification ANSI/AIAA G-043-1992 as "the user definition of how the overall organization will be operated to satisfy its mission. A verbal and graphic statement, in broad outline, of an organization's (enterprise's) assumptions or intent in regard to an operation or series of operations of new, modified or existing organizational (enterprise) systems" (American National Standards Institute, 2012, p. 2).

As described by Hoff (2011), there is "a need for a coordinated and harmonized nexus knowledge-base and database indicators and metrics that cover all relevant spatial and temporal scales and planning horizons" (2011, p. 12). CONOPS can be used to address this need by focusing on "what is there" in the beginning of the design process. The knowledge gained can then be used to further inform, for example, a participatory scenario approach, as suggested by Bizikova et al. (2013).

During the development of the CONOPS, an even focus on the included Nexus subsystems, e.g., water, energy, and food sectors in the WEF Nexus should be ensured. Taking the example of the WEF Nexus, each of the sectors follows its own functional rules and has individual structures and goals (Rasul and Sharma, 2016). The water sector might depend mainly on environmental functions and services, such as nutrient cycles or natural water filtration processes, whereas a technical subsystem, such as an energy supply system, depends more on technical processes such as correct implementation of software and hardware in a bio-energy plant, or reliable maintenance in more complex, large-scale, combined heat and power plants. Every Nexus system has a unique composition of these subsystems and is characterized differently. Therefore, the trade-offs and synergies, such as water quality versus extensive food production systems, or the development of the renewable energy-sector, in line with a high stability of power consumption networks, have to be understood before modeling the system and designing solutions to the integrated problems inside the system.

To describe the operationalization of a Nexus system, we are following Cloutier et al. (2009), who included the following seven elements, formulated as attributes, in our framework (Figure 1):

1. "Scope" of the CONOPS document: The intention of the design process is described. In the Nexus context this should incorporate the definition of a central problem variable or solution strategy that has a high centrality among all subsystems. Current studies suggest the use of the concept of "security" or "risk", to address governance challenges arising from the different logics of the concepts of water, energy, and food systems (Franz et al., 2017; Pahl-Wostl, 2017).
2. "Referenced" documents: To be able to analyze the context and specific conditions for the system design, a comprehensive literature review informs the later steps in the design process.
3. User-oriented "operational description": A description of already implemented policies, management plans, current actor activities, and actor relationships, build up a user-oriented view on the nexus. This can include but is not limited to official government statements, strategic documents, and the actor relationship networks.
4. Basic operational principles or "needs": Description of principles from the actor view that determine their behavior and actions (e.g., how decisions on the uptake of subsidized practices are taken).
5. System "overview": Basic description of the system architecture, relationships, and interfaces. A first conceptual model of the system parts can support the design process in later stages (e.g., a causal model of the actor's operational principles).
6. "Operational environment": Information on the administrative structures in which the individual actors perform their tasks. In the nexus context, this is often the respective subsystem (e.g., water, energy, or food) with which a particular actor is primarily associated.
7. Enabling conditions or "support environment": Conditions that support the achievement of the overall systems' purpose. This could be formal or informal institutions, different actor networks, the degree of multi-level interactions, or governance modes. These factors could be used to understand environmental governance regimes, the design of which can significantly influence the effectiveness of environmental resource management strategies (Pahl-Wostl, 2009).

Requirements and Constraints

Requirements are defined as factors to be fulfilled for an actor to achieve an individual task in the operational environment. Constraints are limitations from the actors' point of view that impact design solutions or the implementation of the engineering process (Department of Defense Systems Management College, 2001, p. 42). Constraints focus on the actual problems by highlighting the limitations of requirements. Therefore, to limit the risks for the design process to fail, requirements and constraints are important to capture during the whole design process. In line with the SE literature, we formulate constraints as a requirement type.

One innovative element of the SE for nexus designs is the requirements quality criteria. These criteria can be used to ensure that the design process follows requirements which are correct, complete, consistent, traceable, unambiguous, testable, and atomic (Crowder et al., 2016) (see also Table 1). Collecting information on requirements and constraints together with the involved actors, by applying participatory modeling exercises, can help to identify trade-offs and synergies within a nexus system, to reveal the limits of physical design solutions, and to build a basis for future stakeholder discussions. According to the SE literature, requirements can be clustered into different categories, such as functional requirements and constraints. To better grasp the complexity of non-technical systems such as social and natural environmental systems, the developed FRESCO framework differentiates between four categories of requirements and constraints:

1. Institutions: Institutions are defined as "rules governing the behavior of actors". They can be further categorized into formal and informal institutions. Formal institutions are "codified in regulatory frameworks or any kind of legally binding documents…Informal institutions refer to socially shared rules such as social or cultural norms" (Pahl-Wostl, 2015, p. 32f) (e.g., a formal institutional requirement for an actor in order to be able to comply with good agricultural practices is to get a specific amount of subsidies).
2. Technology: Technology is defined as "…tools, machines, and knowledge to create and control a human-built world consisting of artifacts and systems, associated mostly with the traditional fields of civil, mechanical, electrical, mining, materials,…chemical engineering…, aeronautical, industrial, computer, and environmental engineering" (Hughes, 2004, p. 4). This particularly includes technical infrastructure (e.g., water treatment plants or electricity networks), as well as natural infrastructure (e.g., river systems, landscapes, or soil composition). For example, one technological requirement for filtering nitrate out of polluted groundwater could be the development of an innovative water treatment plant.
3. Expectation: Expectations "determine what the customer wants the system to accomplish, and how well each function must be accomplished" (Department of Defense Systems Management College, 2001, p. 42). Expectations are qualitative measures of each actors' system requirements. These could be expectations regarding future scenarios, or expectations regarding solutions to actual problems (e.g., an actor expects the increasing amount of conditional agricultural subsidies or the agreement on a new water directive). Expectations are particularly important to understand the motivation behind actions of actors.
4. Interface: An interface represents a crossing point of an object to other objects, or more generally to its environment. It serves to ensure certain rules in the communication between objects and the environment by requiring certain operations to the object implementing the interface (Oracle, 2015) (e.g., an umbrella organization for communicating knowledge through a network of actors). The design of interfaces further specifies the functional model of the system in a later system design step.

These four basic categories can be adopted, depending on the specific need of the applied design process. For example, for the presented exploratory case study, nine requirement types are defined (i.e., economic, financial, institutional, interface, legislative, process, social, structural, and technological) (Figure 1).

A requirements model can be derived in a participatory process by defining requirements and their causal relationships. This can be done by applying participatory modeling with causal-loop diagrams (Inam et al., 2015; Vennix, 1996).

Table 1. Requirements Quality Attributes (following (Crowder et al., 2016)).

Correctness			Disambiguation	Testability	Atomicity
Completeness	**Consistency**	**Traceability**			
No information is undefined. No information is missing from the requirement.	No requirements are allowed to be in conflict with each other, e.g., if requirement "a" enables "b", requirement "c" cannot imply that "a" does not enable "b".	The relationships between the requirements have to be clearly formulated and documented. This is of particular importance for the understanding and management of the objectives.	"An unambiguous requirement contains facts, and is written without negative language or compound statements. The disambiguated requirement does not contain opinions and is not subject to interpretation" (Crowder et al., 2016, p. 110)	The systems engineer has to be able to demonstrate, test, inspect, and analyze the correct implementation of the requirements.	A requirement should not contain connections to other requirements. It has to be the smallest element possible, e.g., "cropping of bioenergy plants" should be divided into "cropping" and "bioenergy plants".

Functions

Functions are defined as "discrete actions…necessary to achieve the system's objectives" (Department of Defense Systems Management College, 2001, p. 45). "Subfunctions" rely on their constituent primary function and specify it. All functions have a structure and processes that further define them. Many functions can build "functional groups". In the context of the WEF Nexus, we support the idea of conceptualizing ecosystem services as functions. Ecosystem Services are defined as "the benefits people obtain from ecosystems" (Millenium Ecosytem Assessment and MA, 2003, p. 3; Millennium Ecosytem Assessment, 2005, p. V). This also allows to integrate the concept of payments for ecosystem services into the scope of our framework. The concept can be used to assess incentives on human behavior to achieve the overarching SoS objectives (Engel et al., 2008).

"Functions" can be either natural, if it is a naturally provided function (e.g., wetlands or pollination), or artificial if the function exists because of human impacts (e.g., pest control). "A process is a sequence of behavior that constitutes a system and has a goal producing function" (Ackoff, 1971, p. 666). Processes can be natural or artificial (e.g., beekeeping or crop rotation). Structures—the structure is specified by the relationships between system elements (Halbe et al., 2014). These elements include functions whose relationships define the functional structure of the system. Functional groups—following Halbe et al. (2014), functional groups are "a concerted set of functions and underlying processes and structures" (2014, p. 83), e.g., a dam that combines more than one function and process. These only develop if a minimum of two functions fulfil a joined objective. Sub-functions—functions which further define a different function are called "sub-functions". Their existence relies on their constituent function (composition).

The formulation and analysis of functions with the above-described structure, results in a detailed model of the "functional architecture" of the assessed nexus system. It is a key element for the optimization of the physical design process in the end of the SoSE process (Department of Defense Systems Management College, 2001, p. 32).

Evaluation

Evaluation from the SE perspective includes “technical management activities required to measure progress, evaluate and select alternatives, and document data and decisions” (Department of Defense Systems Management College, 2001, p. 33). The overall goal is to minimize the risk of the process and failure of the physical system design during implementation. While the SE literature mainly uses the term “technical risks” (Crowder et al., 2016), evaluation in a nexus context should also encompass economic, social, and ecological risk assessments, to meet the requirements of analyzing environmental SoS. Based on the SE literature, the following concepts should be considered for a comprehensive evaluation process—design costs, process costs, design risks, process risks, and Life Cycle Costs. A conceptualization of these cost and risk categories for nexus systems is still the subject of further development. If the framework is applied with participatory processes, these can additionally be evaluated with the COPP framework, for an evaluation of the participatory methods (Hassenforder et al., 2015). Additional evaluation criteria might be the actor’s “level of influence”, “public supervision of the results” or “learning of agents” in evaluation workshops, document analysis, discussion groups, or questionnaires (March, 2013, p. 19). A possible outcome of the evaluation step could be the formulation of the additional value of system design for the actors. This could be achieved by comparing the status quo from the CONOPS step with the new functional design. Checking if the design suggestions are coherent with the actor requirements is required, before comparing the “old” and the “new” system.

Synthesis

Communicating findings, developing strategies, and planning physical system designs is one of the main objectives of the system design process (Crowder et al., 2016). To reorganize the individual objectives of different subsystems, and to allow for a common nexus goal to be defined, ideally means to develop strategies for implementing an overall management plan that is based on the requirements and functional analysis. If this step is carried out with participatory methods such as stakeholder workshops, applying methods which focus on understanding the learning effects and institutionalizing sustainable cooperation between the actors involved might be advisable (Tuler et al., 2017). Attributes of the synthesis-step are (i) “Management Plans”—concrete decision-making plans as a precursor to measures which could be adopted (e.g., adaption of EU water framework directive is needed), as well as (ii) “Physical System Design Options”—the design or redesign processes of real systems, including policy recommendations, as well as practical changes made by the actors of the system (e.g., voluntary self-commitments).

Outputs

Outputs in the SoSE process are defined as “any data that describes or controls the product configuration or the processes necessary to develop that product” (Department of Defense Systems Management College, 2001, p. 33). The outcome of this step is a report of the overall engineering process. We suggest to carry out this step at the very end of the engineering process, to ensure an open design process without decision plans being fixed too early. The latter could, for example, be a risk for a productive participation process (Ridder et al., 2005).

To ensure an effective implementation of the adopted measures, the literature suggests to apply adaptive co-management or long-term oriented monitoring systems (Armitage et al., 2008). Adaptive co-management is defined as “a long-term management structure that permits stakeholders to share management responsibility within a specific system of natural resources, and to learn from their actions” (Armitage et al., 2008, p. 87). For an application in the SoS context, also see the “policy development framework” by Hipel et al. (2010). The latter has to be particularly capable of monitoring different scales in environmental SoS, such as the WEF Nexus, interlinkages between different resources, as well as between the multiple subsystems (Economic Commission for Europe, 2016; FAO, 2014). According to the SE literature, the outputs are basically informed by all SE design steps taken before, but is particularly defined through a set of different document types: (i) Decision database—list of possible decisions designed that could influence the physical system design and the decisions made during the engineering phase.

This includes but is not limited to policy designs, suggestions for changes of the functional structure, or the implementation of new sectoral interfaces; (ii) risk registry—list of risks assessed during the engineering process; (iii) system architecture—description of the alternative system architectures suggested during the engineering process; (iv) system element database—list of all system elements assessed, used, or designed throughout the engineering process; and (v) functional database—list of all functions and processes assessed during the engineering process, including functions and processes of alternative system designs (Crowder et al., 2016).

In addition to the six main steps of the FRESCO framework, three “verification-loops” that connect the steps are included in the framework. These loops are formulated according to the standard SE process (Department of Defense Systems Management College, 2001). Their overall goal is to ensure consistency throughout the process. In the group model building workshop, the translation of requirements into functions, helped the participants to identify which requirements were important to consider for specific functions. They gained an advanced understanding of the others’ solution strategies and a discussion evolved. This identification of interdependencies between requirements and functions helped to better understand different viewpoints of the participants and could lead to the development of an overall SoS objective. However, the latter required a minimum agreement among the participants.

- Loop 1—Requirement Loop: This loop connects the requirement analysis and functional analysis. It is defined as the translation of requirements to functions. The traceability of each system function back to the corresponding requirement has to be verified to understand the SE process and to manage system changes (Crowder et al., 2016, p. 109f).
- Loop 2—Design Loop: This loop connects the functional analysis and synthesis. Actors involved in the SE process have to agree on the designed management plans that achieve the prerequisite system functions.
- Loop 3—Verification Loop: This loop connects the requirement analysis and synthesis. Analogous to the Design Loop, requirements have to be fulfilled by agreements made in the synthesis step.

4. Framework Application

In the following section, we demonstrate how our framework could be applied to guide decision planning through participatory system design, for a specific case study region (Figure 2). For the purpose of defining the CONOPS, we used insights from 14 individual stakeholder interviews on the topic of bioenergy production in the region conducted in 2015. The interviews were conducted in the context of a seminar in the study program "Environmental Systems and Resources Management" in the Osnabrueck University Germany. We identified that "Groundwater Quality" was perceived as the most central and important variable among the stakeholders. As also described by Pahl-Wostl (2016), high livestock densities and excessive manure production in the area has been causing nitrate and phosphorus pollution of water bodies. As additional preparation for our workshop, we asked one scientific expert to conduct a pre-participatory modeling exercise where we already included the nexus perspective.

This preparatory interview (or pre-interview) helped us to better understand the underlying functions and the status-quo in the region and allowed us to better mediate the following workshop. This two-day group model-building workshop with experts from science was aimed at identifying and relating the different levels of complexity of the regional WEF Nexus in the Federal State of Lower Saxony in Germany, to develop a normative conceptual system design, based on the requirements and functions. The combined insights from the pre-interview, individual stakeholder interviews, and the workshop, captured important concepts of the status-quo and facilitated a more precise picture of the requirements and function needed for a sustainable transformation in the case study region.

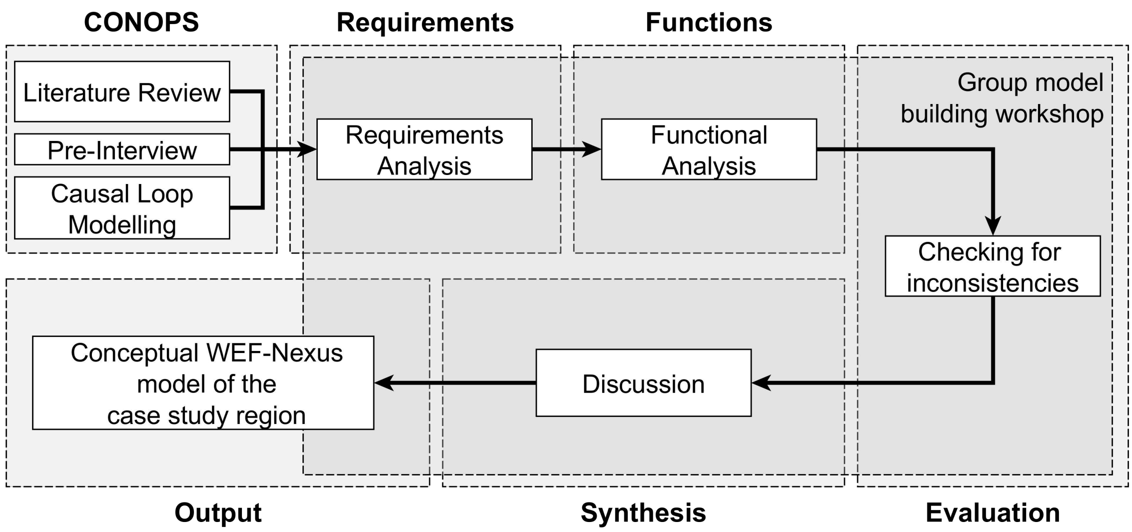

Figure 2. The Nexus Framework application.

Simplified system models that were developed together with the actors participating in the workshop, particularly helped us to understand the linkages of inherent subsystems with different functions in the water, energy, and food domains. This actor-oriented system view enabled decision makers to design or re-design systems that are specifically targeted to the requirements and expectations of the system users (actors) (Crowder et al., 2016, p. 2).

Additionally, the workshop results served as a database for subsequent analyses, in which the focus lay on the trans-sectoral requirement mapping, as well as derivation of important system functions and processes. However, building up a common ground among the experts participating in the workshop was challenging. Therefore, we used parts of the vision modeling approach as a supporting element. As described by Iwaniec et al. (2014), the aim of vision modeling is to express the structure and function of a future system design in a system model and, finally, to guide the system towards an anticipated state. Considering this idea in a participatory setting, such as in a group model-building workshop, we found that talking about visions in the beginning of the engineering process, allows experts and stakeholders to find common ground, align narratives between them, and guide an open discussion. From a SE viewpoint, the visions formulated in the workshop are the representation of CONOPS. They explain how the desired system should be operated. We know that a comprehensive vision modeling exercise includes more steps, such as applying quality criteria for the formulated visions (Wiek and Iwaniec, 2014). However, in our case, we focused on building up a common ground and align the different angles from the participants who had diverse knowledge backgrounds.

Each participant was asked to write down at least two visions which are most important to consider, based on the scientific expertise. In total, 30 visions were mentioned, whereas 16 were related to agriculture, 6 to cooperation and integration, 3 to energy 2 to the region, and one each for structures, technology, and water (Figure 3). All experts, at least, formulated one vision which had a link to cooperation mechanisms and agriculture. As a result, participants chose the vision of a less meat-consuming society, which included the integration of farmers, suppliers, and consumers' viewpoints for the central discussion topic in the workshop.

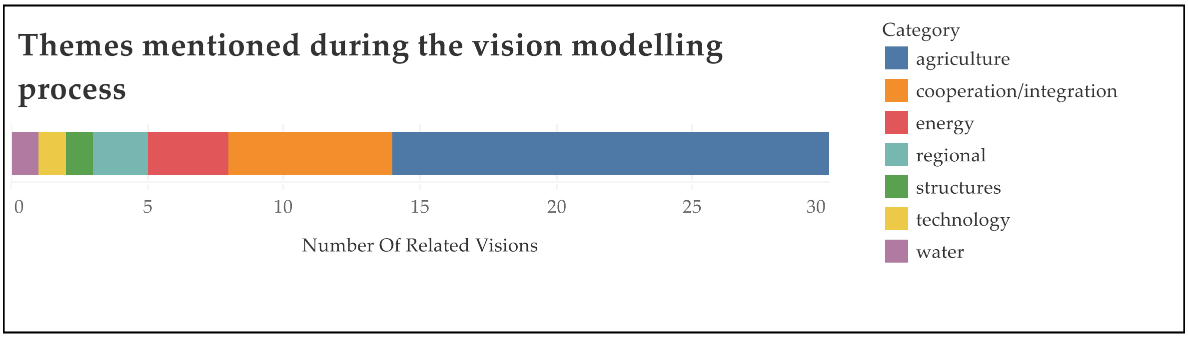

Figure 3. Themes mentioned during the vision modeling process.

Next, requirements that were needed to design the transformative pathway from the current system state to the desired outcome were formulated according to the agreed vision. These requirements were structured according to the requirement types in our framework (Figure 1). The single requirements can be found in Table S2 (Supplementary Materials).

Afterwards, workshop participants defined key-functions and sub-functions for the WEF Nexus model. The requirements from the preceding modeling step were used to define the specific purpose and content of each function. Participants differentiated between ecosystem functions and steering functions, as the main functions of the WEF Nexus model. The developed requirements and functions were discussed in several discussion rounds, with respect to their effect and importance for the regional

WEF Nexus. In addition, the contributions of each expert were discussed by the group to see if they were consistent with the already defined requirements and functions. The outcome of the workshop, a first preliminary and conceptual WEF Nexus model, illustrated how requirements and functions could be modeled with the SE methods and concepts, in a group model-building workshop (Figure S1 (Supplementary Materials)).

5. Results and Analysis

The application of the FRESCO framework illustrated how diverse stakeholders can collaborate in a system design process, develop an overall objective for the WEF Nexus, and support this objective by modeling requirements and functions at the conceptual system level. Our participatory design approach included participatory modeling and group model-building methods to derive CONOPS, requirements, and functions (Figure 2). Stakeholders were able to foster a cross-sectoral design of solutions to interlinked water, energy, and food issues.

5.1. Individual Interviews

To understand the specific relationships between agricultural practices in the area and water pollution, and to prepare a knowledge base for the subsequent two-day workshop with experts from a range of scientific fields, we used data derived from 14 individual interviews with practitioners from the region. These interviews revealed that “water quality” is part of the problem based on the perspective of most stakeholders from the area. We found that “fertilizer use” was mentioned by 50% of the interviewees as a negative influence on groundwater quality, whereas “pesticide use” was mentioned only by two of 14 interviewees. In addition, the literature and the ongoing political debate reveals that the main reason for decreasing water quality is intensive livestock farming, which is leading to the diffuse discharge of nitrate and phosphorus into freshwater bodies. Therefore, we focused on the elicitation of requirements for implementing potential solutions that include alternative agricultural practices, to protect water quality. During our subsequent expert workshop, we developed a requirements typology, i.e., we defined several types of requirements (i.e., economic, financial, institutional, interface, legislative, process, social, structural, and technological requirements). These types helped to structure the ideas put forward by experts. We first tested the applicability of our requirement typologies in a pre-interview, with one scientific expert. The interview revealed a number of requirements that have a positive effect on groundwater quality. These requirements and their causal relationships are illustrated in Table 2. In the left column of the table, the elicited requirements can be found. Each row shows the causal pathway from the requirement on the left to water quality, i.e., the effect of the requirement on water quality. The symbols (+) and (–) indicate the causal relationships between the two variables, e.g., fertilizer use leads to more diffuse discharge, and more diffuse discharge leads to lower water quality. For example, consultancy for farmers was mentioned as one instrument to inform farmers on the long-term effect of diffuse entries in water bodies. This information potentially leads to less fertilizer use in the long-term, which leads to less diffuse discharge of nitrate and phosphorus in the soil, and consequently to better water quality.

Table 2. Basic interventions for ground water quality.

Requirement	Causal Relationships
Restriction of Soils Use	→ (−) Sealing of soil → (−) Soil regeneration capacity → (+) Ground water quality
Lease of Property by the Municipal Utilities	→ (+) organic farming → (−) Diffuse discharge → (−) Water quality
Lease of Property by the Municipal Utilities	→ (−) Fertilizer → (+) Diffuse discharge → (−) Water quality
Consultancy for Farmers	→ (−) Fertilizer → (+) Diffuse discharge → (−) Water quality
CAP Reform	→ (−) Conventional farming → (+) Fertilizer → (+) Diffuse discharge → (−) Water quality
EEG Reform	→ (−) Cropping maize → (+) Monocultures → (+) Fertilizer → (+) Diffuse discharge → (−) Water quality
EEG Reform	→ (−) Cropping maize → (+) Biogas → (+) Cropping bio energy plants → (−) Organic farming → (−) Diffuse discharge → (−) Water quality
EEG Reform	→ (−) Cropping maize → (+) Biogas → (+) Cropping bio energy plants → (+) Pesticides → (+) Diffuse discharge → (−) Water quality
EEG Reform	→ (−) Cropping maize → (+) Biogas → (+) Cropping bio energy plants → (+) Fertilizer → (+) Diffuse discharge → (−) Water quality
Strong Environmental Organizations	→ (−) Pesticides → (+) Diffuse discharge → (−) Water quality
Strong Environmental Organizations	→ (+) Organic farming → (−) Diffuse discharge → (−) Water quality
Effective Fertilizer Law	→ (−) Fertilizer → (+) Diffuse discharge → (−) Water quality
Enforcement of Fertilizer Regulations	→ (−) Fertilizer → (+) Diffuse discharge → (−) Water quality
Need-Based Fertilizer Use	→ (−) Fertilizer → (+) Diffuse discharge → (−) Water quality

Figure 4 shows the resulting causal-loop diagram from the interview that was conducted in preparation to the expert workshop. The red color indicates energy-sector-related variables, orange indicates food-sector related variables, and blue indicates water-related variables. The requirements are marked as green variables. To demonstrate how feedback between specific variables can be analyzed, we visualized the feedback loops between “groundwater quality”, “organic farming” and “conventional farming” as examples. Figure 5 identifies the effect of “strong environmental organizations” and “organic farming” on groundwater quality, where it can be seen that strong environmental organizations are generally affected positively by low water-quality level. In combination with organic farming practices, which lead to less diffuse discharge and less fertilizer use, they can have an overall positive effect on groundwater quality. Furthermore, we identified two balancing loops, which indicated that the causalities did not reinforce themselves over time.

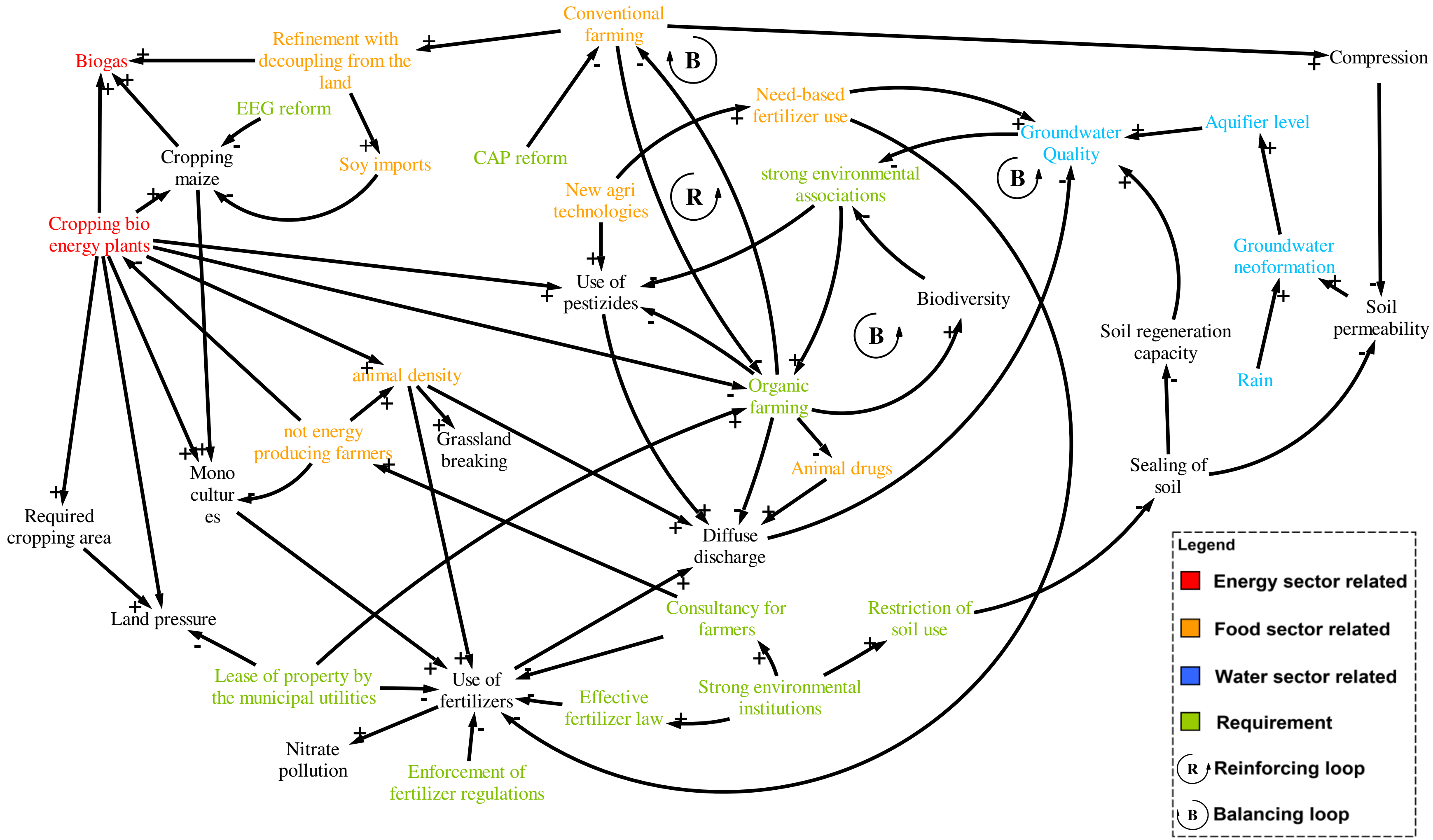

Figure 4. Pre-interview interactions between water-energy-food functions and requirements.

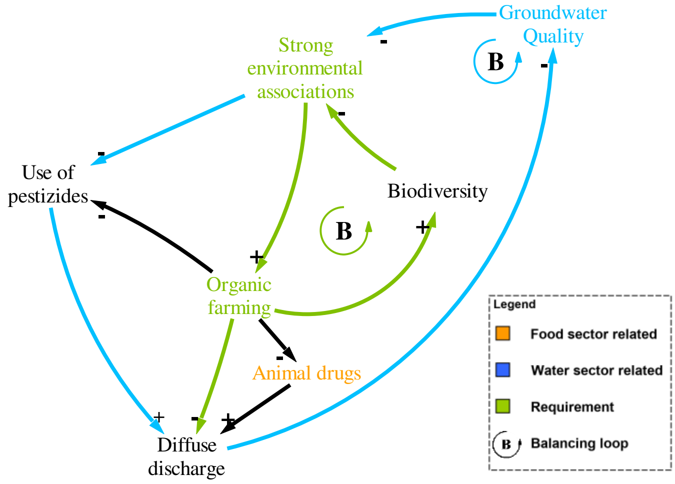

Figure 5. Influence of requirements on the water system.

Figure 6 is one example of cross-sectoral interactions between the nexus sectors—water and food. Although qualitatively interpreted, we observed that conventional farming has a negative effect on groundwater quality, whereas strong environmental organizations and organic farming balance out this negative causal relationship. Of course, the quantitative net effect of organic farming and the positive influence of the environmental organizations needs to be analyzed before assuming that the implementation of these requirements eliminates the negative effect on groundwater quality. Therefore, these findings need to be interpreted carefully.

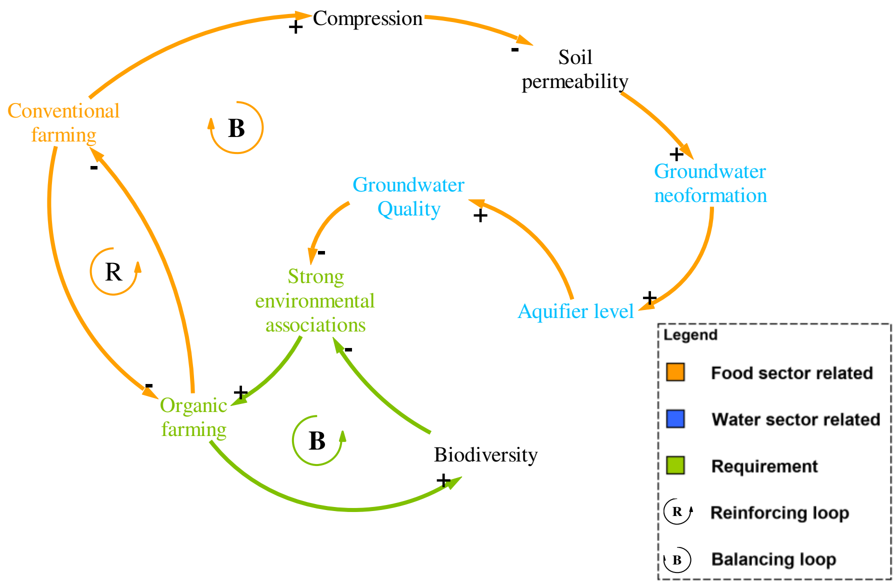

Figure 6. Cross-sectoral interactions between the water and food systems.

The pre-interview also helped us to more clearly define the applied concepts of CONOPS, requirements, and functions, and to adopt narratives from the SE field to make them understandable for the diverse experts in the workshop.

5.2. Scientific Expert Workshop

In addition, the knowledge gained during the pre-interview and the participatory stakeholder interviews helped to mediate the workshop. The workshop participants were already aware of the regional problems. In several discussion rounds, everyone contributed knowledge to the design process from their own expertise. Table S1 (Supplementary Materials) shows the participating actors, their expertise, role, and contribution to the process. The experts acknowledged the solution-oriented approach of the FRESCO framework as it motivated them to formulate specific requirements that are most important to solve the issue of ground water pollution in the region, while considering regional steering functions, i.e., legislation, market structures, individual and collective behavior, and financial incentives, on a higher level of detail. Standard group model-building approaches are usually fostered to enhance learning among the participants and motivate a discussion of different existing mental models of a problem perspective (Stave, 2010). “Mental models are personal internal representations of the surrounding world” (Scholz et al., 2014, p. 578). We add a design perspective to this approach, by combining it with requirements and functional analysis. Participants reported that the focus on process management and system design, helped to include multi-level complexity arising within the application of the nexus concept. Inherent interconnections of water-, energy-, and food-systems were incorporated into a systematic nexus modeling process. More specifically, the stakeholders found that this design perspective enabled them to gain an advanced understanding of complex relationships, not only between general concepts such as sectoral security goals but also the more specific requirements and functions needed to fulfil the overall design objective of the study. For example, one participant from the workshop concluded that this type of modeling allows to directly track down the impact of functions that are beyond the individual’s expertise in their own research field. A second participant argued that the definition and specification of the steering functions helped to emphasize the importance of functions that enables coordination as well as the ability of the actors to cooperate. All participants agreed that defining, grouping, and linking of such functions helps to establish a common context for the complexity of the parts of the WEF Nexus. By defining functions and sub-functions, requirements for different functions can be collectively assigned to the different system levels. Taking a nexus perspective at this point means the consideration of the interaction between these functions.

The importance of coordination and cooperation was also exemplified by the participatory modeling interviews. The interviewed practitioners often highlighted the importance of cross-sectoral communication and collaboration. They agreed on the point that participatory modeling not only builds up a common knowledge baseline but additionally helps to consider viewpoints of others in the individual decision-making processes.

Considering the described potential of such design processes in the SE domain, as described in Section 2.2, and the experiences of the actors in our case study, we believe that this type of stakeholder engagement is a step forward to a solution- and process-oriented operationalization of the nexus approach.

Despite the central importance of water quality for the regional WEF Nexus, the discussion and modeling rounds in the workshop mainly focused on the central importance of meat production and consumption for the area. The experts derived requirements that would lead to a system state characterized by a society that eats less meat (Table S2 (Supplementary Materials)). The derived key-functions that would lead to this type of society, are characterized by stronger enforcement of the existing laws and regulations, openness towards social and technological innovation, and more sustainable consumer behavior, all under the umbrella of coordination and effective communication platforms. The WEF Nexus is characterized by social, economic, natural, and technical subsystems. Participants decided that a model of "steering functions" should be developed to guide the design of natural subsystems of the WEF Nexus. These key-functions should be designed to positively influence the ecological model of water-, energy-, and food-systems, and their corresponding natural functions, such as several regulatory or supply functions (Figure S1 (Supplementary Materials)). Defining the requirements on a functional level that specify the underlying conditions for each of these key-functions, could provide detailed guidance for policy-makers, and could enhance cross-sectoral understanding of the different functions. This might be necessary to identify an overall objective or vision to guide the transformation to sustainable resource management within the WEF Nexus. However, during the stakeholder interviews and the expert workshop, we found that WEF Nexus models often had a high number of uncertainties and ambiguities resulting from the different narratives across sectors. In-depth discussions during the workshop helped to address these uncertainties and to develop alternative conceptual system designs, which could enable practitioners and decision makers to design sustainable and effective strategies, while being aware of those uncertainties. In future studies involving more participants, we encourage the documentation of definitions and concepts discussed during the workshops, to overcome uncertainties and ambiguities.

6. Discussion and Conclusion

Before applying our SoS Nexus design framework in a workshop context, every participant of the design process first needs to be introduced to the elements of the FRESCO framework (Section 3). The application to a specific research question requires the selection of the attributes that are suitable for examination for the case in question and the identification of attributes that need to be added to the case-specific framework.

The Nexus SoS Design Framework is a process- and output-oriented framework to analyze the multi-level complexity of nexus systems such as the WEF Nexus. It supports the understanding of linkages between requirements and functions, which are needed to achieve an overall SoS objective. Our framework realizes these characteristics by supporting the analysis of different nature–human–technology and governance contexts.

One next step to further formalize the framework could be the development of a computer-simulation model, for example, a system dynamic model. Such a model could be used to model data from the field, and compare this model outcome with empirical data. At the same time, our framework could be adjusted according to the specific research question or study intention. With this in mind, our framework makes an important contribution to the often-discussed need for the conceptualization of the WEF Nexus approach.

A design framework should support a solution-guided analysis without being too specific and, thus, non-transferable from a methodological point of view. Therefore, such a framework must involve a holistic system view to deal with multi-level complexity across subsystems. In addition, developing a process-oriented design framework in the nexus domain, requires an interdisciplinary approach across SE and resource management fields.

The SoS Nexus design framework is designed to support collaboration in professional networks of scientific experts and practitioners and to stimulate participation in a collective system design process. However, additional steps should be taken to further explore the potential and the limits of the framework. This includes the need to increase the number of case studies and also the application of the framework with a larger number of participants. This will also reveal the degree to which the framework is able to support studies on a larger scale.

We faced several difficulties in applying our framework during the workshop phase because the experts represented different disciplines, so it was difficult to structure the collective knowledge, and viewpoints. Although we chose a typology of different requirements in the FRESCO framework and adopted it according to the case study content, the discussion rounds and learning processes during the workshop were time-consuming.

Although exploratory, the output of the workshop, a first conceptual WEF Nexus model, reveals that subsystems and functional groups cannot be characterized by Maier's criteria. The key problem with these criteria is that they are not completely applicable to our type of system model. Maier's criteria have originally been designed to describe characteristics of technical SoS. As subsystems in the WEF Nexus are interwoven and change dynamically, they are often neither geographically distributed nor operationally independent. Future research might explore a set of criteria that are applicable to SoS with natural, social, and technical subsystems.

We found that our study was embedded in an ongoing political debate in our case study region. This meant that, on the one hand, we profited from the experience of the stakeholders we interviewed and those that participated in the workshop. On the other hand, many political constraints and opposing opinions among the practitioners limited the creative process of compiling requirements from the stakeholders. We found that it is particularly necessary to be neutral as an interviewer as well as a mediator of a workshop. Promoting the openness of the participatory modeling approach also helps to stimulate more in-depth discussions during the model-building phase. Future work should incorporate these findings to control for such factors that may influence the outcome of the framework application.

During the development of our framework, we identified two possible types of environmental SoS—Type 1, which defines an SoS without an overall objective (e.g., the WEF Nexus), and Type 2, where, in principle, an overall objective exists but is interpreted differently for different subsystems. The engineering literature refers to a Type 1 SoS with virtual or collaborative SoS, and to a Type 2 SoS with acknowledged or directed SoS. In the interviews conducted, we found that no overall objective among the actors existed. Therefore, we used the FRESCO framework to identify possible pathways for identifying such an overarching objective. In a subsequent case study, we will assess a Type 2 SoS—The German sustainability landscape.

In this case, we will demonstrate that overall sustainability objectives are reflected in the German sustainable development strategy at the national level, whereas many sub-strategies exist at the federal state and urban levels that implement their own objectives. In this exploratory case, we use the framework presented to identify overlaps in the sustainability strategies and to develop a methodological structure for carrying out a requirements analysis, using a participatory modeling approach.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/11/12/3464/s1

Author Contributions: Conceptualization, F.H., P., C.P-W., and S.E..; Methodology, F.H. and C.P-W..; Formal Analysis, F.H.; Investigation, F.H.; Resources, F.H.; Data Curation, F.H.; Writing-Original Draft Preparation, F.H.; Writing-Review & Editing, F.H., C.P-W., and S.E.; Visualization, F.H.; Supervision, C.P-W. and S.E.; Project Administration, F.H.; Funding Acquisition, C.P-W. and S.E.

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4. Article 2 – Integrated and participatory design of sustainable development strategies on multiple governance levels

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On a conceptual level, the FRESCO framework has been developed to support the application of a systems design approach on complex resource management problems. As an example, the framework has been tested on the WEF-Nexus in the first article of this dissertation. Testing the presented FRESCO framework in the field with actors from practice is the focus of the second research article presented in this thesis. In contrast to the WEF-Nexus where no overall SoS-objective exists which can be fulfilled by the constituent subsystems, i.e. Nexus sectors, this second case study deals with the design of a type 2 SoS. This type of SoS already has one or more overall SoS objectives. The subsystems may be designed in a way that they pursue these objectives. Therefore, in this case, the system design can be based on already existing strategy documents or implementation plans for these strategies.

To apply requirements analysis together with the participating actors, the underlying idea of a requirements-based solution design was modified and developed further for application in an individual expert interview setting. In general, the focus of the interviews is to elicit requirements needed to implement the German SDS. More specifically, the sub-goal, achieving the sustainable development goal (SDG) 7.2 on the German national level, as well as on the urban level was the central focus of the study. The analysis on the urban level focusses on the cities of Hamburg and Berlin. Both cities have already implemented their own SDS, and urban experts were available for conducting interviews and modeling exercises. The development of a methodological design approach closes the gap of a missing requirements analysis approach for strategy development, and on the same time allows to engage experts and stakeholders in the design process. The latter was particularly important because a requirements based design approach as described in the FRESCO framework, is always based on a users' point of view rather than on a scientific or researchers point of view (The role of the researcher in a design process is described in chapter 2.3). Therefore, the resulting methodological framework is a participatory design framework for requirements elicitation and functional design of strategy systems.

SDG 7.2 effects all aspects of sustainable transformation. “Increase substantially the share of renewable energy in the global energy mix by 2030” means to approach the problem of global climate change from a holistic perspective. Innovative pathways for implementing future renewable technologies are developed to achieve this goal on a global and national level. These technologies include solar, wind, ocean, hydropower, geothermal resources, and bioenergy.

Figure 13 illustrates that there still lies a long way before us to achieve a high proportion of renewable energy production in Germany and other industrial countries.[6]

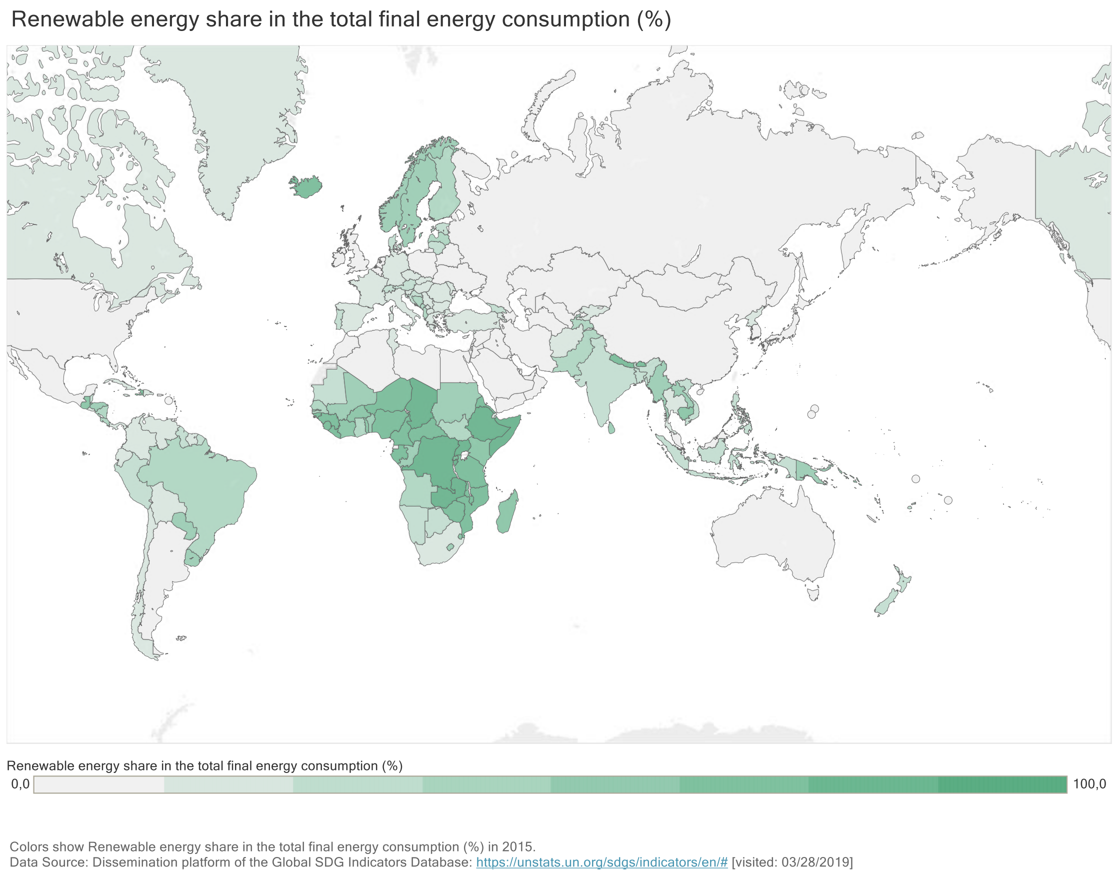

Figure 13 Global renewable energy share in the total final energy consumption (%)

[6] According to the United Nations Statistics Division, the indicator for SDG 7.2 focusses on the total proportion of consumed renewable energy instead of the total capacity for renewable energy production, whereas the latter cannot always be fully consumed, due to significant energy loss in the production chain.

Article 2

Integrated and Participatory Design of Sustainable Development Strategies on Multiple Governance Levels

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Abstract: An increasing number of sustainable development strategies (SDS) is being developed for cities, municipalities and countries. The design of such strategies is inherently complex. This is a result from intricate relationships between different SDS on different levels, and a large number of requirements that need to be addressed in strategy implementation. A particular challenge is the integration of strategies across different governance levels (e.g., city, federal, and national levels). Methodologies are currently lacking to systematically design SDS which take the full complexity of the dependencies of the strategies into account. In this article, we propose a participatory requirements analyses approach to support strategy building across governance levels. Experience from systems engineering (SE) has shown, that requirements are the basis for designing systems or strategies. We elicit requirements by applying a participatory modeling approach with causal-loop diagrams in an individual interview setting. To illustrate our approach, we test the developed design approach and focus on the interdependencies between SDS at the city level (i.e., the cities of Berlin and Hamburg) and the German national SDS. The design process reveals critical factors which are needed for the overall success of the strategies. The resulting causal models reveal that despite coordination activities of the regional objectives with the national targets, trade-offs exist between the strategies regarding the underlying conditions for their implementation (e.g., national law, federal and state law). In addition, the level of detail of requirements for certain objectives at the national level and across sectors is too general. This hinders the emergence of system-wide co-benefits of possible solution strategies. Requirements analysis can highlight interdependencies, such as trade-offs and synergies, between strategies at multiple governance levels and, based upon this, can support a more coherent strategy design.

Keywords: sustainable development; strategy design; stakeholder participation; system-of-systems; requirements analysis; participatory modeling; integrative policy design

1. Introduction

Strategies for sustainable development have a long tradition aiming at the transformation of organizations, cities, regions and nations to transform towards a more sustainable state. These sustainable development strategies (SDS) exist on different governance levels, such as the Paris agreement from 2015 between several states on a supra-national level (UN FCCC. Conference of the Parties (COP), 2015), the EU Agenda 2030 which acts as a guiding framework for the implementation of more specific measures in several EU member states (United Nations, 2015), and the resulting national strategies such as the German SDS (Deutsche Bundesregierung, 2016).

SDS are relevant guiding documents for political decision-makers in all areas of the government (e.g., food and agriculture, water management, energy supply, markets, social capital, or education). They are important guiding frameworks for coping with challenges such as climate change, food -and water safety and many others.

Like many other nations, the German sustainable strategy landscape is very diverse. Overarching objectives such as the Sustainable Development Goals (SDGs) exist which can guide strategies on all levels and connect several different objectives with each other (Le Blanc, 2015). The guiding framework on the German national level, the German SDS, has been revised in January 2017, and states that the German Government has to implement the objectives of the EU Agenda 2030, including the SDGs, and adopt them on the German national level (Deutsche Bundesregierung, 2016, p. 11). Nevertheless, the EU sustainability objectives regarding the proportion of renewable energy (18% in 2020), and many of the specific German sub-objectives, will not be achieved until 2030. However, many cities, including Hamburg and Berlin, as well as regions (e.g., the State of Lower Saxony, North-Rhine Westphalia, or the metropolitan region of Bremen-Oldenburg), have adopted their own SDS to assist in the implementation of the national directive and to integrate regionally important issues and resources into the implementation of their own SDS (Hirschl et al., 2015; Müller and Reutter, 2017; Niedersächsisches Ministerium für Umwelt Energie und Klimaschutz, 2017; Nordrhein-Westfalen, 2016; Reusswig et al., 2014; Senat der Freien und Hansestadt Hamburg, 2015; Senat der Stadt Berlin, 2018). Regional issues are a significant part of the strategies. For example, the resources of water, energy and food have different significance in the respective cities and regions, and the potential for technological innovations is different due to infrastructural constraints. SDS on different levels need to be coherent and designed in line with each other because their implementations often depend on each other. Therefore, SDS cannot be implemented in isolation, and their outcome and feasibility depend on other strategies. In particular, strategy integration across multiple governance levels as well as sufficient stakeholder engagement are major obstacles of all strategies. Therefore, the importance of multi-level governance approaches and participatory approaches for strategy design should not be underestimated. Although methods exist to compare national SDS with each other (Gubaidullina et al., 2018), more focused feasibility studies are important to guide local decision-making processes.

Several feasibility studies, such as the feasibility study of the Berlin Energy and Climate Protection Program 2030 (BEK) by the Potsdam Institute for Climate Impact Research (PIK), have already demonstrated the complexity of strategy documents or action plans in Germany (Reusswig et al., 2014). After 2009 and 2013, the Federal Government has again commissioned the German Council for Sustainable Development to organize a peer review on the German sustainability policy (German Council for Sustainable Development, 2018). The group suggests 11 recommendations based on the revised German SDS and on what has been done so far. These recommendations include but are not limited to the call for more multi-stakeholder approaches to guide stakeholders in implementing the German SDS, “strengthening the science/society interface”, develop “innovative dialogue-based processes” which include economic and social perspectives into strategy development with the aim to generate more relevance of the German SDS for low-level stakeholders, link the German SDS more to regions and cities, enhance policy coherence, “address more directly the challenges of achieving sustainable consumption and production", and enhance "capacity for systems thinking" (German Council for Sustainable Development, 2018, p. 25).

The objectives of a strategy are usually achieved by developing and implementing innovations or by re-designing existing projects. Innovations can be institutionalized by developing policy instruments, measures or projects on a local level. In this context, small and medium sized private and public companies as well as well-known and connected experts play a major role. Several methods exist which help actors and organizations promote sustainable behavior. These methods include design thinking approaches (e.g., knowledge co-production and vision modeling), participatory approaches (e.g., user based design of solutions with focus groups or card-sorting), and many other frameworks with the aim to guide the production of sustainable behavior, products and services (e.g., smart meters) (Baldassarre et al., 2017; Daae and Boks, 2015; Kuo et al., 2018; Shapira et al., 2017).

To design the complex interrelations of the strategies among each other as well as their implications for the environment, society and industry, an integrated and participatory approach is required. System science can support the development of such an integrated perspective, for example by providing tools to understand causal relationships between elements included in SDS (e.g., relationships between SDGs) (Le Blanc, 2015). This creates a simplified structure, a "systems model", which allows for a better understanding of the dynamic complexity of systems (i.e., structures and processes that determine the system's dynamics). To collectively model such systems, participatory modeling as a widely applied approach can be used to combine integrated systems analysis and stakeholder engagement. In particular, conceptual modeling using causal-loop diagrams has been found to be a powerful approach to investigate complex problems in a participatory process (Halbe et al., 2018). While causal-loop diagrams are helpful to deal with the dynamic complexity, issues with a high detailed complexity (i.e., a high number of variables) can render these models unwieldly. The design of SDS at various governance levels requires such a method in order to be able to investigate specific links in between, such as measures and objectives. A methodological framework is currently lacking that allows for an integrated and participatory design of SDS that can deal with this detailed complexity of strategy documents and the description of related requirements.

This article aims at the development of such a methodological framework for the integrated and participatory design of SDS across multiple governance levels (i.e., the national and city level). To deal with the detailed complexity of SDS (resource dependencies, environmental performance, functions, etc.) which could challenge participatory modeling as a method, we use a System-of-Systems Engineering approach (SoSE) to frame the system in a more structured and process-oriented way. SoSE can contribute to the better understanding and inclusion of multi-level complexity into system design (Heitmann et al., 2019b). Originally, SoSE is a widely applied engineering approach which is mainly used in a technological context for complex adaptive system design such as software development, distributed systems management, airplane service design, infrastructural design (e.g., public bus networks), or military command and control systems (Jamshidi, 2008; Valerdi et al., 2007; Weilkiens, 2007). In general, SoSE supports simplification of a system with high detailed complexity through systematic analysis based on system requirements.

Requirements are "the descriptions of properties, attributes, services, functions, and/or behaviors needed in a product to accomplish the goals and purposes of the system" (Carr, 2000, p. 401). In addition, requirements enable the system engineer to include a user oriented perspective into the system design task (American National Standards Institute, 2012, p. 14; Department of Defense Systems Management College, 2001, chap. 4). Therefore, we develop a methodological approach based on the requirements engineering approach from SE.

Applying SoSE on SDS requires a translation and interpretation of SoSE frameworks for natural resource management contexts. In our proposed methodology, we adapt requirement elicitation and modeling as a part of SE to the specific challenges of designing SDS. This includes broadening the scope of requirements to environmental System-of-Systems (SoS), re-defining SoSE elements such as concept of operations (CONOPS) or requirement quality criteria, and defining new requirement types and integrating these elements into a participatory modeling framework. An example application of this methodology is provided in this paper by designing integrated and requirement-based solutions to existing problems in the energy domain in the SDS of the two largest German cities Berlin and Hamburg and their links to the German national strategy, whereas the conceptual foundation is explained in Heitmann et al. (2019b). This underlying conceptual framework is called "FRESCO" (Functions, Requirements, Evaluation, Structures, Constraints, and Outputs) and "is a general process design framework for application on environmental SoS. The framework is derived from SoSE concepts but uses narratives from the re-source management domain. By following the process of the framework, the complexity of environ-mental SoS can be included into a system design task." (Heitmann et al. 2019b, p. 6). Berlin and Hamburg are both federal states and cities at the same time which has consequences with respect to the institutional conditions for implementing environmental measures. This implies that each city is responsible for the achievement of its own regional sustainability goals. Although the regional objectives are specifically targeted towards local issues, some measures also correspond to the national strategy i.e., are officially and directly targeted towards the objectives of the German Agenda 2030 implementation. This article is structured as follows. In Section 2, we give an overview on the methodological background, including SoSE and requirements analysis. Section 3 presents the structure of our methodological framework, whereas Section 4 describes our suggestions on how each step of the methodological approach should be carried out. Section 5 offers the results of an example application to the German sustainability strategy landscape. Section 6 provides a discussion of the results, before the article closes with the conclusions and possible future work in Sections 7 and 8.

2. Conceptual Background: SoSE for Understanding Links between SDS at Multiple Governance Levels

SoS are commonly applied and studied in various engineering disciplines (Crowder et al., 2016). A SoS can be defined as a collective system, which has autonomous and heterogeneous elements that are connected dynamically with each other and have their own goals which contribute to the overall goal of the whole system (Baldwin et al., 2015b). We already showed the potential of the SoS concept to contribute also to the integrative management of natural resource issues (Heitmann et al., 2019b). More precisely, it can be summarized that the SoS concept helps to "include multi-level complexity" into decision making processes, and "to gain an advanced understanding of complex relationships" in a system (Heitmann et al., 2019b, p. 17). The German SDS landscape, which is subject of discussion in this paper, is implemented on different governance levels, and represents a special SoS-type, an "acknowledged" SoS: The subsystems (i.e. urban SDS) follow a high-level objective (i.e., are aligned to the national SDS) which is often through the share of resources (i.e., share of institutions or multi-level actors). Nevertheless, subsystems maintain their own identity and goals (i.e., urban SDS pursue specific regional goals, and the national SDS follows national interest) (Office of the Deputy Under Secretary of Defense for Acquisition and Technology Systems and Software Engineering, 2008). Therefore, applying SoSE on SDS is a new and innovative field. The following capabilities underline the suitability of SoSE to strategy design and development. SoSE provides: (1) a structured design approach to develop, implement, test and evaluate systems; (2) methodological tools to apply each system design step (e.g., requirements elicitation and analysis, functional analysis and risk assessments); (3) a user oriented design approach which ensures a system design which fulfils the user requirements on the system; (4) combined design and project management methods which help to guide also larger design processes; and (5) standard procedures for evaluating to what degree the user requirements are represented in the actual system. Already existing methods for the application in systems design and examples for environmental design are described in Table 1.

Table 1. Strengths of System-of-Systems Engineering (SoSE) for sustainable development strategy (SDS) design.

Strength of SoSE	**Examples from the Engineering Literature**	**Examples for SE in an Environmental Context**
A structured design approach to develop, implement, test and evaluate systems	Detailed description of SoSE steps (Crowder et al., 2016; Kossiakoff et al., 2011)	Conceptual Nexus design framework “FRESCO” (Heitmann et al., 2019b); Sustainable system design concepts (Ceschin and Gaziulusoy, 2016; Shapira et al., 2017)
Provisioning of methodological tools to apply each system design step (e.g., requirements elicitation and analysis, functional analysis and risk assessments)	Requirements analysis (Department of Defense Systems Management College, 2001, p. 35 ff; Nuseibeh and Easterbrook, 2000); Functional analysis (Department of Defense Systems Management College, 2001, p. 45 ff; Halbe et al., 2014); Risk assessments (e.g., (Department of Defense Systems Management College, 2001, p. 135 ff)	Systems Engineering and environmental management (Hipel, 2012; Hipel et al., 2010, 2008c, 2008b); Decision-making tools (Hipel et al., 2008a; Hipel and Walker, 2011; Kilgour and Hipel, 2005); Mental models (e.g. (Lockton et al., 2017))
A user-oriented design approach ensuring a system design which fulfils the user requirements on the system	Participatory modeling with causal-loop diagrams (Halbe et al., 2018; Halbe and Adamowski, 2019; Inam et al., 2015; Vennix, 1996)	User-oriented sustainable product design (e.g., (Baldassarre et al., 2017; Lockton et al., 2017; Ludvig and Daae, 2014; Wever et al., 2008))
Combined design and project management methods which help to guide also larger design processes	Project management and systems engineering overlaps (e.g., (Arnold, 2012; Kossiakoff et al., 2011, p. 112; Sharon et al., 2011; Xue et al., 2015))	-
Standard procedures for evaluating to what degree the user requirements are represented in the actual system	Traceability principles (mainly technological) (e.g., (Blanchard and Blyler, 2016, fig. 2.9; Egyed et al., 2009; Nuseibeh and Easterbrook, 2000) and frameworks for evaluating system interventions (e.g., (Huz et al., 1997))	Dealing with high levels of uncertainty in water resources management (Hipel and Ben-Haim, 1999)

Challenges for the application of SoSE on the design of SDS are (1) the multi-level governance nature of political systems where the strategies are embedded in; (2) the need to represent complexity in a detailed manner to be able to understand and cope with this complexity; (3) and the need for an integrated and solution oriented approach because isolated analysis and design of system parts may have negative effects on other parts of the overall system. Particularly the latter issue requires a holistic approach which designs not only the sub-systems in isolation but takes their interactions into account. These challenges are also met in SoSE, although, up to now, mainly technical systems have been taken into account. The engineering process of a technical SoS mainly focuses on the design of soft- and hardware systems and services, whereas the design of SoS for SDS requires also consideration of social, institutional and environmental aspects.

In this paper, we present a novel requirements engineering approach to design SDS. Up to now, requirements engineering is mainly applied to technical systems design (Carr, 2000) although it is commonly perceived as the most important step in systems design in general (Carr, 2000; Crowder et al., 2016; Nuseibeh and Easterbrook, 2000). Therefore, the standard requirements approach needs to be adapted to the complexity of SDS to be able to also represent social, institutional and ecological aspects. This means that, in addition to multiple possible levels of requirements (i.e., hierarchies, priorities, relative importance), and two existing standard types of requirements (i.e., functional and non-functional requirements), several new requirement types need to be defined.

Functional requirements are understood as tasks the system must accomplish. Non-functional requirements or constraints are considered to be constraining conditions for system design (Carr, 2000). For example, a functional requirement is the development of a sufficient power grid management system which is able to handle the increasing amount of renewable energy supply fed into the energy grid. A non-functional requirement is to allow renewable energy providers to feed in only a specific amount of energy per time unit into the existing energy grid. In addition to these technical requirements, SDS include social, economic, nature environmental, and institutional requirements. This makes the requirements elicitation process more complex compared to technical systems design. Because the dependencies between requirements (high-level and low-level requirements) are also important, these links become more complex with a higher number of requirement types. We adapted the traditional requirements analysis approach by defining new types of requirements. We also complement the requirements analysis approach by using causal-loop modeling as a method to develop the conceptual system models. Causal-loop modeling and requirements analysis both describe a system in terms of hierarchies, i.e., multi-level relationships between the system variables, provide a framework for modeling these relationships, have participatory elements such as involving stakeholders, model the concept of a system which then can be further specified, and both provide an actor-oriented perspective on the system. The latter point is particularly important for the development of an actor-oriented system design. These overlaps are illustrated in Figure 1.

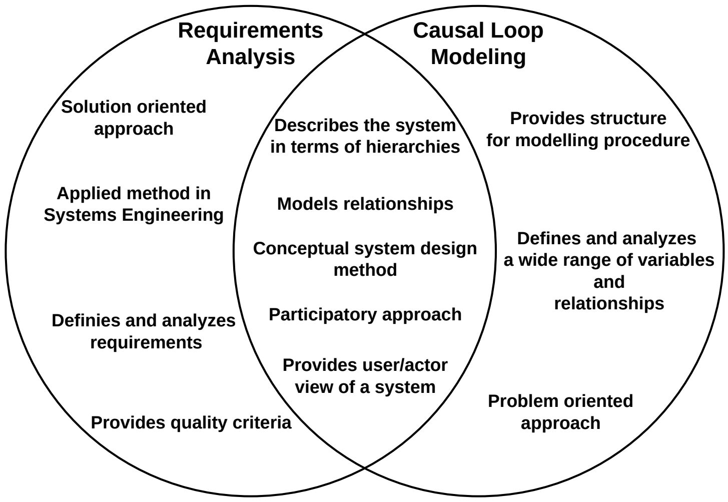

Figure 1. Main aspects and overlaps between requirements analysis and causal-loop modeling.

Table 2 illustrates the variable types we suggest considering when analyzing SDS. This includes the following requirements types: Economic, financial, generic, policy, social and technological. Interactions between these variables and requirements are usually path dependencies. This means that the link of one requirement to another is defined as a uni-directional causal-relationship (i.e., A leads to B), bi-directional relationship (A leads to B and vice versa), or dependency (B is dependent on A). We adopt this approach from Carr (2000) and Nuseibeh and Easterbrook (2000).

Economic requirements are defined as economically related user needs formulated as requirements such as “reduction of final energy demand”. Financial requirements are defined as monetary requirements, for example “investment costs”. Policy requirements are requirements which describe policies or aspects of policies which should be part of the system design, such as “Amendment to climate protection act in Hamburg” or “Energy turn around act”. Social requirements are societal requirements such as changes in sustainable consumption patterns. Technological requirements describe technological system or system parts such as “power to gas applications” or “thermal insulation of new buildings”. Generic requirements are defined as all requirements which do not fit the definition of the other requirement types.

Table 2. Variable types.

Type	Abbreviation	Definition
Actor	A	Describes an actor or actor group which is part of the system design model
Constraint	C	A variable which blocks, limits or mitigates the successful implementation of a system design, i.e., a non-functional requirement
External	E	A variable which is beyond the defined system boundaries
Function	F	“Discrete actions necessary to achieve the system’s objectives.” (Department of Defense Systems Management College, 2001, p. 45)
Generic	G	Variables which cannot be defined as any other variable type
Interface	I	“An interface represents a crossing point of an object to other objects, or more generally to its environment.” (Heitmann et al., 2019b)
Objective	O	A goal or aim which may be implemented by the overall SoS or its subsystems

Type	Abbreviation	Definition
Process	P	“A process is a sequence of behavior that constitutes a system and has a goal producing function.” (Ackoff, 1971, p. 666).
Requirement	R	“Requirements are defined as factors to be fulfilled for an actor to achieve an individual task in the operational environment.” (Heitmann et al., 2019b)
Resource	RS	A resource is a “source of supply or support” (Miriam-Webster dictionary). We refer to a resource as a nature environmental source.
Structure	S	The structure of a system is specified by the relationships between system elements (Halbe et al., 2014 In Heitmann et al., 2019b)

In the following, we explain our detailed methodological framework.

3. Methodological Framework

The proposed methodological framework aims at the integrated and participatory analysis and design of SDS across multiple governance levels.

To inform the current sustainability discussions, this methodology follows a holistic approach from the field of SoSE to successfully design and redesign policy processes, strengthen the integrated management of heterogeneous strategy objectives and enhance cooperation between actors from different sectors. This systematic approach is a counterpart to linear thinking which often has been found in policy making (Sterman, 2000).

Our methodological framework includes six steps (see Figure 2):

1. Literature review: Literature review of available strategy documents to define possible scopes of the design process.
2. Expert interviews: Individual expert interviews are conducted to elicit requirements. This is done by applying an enhanced participatory modeling approach using causal-loop diagrams. By this means, we include stakeholders in the development of a systems model to develop a user-oriented baseline for SDS development and implementation.
3. Digitalization of interview data: This step includes translating and digitalizing diagrams from the interviews as adjacency matrices (Wasserman and Faust, 1994, p. 150 ff) and visualizing them with available software for further analysis, e.g., with “Gephi” (Bastian et al., 2009).
4. Coding of interview data: Specification of variables mentioned in the interviews. This includes the specification of attributes such as requirements types as exemplified in chapter 5.
5. Statistics: This includes the computation of different network measures, i.e. betweenness-centrality (BC) and node degree.
6. Filter and analysis: The outputs include diagrams, tables, and other information which may be helpful to support further steps of the overall system design process.

The application of the methodological framework follows an iterative process that includes three loops (Figure 2):

1. Requirements Loop: Requirements are developed and specified throughout the interview. This means that all necessary information should be documented early in the design process (i.e., during the interview). If information is missing, the already digitalized data may be complemented also in the specification phase. It may happen that the specification phase reveals some missing and important information from the interview phase. In this case, the interviewee could be asked to provide additional information to the process. This bi-directional relationship between interviews and specification is called a “Requirements Loop”.
2. Design Loop: The design loop is the bi-directional relationship between digitalization and analysis. During the analysis, the relationships among the requirements and other variables as well as the result of their implementation and system functions are analyzed. As these findings are maybe interesting to publish or communicate in a digitalized form and fed back into the design process, these steps need to be connected. The digitalized form may work as a direct input for the analysis if a second specification is not necessary.
3. Verification Loop: The verification loop directly connects the analysis step with the interview step. As new insights from the analysis phase may lead to the need to conduct additional interviews, or to “verify” the results with the help of the stakeholders, information between the two steps may be exchanged directly.

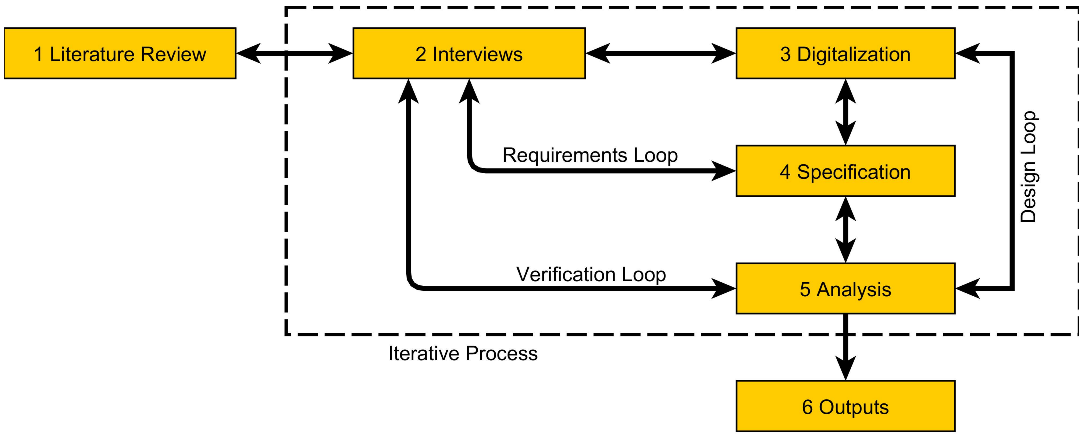

Figure 2. Methodological framework for participatory requirements-based strategy design.

In the following, we explain how each step of the methodological framework should be applied in general. Here, we also provide some examples. The results and content-specific application is presented in Section 5.

4. Methodological Application of the Framework

4.1. Literature Review

The first step of our framework is a comprehensive literature review on the overall sustainability landscape. If the focus of the case study lies on a specific city or region, information on other levels should also be considered to understand the embeddedness of local strategies in the overall strategy landscape. Often, reviewed documents refer to additional sub-strategies, more specific implementation strategies or related projects or initiatives. It is particularly important to additionally review different types of literature such as strategies, reports, white papers, protocols, administrative sources, grey literature, e.g., newspaper articles, or results from participatory processes such as project workshops. This will enable the project to get a more detailed picture of the underlying case and allow a systematic selection of stakeholders for the interview process in Step 2.

As part of Step 1, stakeholders should be selected which are invited to participate in the interview process. The outcome of this step is a list of participants who are willing to participate in the research process, as well as an overview on the overall strategy landscape. Applied criteria for the selection of actors are (1) representation of diversity, (2) willingness to contribute, and (3) number of participants (Ridder et al., 2005). During the stakeholder selection process, we made sure to include several different types of stakeholders in the process to be able to collect more diverse knowledge during the process and therefore to develop more detailed models. Actors came from research institutes, public and private consultancy organizations, the senate-administration, the craft association and political parties, scientific research organizations, and citizenship representative organizations. We found many stakeholders embedded in tight working schedules. Therefore one selection criterion was also availability and willingness to contribute. For our exploratory case, we made sure to conduct a minimum of 10 interviews. However, in future studies this number should be increased to derive more precise insights from the system design models.

4.2. Expert Interviews

We developed a semi-structured participatory interview approach to record different types of variables during the interviews. The interview approach is illustrated in Figure 3. As a formalization approach, we used causal-loop diagrams (CLDs) to illustrate the connection of the requirements inside (subsystem level) and in between the subsystems (SoS-level). The resulting data basis of the diagrams consists of the variables mentioned during the interviews. Variables have been formalized as “nodes”. The nodes are connected through “edges”. Each edge represents a logical connection between two elements. As our focus lies on the requirements, we call the resulting diagram a detailed requirements diagram.

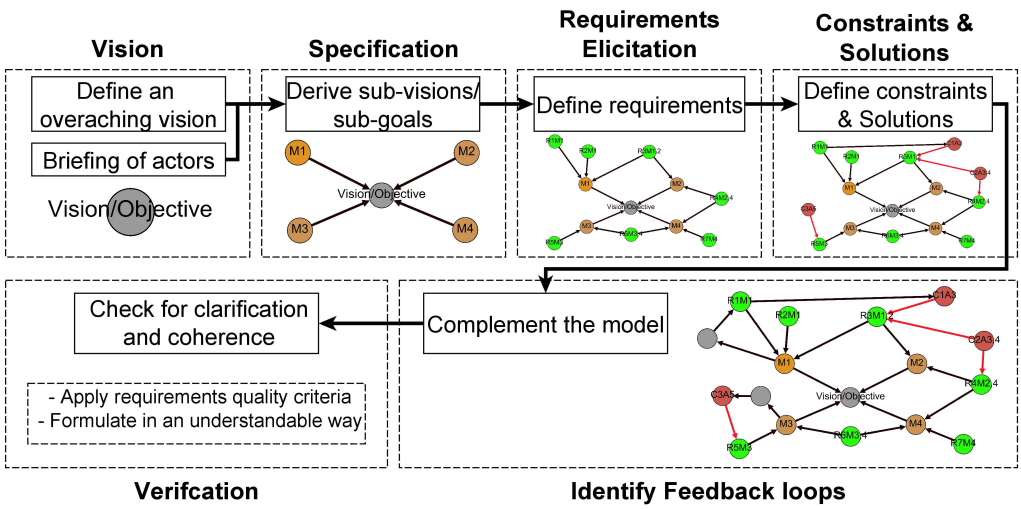

Figure 3. Participatory System-of-Systems (SoS) modeling framework.

The interviews are structured as follows, whereas Steps 1–3 are preparatory and may be communicated to the interviewee prior to the interview. We suggest to plan 90 minutes for each interview. Explaining the interview method takes approximately 15 min time. Formulating requirements should not exceed 60 min in order to have enough time for formulating constraints and validating the model in the end of the interview (~15 min).

1. The interviewee is told how the provided information is handled. Depending on actual institutional regulations, interviewees may have to sign a form in which they agree with the processing of the provided information. Additionally, the interview may be recorded for internal use during later digitalization, coding and merging processes if some aspects of the interview turn out to be unclear for the modeler.
2. The structure of the interview (Figure 3) is provided to the interviewee. All steps are explained and questions answered. It is particularly important to make clear that the applied interview technique may provide a structure for the interview but does not include pre-defined questions which may constrain the information the interviewee could provide. It should be stated that the participatory modeling approach aims at capturing the individual and unbiased mental model of the interviewee. No statements are “wrong” or “insignificant” to the process.
3. Causal models in personal interviews can be drawn by using pen and paper. Online interviews can be developed by a browser-based online app such as the app “participate” by Simon Hötten. (At the time of submission, the app has not been made available to the general public.). The app allows the user to interactively draw causal diagrams via a web-browser. If the interview will be carried out via pen and paper, this requires enough space (e.g., a big table or a pin-wall). We suggest clarifying the space requirements before the interview. If insufficient space is available because of logistical reasons, software could be used to draw the diagrams directly in a digitalized form.
4. In the beginning, the interview material should be prepared by providing material (paper, pen, moderator cards and others) to the interviewee. The central topic of the interview should be written in the middle of the paper (e.g., reduction of CO_2-emissions according to the Paris agreements by 85% by 2030). The topic could be an objective, a solution, or the main design goal. Depending on the experts’ expertise, this central variable can be further specified by defining sub-topics or concrete measures to which the interview is able to provide detailed information.
5. Requirements are elicited. We suggest providing a list of possible requirement types to the interviewee to support this step of the interview process. As time constraints are often the limiting factor for such interviews, effective time-management is essential. The requirements are directly connected to the central variable or the derived sub-variables. If the interviewee struggles with this process, we suggest to first collect a few requirements on sticky-notes on the side and connect them afterwards. Requirements can also be further defined or connected. For example, requirement “A” may be required to achieve objective “X”, and requirement “B” may be required for requirement “A”. The links originating from requirements should be marked

with a "+" symbol which defines a positive relationship from the originating variable (i.e., requirement) to the targeted variable (e.g., requirement, objectives)

6. After requirements have been derived, the moderator should ask the interviewee to name some possible constraints which could hinder the achievement of the objectives. These constraints are connected to other variables with a negative causal relationship ("-" symbol). These relationships help to directly trace back and identify constraints.
7. Next, the causal model may be complemented by adding other variable types (Table 2). This step results in a more detailed mental model and helps to bring the requirements and constraints in an overall context. This is helpful if, for example, the models are communicated back to the interviewees after the analysis. Some requirements also do not make sense if they are not connected to other variable types. For example, leadership may be a requirement for achieving the goals of a specific project, but it may has to be further specified by connecting it to a specific actor or organization which should provide this leadership. In this case, this actor or organization would be one variable of the type "actor" which is connected to the requirement "provisioning of leadership".

Although the focus of the causal diagram lies on the derived requirements, it is important that the interviewee is satisfied with the diagram in the end of the interview. Therefore, each interviewed person should be asked to validate the model in the end (e.g., by asking the question: "Do you think that this model reflects your point of view?"), as the personal viewpoint of each participant will be part of the final interpretation of all merged models. Additionally, during the interview, the moderator needs to check for coherence of the model itself. This means that the model should not include requirements which contradict themselves.

As next steps, the interview data is digitalized, individual causal models merged, statistical analysis applied, and the network data is filtered for presenting it to the stakeholders.

4.3. Digitalization Interview Data

Digitalizing the interviews is particularly important for further analysis of central variables such as requirements or constraints. Because of the large amount of variables, a digitalized version of the data helps to structure, understand, analyze and interpret the resulting CLDs. Another aim of the participatory approach is to report the results back to the stakeholders. We found that Gephi, CMapTools or yEd are helpful tools to illustrate the data and to communicate findings in an easy and understandable way. Gephi is a tool which helps to model, visualize, and analyze causal models. CMapTools and yEd can be used to manually draw models or diagrams and export them into a vector graphic file.

In addition, digitalizing interview data includes translation of CLDs into adjacency matrices, coding of the interviews (i.e., specification by adding different attributes to each variable) and merging individual causal models to one overall model. In the following we will explain each step in more detail.

Adjacency matrices

As shown in Figure 4, graph H consists of 4 variables (a, b, e, and f). “a” and “b” have a negative effect on “e”. The graph can be represented as a 4 x 4 matrix, whereas “a” represents the variable “a” in the graph, and “b” the variable “b”. “a” has a positive causal relationship to “b”. This is represented with a “1” in the matrix.

Each interview is represented as one matrix using Microsoft® Excel®. In a second step, each matrix can be imported into “Gephi” (Bastian et al., 2009).

$$A(H) = \begin{array}{c} \\ a \\ b \\ e \\ f \end{array} \begin{array}{c} \begin{array}{cccc} a & b & e & f \end{array} \\ \begin{bmatrix} 0 & 1 & -1 & 1 \\ 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \end{array}$$

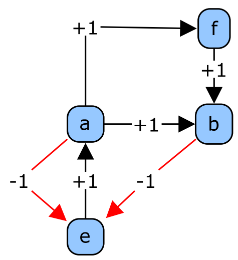

Figure 4. Graph H.

4.4. Coding of Interview Data

Each table can now be specified by adding additional rows which include further information from the interviews, e.g. variable type, governance level, actor who mentioned the variable etc. This information may be helpful in subsequent steps of the analysis. Documenting all information related to one requirement or variable in general is important to maintain traceability of requirements throughout the design process and is part of the requirements management task (Keating et al., 2008). In SE, it is usually realized by documenting information in the requirements allocation sheet (Department of Defense Systems Management College, 2001). Because the software Gephi already provides the function to document variable attributes, we used this platform to keep all available information at one place.

4.5. Merging

The process of merging the different causal-models results in the overall requirements diagram. Each interview is complemented by information from the other interviews. We suggest a three-step approach: (1) Interviews from the same level should be merged. For example, if several interviews in one city have been conducted, these interviews are merged first. Then, (2) the resulting model of each city is combined with the merged causal model of other cities. If also other governance levels are included, such as regional or national levels, these levels are merged in the last step. We suggest saving each step individually to be able to design more specific measures or solutions for stakeholders on each level. As an illustration for the process of merging the causal-model, we define the following graphs:

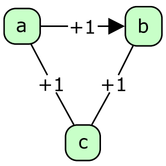

Figure 5. Graph G

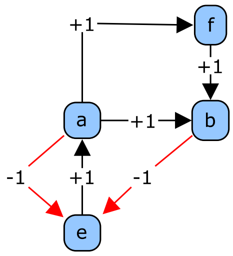

Figure 6. Graph H

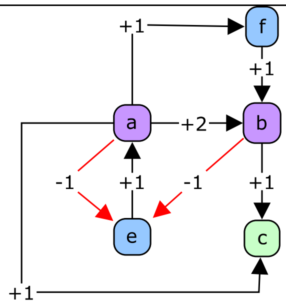

Figure 7. Graph J (sum of G and H)

Graph G (Figure 5) consists of three variables (a, b, and c). They all have a positive effect on each other. As described above, graph H (Figure 6) consists of 4 variables (a, b, e, and f). "a" and "b" have a negative effect on "e". We see that graph J (Figure 7) is the sum of G and H. Let $A(G)$ be the adjacency matrix of graph G, and $A(H)$ the adjacency matrix of graph H. Therefore, the sum of $A(G)\ and\ A(H) = A(G) + A(H)$.

$$A(G) = \begin{array}{cc} & \begin{array}{ccc} a & b & c \end{array} \\ \begin{array}{c} a \\ b \\ c \end{array} & \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{array}, \quad A(H) = \begin{array}{cc} & \begin{array}{cccc} a & b & e & f \end{array} \\ \begin{array}{c} a \\ b \\ e \\ f \end{array} & \begin{bmatrix} 0 & 1 & -1 & 1 \\ 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \end{array}, \quad A(G) + A(H) = \begin{array}{cc} & \begin{array}{ccccc} a & b & c & e & f \end{array} \\ \begin{array}{c} a \\ b \\ c \\ e \\ f \end{array} & \begin{bmatrix} 0 & 2 & 1 & -1 & 1 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

It could be especially challenging, to combine two variables which mean the same, but are formulated differently. For example, the variables "Coal Phase-Out" and "No Coal" which have been mentioned by two different actors could mean the same but are formulated in two different ways. To be able to combine these variables in one variable, clarification of the underlying meaning of the variable should be ensured with the stakeholder who mentioned this variable. If available, a recording of the interview could help to understand the underling meaning from the context. After importing the matrices into Gephi, each node has the following attributes: "Label" and "id", whereas the "id" is the final identifier for Gephi, and the "label" can be edited by the user. By applying statistical analysis on the CLDs, Gephi adds additional nodes to the table which include the results of the analysis (e.g., clustering coefficient, In –and Out-Degree, total degree, eccentricity, closeness-centrality, and BC). Although Gephi has an option to merge two nodes with the same name, this option is only helpful if the same string is used for two variables. However, this is often not the case. Therefore, manually merging two nodes and then renaming the merged node in Gephi is the best option we identified (not at least because the edges will be added/complemented during the automated merging process by Gephi which makes the automatic merging process intransparent).

4.6.Statistics

With analyzing requirements diagrams, it is possible to gain an advanced understanding of the underlying data, e.g., identify indicators on what requirements are most important, what linkages are most significant, and to what degree specific requirements types are represented in the diagram. We suggest calculating the BC to be able to compare the embeddedness of each node in the network (Freeman, 1979, 1977), as well as the degree distribution of the network to see how many nodes are included with an either high or low number of links. Although the results of this analysis may suggest to prioritize the implementation of specific requirements, an interpretation should be done with care. The high centrality of one specific requirement is not necessarily an indicator for a low importance of other requirements. However, a high centrality of one node always indicates that this node has been mentioned by many stakeholders during the elicitation process. This insight can be helpful to concentrate on a topic or theme during the implementation phase and to bring stakeholders with different perceptions of a problem perspective together. If different CLDs are combined, a normalized BC should be calculated to identify important nodes which link different CLDs. "The normalized betweenness centrality is the betweenness divided by the maximum possible betweenness expressed as a percentage" (Grebitus 2008, p. 85). Calculating the degree distribution could be helpful to identify the centrality of the CLDs or communities inside each CLD. For the spatial topology of our CLDs, we applied the “ForceAtlas2” algorithm. The algorithm organizes a CLD by repelling its nodes while the edges pull the nodes towards each other. The result may help to better understand the visualized CLD data (Jacomy et al., 2014).

4.7. Filter and Analysis

The process of filtering the variables in the CLD has the main objective to prepare the data for presentation to the stakeholders or publishing it in an understandable and focused manner. We encourage to filter the CLDs by using the measures from the statistical analysis such as BC or node degree to only visualize nodes with a high BC or node degree larger than zero. Particularly studies with a large N would profit from this approach, because large CLDs are maybe inconvenient to display or to discuss with stakeholders. For communication purposes, we suggest to take advantage of additional visualization tools. For example, “yEd” will enable the user to present parts of a graph for as a discussion baseline which is easy to understand also in presentations (https://www.yworks.com/products/yed). Figure 8 represents the multi-level nature of a causal-loop model using yEd. National goals (i.e., 95% “CO2 reduction” and “Coal phase-out”) are linked to requirements on other levels (e.g., “Use of renewables in heating grids” or “Expansion of solar energy use”).

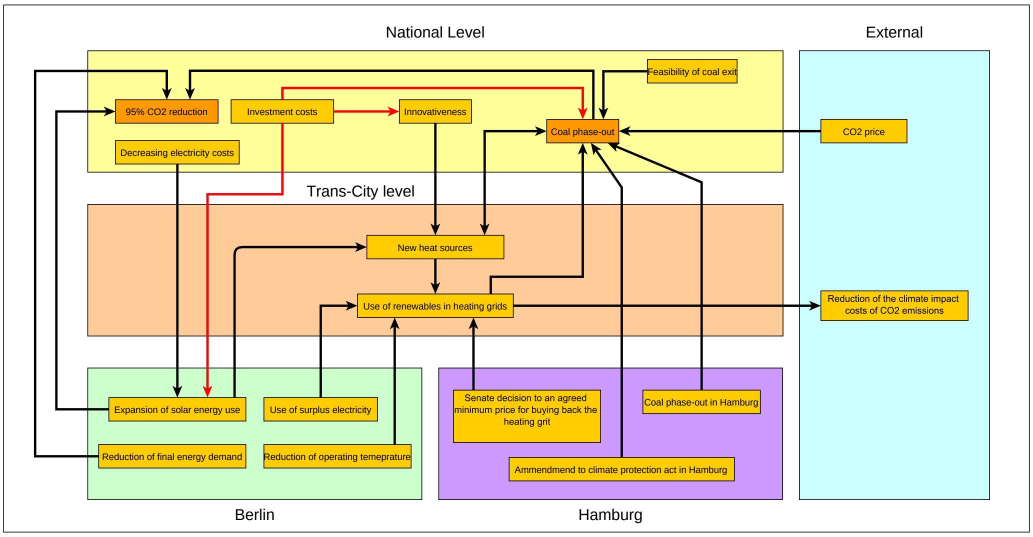

Figure 8. Multi-level representation of a causal-loop model.

5. Results of the Methodology to Energy-Related Parts of SDS in Germany

To illustrate our methodological approach, we modeled user requirements of the energy-related parts of the SDS of Berlin and Hamburg and their links to the national directive of Germany and re-veal critical factors needed for the overall success of the strategies. In particular, we investigated how the national target to reduce CO2-emissions, according to the Paris agreement, by 80–95% until 2050 compared to 1990 can be addressed on the national and urban levels.

On the urban and national level, we conducted (1) a literature review on available strategies and inherent objectives, measures and requirements with a focus on the energy sector (Section 4.1); (2) conducted individual expert interviews where we apply our semi-structured participatory interview approach (Section 4.2); and (3) applied requirements analysis on our data. Requirements analysis included the collection and analysis of the requirements of the cities needed to achieve the regional SDS as well as a comparison with the national requirements (top-level vs. low-level requirements) (Section 4.3-4.6).

In the following, we show how we applied each step from our methodological framework and present the detailed results.

5.1. Literature Review

The German SDS provides a conceptual framework that aims at providing guidance for a sustainability transformation in Germany. The German SDS includes information on further development of the overall strategy, the role high level actors (federate level) responsible for coordination of the strategy implementation and development, and strategic pathways of the federal government for sustainable development. It describes 63 key indicators which are monitored every two years. According to Singh et al. (2012), the German SDS has some shortcomings, as it does not provide: (1) specific tools or instruments to be implemented, (2) important actors needed to implement the strategy, (3) responsibilities of actors who are needed for the strategy implementation, nor (4) a comprehensive framework for contributing towards more diverse and comparable indicator sets (Singh et al., 2012).

We reviewed strategy documents on the sustainability agenda of Germany, and the cities of Hamburg and Berlin. This includes but is not limited to official SDS of Germany (Deutsche Bundesregierung, 2016), Berlin (Senat der Stadt Berlin, 2018) and Hamburg (Senat der Freien und Hansestadt Hamburg, 2015), older versions of the national strategy (Deutsche Bundesregierung, 2012), and several sub-strategies, such as the German plan on energy efficiency (NAPE) (Bundesministerium für Wirtschaft und Energie (BMWi), 2014). In a second step, we focused on related projects in each city.

In the case of Hamburg, this particularly includes the NEW4.0 project, a joined project by the city of Hamburg and the federal state of Schleswig-Holstein with the objective "to have a safe, cost-efficient, environmentally compatible and socially accepted regenerative power supply by 2035, based entirely on renewable energies [in the study region]." (Capel and Beba, 2017). In addition, we reviewed key documents on the implementation strategy of the SDGs in Hamburg, which has been published by the senate of Hamburg. More specific information on the citizens' viewpoints on this topic was gathered from reports of a broad participation process on the SDG implementation. This process was conducted as part of an inter-agency project group which has set itself the goal to develop an evaluation scheme of the Hamburg government program, to discuss and identify requirements for taking action, and to identify approaches for the implementation of the SDGs. For Berlin, we particularly reviewed the draft and the final BEK (Hirschl et al., 2015; Senat der Stadt Berlin, 2018), ideas for the implementation of measures (Senatsverwaltung für Umwelt, 2016), as well as the results of the BEK feasibility study (Reusswig et al., 2014) and plans for adaptive management in the field of climate change (Reusswig et al., 2016).

Our original plan was to also compare the strategies with available indicators of each city. Therefore, we reviewed existing indicator reports and found that indicators are not coherent across cities. We thus advocate to use our interview approach to get a knowledge baseline for comparing different strategies which is formulated in terms of variable types as defined in Table 2.

With respect to the variable types in the underlying strategy documents, we found a strong focus on the formulation of overall visions and general objectives, rather than on actor requirements. This becomes particularly clear in the German SDS: Whereas the role of specific actors as well as their interdependencies only plays a minor role, the general pathway for sustainable development as well as the dependencies of the different objectives and measures are elaborated in detail. This may be particularly important for finding common ground among participating stakeholders during the implementation phase. Often, this common ground is necessary for coordination and cooperation of actors and more helpful then discussing the importance of single variables or individual attributes (Ostrom, 1998). On the other side, the reviewed urban strategies include in addition to several objectives, measures and indicator-sets also specific instruments, actors, requirements, and constraints. These measures are grouped into different fields of action such as energy, buildings, mobility, economy, or education. The BEK defines two fields of action types: fields of action for climate safety, and for adaptation to the effects of climate change.

5.2. Interviews

From May to July 2018, the first author of this paper conducted a series of 10 expert interviews (3 on the national level and 7 on the urban level). In these interviews, 322 variables were collected. To assess requirements and constraints in detail, we conducted these interviews with experts from research institutes, public and private consultancy organizations, the senate-administration of Berlin, the craft association and political parties, scientific experts and citizenship representatives. Interviewees were provided with a flyer with information on the motivation and importance of the process (Document A 2).

All interviews took 60 to 120 min. Seven interviews were conducted personally via pen and paper. Three interviews were conducted via telephone, using the software Participate to draw causal diagrams online.

The focus of the interviews in all cases was the national target of reducing CO_2-emissions according to the Paris agreement by 80% to 95% until 2050, compared to 1990. Depending on the interview partner, this target was further specified by adding sub-objective variables such as “coal phase-out” or sub-strategies such as the BEK. As the interview partners were experts from diverse fields, it was important to allow everyone to formulate requirements according to his/her field of expertise. Therefore, on the one hand, we made sure to keep the connection to the national target, while, on the other hand, draw specific diagrams according to the experts' field of expertise. These fields were: Sustainable energy systems, consultancy of the craftsmanship, energy policy and governance, energy grids, civil society and sustainable energy production, political sciences, sustainable energy policy and multi-level governance, city administration, political consulting, climate change adaptation, future energy -and mobility structures, sustainability indicators, and SDG implementation.

5.3. Digitalization

After conducting each interview, we digitalized the resulting CLDs.

Digitalizing the causal-models helped us to sort und specify the nodes, and understand and interpret the causal relationships between them. We found that the easiest way of digitalizing the written diagrams is to first translate them individually into adjacency matrices and afterwards into Gephi. All variables of the digitalized interviews can be found in the supplemental materials (Table A 8). Our methodological framework suggests defining several variable types which all could be identified during the interviews (Table 2). As the main focus of this paper are the requirements and their connection to objectives and actors, we included requirements, constraints, objectives, actors, and external variables in our graphs.

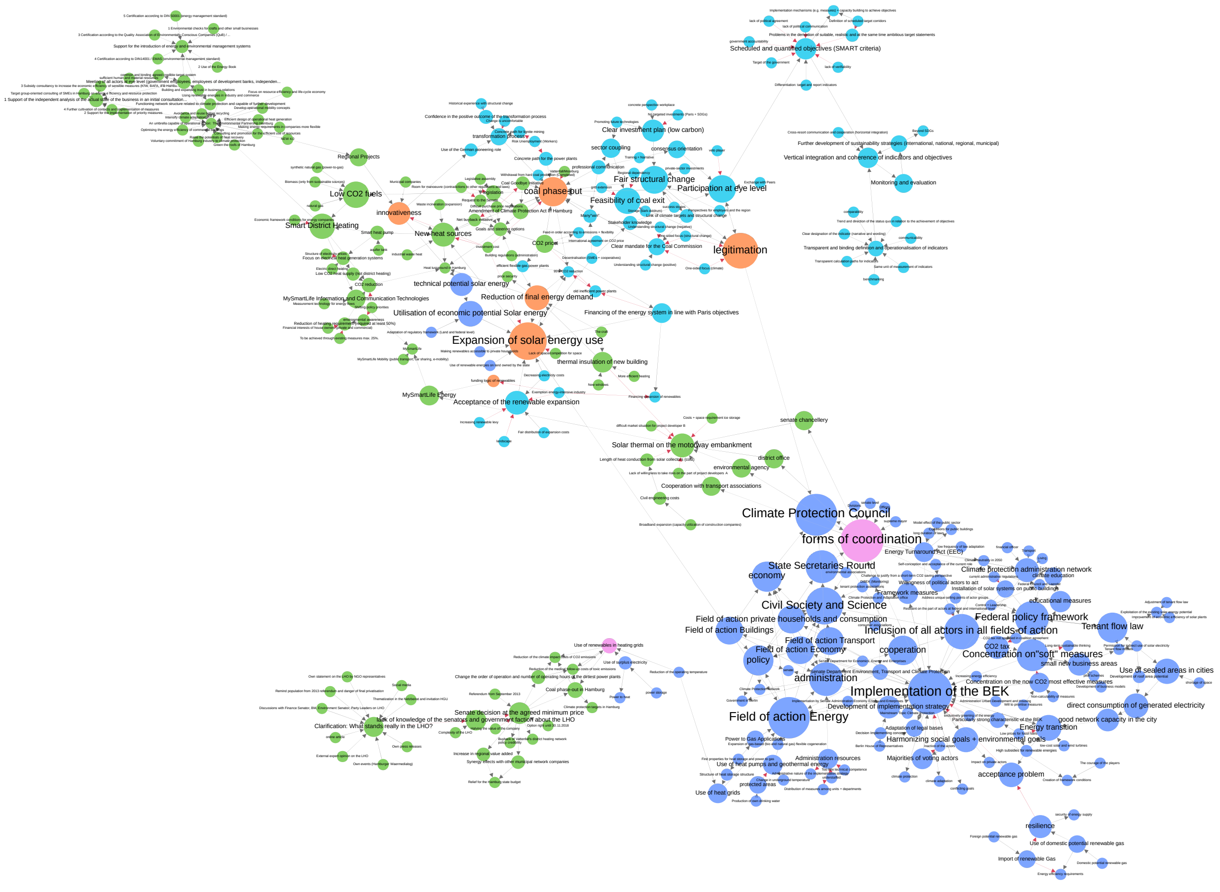

Figure 9. Final overall CLD.

These graphs include 114 requirements, 45 objectives, 40 constraints, 36 actors, 19 general variables, and others (Figures 9 and 10). The focus of the interviews was the derivation of requirements which are needed for strategy implementation from the experts' point of view. Therefore, in each interview, one

CLD has been developed by the interview partner. These CLDs are coupled to other variable types, as described above. To support a systematic requirements derivation, we define different types of requirements and constraints according to our FRESCO framework: economical, financial, general, policy, social, and technical requirements.

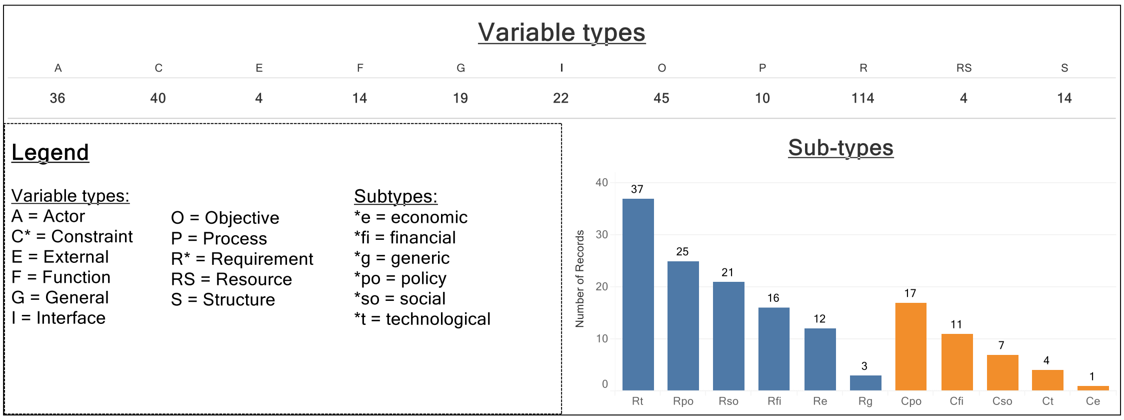

Figure 10. Interview variable types.

To understand the role of each field of action in the strategy documents of Hamburg and Berlin for reducing CO2-emissions, we linked the fields of action to the variable types gained in the inter-views. The resulting CLDs revealed the variables with the highest importance for reducing CO2 emis-sions from the stakeholders' point of view (Figures 13-16). For example, in Berlin, the high importance of the city administration for coordinating the implementation of related measures stands out. Additionally, civil society and science are seen as major actors for implementing the BEK and are related to all mentioned fields of action. In Hamburg, the Environmental Partnership and regional projects such as the "NEW4.0" or the "Coal goodbye" initiative are seen as important actors for implementing energy related measures.

As described above, the resulting CLDs from the interviews were quite complex, revealing a high complexity of the German sustainability landscape. In the following, we illustrate how coding and filtering of such CLDs can help to better understand the most important content.

5.4. Coding

We added the following attributes to the interview data tables: "source" for identifying the governance-level the variable originates from (Hamburg, Berlin or national level) combined with actor information (anonymized for publication); "actor" for identifying the actor who mentioned the variable (anonymized for publication); "type" which is defining the variable type (Table 2), "level", which defines the level of the variable (urban or national) and the city, i.e., "Urban_Hamburg" and "Urban_Berlin". It also identifies if the variable was mentioned by different actors ("Actor_Interface"); "type_interface" which helps to filter variables of the type "interface"; "level_interface" for identifying variables which have been mentioned on the city level and national level.

5.5. Merging

Next, we merged the resulting individual models of the interviews and developed one overall causal model, the requirements diagram. In some cases, actors used different explanations for one requirement but with the same meaning. For clarification, we used the recordings made of the interviews and analyzed the context where the variable was mentioned. Finally, we decided whether we merge the two variables or not. We found that first importing the matrices into Gephi and then editing the nodes-tables was the best order to have the most productive merging process.

5.6. Statistics

As the main objective of our method is to assess concepts and solutions to integrated management problems across multiple levels, we calculated the normalized BC of each node. The BC particularly helps to identify the nodes which connect different CLD clusters, i.e., nodes which connect the mental models of the interview partners the most. A high BC indicates these connecting nodes.

For visualizing the connectedness of the different interviews, we applied different colors to the nodes. Colors indicate from which level the variable originates (Hamburg, Berlin, or Germany). Cross-level variables (i.e., urban-national), are marked as orange. To access the importance of each node for the whole CLD, we calculated and visualized the BC of each node (the larger the node, the higher the BC) (Figure 9).

The final CLD was analyzed regarding normal distribution (Figure 11) of the CLD and normalized BC [0,1] of the nodes. Probability means the probability that any edge in the CLD has a specific number of edges, i.e., links to other nodes. For BC calculation, we used the algorithm by Brandes (2001) and calculated the standard derivation of the BC for each node (Figure 12). The nodes with the highest BC are interpreted as the nodes which are most important in the CLD. For example "Civil Society and Science" has a BC of 0.014755. Only 17 nodes have a BC higher than 0.005 (Figure 11). Therefore, the node has a high importance for the CLD compared to most of the other nodes.

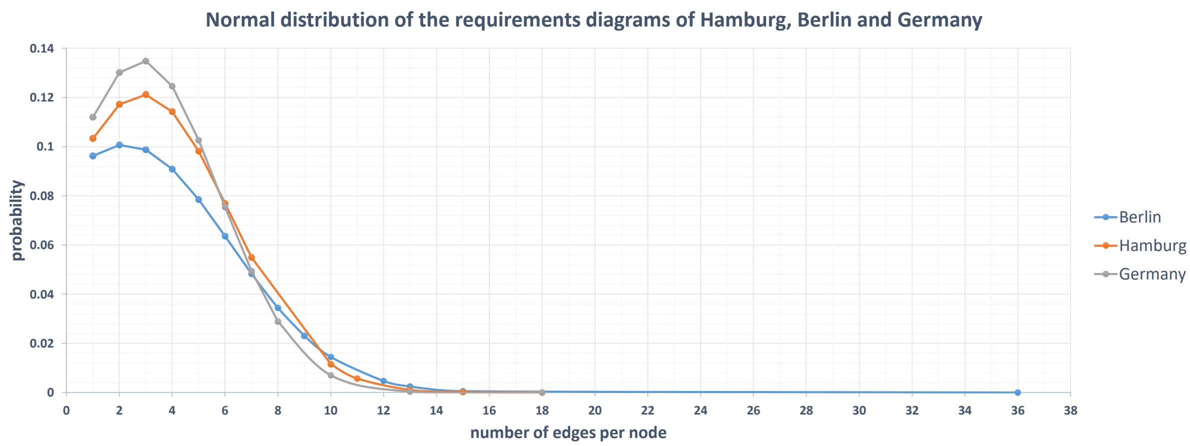

Figure 11. normal distribution of the requirements diagrams of Hamburg, Berlin, and Germany.

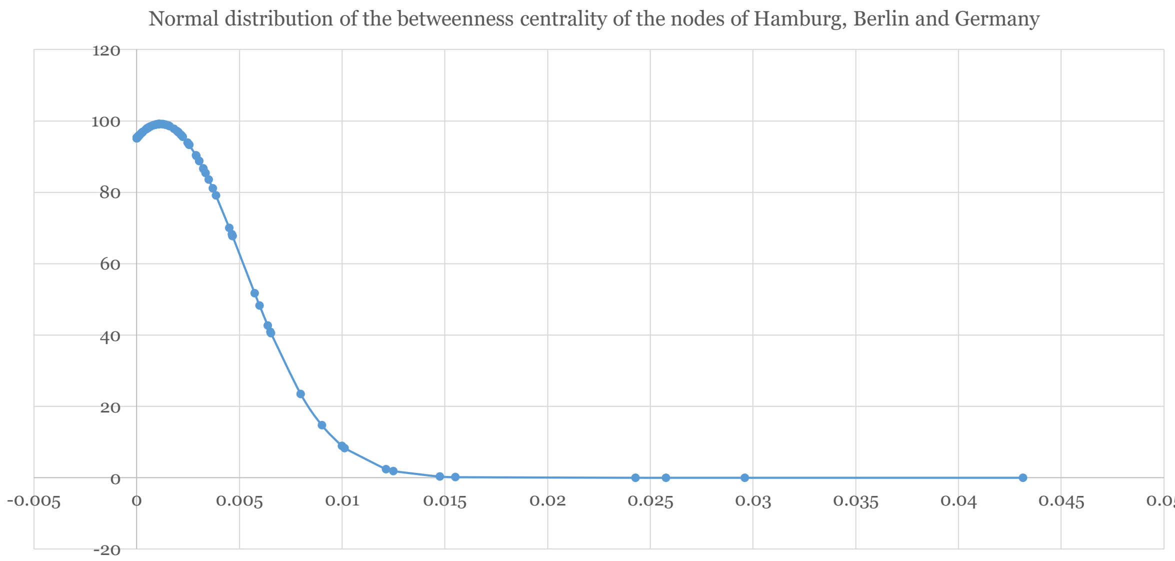

Figure 12. Normal distribution of the betweenness-centrality of the nodes of Hamburg, Berlin, and Germany.

Analyzing the BC distribution of the CLD, we find that 62 nodes are in the 80% quantile (19.25%), and 33 nodes are in the 95% quantile (10.25). The 80%-quantile equals 0.000438, the 90%-quantile equals 0.0028532.

We also applied a modularity optimization method to identify communities inside the CLD. The communities are defined through the strength of the relationships of each node to its neighbors (Blondel et al., 2008). By definition, nodes which have a high BC are more likely to link different communities of the CLD. Figure 9 illustrates the variables which are connecting different governance-levels, i.e., the urban with the national level. Although exploratory, the findings indicate that the BEK implements many of the requirements mentioned also in Hamburg and on the national level. Whereas the "Implementation of the BEK" is naturally very central, "forms of coordination" as an interface variable and "expansion of solar energy use" as an economical requirement connect the BEK to the requirements and objectives of other subsystems, such as to the coal phase-out on the national scale.

Thus, a preliminary conclusion might be that key requirements exist in the strategies that are not only needed to achieve certain objectives in the particular subsystem but also to provide an interface to other subsystems. This finding is particularly important to assess in future studies because interface variables could be significant factors for enhancing coordination and cooperation across governance-levels in strategy implementation. The latter is a necessary factor for a successful energy transition in Germany (Deutsche Bundesregierung, 2016; German Council for Sustainable Development, 2018).

5.7. Filter

Figures 13-15 show the most central variables from the 80%-quantile which are related to the implementation of energy related sub-objectives of each strategy. Figure 16 shows the complete 80%-quantile CLD (82 nodes and 130 edges).

All in all, we found that "innovativeness", "reduction of final energy demand", "expansion of solar energy use", the "funding logic of renewables", and "legitimation" are the variables which connect different governance-levels (i.e., city-national and city-city level). Therefore, these variables are most important for a cross-sectoral design of all analyzed strategies. These variables belong to the 86%-quantile of all variables, according to their BC. This underlines their importance for connecting different CLDs of strategies. In the following paragraph, we provide a detailed explanation of each of these key variables.

Innovativeness was described as important for promoting new heat sources, and for improving the technical potential of solar energy. Regional projects and municipal companies are the main drivers for innovativeness. This may be particularly important for the future use of the German pioneering role in promoting renewable energies. *Reduction of final energy demand* was perceived as important for CO2-reduction on the national level, heat turnaround and price security on the urban level and for expansion of solar energy use. Requirements for a successful reduction of the final energy demand are new building regulations, consultancy (e.g., for the craft sector), and thermal insulation of new buildings. The most central cross-sectoral variable was "*Expansion of solar energy use*". It is seen as the main driver for implementing and developing new heat sources rather than decentralized energy production. This may be the result of decreasing subsidies for solar power by the national government, and its importance for hot water production. Expansion of solar energy use mainly depends on the social and economic acceptance of the renewable expansion. However, this finding ought to be interpreted with caution with respect to the low number of participants in our study. Another key requirement was "decreasing of electricity costs".

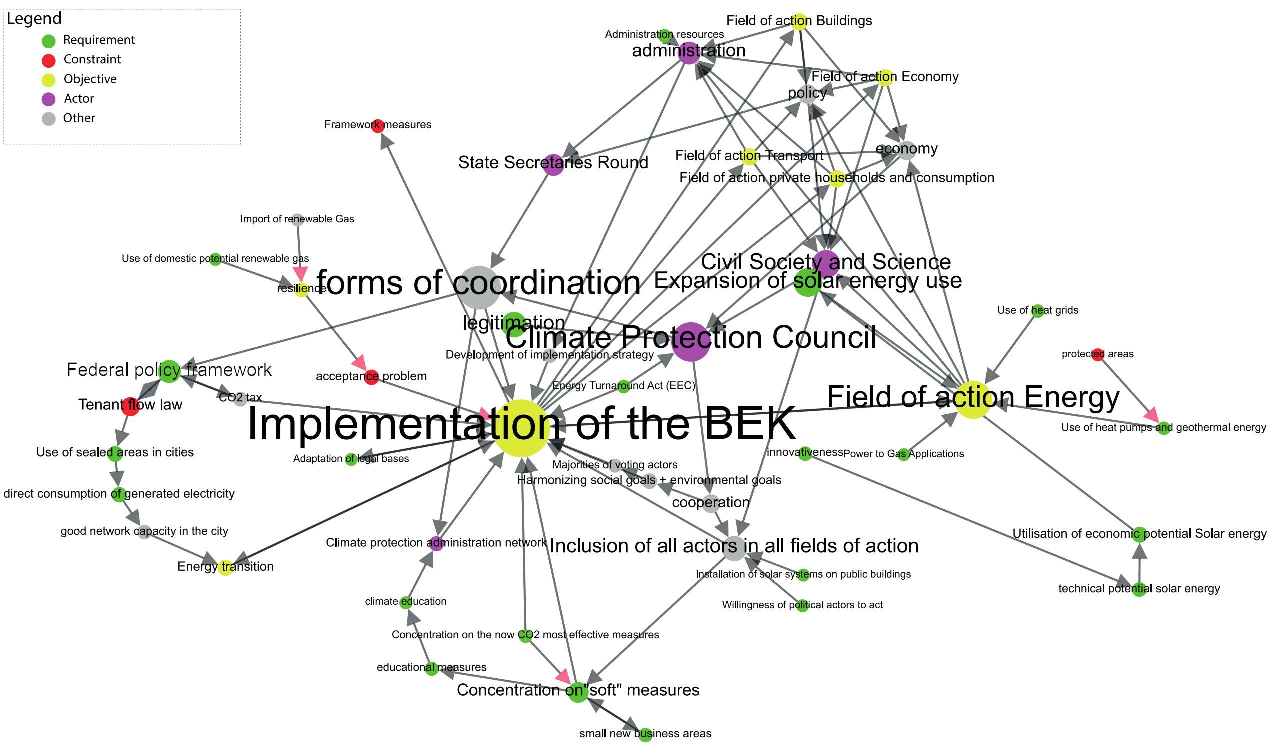

Figure 13. Berlin

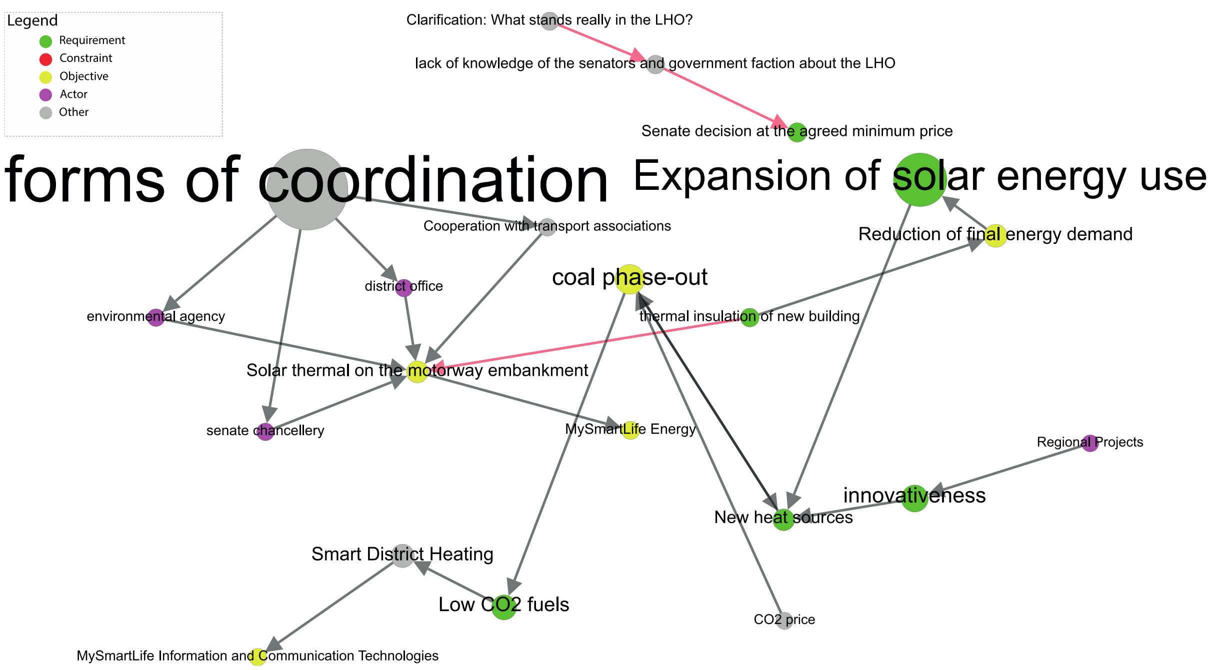

Figure 14. Hamburg

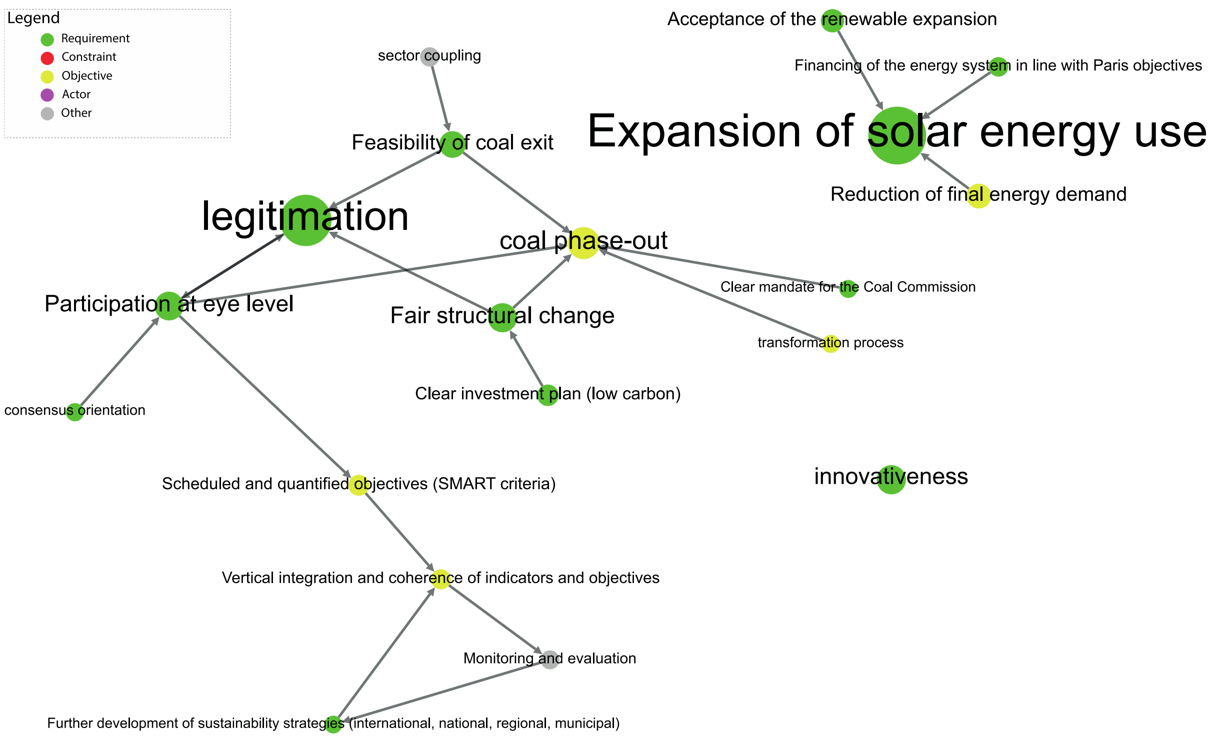

Figure 15. Germany

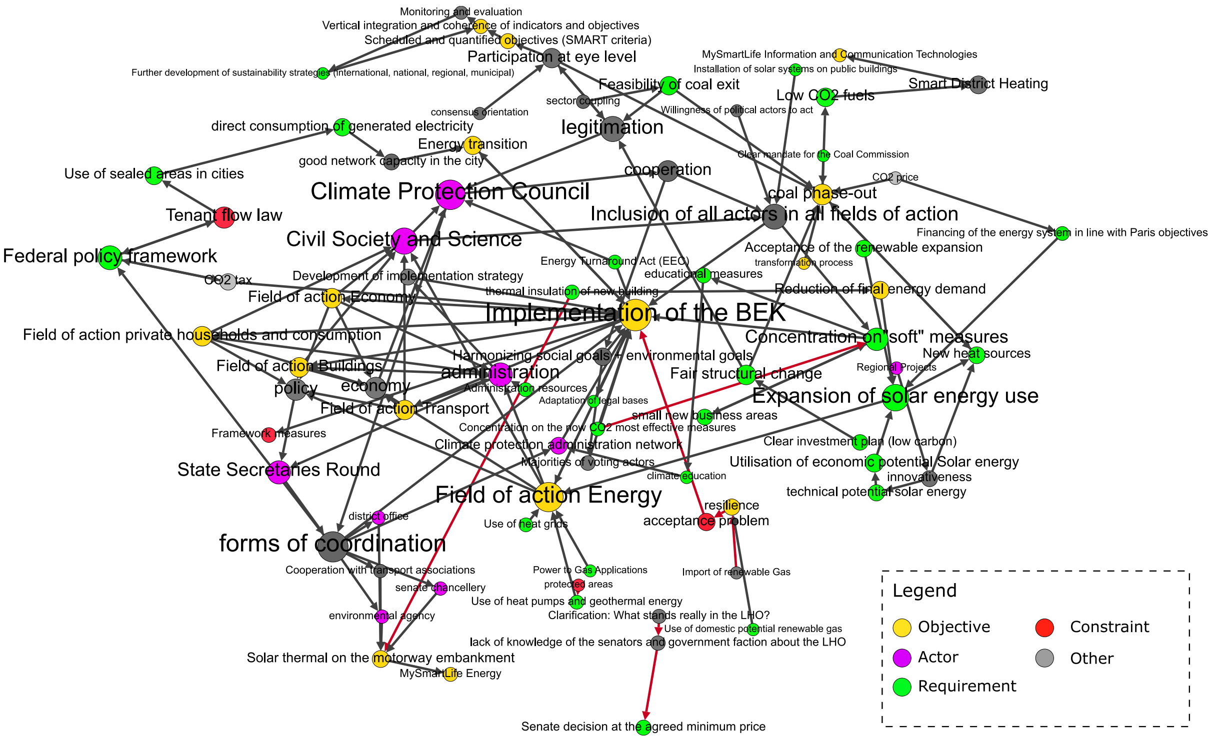

Figure 16. 80% quantile CLD (Hamburg, Berlin, Germany).

Other important requirements were "accessibility of renewables for private households", the "use of renewables on land owned by the state", "utilization of economic potential of solar energy", and the "financing of the energy grid in line with the Paris objectives". According to one actor, decentralization cooperatives founded by small and medium sized companies or cooperatives are a significant source for providing stakeholder knowledge to the expansion of solar energy. However, the main constraint for solar energy expansion in general are still the lack of space (e.g., rooftops in cities) and high investment costs. In Berlin, a further constraint is the current tenant flow law which does not permit the indirect use of solar energy. However, a good network capacity of the energy grid in the city may lead to a faster energy transition. Although the "*Funding logic of the renewables*", which refers to the subsidies by the state which is a significant factor for the actual usage of renewables, is described as important for reducing CO_2-emissions in Germany (Deutsche Bundesregierung, 2016), it only plays a minor role in our CLD because it was only mentioned by one actor. However, it is connected to a regional project "My Smart Life" in Hamburg, which is develops and implements smart district heating systems in the city district of Hamburg Bergedorf. Sufficient funding of the used technology is a key requirement for these projects. Therefore, we find that this variable was underrepresented in our model. *Legitimation* is perceived as important for participation on the eye level of decision-makers in the process of promoting renewable energies in Germany. Legitimation requires fair structural change and a feasible coal exit in Germany. A one-sided focus on either climate or structural change might be a constraint for achieving legitimation in the political debate on climate change and renewables in Germany.

6. Discussion

We identified various interesting results which can inform different stakeholders on the German strategy landscape. These stakeholders are (1) the strategy development teams, (2) actors involved in strategy implementation, (3) experts, and (4) other stakeholders such as the civil society and other practitioners who are influenced by the strategies or its objectives.

When reviewing the German SDS, it becomes obvious that the central topics, for which specified measures were defined, are linked to the SDGs. We found however, that the SDGs do not represent most of the connecting variables based on the interviews. Our hypothesis is that they have been designed as a guiding framework on a global and national level and are originally not steered towards lower levels such as cities. Whereas the German sustainability agenda may provide helpful guidance to establish and implement a German Agenda 2030, the connection of the national directive to the urban level is still rather unspecific. Various themes could provide a basis for cooperation between state and city actors. For example, innovativeness which is described as important by our interviewees for promoting new heat sources and for improving the technical potential of solar energy, has the potential to be a guiding topic for cooperation across governance levels. This can be achieved by coordinating the low-level requirements of urban actors with the high-level requirements of governmental actors. The actual political agenda could be designed in a way that it fulfils the needs of urban actors and at the same time, the strategic requirements on the governance level.

Although exploratory, we can draw some first insights from our case study.

Whereas the literature review provided a good starting point for us to understand the situation, and to approach the correct experts for the interviews, the interviews were necessary to get more detailed and “hands-on” knowledge on the specific regional settings in Hamburg and Berlin.

All in all, we identified a strong dependency of the national strategy on the success of the urban strategies. Especially, the development and implementation of decentralized renewable energy sources such as CHP (combined heat and power) have been done by urban actors, such as municipal utilities, private energy suppliers, or innovative projects such as the NEW 4.0 project in Hamburg. However, financial support for these projects is often provided by the national ministries such as the Federal Ministry of Economics and Energy. Based on individual regional settings, the requirements of the cities are very different. Cities "demand" different functions and policy changes which lead to various implications for the implementation of the respective SDS.

Therefore, our findings strongly support the view that systematic and holistic approaches are important to consider for strategy development and communication across different strategies. Particularly in Germany, the federal governance system implies a multi-level policy system, where coordination across governance levels may be challenging. Participatory modeling can support this process by linking different viewpoints on these levels and building a foundation for learning and understanding different actor objectives. In addition, our methodology can help to report results from the process to the participating actors as well as inform the debate on strategy analysis while considering multiple inherent actor roles. We therefore advise policy makers of cities and on the national level, as well as responsible experts, to focus on shared key-requirements for strategy implementation and to collaboratively design holistic solutions.

During our interviews, we experienced that, with respect to our research approach, the interest for interactive, easy-to-use and structured participatory methods was very high. We responded to this need by developing and applying an enhanced participatory modeling method which combines elements from causal-loop modeling and requirements engineering. Regarding the study content, participating experts were most interested in our goal to describe multi-level government systems and strategy documents in terms of requirements based upon the individual viewpoints and objectives of actors who have a role in implementing the strategy (actor/user requirements). Thus, we found ourselves in the trade-off of structuring the interviews according to the requirements engineering literature, while not limiting the ability of stakeholders to provide their personal viewpoint in an open way. Therefore, we first introduced all interview partners to our set of different variable types, started the interviews by formulating objectives and measures together with the experts, and then derived requirements, followed by formulation of constraints, actors, objectives, and other variables. Future research might explore if the introduced variable types are sufficient to model the complexity of our type of systems. Although it was helpful to conduct most of the individual interviews face-to-face, it would be less time consuming to use an online platform for data collection. It might be considered to further develop and enhance such tools (i.e., to develop business models such as workshop formats), which also should incorporate helpful methodological guidance for the interviewee and moderators.

A comparison of SDS and monitoring their success usually requires comparable indicator-sets (Albert et al., 2016).The revision of the German SDS as well as the poor coherence between the indicator sets of the strategies makes it very difficult to compare them. Therefore, an effective typology of comparable indicator sets is needed (Smeets et al., 1999). Alternatively, a different approach for comparing the success and the feasibility of current SDS in Germany could support more coherence inside the German strategy landscape and multi-level cooperation across governance-levels. In this paper, we have demonstrated such an approach to compare and link different SDS by applying a participatory requirements analysis method.

In political agendas and in private companies, prioritization of tasks plays a major role for success. For example, this is exemplified by election campaigns which often emphasize a central theme that has the potential to mobilize most undecided voters, or marketing campaigns of companies which manage the process of focusing on specific products in a specific time. Although prioritization may be helpful in setting a political agenda, our actual problems of climate change and already existing goals, such as the ambitious CO_2 reduction goal of Germany, require fast changes in several aspects and dimensions. Many interviewees stated that if we do not follow all of the sub-objectives which are needed to achieve or goals, we might end up in a situation where trade-offs between these objectives hinder the effective and successful implementation of other planned measures. Therefore, based on our interviews, it may be advisable to step back from political prioritization of measures more to a trans-objective oriented approach with a focus on synergies of these objectives and related requirements and design integrated solutions based on these interlinked requirements.

7. Conclusion

We present a novel approach to describe expert knowledge on strategic documents such as SDS with causal models in terms of requirements. The aim of our approach is to make complex relation-ships between measures, actors, and requirements available for decision makers and to reveal constraints on the implementation of specific measures inside strategy documents. To realize this, a solution and user-oriented design approach to develop, manage and understand SDS is required. The challenge of existing strategies to connect the inherent objectives with each other, to build up coherence and to cooperate across multiple governance levels, leads to a sub-optimal effectiveness of the German SDS in relation to urban strategies. To strengthen the interface between these strategies, we developed a methodological framework which describes the application of a combined participatory modeling and requirements analysis approach. The framework suggests using requirements analysis from the SE domain to understand existing SDS, to formulate requirements for achieving these strategies, and to define linkages among several different strategies. The outcome of this qualitative modeling process are causal-loop diagrams which represent the available knowledge from the user point of view on these strategies. Because these models can become very complex, we suggest defining different types of requirements which help to structure the existing knowledge. These are economic, financial, generic, policy, social, and technological requirements. In addition, we define in total 12 variable types (actor, constraint, external, function, generic, interface, objective, process, requirement, resource, structure) which should be considered during model development.

To exemplify our approach, we applied the framework in an exploratory case study in the con-text of the German sustainability landscape. In Germany, an overall sustainability strategy, the Ger-man SDS, exists as well as action plans for federal states and cities.

We chose to focus on the German strategy as well as the strategies of the cities Berlin and Ham-burg. Berlin and Hamburg have long traditions in sustainable development. Many local initiatives exist which help to implement the cities objectives for sustainable development. These initiatives also provide a significant contribution to achieve the national agenda. The specific tasks and working packages of these strategies are explained in the strategy documents which have been reviewed before the interviews were carried out.

The results of this review indicate that although specific tasks are formulated on the urban level, the strategies are not sufficiently connected with each other. In addition, we identified that, despite the intended general character of the national strategy, the added value of the national directive for individual actors on the urban level remains low. One reason is that mainly urban SDS provide the tools and mechanisms to implement national sustainability goals which have been formulated in the German SDS. However, the concrete role of urban strategies is not mentioned in the German SDS. Secondly, the national strategy does not specify concrete approaches which could be implemented by urban actors because, in relation to many urban strategies, the national directive is formulated in more general terms. This may hinder the German SDS in becoming a guiding framework for some actors on the urban level. What makes the German sustainability landscape even more complicated are different sustainability indicators of cities, federal states, and the country for measuring the effectiveness of the strategies applied. Hence, this makes it very complicated to compare them. We argue that the German SDS could provide more effective guidance, if low- and high-level requirements and constraints of actors would be integrated more into the strategy itself. One specific example is the willingness of actors on the urban and national levels to cooperate. To build up more platforms and also to highlight the role of political consultancies to provide helpful methods for networking and linking actors on different levels is necessary. Another example are concrete themes and objectives which exists on all governance levels and which could act like bridges across these levels. We found that “Coal phase-out”, “expansion of solar energy use”, “innovativeness”, “reduction of final energy demand”, the “funding logic of renewables”, and “legitimation” are could work as such cross-governance themes.

Such cross-sectoral themes have also been identified in the BEK which implements many of the requirements mentioned also in Hamburg and on the national level. These themes are “forms of co-ordination” as an interface variable and “expansion of solar energy use” as an economical requirement. They connect the BEK to the requirements and objectives of other SDS, such as to the coal phase-out on the German national scale. We conclude that key requirements exist in the strategies that are not only needed to achieve certain objectives in the individual SDS but also to provide an interface to other strategies. Identifying these key requirements is one of our main contributions in this paper.

Even though scientifically grounded and well formulated SDS exist for specific sectors, they are often insufficiently linked to each other. However, coordination between SDS has to be ensured, as their success might depend upon each other (e.g., national CO2 reduction goals can only be achieved if cities implement specific instruments). Therefore, we suggest a requirements-based analysis approach to reveal missing links between SDS, to design these links together with stakeholders and, therefore, to come up with holistic and integrated solution strategies to deal with implementation challenges.

Future Work

Our methodological framework offers an innovative way on how to approach coordination defi-cits among multiple SDS. The framework is steered towards dealing with complex relationships be-tween several requirements to achieve these SDS. For example, it can be used by governmental actors and policy makers to implement existing SDS more effectively, and to enhance collaboration and cooperation between important actors.

In SE terms, our methodological framework represents a conceptual system design approach. Conceptual design is usually followed by a specific or detailed design process. This means that requirements are translated into functions. By this means, their effect on the overall system can be assessed and the system can be analyzed, tested, and implemented. Therefore, the next step would be a functional analysis as it has been applied by Halbe et al. (2014). Functions are defined as elements which consist of at least one structure (e.g., policy or measure) and one process (e.g., actions by an actor). This results in a model of the overall system structure, processes, and functions. However, challenges of our approach are the high complexity of the design process and the resulting models. Therefore, an easy and transparent communication of the results to stakeholders who are not familiar with the approach should be provided.

Functional analysis, as well as later steps, i.e., systems analysis including cost analysis, risk analysis, interface analysis, and data analysis, have to be further examined. This also includes the development of management plans for designing or redesigning real systems and the definition of physical architectures, processes and interfaces. Additionally, future studies can also identify the above-mentioned interface variables as they could be significant factors for enhancing coordination and cooperation across governance-levels in strategy implementation. This coordination is required for a successful energy transition in Germany (German Council for Sustainable Development, 2018).

Author Contributions

Conceptualization, F.H.; Data curation, F.H.; Formal analysis, F.H.; Funding acquisition, C.P.-W.; Investigation, F.H.; Methodology, F.H. and J.H.; Project administration, F.H.; Resources, F.H.; Supervision, C.P.-W.; Visualization, F.H.; Writing – original draft, F.H.; Writing – review & editing, F.H., J.H. and C.P.-W.

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5. Article 3 – Evaluating the effects of alternative system designs in multi-actor environmental System-of-Systems

Heitmann, F., Agusdinata, B., Evaluating the effects of alternative system designs in multi-actor environmental System-of-Systems. Working paper

In this paper, the data from the expert interviews of the second research article has been used. This includes the key requirements for CO_2-emission reduction in Germany and in the city of Berlin which are compared against statements made in the corresponding strategy documents. The analysis is carried out by applying a comprehensive qualitative text analysis with MAXQDA as well as the development and application of a requirements evaluation scheme. This novel design approach helps to (1) specify important interfaces between governance levels in strategy design, and (2) reveal knowledge gaps in strategy documents. By comparing the statements of interviews with SDS, the approach helps to evaluate the effectiveness behind the presented PM approach. To measure the added value of the interview data for these strategy documents, an evaluation scheme has been developed. The scheme helps to measure the degree of detailed expert knowledge inherent in strategy documents compared to expert interviews which are formalized as causal-loop diagrams. The analysis reveals that detailed information on requirements is missing in the German SDS, whereas in the BEK the interviews mainly provide additional knowledge on relationships between objectives, actors and interfaces.

Article 3

Evaluating the effects of alternative system designs in multi-actor environmental System-of-Systems

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Abstract: Strategy design for sustainable development becomes increasingly complex. The complex nature of multi-level governance systems where sustainability strategies are often embedded in, is one of many reasons for this complexity. In addition, expert knowledge, which is needed for guiding strategy development, is scattered across governance levels and not always represented in strategy documents. Therefore, to follow a joint pathway for implementing sustainability strategies, actors need to agree on certain key requirements. These key requirements are important to cope with the main challenges each strategy is dealing with. In this paper, we use data from several expert interviews from a participatory modeling task. The data includes key requirements for CO2-emission reduction in Germany and the city of Berlin, which we use for comparison with statements made in the corresponding strategy documents. This includes a comprehensive qualitative text analysis with MAXQDA and the application of a developed evaluation scheme. This novel design approach helps to (1) specify important interfaces between governance levels in strategy design, and (2) reveal knowledge gaps in strategy documents. By comparing the statements of interviews with the strategies, the approach helps to evaluate the effectiveness behind our participatory modeling approach. To measure the added value of the interview data for these strategy documents, we developed an evaluation scheme. Our scheme helps to measure the degree of detailed expert knowledge inherent in such documents compared to expert interviews which are formalized as causal-loop diagrams. Our analysis reveals that detailed information on requirements is missing in the German sustainable development strategy (SDS), whereas in the Berlin Energy and Climate Protection Program (BEK) the interviews provide additional knowledge on relationships between objectives, actors and interfaces.

Keywords: multi-level governance, policy requirements, coding and analysis of interview data

1. Introduction

Decision making for actors is often complex because of diverse effects of the decision on the overall system in which the decision takes place. This particularly becomes clear for decisions taken in complex adaptive and goal-driven systems with inherent subsystems which maybe follow a different functional logic, i.e. System-of-Systems (SoS) (Boardman and Sauser, 2006; Lane, 2013). For example, if one actor in a subsystem decides on a specific structural change, this change could have unintended positive (synergies) or negative (trade-offs) consequences for other subsystems (Raz et al., 2018). One more specific example for a SoS which is used to illustrate the methodological approach presented in this article, are sustainable development strategies (SDS) and the decisions which need to be taken by political decision makers on different governance-levels.

SDS are often implemented to achieve long-term sustainable benefits for the nation, federal state, region or municipality on which they are focused on. The development, implementation and re-development of SDS requires complex decisions from several actors. SDS originally included the three dimensions of sustainability, i.e. social, economic and environmental sustainability (Passet, 1996). Nowadays, the scope of SDS is often extended and also includes more specific fields of action such as water, energy and food security, and at the same time broadens the scope to a larger degree of topics. The latter particularly includes the implementation of the Sustainable development goals (SDGs) by SDS. The diversity of objectives and the broad variety of themes makes it particularly complex to design these strategies. Additionally, SDS are implemented on multiple governance levels. For example, the Paris agreement from 2015 includes several states on a supra-national level (UN FCCC. Conference of the Parties (COP), 2015), or the EU Agenda 2030 provides a guiding framework for the implementation of more specific measures in several EU member states (United Nations, 2015). Even national SDS can still be complex depending of the political system where they are embedded in. For example, the German SDS needs to take into account the different federal states because they partly have their own legislation (Deutsche Bundesregierung, 2016).

In case different SDS overlap, such as in Germany where the national SDS exists in parallel to several SDS on federal and urban levels, the problem of missing or insufficient coherence between those strategies derives. In reality, different sustainability strategies often follow a different objective. The reason is that sectoral focused strategies, such as urban strategies, often have to adapt a general overall pathway (i.e. a higher level strategy) to follow their self-interest by pursuing regional goals instead of fully considering an overall "inter-sectoral" solution for integrated problems. Additionally, policy decisions in a low-level strategy can have unintended side-effects or trade-offs on other parts of the overall strategy landscape, i.e. the higher level strategies. To minimize these trade-offs, we suggest to design interfaces between the strategies. These interfaces can be requirements, actors, processes (or functions) and components which can re-define the connections among different hierarchical levels. In this article, we give an example for such interfaces and show how they can contribute to more coherence among the strategies.

One key factor for taking decisions in the above mentioned systems, is enough available knowledge for the decision makers. However, the main problem is that this required expert knowledge, which is also needed to guide strategy development, is scattered across governance levels and not always represented in strategy documents. Therefore, if for example national strategies are taken as a decision baseline of other low-level decision makers on an urban scale, there is a risk of overestimating the value of the strategy as a document for providing sufficient information on the overall SoS where the strategy is embedded in. But, to design sustainable decision making processes and therefore sustainable solution strategies in SoS, it is very important to make this information available in the correct form. From Systems Engineering (SE) we know that user oriented systems are designed by incorporating user requirements into system design. Requirements are defined as factors to be fulfilled for an actor to achieve an individual task in the individual operational environment (Heitmann et al., 2019b). This operational environment is also sometimes referred to as decision or design space (Raz et al., 2018).

SE provides several tools and frameworks to cope with the complexity arising from the requirements concept. One important aspect of modeling requirements is the traceability of requirements (Egyed et al., 2009). This means that it should be well documented which actor requires what and why.

In this article, we use the requirements concept to understand actor needs in such a multi-governance system and compare these requirements to the available knowledge in existing SDS. We see this as a promising way to overcome the above mentioned problems of information deficits in such strategies for their implementation, re-design and development.

More specifically, we address this problem by presenting a strategy evaluation scheme for comparing detailed expert knowledge with existing SDS. This evaluation scheme provides an indicator for the value of such documents by revealing the degree of detailed expert knowledge which is needed to achieve specific objectives which are formulated by the strategy itself. The scheme can be embedded in the FRESCO framework by Heitmann et al. (2019b).

However, as described by Schlüter et al. (2012, p 255), there is “ no single correct or best model for a given problem setting”. Additionally, it is often not possible to find a “single best solution that one can find through optimization” (2012, p. 255). Therefore, the requirements concept is presented as an approach to include many “small” solutions into a model and illustrate their causal relationships by defining their dependencies.

For that reason, our question is to what degree qualitative causal-loop diagrams which represent social, environmental and technical requirements, constraints, functions, structures and processes can be used to reduce uncertainty with respect to the effects of implementing a specific solution in strategy design.

In addition, our question is to what degree causal-loop models can support strategy design to overcome coordination deficits among actors in different subsystems.

To develop these causal-loop models, we conducted several expert interviews with experts of three SDS in Germany in 2018: The national SDS which is the national interpretation of the EU Agenda 2030, the BEK, and the Hamburg Climate Plan. A previous publication revealed how such strategies can be described with causal models in terms of requirements, and that the value of high-level strategies for low-level strategies remains low if they are not connected explicitly. This is because high-level strategies usually provide guidance to lower-level actors and illustrate to them how they can align decision making processes to the overall guidelines. The data used in this article includes key requirements for CO_2-emission reduction in Germany and the city of Berlin, which we use for comparison with the statements made in the corresponding strategy documents. Comparing SDS documents with actor requirements illustrates (1) if the statements in the documents and the requirements are coherent; (2) the degree to which the documents represent the requirements (i.e. completeness); (3) the causal relationships between statements, topics and requirements (i.e. overlaps and connections of statements, topics and requirements); and (4) the added value of the requirements from the expert interviews to inform the strategies.

On a conceptual level, we follow the idea of framing a complex adaptive system such as the German sustainability strategy landscape as a SoS. Heitmann et al. (2019b) applied a standard procedure for requirements analyzes by using participatory modeling with causal-loop diagrams (Vennix, 1996). The requirements based diagrams developed with the interviewed experts represent alternative system designs compared to the system designs described by the strategies. For the evaluation of these alternative system designs, we adapt the work of Agusdinata and DeLaurentis (2011) who defined "iso-performance solutions" to illustrate the decision-making space for the actors. We identify interfaces in terms of requirements and constraints between different sustainability strategies, and explore interdependencies between the SDS on the German national level and the urban SDS of the city of Berlin.

This novel design approach helps to (1) specify important interfaces between governance levels in strategy design, and (2) reveal knowledge gaps in strategy documents. By comparing the statements of interviews with the strategies, the approach helps to evaluate the effectiveness behind our participatory modeling approach. To measure the added value of the interview data for these strategy documents, we developed an evaluation performance scheme. Our scheme helps to measure the degree of detailed expert knowledge inherent in such documents compared to expert interviews which are formalized as causal-loop diagrams. By this means, we show how the analyzed strategies which are modeled as subsystems could be connected by the design of interfaces to achieve an overall SoS objective.

In the first part of the paper, we give a short overview on the theoretical and conceptual background and our methodological framework. Afterwards, we present our qualitative evaluation scheme. In chapter 4, we illustrate the possible effect of interfaces by comparing our interview data with two actual SDS. Afterwards, we evaluate their effect on an organizational, functional and component level.

On a methodological level, we conclude that our approach can contribute to a more structured and outcome oriented re-design and development of SDS. This is done by developing interfaces between the strategies and defining joined requirements of the strategies. Additionally, information gaps are identified and highlighted. Content-related, this re-design and development of the strategies is an ongoing political process. Therefore, we would like to highlight the importance of up-to-date information on the processes, and about involved actors and objectives. Embedding our presented framework in and the ongoing political debate may be advisable to derive more helpful insights into the process. Therefore, as a next step, we suggest to further formalize our framework to develop a tool which can be easily used by political decision makers and other actors. This type of formalized models can provide helpful guidance for policy making in general.

2. Methodological background

SoS are defined as "a collective system with autonomous and diverse subsystems, which are connected dynamically with each other and have their own goals contributing to the overall goal of the SoS (Baldwin et al., 2015a in Heitmann et al. 2019b). A complex adaptive system (CAS) can be defined as "a complex, nonlinear, interactive system which has the ability to adapt to a changing environment" (Pahl-Wostl, 2009, p. 357). What differentiates a SoS and a CAS is the alignment of objectives or actions of the constituent parts of the overall system.

The framing of a complex adaptive goal-driven system such as a SoS has the following strengths: (1) the SoS framing values interactions among different subsystems; (2) it accepts the fact that complex adaptive systems are often comprised by subsystems with a different functional logic; (3) it indicates that the system is a result of the implementation of several user requirements which lead to an overall SoS behavior. Particularly the latter is important for our context, because a complex adaptive system is not necessarily aligned towards a common goal nor, by definition, the subsystems in a complex adaptive system need to have their individual goals (Miller and Page, 2007). By framing the German SDS landscape as a SoS, we include the fact of existing, sometimes conflicting, goals into perspective of modeling the SoS. An important implication of using a SoS framing is also the methodological toolbox which comes with the approach. The correlation of system framing and analysis approaches as well as the differentiation between the engineering of SoS and monolithic systems thinking which is commonly applied to CAS is illustrated in Mahmood (2016).

Understanding relationships between actors and their requirements for achieving the actor goals in the German SDS landscape, is a challenging task as the interplay and the number of actors and requirements is high. Because this is not only a challenge for research but in the first place for the actors themselves, actors often do not understand the big picture. Relationships to other actors often lack coordination and developed strategies do not include enough requirements for the implementation of objectives without causing trade-offs to other actor objectives. The main reasons for that are high uncertainties and an information gap of important expert knowledge (Heitmann et al., 2019b; Raz et al., 2018). Additionally, the dynamic nature of the SDS landscape makes it complicated to derive meaningful results out of an analysis which could help actors to have a more grounded information baseline which they could use as a basis for decision making processes.

Decision making processes in the German SDS landscape face a high degree of uncertainty because one decision could possibly have several unexpected causes on the overall SoS level (Heitmann et al., 2019a). The concept of emergent behavior illustrates this example. Following Maier (1998), "emergent behavior can be defined as the development of new emerging properties through interconnectivity of subsystems.", (Heitmann et al., 2019b). Emergent phenomena can be positive or negative with respect to a possible overall SoS goal.

To better understand these causes of decisions, and to minimize the complexity of the interconnections of SoS parts, we propose to adopt the concepts of ISO-performance schemes (Agusdinata and Delaurentis, 2011) and design by interface (Parraguez et al., 2016) and make them applicable in a SDS environment. Design by interface is a system design approach which focusses on the interconnections between system parts such as subsystems or elements inside these subsystems. Generally, "an interface is where two elements meet and interact" (Parraguez et al., 2016, p. 159). More specifically, it can be defined as "a crossing point of an object to other objects, or more generally to its environment. It serves to ensure certain rules in the communication between objects and the environment by requiring certain operations to the object implementing the interface (Oracle, 2015) (e.g. an umbrella organization for communicating knowledge through a network of actors)" (Oracle, 2015 In Heitmann 2019b). Parraguez et al. (2016) define three types of interfaces: Product, process and organizational interfaces. Product interfaces connect two general components with each other;

Process interfaces allow for the exchange of information needed to achieve a process, for example a decision making process; Organizational interfaces connect people or organizations and therefore enable interaction among them (Parraguez et al., 2016). The concept of interface design is a promising approach for evaluating existing connections of different SDS and for defining possible new ones. For our purposes, we follow the interface definition by Parraguez et al. (2016) but describe each interface type either through requirements, functions, actors, objectives or generic variables. These variables originate from expert interviews on the analyzed SDS which we conducted in 2018 and are defined in Table 1.

Table 1 Definition of variable types adopted from Heitmann et al. (2019a)

Variable type	Definition
Requirement	factors to be fulfilled for an actor to achieve an individual task in the individual operational environment (Heitmann et al., 2019b)
Function	"discrete actions [...] necessary to achieve the system's objectives", (Department of Defense Systems Management College, 2001)
Process	A process is a sequence of behavior that constitutes a system and has a goal producing function" (Ackoff, 1971, p. 666).
Structure	The structure of a system is specified by the relationships between system elements (Halbe et al., 2014 In Heitmann et al., 2019b)
Actor	"one that takes part in any affair", Merriam-Webster
Objective	"a strategic position to be attained or a purpose to be achieved [...]", Merriam-Webster
Interface	"An interface represents a crossing point of an object to other objects, or more generally to its environment." (Heitmann et al., 2019b)
External	A variable which is beyond the defined system boundaries
Generic	A variable which does not meet the definition of the above mentioned variable types

The subjective knowledge of the experts which is formalized as causal-loop models is defined as a "mental model". "Mental models are personal internal representations of the surrounding world" (Scholz et al., 2014, p. 578). With our approach, we demonstrate to what degree expert knowledge, framed as requirements, functions, actors, objectives or generic variables, can contribute to an evaluation of policy options. We think that individual mental models of experts have the potential to reveal critical factors for the efficiency of sustainability strategies and related policy decisions.

By defining such interfaces and by applying the evaluation scheme, we additionally highlight the importance of a joint pathway for implementing sustainability strategies among involved policy makers. This means that actors need to agree on certain key requirements to achieve their tasks and objectives. These key requirements are important to cope with the main challenges each strategy is dealing with. For the identification of these key requirements between the strategy documents and the requirements diagrams from the conducted interviews, we use "MAXQDA", which is a computer software specialized on qualitative and mixed-methods analysis[9].

[9] https://www.maxqda.com/ [May 25th, 2019]

Examples for alternative tools are ATLAS.ti, NVivo, HyperRESEARCH, KEDS and others (Alexa and Zuell, 2000; Franzosi et al., 2013). This type of software can be used for several types of analysis such as narrative analysis (Franzosi et al., 2013) or discourse analysis (Leipprand et al., 2017). MAXQDA displays the underlying SDS documents, allows to highlight text and to allocate terms, i.e. "codes", to these text-parts. This means that every part of the text could be highlighted several times with different codes. The overlaps of these codes can be analyzed and relationships displayed. Variables from causal-loop models can be used to inform the definition of codes. To maintain the information on the variable type (e.g. requirements, functions, actors, objectives or generic variables), each code can be assigned a "memo" or "note" which can include additional information about the code.

To conclude, structural complexity and uncertainties for policy makers in environmental SoS are one factor for suboptimal outcomes of strategy implementation on a macro SoS scale. One example for such a context is the German SDS landscape in which several SDS exist which are only partly coherent with each other. Designing interfaces between these strategies may help to enhance coherence, to reduce uncertainties in decision making processes for political decision makers and to overcome knowledge gaps.

In the following, we propose an adopted design by interface approach and test the added value of a data set from a participatory modeling interview series for SDS by applying an evaluation scheme. The underlying data has been collected by Heitmann et al. (2019a) to reveal critical factors which are required to achieve energy related sub-goals of the German SDS and the urban strategies of Berlin and Hamburg. Interviews and strategies are compared with the qualitative text analysis tool MAXQDA.

3. Methodological framework

In the following, we present our methodological framework which includes the evaluation scheme. The framework can be applied to measure the information variety of strategy documents and to validate the effectiveness behind a participatory modeling approach. The evaluation scheme helps to compare variables from participatory modeling with causal-loop diagrams as described by Vennix (1996) to the content of written SDS documents.

The underlying question which can be answered with our methodological framework is, if the nodes and their causal relationships from participatory modeling with causal diagrams are represented in specific documents, and if these relationships are coherent with the statements made by the strategies. To assess degree of representation and coherence in the analyzed documents, an evaluation scheme has been developed. Each variable which is represented in both, interview data and SDS document, is assigned a category depending on its added value for each identified paragraph in the strategy document. The categories and their definitions are illustrated in Table 2.

Table 2 Scaling Scheme

Category	**Description**
Not coherent	The relationships are not coherent with each other.
Same link (verification)	The causal relationship defined in the causal-diagram also exists in the strategy document.
added coherent link (information)	The relationship in the causal-diagram is not represented in the strategy document and adds additional information to the document which is consistent with possible other existing relationships.
Does not exist (added, coherent link) (innovation)	The relationship and the originating variable in the causal-diagram are not represented in the strategy document and add additional information to the document which is consistent with possible other existing relationships.

The scheme shows, to what degree different types of variables and their causal relationships are represented in a SDS document. If the scheme is applied to several documents, the outcomes can be compared against each other.

3.1. Steps of the framework

The framework application includes the following steps:

1. Analysis of interview data, i.e. allocation of variables types
2. Identification and filtering of the most important variables from the interview data which are represented by nodes in a network. This includes the calculation of the betweenness-centrality (BC) of the nodes.
3. Qualitative document analysis
4. Development of causal models
5. Interpretation of the results

1. Analysis of interview data, i.e. allocation of variables types

The data which should be used for comparison with written SDS documents has to be prepared for using it within our framework and in MAXQDA. This includes to categorize the interview data into several variable types. This procedure is described in Heitmann et al. (2019a). The step is important to reveal which types of search terms can be defined in a later step of the framework. Additionally, the focus of the analysis maybe requires different types of variables as an input for the comparison; if the focus lies more on the requirements analysis, it is advisable to define several different types of requirements. If the analysis should mainly reveal the relationships between actors, different actor types should be identified.

2. Identification and filtering of the most important nodes in the interview network, i.e. calculation of the betweenness-centrality of all nodes

The underlying data basis for the codes should focus on the specific geographical region and research question. For example, if several interviews on different regional challenges have been conducted, only the interviews connected to the strategy document which should be analyzed are considered.

Additionally, we suggest to compute the BC of each node of the underlying interview network, and highlight the nodes with the highest BC in the analysis. This can help to deal with large networks and to come up with more focused interpretations in the end of the process.

3. Qualitative document analysis

For comparing the interview data with written SDS documents, codes need to be defined. Codes are the representation of "nodes" from causal-diagrams which have to be developed during a previous participatory modeling exercise, such as described by Heitmann et al. (2019a, 2019b). Each node can be assigned to several attributes which include information from the interview or a later analysis, for example the type of the variable, its "source", or statistical measures such as BC. We suggest to keep the original node tables from the interviews for later interpretation of the results.

For coding the documents, we suggest the following step-by-step approach:

a) Defining codes for each level of analysis separately (i.e. urban level, federal state level, national level or others).
   Often SDS are implemented on multiple governance levels. To include this complexity in the analysis, these governance levels have to be identified and described (Pahl-Wostl, 2015, chap. 3.3, 2009).
b) Defining and documenting search terms and connectors for each code (e.g. "climate" AND ("adapt" OR "transform" OR "cope")
   Search terms help to identify paragraphs or sentences which deal with a specific topic or theme. Defining proper search terms significantly influences the outcome of the analysis. Therefore, it is important to make the applied search terms transparent to maintain the reproducibility of the study.
c) Searching with the terms and auto-code for each code.
   This step can be automated by using MAXQDA. For a detailed description on this function see Franzosi et al. (2013) and the MAXQDA manual.
d) Reviewing each auto-coded sentence or paragraph to check if the meaning of the code is represented in the document.
   Finding and coding with search terms does not guarantee that the identified part of the text actually deals with the topic which should have been identified. Therefore, if the context deals with a different topic, the document part should not be considered for further analysis with the specific code.
e) Calculation of a correlation matrix of codes with the underlying documents
   The overlaps and proximity of the identified sentences or paragraphs can be identified with MAXQDA. This function is helpful to identify if specific topics are mentioned in the same or a similar context. Our framework uses this option to create so called "correlation matrices". These are tables which include each code and its overlaps with the other codes. Examples for these tables can be found in the supplemental material (Table A 9 and Table A 10).

4. *Interpretation of the results*

Interpreting the results of the correlation matrices may be the most important step. The correct interpretation of the meaning of the overlaps highly depends on the correct understanding of the used variables, codes and strategy documents.

4. Application of the methodology to SDS in Germany

As an illustration example, we apply our methodological framework including the evaluation scheme to the German SDS on the national level, and the BEK on the urban level.

1. *Analysis of the interview data*

We use data from a modified participatory modeling exercise from 2018 on the German SDS and the urban SDS of Hamburg and Berlin. In our case, the underlying data-basis for the analysis consists of 322 variables.

For comparison, we extracted text from the German SDS (Deutsche Bundesregierung, 2016) and the BEK (Senat der Stadt Berlin, 2018). For analysis, we use the official English version of the German SDS and the German version of the BEK. We had access to the original German data from the interviews for analyzing the BEK. After the analysis, we translated the variables into English for publication purposes. For the analysis of the German SDS, we directly used the translated interview data for the German national level.

2. *Identification and filtering of the most important nodes in the interview network, i.e. calculation of the betweenness-centrality of all nodes*

The computation of the BC of each node in the network and the identification of the 80% quantile of the nodes to reduce complexity allows to identify the most important nodes in the network. This results in two networks containing in total 82 nodes with 130 causal relationships. This includes 50 nodes with 87 causal relationships for the Berlin case, and 19 nodes with 20 causal relationships for the German case (Heitmann et al., 2019a). Three nodes exist in both networks which means that these variables have been mentioned by interviewees from the German and the Berlin level. These are “expansion of solar energy use”, “innovativeness”, and “legitimation”.

3. *Qualitative document analysis*
    a) In Table 3 and Table 4, we define codes for the analysis for each level separately (i.e. urban level (Berlin) and national level (Germany)). For comparing the interview data with the written documents, we defined as many codes as we have variables from the interviews (19 codes for the German level and 50 codes for the Berlin case). We also imported the variable types of each node as a “Memo” into MAXQDA to maintain this information.
    b) Table 3 and Table 4 also reveal the search terms and their connectors. We made clear that we included all forms of a noun (singular and plural) as well as possible other forms (adjectives and adverbs) by shortening the search terms or adding other forms of the same word. For example, the variable “Expansion of solar energy use” is represented by the search

term (“Expan” AND “solar”). Therefore, we make sure to automatically identify not only “Expansion” but also other forms such as “Expand”, or “Expanding”.

c) We applied a search for all defined search terms and highlighted the results with MAXQDA.

d) Afterwards we reviewed all highlighted sentences and paragraphs to check if the meaning of the code is represented in the document. This step took a significant amount of time, because each highlighted sentence has to be read, understood and checked for concordance with the originating statement from the interview. In some cases, we had to listen to the original recordings of the interviews to make sure that the core idea of the statement equaled the statement in the SDS document. Applying the principles of requirements traceability is important at this point to be able to trace back the requirement used in the analysis to its source (Egyed et al., 2009).

e) Each code has a number of assigned text passages. As the last step, MAXQDA supports an automated function for calculating code correlation matrices of the codes with the underlying documents (i.e. code-relations browser). This means that the overlaps of each identified text passage with another text passage which is assigned a different code are analyzed. This results in a matrix of code overlaps where the number of overlaps is entered in the matrix. The resulting tables can be found in the supplemental online material (Table A 9 and Table A 10)

Table 3 Germany - codes

Code	type	Search term
Acceptance of the renewable expansion	R	Accept AND (renew OR solar OR energy OR turn)
Clear investment plan (low carbon)	R	Invest OR plan
Clear mandate for the Coal Commission	R	Coal AND commission
coal phase-out	O	Coal NOT commission
consensus orientation	R	Consens OR agree
Expansion of solar energy use	R	Expan AND solar
Fair structural change	R	(Structural OR change) AND (fair OR equal)
Feasibility of coal exit	R	Feasib AND coal
Financing of the energy system in line with Paris objectives	R	Finan AND energy AND Paris
Further development of sustainability strategies (international, national, regional, municipal)	R	Develop AND strateg
innovativeness	R	Innovation OR innovativeness
legitimation	R	Legitimation OR legitimate
Monitoring and evaluation	F	Monitor OR evaluation OR evaluate
Participation at eye level	R	Participation OR participatory OR participate OR eye-level
Reduction of final energy demand	O	(Energy OR demand) AND reduction
Scheduled and quantified objectives (SMART criteria)	O	objective AND (schedule OR SMART)
sector coupling	I	Sector AND (couple OR coupling)
transformation process	O	Transform
Vertical integration and coherence of indicators and objectives	O	(Integrat OR coherent OR coherence) AND (indicator OR objective)

Table 4 Berlin codes

Code	Type	Search term
acceptance problem	C	Accept
Adaptation of legal basis	R	Adapt AND legal
administration	A	Administration
Administration resources	R	(Admin OR human) AND resource
Civil Society and Science	A	Civil OR society OR science
climate education	R	Climate AND education
Climate protection administration network	A	Climate AND network
Climate Protection Council	A	Climate AND council
CO2 tax	E	CO2 AND tax
Concentration on "soft" measures	R	Soft AND measure
Concentration on the now CO2 most effective measures	R	Measure AND now
cooperation	I	Cooperation
Development of implementation strategy	P	Implementation AND strategy
direct consumption of generated electricity	R	(Consumption OR consume) AND direct
economy	G	Economy
educational measures	R	Education
Energy transition	O	Energy AND (transition OR transform)
Energy Turnaround Act (EEC)	R	Energy AND turn
Expansion of solar energy use	R	Expan AND solar
Federal policy framework	R	Federal AND policy
Field of action Buildings	O	Field AND Building
Field of action Economy	O	Field AND Economy
Field of action Energy	O	Field AND energy
Field of action private households and consumption	O	Field AND (household OR consumption OR consume)
Field of action Transport	O	Field AND transport
forms of coordination	I	Coordination
Framework measures	C	Framework AND measure
good network capacity in the city	I	Network AND capacity
Harmonizing social goals + environmental goals	I	Social AND environment
Implementation of the BEK	O	BEK OR climate action plan OR climate-action-plan
Import of renewable Gas	P	Import AND gas
Inclusion of all actors in all fields of action	I	(Participate OR participatory) AND field
innovativeness	R	Innovation OR innovativeness
Installation of solar systems on public buildings	R	Solar AND building
legitimation	R	Legitimation OR legitimate
Majorities of voting actors	G	Major AND (vote OR voting)
policy	G	Policy
Power to Gas Applications	R	Power to gas OR p2g OR power-to-gas
protected areas	C	Protect AND (land OR area)
resilience	O	Resilience
small new business areas	R	Start-up OR startup OR (new AND business)
State Secretaries Round	A	State AND secretary
technical potential solar energy	R	Potential AND solar
Tenant flow law	C	Tenant AND law
Use of domestic potential renewable gas	R	Potential AND gas
Use of heat grids	R	Heat AND grid
Use of heat pumps and geothermal energy	R	Heat AND pump OR geotherm
Use of sealed areas in cities	R	Seal
Utilisation of economic potential Solar energy	R	Solar AND economic
Willingness of political actors to act	R	(Motivation OR motivate OR will OR act) AND (actor OR politic OR decision)

4. Interpretation of the results

As a baseline for interpreting the results of the code relation matrices, we created a "code segment matrix" with MAXQDA. This matrix does not only include the number of overlaps of each code, but additionally includes the raw text passages which have been highlighted in MAXQDA. We use these passages as input for our evaluation scheme. Each causal statement in the passages is compared to the statements made by the interviewees and evaluated according to the scheme. Although exploratory, we were able to derive several insights from this review. These results are illustrated in the following section.

5. Results

The application of our framework allowed us to derive some interesting results from the interview data and the SDS documents. At first, the calculation of the 80% quantile of the nodes from the interviews already revealed the most central nodes from the interviews (Heitmann et al., 2019a). Figure 4 illustrates how these are represented in the analyzed German SDS. The bigger the node, the higher the BC of the node in the network. The links between the nodes represent a close proximity between the variables in the strategy document. Most connected nodes are shown in Table 5. All correlations can be found in the supplemental online material (Table A 9 and Table A 10). The left and middle rows in Table 5 show the connected nodes, whereas the row "Results" shows how often these nodes are mentioned in close proximity in the SDS document (next or previous paragraph). Taking the variable "Monitoring and evaluation" as an example, we see that this requirement seems to be important to be implemented specifically together with "Financing of the energy system in line with Paris objectives", "Innovativeness", "Vertical integration and coherence of indicators and objectives", "Acceptance of the renewable expansion" and "Clear investment plan (low carbon)". The connection to "Vertical integration and coherence of indicators and objectives is verified by the conducted expert interviews in (Heitmann et al., 2019a). Therefore, this finding in the strategy document is coherent with the interview data. Although the other results from the SDS document analysis regarding "Monitoring and Evaluation" are not represented in the interview data, they are not necessarily wrong. They may help to inform the interview results. Although, it might be an interesting question to what degree the strategy documents inform the underlying interview data, we focus on the inverse research question and identify the added value of the interview data for the SDS documents. Therefore, we fed in the findings for all variables from the analysis into the developed evaluation scheme.

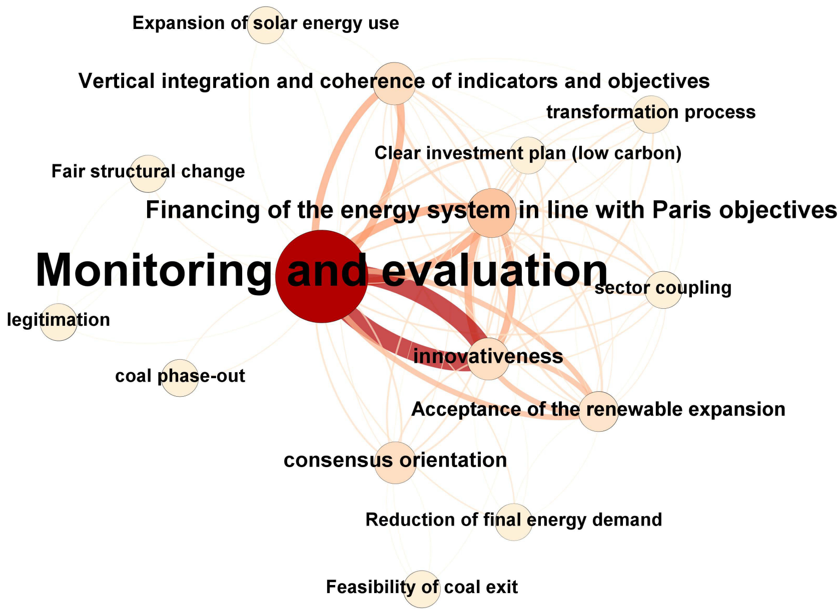

Figure 4 Preliminary coding result of the German sustainable development strategy

Table 5 Most identified overlaps (National level)

Source/Target	Source/Target	Results
Monitoring and evaluation	Innovativeness	39.0
Monitoring and evaluation	Financing of the energy system in line with Paris objectives	18.0
Monitoring and evaluation	Vertical integration and coherence of indicators and objectives	16.0
Financing of the energy system in line with Paris objectives	Innovativeness	16.0
Acceptance of the renewable expansion	Innovativeness	12.0
Acceptance of the renewable expansion	Monitoring and evaluation	12.0
Vertical integration and coherence of indicators and objectives	Financing of the energy system in line with Paris objectives	6.0
sector coupling	Financing of the energy system in line with Paris objectives	6.0
Monitoring and evaluation	Clear investment plan (low carbon)	6.0
Acceptance of the renewable expansion	Financing of the energy system in line with Paris objectives	5.0

The correlation network of the interviews with the BEK is illustrated in Figure 5. The underlying data can be found in Table 6. First, the number of nodes in the BEK diagram is much higher than for the German level. The reason is that interviewees on the Berlin level contributed more requirements to the modeling process. Therefore, a word of warning is in order about drawing conclusions out of the analysis with our evaluation scheme; It is very doubtful whether a meaningful content-related comparison can be made between both levels of analysis in our exploratory case, i.e. the German level and the city of Berlin.

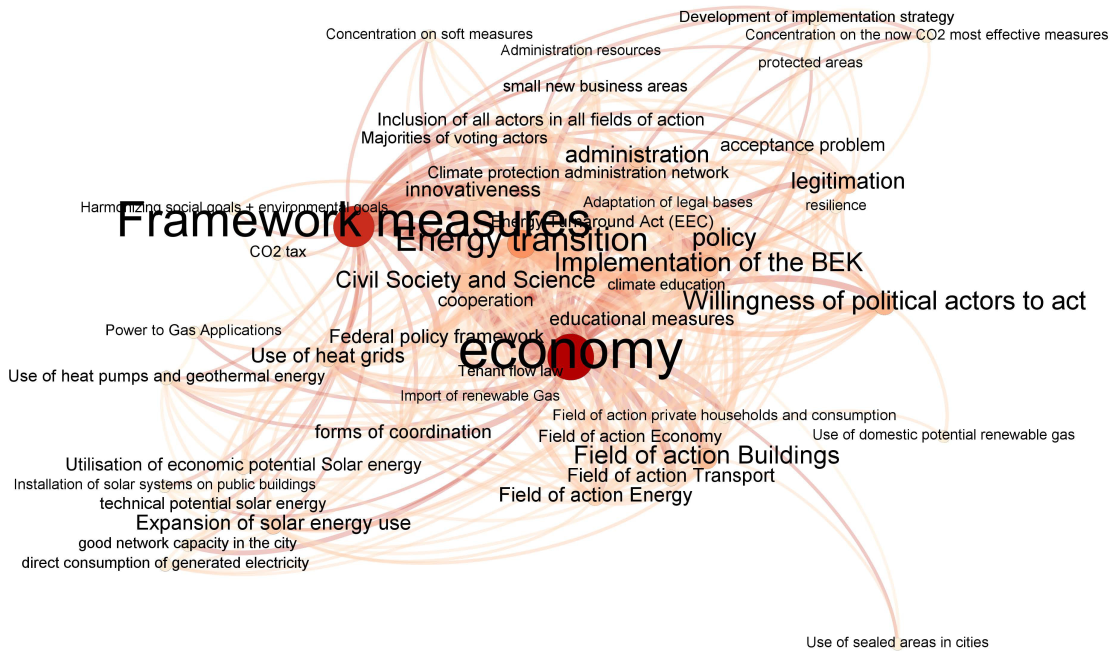

Figure 5 Preliminary coding result of the BEK

Table 6 Most identified overlaps (Berlin level)

Source/Target	**Source/Target**	**Results**
Energy Turnaround Act (EEC)	Energy transition	46.0
climate education	educational measures	38.0
economy	Field of action Economy	26.0
acceptance problem	legitimation	18.0
economy	Civil Society and Science	18.0
innovativeness	Energy transition	16.0
economy	Implementation of the BEK	14.0
economy	policy	14.0
Framework measures	economy	14.0
administration	Climate protection administration network	12.0
Civil Society and Science	Energy transition	12.0
Framework measures	cooperation	12.0
Implementation of the BEK	Civil Society and Science	12.0
technical potential solar energy	Utilisation of economic potential Solar energy	12.0
Civil Society and Science	educational measures	10.0
economy	administration	10.0
economy	Field of action Transport	10.0
Field of action Buildings	Field of action Transport	10.0
Framework measures	Federal policy framework	10.0
Implementation of the BEK	educational measures	10.0

5.1. Results from the evaluation scheme

We found interesting results on the added value of the interviews for the analyzed SDS documents. For the German SDS, we found 36 causal bi-directional relationships from the interviews which provide an added value to the German SDS, and four causal bi-directional relationships which verify statements from the German SDS (Table 7). In total, the code relation matrix includes 205 individual bi-directional causal relationships between 20 codes (Supplemental online material Table A 10). These equals 10.79 results per code. The original interview dataset (80% quantile) includes 20 uni-directed causal relationships. The total number of identified variables from the analysis (36) exceeds the number of relationships in the interviews (20) because also the target nodes have been analyzed for the origin of their incoming edges. This means that we basically transformed the original uni-directional network into a bi-directional network for our analysis. The aim of our analysis is to reveal, if a specific relationship between two variables is mentioned in the SDS document or not rather than revealing the direction of this relationship. Specifically, requirements provide an added value for the SDS document (23), followed by objectives (11) (Figure 6). Therefore, even though the total number of results remains low, we find that the interview strongly informs the SDS document with respect to the low number of variables and relationships.

Table 7 Evaluation scheme (Germany)

Definition	German case				
	R	O	F	I	S
Not coherent	0	0	0	0	0
same link (verification)	2	1	1	0	0
added coherent link (information)	23	11	1	1	0
Does not exist (added, coherent link) (innovation)	0	0	0	0	0

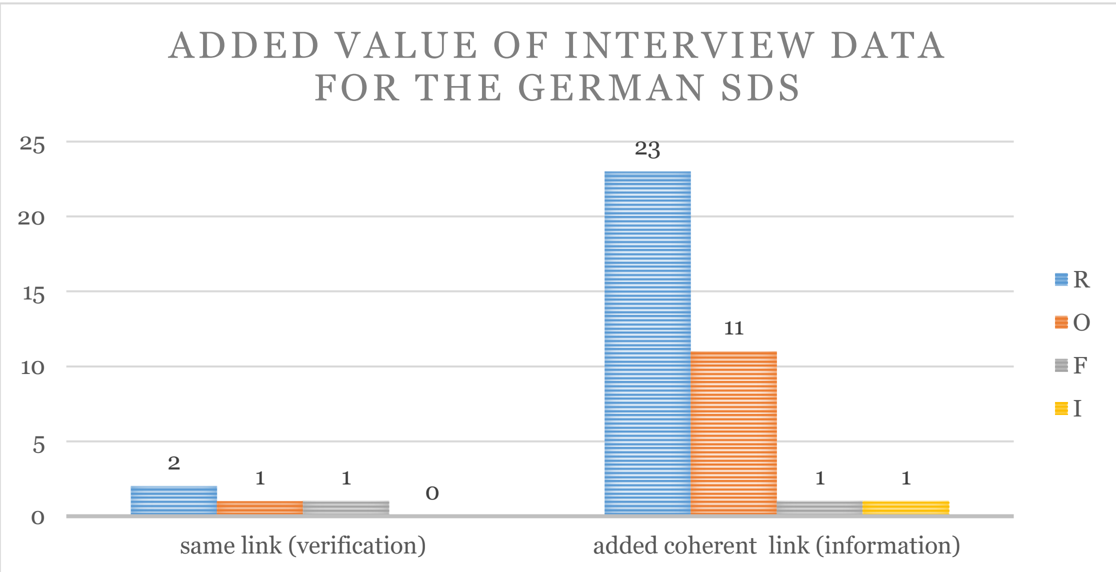

Figure 6 Added value of interview data (Germany) - variable types

Regarding the Berlin case, we found that 103 bi-directional relationships from the interviews provide an added value to the strategy, and 56 relationships verify the statements in the SDS document. In total, the code relation matrix for the BEK includes 473 bi-directional causal relationships between 50 codes (Supplemental online material Table A 9). This equals 9.46 results per code. Compared to the German level, we find that the proportion of verifying results to informative results is higher in the Berlin case (Figure 7). Although the total number of the results is too low to derive statistical insights, a tentative conclusion at this point would be that the information which is inherent in the underlying interview data better describes the status quo of the SDS document for Berlin than for the German case. On the other hand, spoken in absolute numbers, the interview data for the Berlin case also provides more added value for the SDS document. Particularly information on requirements (24), objectives (24), actors (21) and interfaces (16) inform the BEK. In total, objectives (45) and requirements (41) provide the most input to the document (Figure 8).

Surprisingly, much additional information on actor relationships has been identified for the Berlin strategy from the comparison with the interview data. This indicates that actor relationships are not well represented in the strategy document compared to the interviews.

Table 8 Evaluation scheme (Berlin)

Definition	**Berlin case**									
	R	C	F	P	S	I	O	A	E	G
Not coherent	0	0	0	0	0	0	0	0	0	0
same link (verification)	13	3	0	1	0	3	21	6	0	9
added coherent link (information)	28	4	0	2	0	16	24	21	3	5
Does not exist (added, coherent link) (innovation)	0	0	0	0	0	0	0	0	0	0

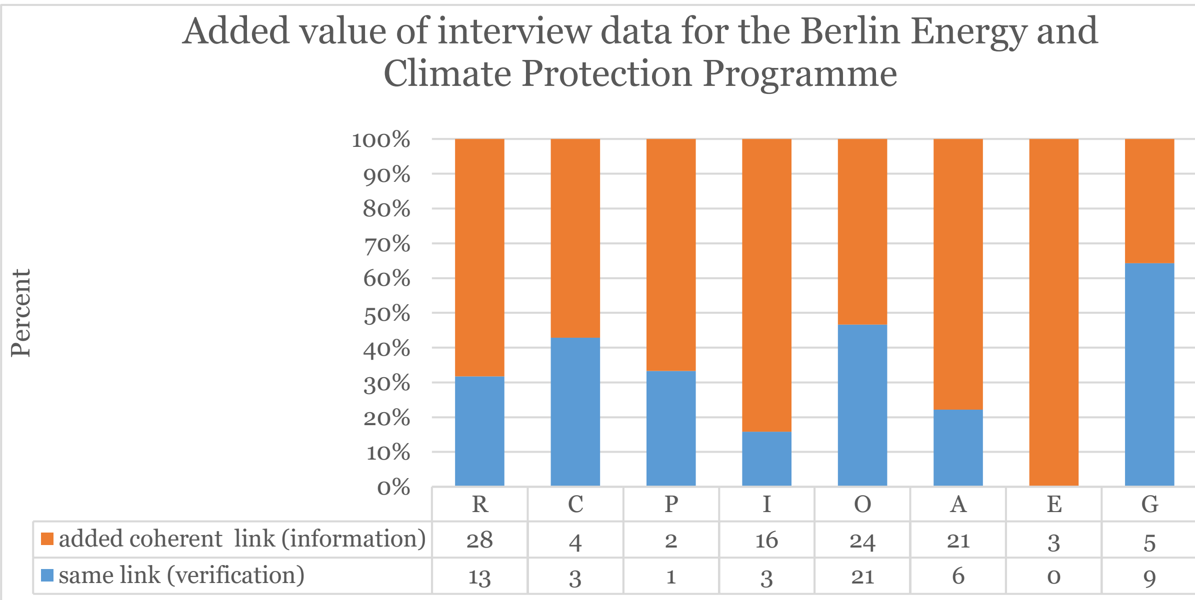

Figure 7 Added value of interview data (Berlin)

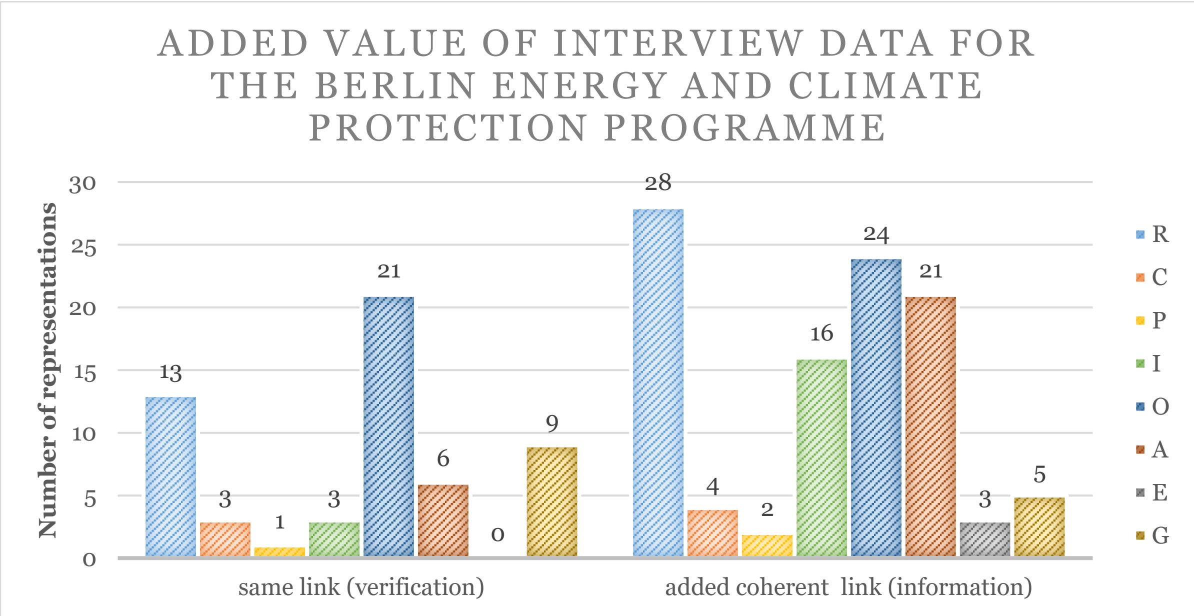

Figure 8 Added value of interview data (Berlin) - variable types

6. Discussion and Conclusion

In this article, we introduced a requirements based analysis approach of SDS documents. We introduced a methodological framework which includes the definition of interfaces between causal models from participatory modeling interviews and strategy documents. This is done by comparing the causal relationships from interviews with statements made by the strategy documents. On a methodological level, we conclude that our approach can contribute to a more structured and outcome oriented re-design and development of SDS. Although exploratory, we found that a significant number of variables and relationships from the interviews is represented in the strategy documents. An even larger number of relationships is not represented in the strategy documents but in the interviews, which indicates that the interviews are able to inform the strategy documents. These information gaps in the documents need to be filled if the strategies should also include detailed requirements for their implementation. However, we need to keep in mind that the re-design and development of the strategies is an ongoing political process. The sustainability landscape in Germany is rapidly changing as new strategies are being developed, and existing strategies revised. Therefore, the interpretation of the results in this article should be done with care because it could be partly outdated on the time of publication. However, the presented approach is able to provide insights to ongoing debates on requirements based re-design of strategies and their implementation if it is applied together with stakeholders. Therefore, as a next step, we suggest to formalize the framework and develop a tool which can be easily used by political decision makers and other actors.

We found that the strategy documents only reveal a small percentage of actors needed to implement the strategies. Particularly the German SDS misses low-level actors who are responsible for the strategy implementation on the urban level. But also urban strategies do not include a full picture of actor roles such as the district offices role in strategy implementation which was mentioned as highly important by one expert for the BEK. This partly explains that a comparably high number of actor information informs the strategy document.

All in all, our findings should be interpreted with caution. For example, the fact that much information on actor relationships has an added value to the strategy document of Berlin does not necessarily mean that we should first focus on this type of information to be included into the strategy document to make it more comprehensive or effective. Also other requirements such as the implementation of cooperation mechanisms could help to reduce conflicts in the system. Cooperation among different decision makers and actors in general can lead to better solutions on an overall SoS level because cooperation can build trust and reputation among actors (Ostrom and Walker, 2003b; Poteete et al., 2010). This is particularly true if these actors share a common resource (Ostrom et al., 1994). In this case, actors have a common interest in implementing the overall strategy. Therefore, information on actor relationships may be important, but the effect of implementing alternative variables should not be underestimated. Therefore, we find it important to highlight that our methodological framework can reveal information gaps in strategy documents and compare expert knowledge with these strategies without implying what aspects are most important to additionally consider.

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6. Results

Main result I:
A System-of-Systems Design framework "FRESCO" has been developed and tested to guide the structured design of and to support decision making in environmental System of Systems.

Box 6 Result I

A design framework should support a solution guided analysis without being too specific and therefore not transferable from a methodological point of view. The FRESCO framework aims at strengthening collaboration between participating actors. This is done by using a systems thinking approach to design solutions in environmental SoS. Therefore, such a framework has to implement a holistic system view to deal with multi-level complexity across subsystems. Additionally, developing a process-oriented design framework in the context of environmental SoS requires an interdisciplinary approach across SE and resources management fields. However, actors from different fields often have different viewpoints on the same problem. This can cause ambiguities during discussions among the actors. Therefore, a minimum degree of transferability of the FRESCO framework may help to overcome these ambiguities by providing a common language for the design process. These design processes in SE depend on a user point of view and on what a system has to achieve and how. Therefore, CONOPS, requirements analysis and functional analysis are adopted and informed by the concept of PM in individual and group settings. Standard group model building approaches are usually fostered to enhance learning among the participants, and motivate to discuss different existing mental models of a problem perspective (Stave, 2010). "Mental models are personal internal representations of the surrounding world" (Scholz et al., 2014). The FRESCO framework adds a design perspective to this approach by using mental models as inputs to develop a system design model. During the application of the framework, participants from science reported that the focus on process management and system design helped to include multi-level complexity into system analysis. Participants from practice state that the approach allows them to include the complexity of the modeled system into their decision-making processes. More specifically, stakeholders encountered that the approach enabled them to gain an advanced understanding of complex relationships, not only between general concepts such as sectoral security goals, but also more specific requirements and functions needed to fulfil the overall design objective of the study.

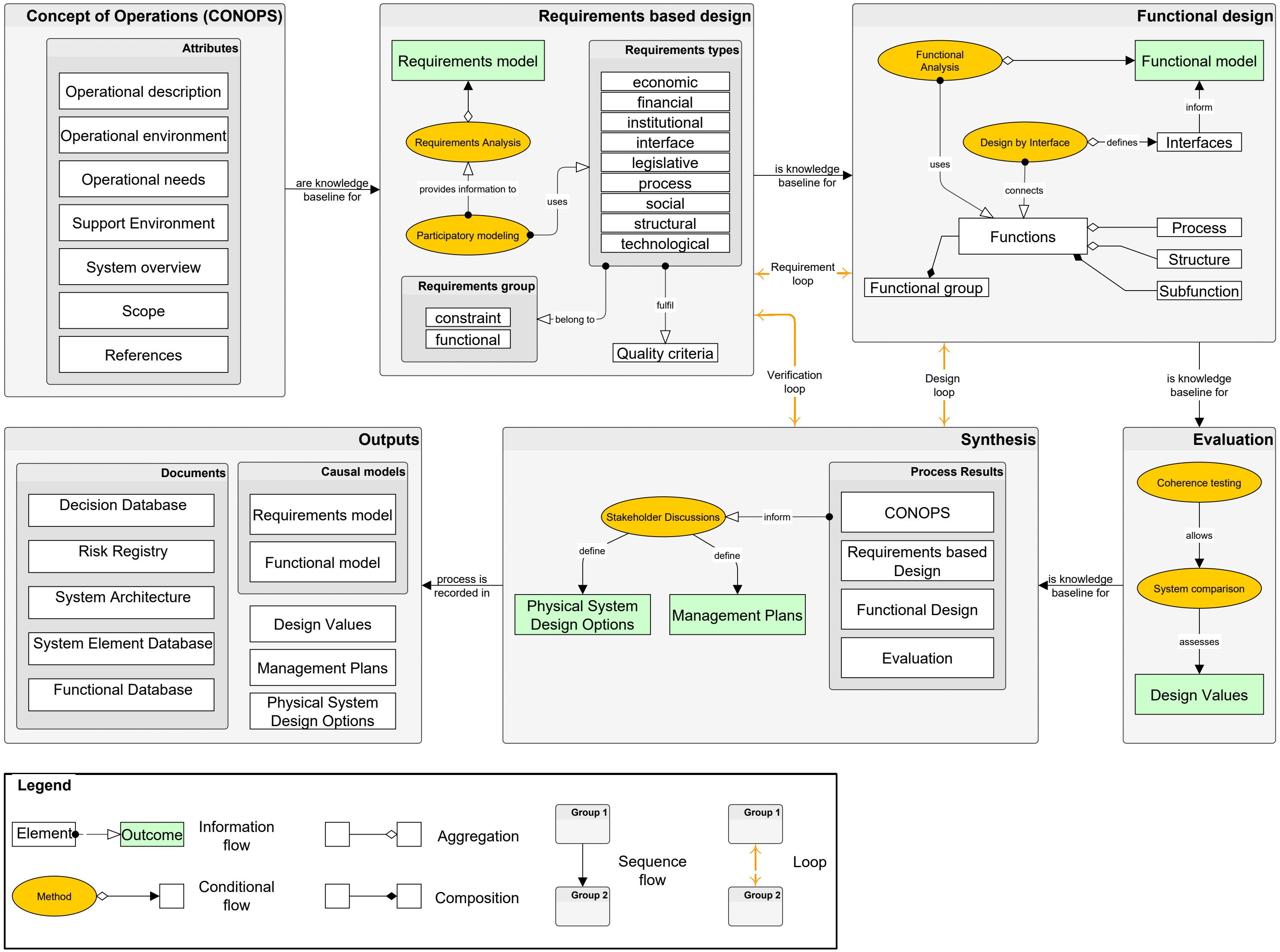

Figure 14 The FRESCO Framework (Heitmann et al., 2019b)

Main result II:
A methodological framework has been developed and tested to apply requirements analysis in participatory settings on multi-level-governance in human-nature-technology systems.

Box 7 Result II

The development of a methodological design approach in the context of multi-level-governance in human-nature-technology systems closes the gap of a missing requirements analysis approach for strategy development. Its participatory elements help to engage scientific experts and non-scientific stakeholders in the design process of Nexus systems. The application in the first case study on a regional WEF Nexus revealed that solutions towards security and resilience in the study region are already developed, but often not taken into account because of high transaction costs, constraining institutions (formal & informal), and a missing holistic viewpoint on the system by decision makers. The high complexity of WEF-Nexus governance and multi-level governance structures make it particularly difficult to implement integrated solutions in the system. To overcome this complexity during the conceptual design phase, coordination and cooperation among scientific experts can help to overcome the problem of “knowledge islands” in different scientific disciplines. This may be achieved by building up a common knowledge baseline in group model building workshops. Combined workshops or discussion rounds may enhance learning and help actors to consider viewpoints of others in individual decision-making processes. In this context, cross-sectoral communication and collaboration is a key-factor. In addition, PM interviews can help to enhance communication among non-scientific stakeholders. In the second case study, several PM interviews with stakeholders from practice and the analysis of the resulting causal-loop diagrams revealed that key requirements exist in SDS that are not only needed to achieve certain objectives in the particular strategy but also to provide an interface to other strategies.

Considering the described findings of the applied design processes, as described in chapter 3 and chapter 4, and the experiences of the participating actors in the conducted case studies, it can be concluded that the applied types of stakeholder based system design are a step forward to a solution and process oriented operationalization of SE in the NRM domain.

Main result III:
A requirements evaluation scheme has been developed and tested to assess the additional value of requirements analysis with causal-loop-diagrams for detailed strategy design.

Box 8 Result III

After conducting a series of mainly non-scientific expert interviews on the German SDS, several urban actors from Hamburg and Berlin in Germany have been asked to provide requirement based causal-loop models to study the conceptual and detailed design of long-term strategy finding and development processes. To evaluate this data, an evaluation scheme has been developed in collaboration with the System-of-Systems laboratory at the Julie Ann Wrigley Institute of Sustainability of the Arizona State University (ASU), USA. The scheme includes a qualitative document analysis and a comparison of variables from these documents with requirements-based causal-loop models from PM interviews. The analysis with the scheme reveals that strategy documents on the German national level include mainly conceptual and general requirements for strategy implementation. Urban SDS of the cities of Hamburg and Berlin include more detailed and diverse types of requirements. Many requirements are important for successful system/strategy design. Requirements from the cities point of view are also valid on the national level. Although cities have requirements to satisfy regional demands, the national directive could support cities by formulating more detailed action plans which are particularly steered towards federal-state and urban actors on lower levels. On a methodological level, the conducted analysis could also be applied on other cases where users are obliged to implement high level strategies which do not include a detailed description of functional requirements.

Main result IV:
A new classification of environmental System-of-Systems has been developed:
SoS-Type 1*, where the overall objective is designed, and* ***SoS-Type 2****, where the subsystems are designed to align to an already existing overall objective.*

Box 9 Result IV

During the development of the FRESCO framework, two possible types of SoS have been identified: Type 1, which defines a SoS without an overall objective (e.g. the WEF Nexus), and Type 2, where, in principle, an overall objective exists but is interpreted differently for different sub-systems. In the conducted interviews, no overall objective among the actors exists. Therefore, the FRESCO framework has been used to develop such an overarching objective for case study one. The system in case study two, i.e. the German SDS landscape, is defined as a type 2 SoS: Several existing sub-goals have to be aligned to fulfill an existing overarching SoS goal. For the purpose of case study two, sub-goals are defined as urban or city goals. The SoS goals are defined as the objectives of the overall national strategy which is also divided into several sub-goals on the same level. A detailed description of the different identified SoS-types can be found in chapter 2.1.

Additionally, a supervised Bachelor's thesis shows that WEF Nexus systems can be considered as environmental SoS: Although, functional and operational independence as parts of the SoS definition cannot be applied to the WEF Nexus (the WEF Nexus sectors are not maintained or operated isolated, and the functions of one sector may depend on the functions of other sectors), the WEF Nexus is usually considered as a CAS. Therefore, other SoS criteria, i.e. emergent behavior and evolutionary development, also hold true for the WEF Nexus. The thesis also illustrates that each sector in a WEF Nexus system has individual sectoral drivers for taking action, is exposed to (environmental) pressures which are produced by these drivers, produces several system states through these pressures, which have an impact on other (sub) system states, and response to these impacts. The overall SoS objective which is implied by the definition of SoS-type-1 and type-2, may also be interpreted as a common state which is shared by the sectors in a WEF Nexus system (Austrup, 2017).

7. Discussion & Conclusion

In this doctoral dissertation, a conceptual and engineering oriented framework has been developed to guide system design in human-nature-technology systems. The framework development includes (1) reviewing and studying SE and SoSE literature, with a close focus on multidisciplinary system design (Crowder et al., 2016), in this context, understanding the concept of complexity (Mahmood, 2016), design of non-technical systems (Hipel, 2012; Hipel et al., 2010, 2008a, 2008b, 2008c; Hipel and Ben-Haim, 1999), history and origin of these approaches, and frameworks for complex system design (Kruchten, 1995; Zachman, 1987); (2) defining overlaps from the reviewed approaches to human-nature-technology systems such as the WEF Nexus (see also (Austrup, 2017)); (3) defining a structure for non-technical system design; (4) translating SE language into NRM language; and (5) testing the framework in two case studies on the WEF Nexus and on the requirements based design of SDS.

Reflection on the FRESCO Framework

During the development of the FRESCO framework, several concepts and methods have been developed and applied in different contexts. The honest and critical reflection on the conceptual part of this thesis includes factors such as completeness, depth and innovativeness of the approaches developed and used. The main conceptual part of the thesis, the FRESCO-framework, is one first step towards the adaptation of a combined SE process-framework, role-model of system design as well as view-model of system analysis and management with the purpose to support complex systems thinking and system design in an environmental SoS context. The framework is “complete” in the sense that it includes the main aspects of SE (conceptual and detailed system design, analysis, test, implementation, evaluation and support). The framework is “incomplete” with respect to a tool or software which supports its application. However, if the framework is formalized with a programming language such as UML or SysML, it may supports the development of such tools (Omg, 2015; Rumpe, 2011; Weilkiens, 2007). The depth of the FRESCO-framework with respect to the information it can collect, can be valued as high because it does not put constraints on the user in terms of possible methods or application domains. Nevertheless, it is steered towards analyzing and understanding environmental SoS such as WEF Nexus systems or SDS. Studying the underlying engineering concepts and their applicability for the NRM has been supported by a bachelor thesis which deals with the general applicability of the SoS approach on the WEF Nexus concept (Austrup, 2017).

The innovativeness of the framework is considered as high. Although engineering approaches for SES design are not a novelty, they are still rare. To the best of knowledge, it is the first comprehensive framework which can support the whole design process of SoS while considering also nature-human-technology systems as the object of design. Traditional engineering frameworks only consider technical elements as designable. Considering that the WEF Nexus concept deals with the sub-systems Water, Energy and Food as equal parts of the system, and, besides that, no user can decide that one part of the system is more important than another part, the FRESCO-framework could act as a tool to support the design of several dimensions and types of a nature-human-technological system.

On a methodological level, a workshop structure for implementing conceptual system design tasks in a group-model building setting has been developed and tested, a methodological framework for participatory requirements analysis has been developed and tested, as well as an evaluation scheme for requirements-based system design models has been developed and applied. These methods are qualitative modeling approaches which can generally support learning, communication and cooperation among diverse actors such as scientific experts from different disciplines, non-scientific experts from practice, and decision-makers in NGOs, public administration units, consultancies, or private research institutes.

Reflection on the developed participatory modeling frameworks

PM methods which have been developed and applied in this thesis, i.e. PM with causal-loop diagrams in a group-model building workshop setting (case study 1) and in individual interview settings (case study 2) are used within the presented FRESCO-Framework to elicit "CONOPS", "requirements", and "functions" to build system design models.

In case study one, it is presented that combined PM and requirements analysis and functional analysis approaches can help to design an overall objective on a SoS scale (Type 1 System-of-Systems design). This type of system design refers to the design of an acknowledged SoS. In comparison to technical system design, where SoS are often designed from scratch, system design of combined human-nature-technology systems refers to a re-design of one system or SoS to another SoS. In case study 1, the underlying system is a WEF Nexus system, which is defined as a virtual SoS where no central control entity exists. This leads to a sub-optimal outcome on a macro scale, i.e. damages to the environment of the system (Water and Food subsystems) as well as higher risks of failure for the technical subsystems. Therefore, the overall aim of a type 1 design process in this case study is to develop such an overarching objective which transforms the system into either a directed or acknowledged SoS.

In this thesis, the first case study deals with such a conceptual re-design of a virtual SoS, i.e. the regional WEF Nexus. A possible common goal is conceptualized in a participatory group-model building workshop with scientific experts. During this workshop, some challenges appeared: (1) after the vision modeling phase, participants felt uncertain what central vision should be pursued for the subsequent modeling steps (requirements analysis and functional analysis). Developing some criteria for choosing such a central SoS variable could be helpful to minimize this uncertainty. Participants could learn what criteria such a central variable should fulfill to formulate their vision appropriately; (2) during the requirements analysis phase, participants were struggling to agree on certain requirements for adding them to the overall requirements model. Because many participants came from different disciplines, each participant had to explain the meaning of the requirement and its importance for the overall model. This is particularly important to build up common ground (Voinov and Bousquet, 2010). Additionally, each participant argued for the individual requirement with the aim to include it in the model. However, the idea of the requirements modeling process is not to include all mentioned requirements, but rather to focus on the most central or important aspects of the model. Discussions during the model phase have been long but necessary to build up a common understanding among the participants and to proceed in the workshop. Kotir et al. (2017) described similar experiences in a larger group model building workshop with 27 participants. Kotir et al. (2017) also experienced that actors perceived the time available for the model building as too short because they were not experienced in group model building. In the case presented in this thesis, the number of participants was lower (eight). Nonetheless, the workshop has been successfully planned for two days to overcome the issues described by Kotir et al. (2017).

The second case study follows the coherent design of different strategic pathways inside a SoS to align different sub-objectives with each other. This supports the alignment of several subsystems to an overall SoS goal (Type 2 System-of-Systems design). More specifically, for case study two, these strategic pathways are defined as the urban SDS of Berlin and Hamburg, and the German national SDS. The overall SoS goal, the German national SDS, is already existing. However, the urban strategies have to be better aligned to the central strategy. To reorganize these strategies, a design approach has been developed. It includes a methodological framework to conduct PM interviews with causal-loop diagrams in an individual interview setting with actors from practice. In these interviews, requirements-based models have been developed and combined. This combination reveals an overall requirements-based management plan which can be used to inform the future policy process to implement and align the different strategies (see chapter 4).

Reflection on learning in Systems Engineering processes

Both case studies highlight the importance of learning for the participants. In the first case study, learning occurred during the participatory group-model building workshop among the participants. The degree of learning has not been analyzed because this would have been out of the scope of this thesis. However, as the participants came from different scientific domains, they brought their individual and different viewpoints about the workshop theme into the discussions. On the one hand, this increased the complexity of the workshop content. Therefore, the workshop has been planned for two days, plus a two hour preparatory expert interview and one individual expert interview to complement the workshop outcome. On the other hand, this diversity led to fruitful discussions during the workshop. Participants discussed their different conceptions of the problem perspective and had to achieve a compromise to develop a common causal model (Figure A 3). This compromise could only be developed because the participants agreed on the variables and connections of this causal model. The ability to accept others viewpoints by understanding them during the discussions, refers to what the literature calls social learning (Scholz et al., 2014).

In comparison to other approaches which may support social learning and collective action such as some PM approaches using system dynamics or companion modeling, learning in a SE approach which focusses on integrated system design occurs on several levels:

Learning occurs on the level of the system engineer. The role of a systems engineer is to make sure that the overall goals of the system design process are achieved (chapter 2.3). To accomplish this complex task, a lot of knowledge about the design process (content specific and project management) is required. To gain this knowledge, the CONOPS step of the FRESCO framework has been applied to (1) gain knowledge about the underlying system and its current configuration and problem perspective by reviewing literature and by conducting a preparatory stakeholder interview; and (2) to analyze important stakeholders and to identify the correct method for conducting the PM approach. Additionally, during the actual participation process, i.e. requirements elicitation and analysis, the participants provided their knowledge not only to the overall design process, but also to the systems engineer as the moderator and/or conductor of the design process. Therefore, learning is understood as an important aspect in a system design process, also for the system engineer; *Learning occurs on the participant level*. Participants in the design process are actors, stakeholders or other system users. In the beginning of the system design process, each participant has a specific degree of knowledge. This knowledge can be framed as specific needs which could be included in the system design as requirements. Depending on the level of participation (see also Figure 11), the participants interact with each other during the design process (case study one), or have the opportunity to discuss the model outcome afterwards (case study two). In the first case, as described above, participants could directly learn from each other during the workshop discussions. In comparison to the original group model building approach, SE provides a more structured learning approach because it structures the available knowledge into different categories (requirements types) and models their relationships. The resulting requirements model can then be additionally discussed by the participants. The latter step may be a system design evaluation which can include the discussion of additional quality criteria for the requirements, i.e. correctness, completeness, consistency, traceability, being unambiguous, testability, and atomicity (chapter 3).

Reflection on the feedback of the case study participants

The feedback from the participants from case study one and two regarding the above-mentioned design processes was mainly positive. The participants reported that applying the system design approach, either on a conceptual or detailed level, helps to capture complexity and include complex relationships into their decision making or future research and work.

Many participants in the second case study were particularly interested in the developed PM approach with requirements. They reported that (1) causal-loop diagrams helped them to overcome linear thinking in their daily work; (2) causal diagrams helped to get a different perspective on the knowledge which has been already available but in a different, sometimes unstructured, form; (3) the diagram motivates to discuss the content of the causal model with colleagues inside the organization. In one specific case, the individual expert interview developed to a group-model interview with three participants from the same organization. Although these participants were embedded in other work intensive tasks, they have been motivated to creatively engage in the model process; (4) the framing of actor needs as "requirements" helped to first think about possible solutions and second about constraints rather than focusing too much on the problem and therefore maybe forget about solutions to this problem; (5) the interview structure has been perceived as a novel and innovative approach to include practitioners in a research study because it does not constrain the interviewee to a specific topic and gives space for a unbiased reflection on a specific solution strategy or problem. Although this was perceived as positive by most participants, some actors also raised the point that they felt "lost" and "uncertain" if the provided information was sufficient enough for the design process. In these cases, it was explained that the design process is planned as a "exploratory" study for methodological development and testing, and that (1) no personal information such as name or affiliation will be shared with any third party, and (2) that there is no "right" or "wrong" in providing information to a PM approach because each contribution is a subjective mental model of an individual person which cannot be wrong by definition. However, if one actor stated a requirement which was not coherent to other actors' statements, this issue has been discussed with the interviewee.

Reflection on the applicability of the developed approaches in different contexts

The role of the FRESCO framework in research and the role in practice differ in several aspects. For example, the role of each step of the FRESCO framework differs slightly from case to case. Additionally, whereas the general outcome of each framework step might be the same in research and in practice, the reason why each step is carried out can differ.

More specifically, applying the FRESCO framework in research generally means to analyze the existing system and to design a "What –If" scenario, i.e. the system design model. The research design may be an inspirational source for policy makers or practitioners who can be partly involved in the study or read the study outcome. However, the system design follows the main objective to create new knowledge which then can be taken up by third parties to design physical systems or to co-create new scientific knowledge. This is referred to a "virtual system design", "management plans" or "physical system design options" for a possible future implementation of the system design (Figure 14). However, the outcome of a research study may not reach practitioners because of the current scientific publication system which is too isolated from practice (Senge and Scharmer, 2008). Involving practitioners in a scientific system design process may bridge this gap between science and practice as it has been done by students within the teaching curriculum at Osnabrueck University where several stakeholders have been involved in a PM exercise which focused on cultivating plants to produce bioenergy (see also chapter 2.3.3).

Applying the FRESCO framework in practice goes a step further. This can include virtual system design but also physical system design processes such as the guidance of a process that is convened by a ministry. If participants are included in the design process and are in charge of taking action in the desired system, the system design models developed within FRESCO may be directly tested and implemented. Because the objective of a system design process can be diverse, such as the design of processes, functions, subsystems or whole SoS, the outcome can vary from political processes, decision-making strategies, embedding new systematic functions, re-designing subsystems (e.g. urban SDS) to the re-design or re-organization of whole SoS such as complex human-nature-technology systems.

Some parallels of system design processes can also be drawn to project management (see also chapter 2.3) and consulting tasks (Kasser and Hitchins, 2013). Whereas SE is described as important to create the CONOPS and to elicit user needs and requirements, i.e. the conceptual design phase, project management is described as important for the detailed design phase where risk assessments, tracking and planning of time and human resources and other organizing and planning tasks are important. However, SE is applied during the whole system design process as it is understood as a concept which designs the overall system, and/or its constituent subsystems in the case of a SoS (Kasser and Hitchins, 2013). Project management tasks run in parallel for planning, organizing and monitoring these tasks. System thinking may be used to understand the underlying problem which should be resolved during the overall system design process.

Although the presented methods in this thesis focus more on a scientific application and design of complex governance systems, participating actors from practice reported that the following aspects of the modeling methods are arguments in favor of applying requirements-based PM approaches also in a business context: (1) Knowledge of the actors is connected during the modeling process and summarized to develop a systems model; (2) individually (single actor interviews) or collectively (group model building) modeling is possible which can support either building trust or supporting collaboration among several actors; (3) causal-relationships are clearly visible also in complex environments (by developing requirements-based causal-loop models); (4) linear thinking is avoided; (5) macro-effects of the micro-level can be assessed and their importance for the overall system evaluated (linkages between conceptual and detailed system design); and (6) planning with this approach is possible by focusing on "What is there?" before thinking about "How things can be done?".

Critical Reflections on the presented research approach

When examined critically, the presented FRESCO framework is limited in the sense that not every step of the FRESCO-framework has been tested to its end. Only CONOPS, requirements analysis, functional analysis, evaluation, and parts of the output step have been fully applied. The reason is that the object of design, i.e. the regional WEF Nexus in case study one and the German sustainability landscape in case study two, cannot just be designed or re-designed by a single person or research team. In comparison to standard engineered systems such as soft –and hardware systems, the implementation and testing parts of the study are not supposed to be carried out by research. These circumstances are also described in chapter 2.3.

Some doubts may also be raised as to whether the linked methodological frameworks for individual expert interviews and the design workshop have a sufficient number of participants to derive contextual insights from the case studies. With the relatively low number of participants in the presented case studies, the study is not to be understood as a comprehensive SoS design process. A more comprehensive SoSE process requires a high number of actors who can provide a sufficient amount of actor requirements to the process. This is why the studies in this thesis have been designed as exploratory case studies. Their main objective was to build up a first use-case scenario for SE and SoSE approaches in the NRM domain. At this point, the question remains open, how high this number of requirements should be to be sufficient enough.

A system design which is grounded on enough and well formulated requirements may be achieved, if risk management is applied iteratively and consistently during the design phase. As exemplified in chapter 3, risk management is divided into two types: Design risk management and process risks management. Design risks relate to the risks of the system design implementation, e.g. costs related to the actual physical implementation of the system design. Missing requirements could lead to an unfeasible system in the end and therefore the sustainable operation could fail. More specifically, if a design process in the WEF Nexus tries to design a policy instrument to strengthen specific synergies among the Nexus sectors, missing functional requirements on a subsystem level, i.e. sectoral level, could lead to unintended consequences in the interaction of those sectors. For example, if the goal is to re-design the EU common agricultural policy and to strengthen the position of the farmers to sustain their livelihoods inside a WEF Nexus system, the underestimation of environmentally-related requirements, such as requirements related to water quality management, could lead to damages in the environment where the food sector is embedded in (for example through high diffuse entries in the groundwater bodies). This may also has additional consequences for other sectors such as the water or energy sector, as the interaction between those sectors are typically strong in a WEF Nexus system.

8. Limitations of the presented research approaches

The main results of this thesis, (1) the FRESCO framework, (2) the methodological framework for participatory design, and (3) the evaluation scheme for these designs have been described in the context of coupled human-nature-technology systems. Although, the methodological applications in the presented case studies have been proven well (as it is shown in chapter 7), the transferability of the approaches to other cases should be examined critically as follows.

Limitations of the FRESCO framework

Standard SE approaches claim to be applicable in many diverse engineering applications. Many general and specialized SE frameworks exits which guide the design of mainly technical systems. These systems might be diverse for example in terms of their structural complexity, size or overall objective. SoSE also provides frameworks and tools to design CAS which follow an overarching objective, i.e. SoS. In general, engineering frameworks assist in the design of software systems, hardware systems, or coupled versions of these systems.

The SE approach which has been developed in this thesis, claims to provide conceptual guidance in the design of coupled human-nature-technology systems. This is done by providing a narrative for applications outside the engineering domain, and conceptualizing this with the FRESCO framework. Therefore, the concept describes how the engineering process can be applied for non-technical system design. However, the concept is not developed as a “one fits all” solution. It is particularly steered towards the design of (1) WEF Nexus systems, and (2) SDS. This thesis shows that the concept has the particular strength to design interconnected governance processes inside environmental SoS, and to include the complexity of a system in the design of such processes. If the framework is applicable in a different context has to be assessed individually.

Limitations of the methodological framework (participatory modeling process)

One of the exploratory case studies in this thesis includes a PM exercise with stakeholders from practice (chapter 4). In this participation process, ten stakeholders have been interviewed in an individual interview setting to provide their knowledge to the requirements based design of an implementation strategy for the current German SDS and the SDS of Hamburg and Berlin. All in all, 322 variables were elicited in the interviews and connected to causal-loop diagrams. There has been a high demand of human resources to conduct this process. Also specific methodological skills were required to carry out the interviews. In addition, expert knowledge was needed to understand the underlying SDS and to be able to conduct the interviews. Often, the needs for such skills are underestimated in participatory processes, in particular in domains of practice with technocratic traditions like water management. Most parts of this thesis such as study design, stakeholder selection, conceptual and methodological development, interviews, modeling, organizational tasks (e.g. workshop organization and conduction, communication with actors) and analysis have been carried out by a single person. Therefore, the number of stakeholders was minimized to reduce the workload for the methodological implementation and subsequent analysis. However, this process took over three years. If the developed approaches are carried out outside research, it is suggested to organize a team to handle also larger case studies in a shorter time frame. Additionally, even if the number of stakeholders remains low, a deeper level of analysis requires also additional human resources.

Limitations regarding stakeholder participation

In addition to the methodological challenges, availability of the invited stakeholders has been a major obstacle for the research process. The first case study was originally planned to include practitioners from the region of Osnabrueck, Germany in the modeling process. However, the motivation for the stakeholders to participate in the research study was relatively low because the underlying topic has been discussed in the region for many years. Therefore, actors who have been invited saw no additional value for themselves and did not take part of the study. Because of this, the case study has been split into two case studies: (1) a participatory process with experts from science, and (2) a participatory process on a different topic, i.e. the German SDS landscape, with experts from practice. Although this has been a good solution to illustrate and test the presented approaches, future studies should take care to apply a well-organized stakeholder selection process from the very beginning. Based on experience, this includes the precise definition of the target group, the detailed formulation of the target group's motivation, transparent communication of the objective of the study, and a high flexibility for setting meetings for interviews.

9. Opportunities for Future Research

Deeper operationalization of Design Thinking approaches for sustainable development

Since decades, humanity exceeds the planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). However, after the first report for the Club of Rome in 1972, "The Limits to Growth" (Meadows, DH., Goldsmith and Meadows, 1972), a large number of scholars achieved first steps towards a great mind-shift with respect to sustainable thinking worldwide. In spite of this, a growing world population, increasing resource scarcity, resulting poverty and more misbalance in terms of prosperity are factors which accelerate negative impacts on our planet, such as CO2-emissions, climate change, extreme weather events, biodiversity loss, decreasing ecosystem services or mass extinction of marine life (Dirzo et al., 2014; Steffen et al., 2011; von Weizsäcker and Wijkman, 2018). Design thinking may be one creative way to come up with effective solution strategies to cope with such sustainability problems.

Whereas in the past mostly material things have been designed, nowadays nearly everything is being designed. Not only objects, such as buildings, transportation systems or machinery, processes such as management processes, production chains, or functions such as water provisioning, but even the climate is object to design in geo-engineering studies, although those studies would fail without removing CO2 from the atmosphere (Bony et al., 2013). Design thinking can be found in all parts of our society (von Borries, 2016). Von Borries (2016) postulates a new design theory which implicates that humans are forced to design the requirements under which they are living by themselves. Design which is constraining opportunities for action, is surrender (von Borries, 2016). The need to promote design thinking also in the fields of system science, NRM, and last but not least SE is obvious. For example, NRM per se is more than "just" managing a resource. It is about holistically understanding and managing the use of natural resources while considering the effects of its use to the society. System science offers tools and methods which should allow to deal with the complexity which arises when analyzing different system types and inherent elements. Engineering these systems includes the design of products, material or non-material. Whereas the product of design can be the own individual environment or the external natural or technological environment, the subject of design is always the individual. Therefore, we all have a responsibility to fulfill our role as designer in a complex and globalized world. The role of design for this thesis becomes clear, when we have a closer look at our world we live in today. Some call it the Anthropocene (Göpel, 2016; Lewis and Maslin, 2015; Steffen et al., 2011), some call it the "full world" (von Weizsäcker and Wijkman, 2018). What these definitions all include is the fact that our world is not given anymore but is designed by its inhabitants, the humans. Examples are huge river dams, the extinction of whole species or the disappearance of the Amazonas rainforest.

The resources of our planet are currently overused and the utilization rate is still increasing. The underlying reasons are not only increasing population and globalization. It is also the way we behave, the way we live and the way we promote this living style in our education systems.

A toolbox for FRESCO for an easy application with actors in different contexts (Business idea)

As described in chapter 2.3.2 and 2.3.3, approaches such as FRESCO have the potential to be implemented as frameworks for designing policy processes in human-nature-technology systems, and to use project management approaches in parallel to organize these design processes. However, as the approach which is presented in this thesis is designed as a scientific framework which can be applied with scientists and practitioners, it can be developed further to be applicable also in a business context. This can include the application by an organization to provide consultancy services for actors who have an interest in the design of human-nature-technology systems such as policy makers, city planners or governmental organizations. As described above, the application of FRESCO requires a high amount of human resources. Therefore, it is suggested to build up a team which can guide the application of FRESCO. Such team could consist of a research assistant who can provide scientific advice to the process such as expert knowledge on methods, a project manager who is capable of organizing the design process and is responsible for achieving milestones and reaching deadlines, and a communications person who is capable of moderating workshops, communicating with stakeholders and reporting back to the design team. Alternatively, this tool can also be a service delivered by a company to its customers. Developing a sustainable business-plan for such an organization would be the logical and next step if this idea would be realized. Such a business-plan should also include social, economic and environmental aspects (Heitmann, 2013). However, if the FRESCO approach would be used to develop such a toolbox, it may be advisable to develop a software which is capable of applying, monitoring and evaluating the whole process.

There might be also other opportunities to further develop the FRESCO framework (chapter 3), the related methodological framework for participatory design (chapter 4), or the evaluation scheme which is illustrated in chapter 5. However, we always have to keep in mind that there is no single optimal solution to a problem which exists in a CAS such as human-nature-technology systems. Approaches like FRESCO may help to solve single issues in such systems with the help of the system users (e.g. re-designing failing policy processes by including political decision makers, or minimizing high trade-offs among two subsystems such as two sustainable development strategies by including key actors working in and with these strategies). Although these frameworks provide a structure and methodological guidance to solve these issues, a content-specific guidance always depends on the actual actors of the system and how they are included in its design.

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Appendix

Appendix - Article 1

Table A 1 Script of a participatory requirements engineering workshop with the aim to develop a conceptual model of a Water-Energy-Food system

Description	Script of a participatory requirements engineering workshop with the aim to develop a conceptual model of a Water-Energy-Food system.
Context	Elicitation of requirements and functions together with scientific experts from different fields of expertise, based on a future vision of a system.
Purpose	Gaining an expert-based, solution oriented and holistic perspective on existing (inter-) sectoral problems in Water-Energy-Food systems.
Primary nature of group task	Divergent: activity designed to produce an array of different ideas and interpretations
Time	**Preparation:** approx. 2 months **Session:** min. approx. 6 hours depending on number of stakeholders and number of facilitators and modeling team-members (possibly two or more days to provide time for reflecting on the workshop process) **Follow up:** approx. 1.5 months
Materials needed to complete the script	Laptop (minimum 1 for presenting + 1 backup laptop; optional: additional laptops for modeling digitally), Beamer, USB Stick and Wireless Pointer, moderator case (fully equipped with pens, masking tape x 2 rolls; scissors, regular tape, stapler, staples, pins; Flipchart markers – 3*4 of each color), voice recorder, extension cords, information material for participants (information folders with program, participant list, and other information), camera, flipchart paper, large paper sheets (pinboard paper) signs for directions to rooms, snacks and non-alcoholic drinks
Inputs	Basic causal model, e.g. from a preparatory expert interview to inform the workshop process
Outputs	List of visions, list of requirements, list of functions, list of constraints, mixed causal diagram of requirements and functions (steering functions and ecosystem functions) Final report of the workshop for the participants Optional: Scientific publication about the workshop content
Team roles required and expertise needed	• Facilitator with experience in stakeholder participation, workshop moderation and presentation of scientific concepts and methods • Modeler with experience in causal-loop modeling, knowledge about the WEF-Nexus, and ideally proficiency in requirements elicitation, requirements modeling and functional analysis • Recorders (number depending on size of the workshop)
Steps	Figure A 1 and Figure A 2
Evaluation criteria	• Participants are motivated to work further on the discussed topics • A conceptual causal model of the underlying WEF-Nexus which includes possible solutions to a central problem formulated as requirements and functions
Author(s)	(Heitmann et al., 2019b)
History & basis for the script	Underlying framework (FRESCO framework) by (Heitmann et al., 2019b)
Revisions	Revised on August 20, 2019 to include feedback of workshop participants
References	(Halbe et al., 2014; Heitmann et al., 2019b; Hovmand et al., 2013; Howarth and Monasterolo, 2017; Lopes and Videira, 2015; Stave, 2010; Vennix, 1996)
Notes	None

Document A 1 Workshop - Stakeholder Information (original German source)

EXPLORATORY DESIGN WORKSHOP ZUM WASSER-ENERGIE-NAHRUNGS NEXUS IN NIEDERSACHSEN

Über den Workshop

Der Experten-Workshop dient primär zur explorativen Anwendung eines entwickelten Frameworks als Teil der Dissertation von Fabian Heitmann. Er soll außerdem eine Plattform bieten, bestehendes Wissen über die komplexen Verknüpfungen von Wasser-, Energie-, und Nahrungssystemen in Niedersachsen zu diskutieren. Seit mehr als zwei Jahrzehnten werden in Niedersachsen bspw. in den Regionen Osnabrück, Weser-Ems und Cloppenburg Fragen zur Intensivlandwirtschaft und der daraus resultierenden Grundwasserverschmutzung diskutiert. Jüngere Entwicklungen wie bspw. Probleme bei der Umsetzung des EEG, der Wasserrahmenrichtlinie oder der Gemeinsamen Agrarpolitik (GAP) zeigen die Komplexität und Reichweite dieses Themas. Viele Forschungsprojekte an Hochschule und Universität Osnabrück haben dies bereits aus unterschiedlichen Perspektiven beleuchtet. Im Rahmen des Zukunftskonzepts UOS 2020 der Universität Osnabrück sowie im Detail der Profillinie „Mensch-Umwelt-Netzwerke“ bietet sich nun an, dieses Wissen gezielt zu synthetisieren und die Kollaboration zwischen den teilnehmenden Experten zu vertiefen. Um diesen Prozess zu unterstützen, wurde ein Workshop entwickelt, welcher auf dem „FRESCO“ Framework basiert (Heitmann et al., 2019b). Das Framework wurde im Rahmen einer Doktorarbeit erstellt und verfolgt einen Design-Ansatz. D.h., dass auf Basis von Expertenwissen Anforderungen an und Funktionen von zukünftigen hypothetischen Transformationsprozessen gestaltet werden.

Methodischer Ansatz

Group Model Building

Group Model Building als eine Form der partizipativen Modellierung, ist ein Prozess zur Visualisierung und Analyse von Systemsichten (Vennix, 1996). Bei der partizipativen Modellierung können je nach Anwendung sowohl individuelle Interviews, als auch Gruppenprozesse initiiert werden. Group model building ist ideal um unterschiedliches Wissen zu bündeln und in einen gemeinsamen Zusammenhang zu bringen, besonders dann, wenn sozialer Austausch in einer Gruppe gefördert und Erwartungen bspw. an mögliche Lösungen eines diskutierten komplexen Problems ermittelt werden sollen (Pahl-Wostl, 2007). Der Prozess wird ohne strenge inhaltliche Vorgaben stattfinden, so dass alle Teilnehmenden die Möglichkeit haben, Ihr eigenes Mentales Modell zum Prozess beizutragen.

Anforderungsanalyse

Die Anforderungsanalyse hat das Ziel, integrative Anforderungen an eine gemeinsam entwickelte Vision zum zentralen Thema „Grundwasser“ zu verstehen und deren Abhängigkeiten, Potentiale, Schnittstellen sowie Grenzen aufzuzeigen. Dazu werden alle genannten Anforderungen verknüpft, um eine ganzheitliche Sicht auf eine entwickelte Vision oder ein Ziel zu erreichen (Heitmann et al., 2019b). Die Methode wird in das Group Model Building integriert.

Funktionale Analyse

Die Funktionale Analyse hat das Ziel, Funktionen und Prozesse eines Systems zu verstehen und Zusammenhänge zwischen Ihnen darzustellen. Funktionen stellen im Gegensatz zu Anforderungen Aktionen dar, welche nötig sind, um ein bestimmtes Ziel zu erfüllen. Eine sowohl technische als auch natürliche Funktion zur Herstellung von Trinkwasser ist bspw. die Wasseraufbereitung. Sowohl Technische Prozesse (Wasseraufbereitungsanlagen) als auch natürliche Strukturen (Feuchtgebiete) können diese Funktion ermöglichen (Halbe et al., 2014). Solche und weitere Zusammenhänge werden in dem Workshop bezogen auf die Region gemeinsam erarbeitet.

Ziel des Workshops

Inhaltliches Ziel des Workshops ist es, einen strukturierten Überblick über den Wasser-Energie-Nahrungsnexus in Niedersachsen mit Hilfe des vorgegebenen Frameworks zu erarbeiten und verfügbares Wissen über mehrschichtige Politikprozesse, sektorale Schnittstellen und Anforderungen an zukünftige Veränderungen wie bspw. technologische Innovationen oder gesetzliche Rahmenbedingungen sowie die daraus resultierenden Funktionen zu erarbeiten. Als Output des Workshops sollen eine Anforderungskarte (Requirements Map), eine Funktionale Karte (Functional Map) sowie konkrete Vorschläge alternativer Systemdesigns entwickelt werden.

Übergeordnete Ziele des Workshops sind 1. das im Rahmen einer Dissertation entwickelte Meta-Framework "FRESCO" in einem wissenschaftlichen Kontext zusammen mit Experten anzuwenden und kritisch zu reflektieren, und 2. Kollaboration zwischen den teilnehmenden Experten im Rahmen des Strategieprozesses UOS 2020 der Universität sowie den Profillinien zu fördern, mit der Option, langfristig ein oder mehrere wissenschaftliche Strategieartikel zu veröffentlichen.

Ablauf des Workshops (vorläufig)

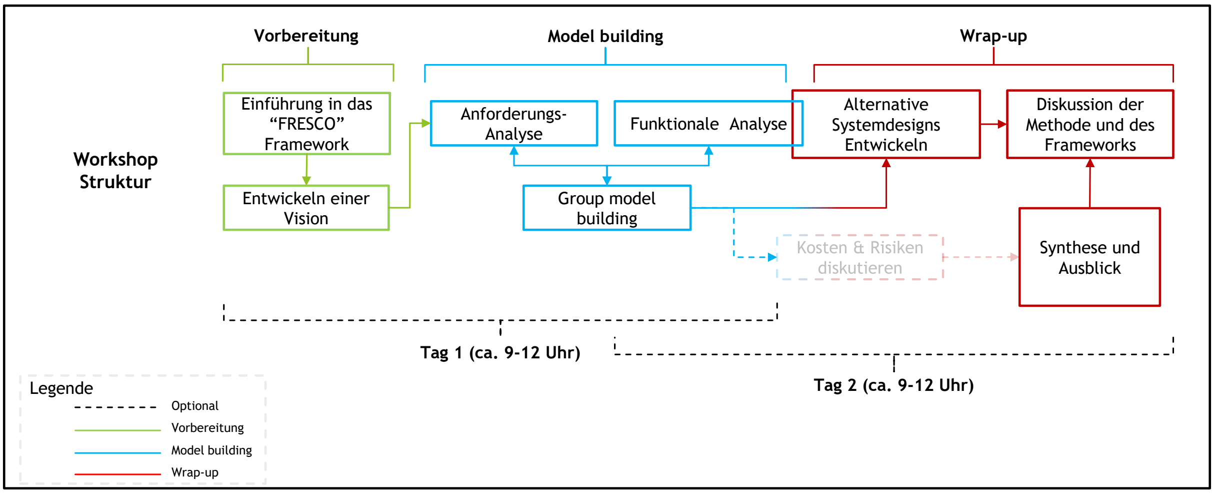

Figure A 1 Ablauf des Workshops (vorläufig) (original source)

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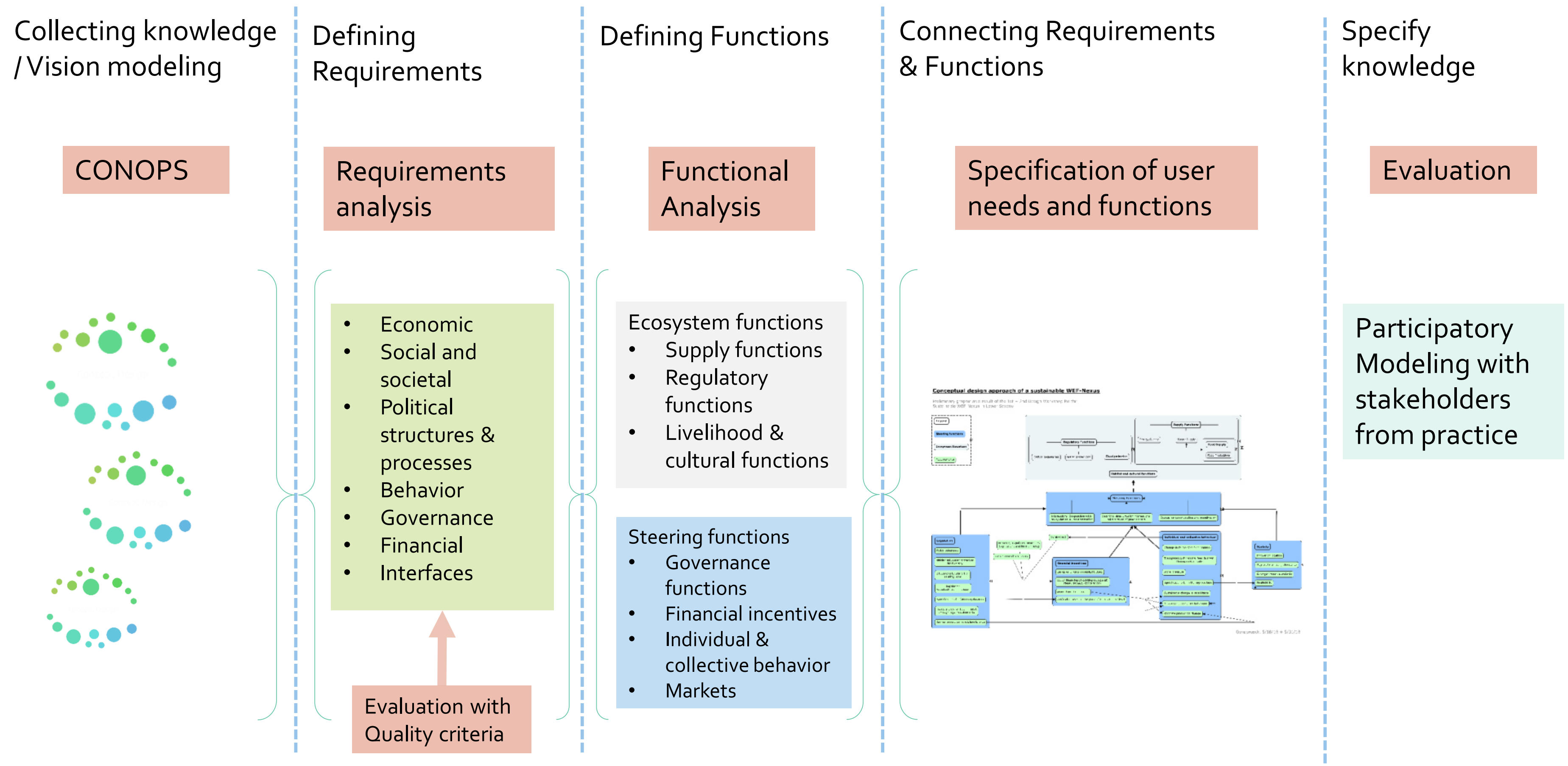

Figure A 2 Structure of the Nexus design workshop

Table A 2 Actors and stages involved in the participatory design process (anonymized)

Actor	type	Expertise	Related Nexus sector(s)	scale	System design level	Level of engagement	Available data type
Professor 1 (workshop)	Science	Water management	W	R; N; I	Conceptual	Consult	Causal diagram
Professor 2 (workshop)	Science	Environmental Economics	W; F	R; N; I	Conceptual	Consult	Causal diagram
Professor 3 (workshop)	Science	Political Science	W; F	R; N; I	Conceptual	Consult	Causal diagram
Professor 4 (workshop)	Science	Human Geography	F	R; N; I	Conceptual	Consult	Causal diagram
Professor 5 (workshop)	Science	Geography	W; F	R; N; I	Conceptual	Consult	Causal diagram
Post-Doc (workshop)	Science	Transition Research	W; E; F	R; I	Conceptual	Consult	Causal diagram
Doctoral Candidate 1 (workshop)	Science	Environmental Economics	F	R; N; I	Conceptual	Consult	Causal diagram
Doctoral Candidate 2 (workshop)	Science	Social Science	W; F	R; N; I	Conceptual	Consult	Causal diagram
1 (interview)	Governmental ministry	Environmental protection organization	W	federate state	Detailed	Consult	Causal diagram
2 (interview)	Self-governing organization	Interest group, agriculture	F	federate state	Detailed	Consult	Causal diagram
3 (interview)	Governmental agency	Agricultural agency	W	regional	Detailed	Consult	Causal diagram
4 (interview)	Public-law organization	Water provisioning and protection	W	regional	Detailed	Consult	Causal diagram
5 (interview)	Professional association	Biogas	E	regional	Detailed	Consult	Causal diagram
6 (interview)	Public holding company	Water and energy provider	W; E	regional	Detailed	Consult	Causal diagram
7 (interview)	Maintenance association	Water maintenance	W	regional	Detailed	Consult	Causal diagram
8 (interview)	Science	Agricultural	F	regional	Detailed	Consult	Causal diagram
9 (interview)	Agricultural production	Agricultural	F	regional	Detailed	Consult	Causal diagram
10 (interview)	Science	Energy-, Environmental- and Process Engineering	W; E; F	Regional	Detailed	Consult	Causal diagram
11 (interview)	Science	Sustainable Bioprocess Engineering	W; E; F	National	Detailed	Consult	Causal diagram
12	Governmental ministry	Control agency for food, agriculture and consumer safety	F	federate state	Detailed	Consult	Causal diagram
13	NGO	Environmental protection organization	environment	regional	Detailed	Consult	Causal diagram
14	Registered association	Developmental work	W; F	regional; global	Detailed	Consult	Causal diagram

Table A 3 Requirements mentioned during the pre-interview and expert workshop (original data)

Gesetzgebung	Schnittstellen	technische Innovationen	finanzielle Aspekte	wirtschaftliche Aspekte	soziale + gesellschaftl. Aspekte	politische Strukturen + Prozesse	Werte	Verhalten
Biodiversität	Anreizstrukturen für intersektorale Zusammenarbeit von Praxisakteuren	Ausbau von Speichertechnologien	bessere Finanzierung bestehender (erfolgreicher) Maßnahmen (zB. Kooperationen)	Kreislaufwirtschaft	Gesellschaftlicher Druck	Aufbrechen politischer Strukturen (Agrar + Umwelt)	Bewusstsein für Energieverbrauch	Bedarfsgerechter Gülleeinsatz
CO_2 Steuer	Ausbau von Kooperationen	Erhöhung des Wirkungsgrades von KWK Anlagen	Einbezug von Umweltkosten	Pachtung von Landwirtschaftlicher Nutzfläche zur Intensivnutzung	Arbeit von Umweltverbänden	Durchsetzung der Düngeverordnung	Landschaftsbild	effizienterer Düngeeinsatz
EEG Reform	Ausbildung	neue landwirtschaftliche Technologien	klarer Investitionsplan	Profitabilität	Verfügbarmachen von Stakeholderwissen	Effizienzstrategie	Naturschutz	Nachhaltiges Konsumverhalten
Effektive Durchsetzung bestehender Gesetze	Datentransparenz	neue Nitratfilteranlagen		Regionale Vermarktungsstrukturen	Versorgungssicherheit W + E + F	Innovationsstandort	Umweltberatung für Landwirte	Nachhaltigkeitswandel im Einzelhandel
effektives Düngegesetz	Integriertes multifunktionales Landschaftsmanagement	Verbesserung der Wirtschaftlichkeit von Solaranlagen		technische Innovationen		Kohleausstieg		Nicht energieproduzierende Landwirte
Förderung ökologischer Landwirtschaft	Intersektorale Kooperation bei Policy Design + Implementierung	Wärmekomplettnutzung				Konkreter Pfad für die Braunkohleförderung		Politischer Wille
GAP Reform	Nationale + Internationale Netzwerke					Starke Umweltverbände		Veränderung des Selbstverständnisses der Landwirte
Gesetzgebung (Standards als Vorschrift)	Räume zur Kommunikation und Koordination					Zukunftsfähige Agrarpolitik		
kohärente Gesetzgebung (nationale/EU Strategie für WEF-Nexus)								
Strengerer Boden/Wasserschutz								

Table A 4 Temporary result of the vision modeling process in the workshop (original data)

Agriculture	Coopera-tion/inte-gration	Energy	Water	Regional	Structures	Technology
Nachhaltige Land-wirtschaft mit der sich Landwirte in der Region identifi-zieren können	Enge Ver-netzung von Konsument + Nahrungs-mittelerzeu-ger	Regionales Energiesys-tem (Power to X: Solar + Wind, Bio-masse, Ge-othermie, Wasserkraft)	Wasserquali-tät von Flüs-sen, Seen + Grundwasser deutlich ver-bessert (EU Standard o. mehr) --> Ar-tenschutz + gesundheitli-che Risiken minimiert	Region als po-sitives Bei-spiel für ge-lungene Transforma-tion	ökologische "funktionie-rende" Dorfstruktu-ren	Neue techni-sche Möglich-keiten haben sich durchge-setzt (z.B. Gülle-Separa-tion)
Landwirte werden besser beraten, re-flektieren ihre Rolle, haben geeignete In-strumente zur Hand	Integration der Poli-tiksektoren W-E-F	Regionale Energie- und Nahrungssys-teme, einge-bettet in nati-onale und in-ternationale Systeme --> "Subsidiari-tät"		Niedersach-sen als ökolo-gische "Mo-dellregion" (analog zu Freiburg als "Ökostadt"		
Landwirte haben neues Selbstver-ständnis (Ecosystem Services + Gesunde Ernährung als wich-tiger Beitrag zur Ge-sellschaft)	Innovati-onszentren (z.B. Koope-ration "Ret-tet ..." sind internatio-nal vernetzt	Stark redu-zierter Ener-gieverbrauch - Energieexpor-teur durch Wind und Sonne				
Gesundes, er-schwingliches regio-nales Nahrungsan-gebot, das von Kon-sumenten geschätzt und priori-siert/nachgefragt wird	gemeinsa-mes Prob-lemver-ständnis al-ler Akteure + Verände-rungsbe-wusstsein					
Regionales Nah-rungssystem (ökolo-gischer Landbau, diversifiziert, regio-nale Vermarktung XXXX)	Aktive Ein-bindung der Stakeholder (v.a. Land-wirte); frei-willig, funk-tionierende Anreizsys-teme					
Nutzung von Öko-systemleistungen in der Landschafts- und Regionalpla-nung; Prämien zur Förderung von Öko-systemleistungen	Umweltindi-katoren im Netz verfüg-bar - Bürger sind aktiv in Monitoring einbezogen					
Bewusster Konsum						
Multifunktionale Landwirtschaft ist umgesetzt						
Diversifizierte Land-wirtschaft + Exten-sivierung der Pro-duktion						

nachhaltig produziertes Nahrungsmittelangebot - leistbar für "Jedermann"	
Weniger Nachfrage nach Fleisch	
Dezentralisierung der Fleischproduktion	
Nachhaltige Futtermittel	
Ein(e) "grüne(r)" Landwirtschaftsminister(in)	
Einführung von Geschäftsmodellen mit positiven Auswirkung auf ÖSL	
Integriertes Landschaftsmanagement --> Kooperationsmodelle	

Table A 5 Temporary result of the requirements elicitation process in the workshop (original data)

Gesetzgebung	Biodiversität	CO_2 Steuer	EEG Reform	Effektive Durchsetzung bestehender Gesetze	effektives Düngegesetz	Förderung ökologischer Landwirtschaft	GAP Reform	Gesetzgebung (Standards als Vorschrift)	kohärente Gesetzgebung (nationale/EU Strategie für WEF-Nexus)	Strengerer Boden/Wasserschutz
Schnittstellen	Anreizstrukturen für intersektorale Zusammenarbeit von Praxisakteuren	Ausbau von Kooperationen	Ausbildung	Datentransparenz	Integriertes multifunktionales Landschaftsmanagement	Intersektorale Kooperation bei Policy Design + Implementierung	Nationale + Internationale Netzwerke	Räume zur Kommunikation und Koordination		
Technische Innovationen	Ausbau von Speichertechnologien	Erhöhung des Wirkungsgrades von KWK Anlagen	neue landwirtschaftliche Technologien	neue Nitratfilteranlagen	Verbesserung der Wirtschaftlichkeit von Solaranlagen	Wärmekomplettnutzung				
Finanzielle Aspekte	bessere Finanzierung bestehender (erfolgreicher) Maßnahmen (zB. Kooperationen)	Einbezug von Umweltkosten	klarer Investitionsplan							
Wirtschaftliche Aspekte	Kreislaufwirtschaft	Pachtung von Landwirtschaftlicher Nutzfläche zur Intensivnutzung	Profitabilität	Regionale Vermarktungsstrukturen	technische Innovationen					
Soziale + gesellschaftl. Aspekte	Gesellschaftlicher Druck	Arbeit von Umweltverbänden	Verfügbarmachen von Stakeholder Wissen	Versorgungssicherheit W + E + F						
Politische Strukturen + Prozesse	Aufbrechen politischer Strukturen (Agrar + Umwelt)	Durchsetzung der Düngeverordnung	Effizienzstrategie	Innovationsstandort	Kohleausstieg	Konkreter Pfad für die Braunkohleförderung	Starke Umweltverbände	Zukunftsfähige Agrarpolitik		
Werte	Bewusstsein für Energieverbrauch	Landschaftsbild	Naturschutz	Umweltberatung für Landwirte						
Verhalten	Bedarfsgerechter Gülleeinsatz	effizienterer Düngeeinsatz	Nachhaltiges Konsumverhalten	Nachhaltigkeitswandel im Einzelhandel	Nicht energieproduzierende Landwirte	Politischer Wille	Veränderung des Selbstverständnisses der Landwirte			

Table A 6 Temporary result of the constraints elicitation process in the workshop (original data)

Hemmnisse								
Gesetzgebung	**Schnittstellen**	**Technisch**	**Finanziell**	**Wirtschaftlich**	**Sozial + gesellschaftlich**	**Politisch**	**Werte**	**Verhalten**
EEG (aktuell)	verhärtete Fronten zwischen Stakeholdern	Antibiotikaeinsatz in der Intensivtierhaltung	Wille nach monetärer Sicherheit (Betreiber und Produzenten)	zentrale Vermarktungsstrukturen	fehlendes gesellschaftliches Verantwortungsbewusstsein	Schwach durchgesetzte Düngeverordnung	konventioneller Einzelhandel	Fleischorientiertes Konsumverhalten
GAP (aktuell)		Versiegelung	Einkommenssicherheit	Konventionelle Landwirtschaft		Förderung von Next-Generation-biofuels	zu wenig Know-how bei Umweltberatung für Landwirte	mangelnde Bereitschaft der Landwirte zu Transformation
Fehlende legitime Kontrolle des Einzelhandels		Nitrateinträge	steigende Nahrungsmittelpreise	Veredelung mit Abkopplung vom Land		fragmentierte politische und administrative Strukturen		
		Phosphoreinträge	sinkende Nahrungsmittelpreise	Viehdichte		Nachfrage auf dem Agrarmarkt nach Energiepflanzen		
		steigender Energiebedarf	steigende EE Umlage	Anbau von Pflanzen zur Energiegewinnung		Subvention von Biogas		
		alte + ineffiziente Kraftwerke		Verfügbarkeit (Ackerland)				

Table A 7 Temporary result of the functional derivation process in the workshop (original data)

Funktionen						
Natürlich	**Technisch**	**Ökosystemleistungen**	**Sozial**	**Finanziell**	**Wirtschaftlich**	**Politisch**
Wasseraufbereitung		Wasserbereitstellung	Gesellschaftliche Verantwortung	Finanzierung	Verkauf nachhaltiger Nahrungsmittel im Einzelhandel	politische Verantwortung
ökologische Landwirtschaft als Treiber für Transformation	Wasserbereitstellung	Produktion von Nahrung	Innovation	Förderung	Landwirtschaft	
Grundwasserneubildung	Wassertransport	Produktion von Futter	Ausbildung	Subventionen		
Düngung		Speicherung von CO2	Aufklärung	Entrepreneurship		
	Einzelhandel (Verkauf)	Bestäubung	Beratung			
Produktion von Nahrungsmitteln		Bodenneubildung	Genossenschaftsarbeit			
Produktion von Futtermitteln		Primärproduktion				
Nitratfiltration		Erholung				
Produktion von Energie		Schädlingsbekämpfung				
Fütterung		Schutzleistung für Erosionsgefahr				
		genetische Vielfalt				

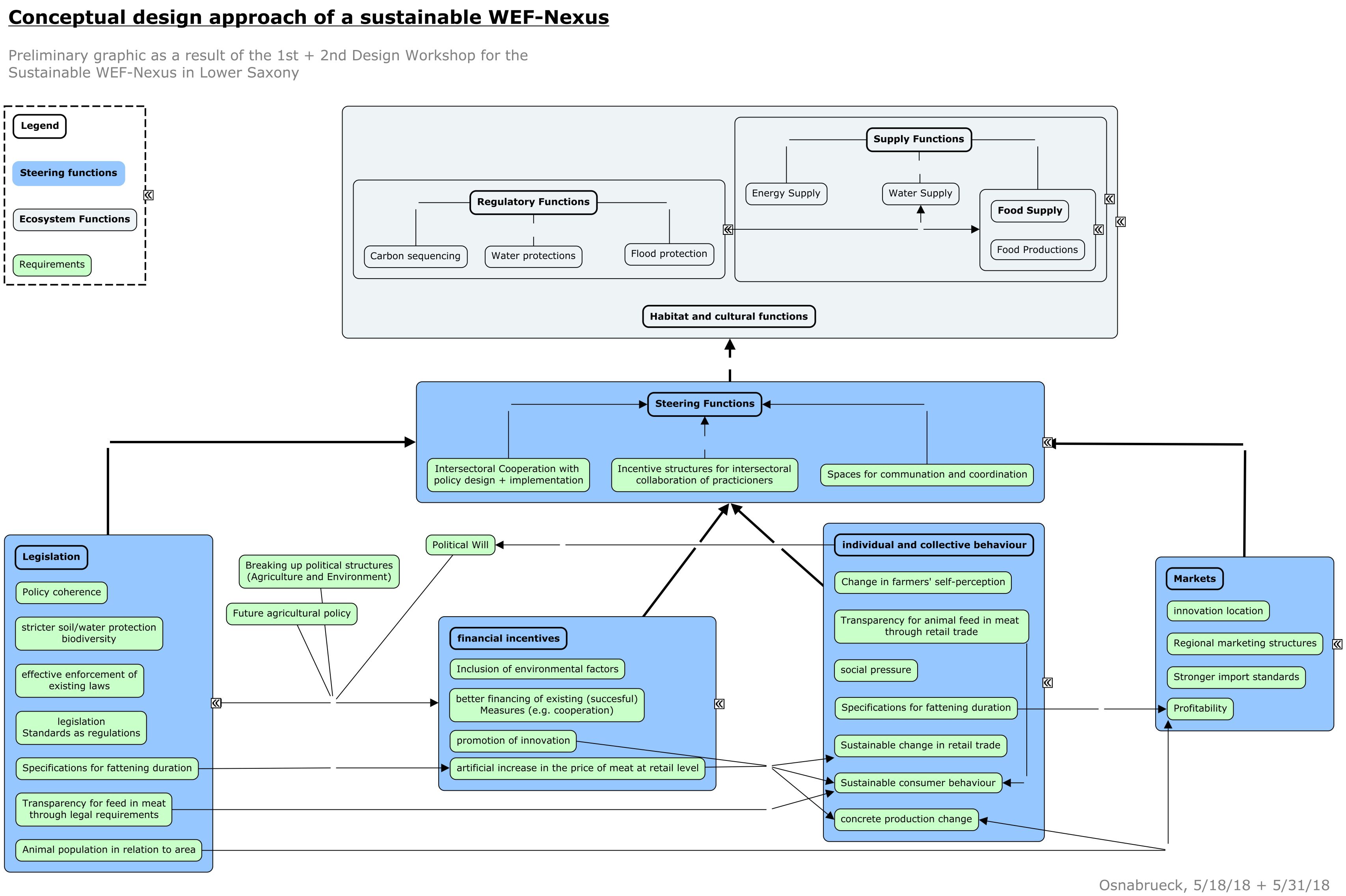

Figure A 3 Preliminary workshop results

Appendix - Article 2

Document A 2 Stakeholder Information Flyer (German)

UNIVERSITÄT OSNABRÜCK

Anforderungsanalyse & Funktionale Analyse der Agenda 2030 für nachhaltige Entwicklung

Detailinformationen 4 \ 2018

Konzept zur Analyse der Deutschen Nachhaltigkeitsstrategie - Agenda 2030
Eine ganzheitliche Designstudie zur Agenda 2030 für nachhaltige Entwicklung

Herzlich Willkommen

\ **Regenerative Energien**
Der Ausbau regenerativer Energien und damit verbundene Ziele zur CO_2 Reduktion sind von großer Bedeutung für das Erreichen der Agenda 2030. Während Wasser ein regional „noch" im Überfluss verfügbares Gut ist, ist die nachhaltige Erzeugung von Energie auch entscheidend für den Gewässerschutz. Auch auf den Bereich „Nahrung" hat die Energieerzeugung signifikanten Einfluss. Die wissenschaftliche Untermauerung und Initiierung von Kooperationen von Akteuren aus den Bereichen Wasser, Energie und Nahrung ist dabei nicht ohne Grund eine oft genannte Teillösung in Nachhaltigkeits-strategien.

\ **Lösungen sind systemisch und komplex**
Die Umsetzung nachhaltiger Strategien wie der Agenda 2030 erfordern ganzheitliche Ansätze, welche auch Anforderungen an Maßnahmen von Akteuren sowohl aus verschiedenen Sektoren als auch auf verschiedenen Entscheidungsebenen berücksichtigen.

\ **Praktische Umsetzbarkeit aktueller Forschung** Wissenschaft wird oft als „weit entfernt" von praktischer Umsetzung angesehen. Ob theoretische Ansätze aus der Forschung den Anforderungen der Praxis gerecht werden, soll partizipativ mit Ihnen als Experte Ihrer Stadt oder Ihres Landes sichergestellt werden.

Die Agenda 2030 für nachhaltige Entwicklung

\ **Die deutsche Nachhaltigkeitsstrategielandschaft** ist sehr vielfältig. Die Bundesregierung sowie viele Städte, darunter Hamburg, Berlin und München aber auch Regionen (bspw. das Land Niedersachsen oder die Metropolregion Bremen-Oldenburg) haben sich zur ehrgeizigen Umsetzung der Ziele der Agenda 2030 auf nationaler und regionale Ebene verpflichtet. Regionale Strategien sollen die Umsetzung der nationalen Richtlinie unterstützen, als auch die regionale Bedeutung von Ressourcen und regionalen Bedürfnissen in die Umsetzung ihrer eigenen Nachhaltigkeits-strategien integrieren.

\ **Regionale Bedürfnisse** sind dabei ein wesentlicher Bestandteil der Strategien. So haben beispielsweise die Ressourcen Wasser, Energie und Nahrung in den jeweiligen Städten und Regionen unterschiedliche Bedeutung. Ursache hierfür ist oft die unterschiedliche Nutzbarkeit des Bodens für die Nahrungsmittel- oder Energiegewinnung, Unterschiede der Infrastruktur oder der Bedarf an bestimmten Roh -und Hilfsstoffen durch bestehende Produktions-betriebe, die in den jeweiligen Regionen verwurzelt sind.

\ **Das Forschungsvorhaben** zeigt exemplarisch die große Bedeutung der regionalen Strategien für den Erfolg der nationalen Nachhaltigkeitsstrategie. Ausgehend von den individuellen regionalen Gegebenheiten sind die Anforderungen der Städte an die genutzten Ressourcen sehr unterschiedlich. Städte "konsumieren" unterschiedliche Ökosystemleistungen, was zu unterschiedlichen Implikationen für die Umsetzung der jeweiligen Nachhaltigkeitsstrategien führt.

Methodik

Der Studie liegen mehrere angewandte Methoden zugrunde:

\ Partizipative Modellierung

Partizipative Modellierung ist ein Prozess zur Visualisierung und Analyse von Systemsichten. Hierfür können je nach Anwendung sowohl individuelle Interviews, als auch Gruppenprozesse initiiert werden. Die in dieser Studie verwendeten individuellen Interviews sollen ohne strenge inhaltliche Vorgaben stattfinden. So haben alle Teilnehmenden die Möglichkeit Ihr eigenes *Mentales Modell* zum Prozess beizutragen, welches als *Kausalmodell* festgehalten wird.

\ Anforderungsanalyse

Die Anforderungsanalyse hat das Ziel, Anforderungen an das zentrale Thema *regenerative Energien* eines jeden Teilnehmers zu verstehen sowie Abhängigkeiten und Potentiale aufzuzeigen. Dazu werden Anforderungen aus allen Interviews verknüpft, um eine ganzheitliche Sicht zu erreichen.

\ Funktionale Analyse

Die Funktionale Analyse hat das Ziel, Funktionen und Prozesse eines Systems zu verstehen und Zusammenhänge zwischen Ihnen darzustellen. Funktionen stellen im Gegensatz zu Anforderungen gezielte Aktionen dar, welche nötig sind, um ein bestimmtes Ziel zu erfüllen. Eine Funktion ist bspw. die Bereitstellung von Energie (Wind, Sonne, Wasser), welche zur Stromerzeugung benötigt wird.

Abbildung 1
Wasser, Energie, Nahrungsnexus am Beispiel der SDGs

Abbildung 2
Die 17 Sustainable Development Goals

Konzepte

\ Systemwissenschaft

Das Ganze ist mehr als die Summe seiner Teile: Ziel der Systemwissenschaft ist es, **die Struktur und die Wechselbeziehungen eines Systems** zu analysieren, um so das Verhalten des Systems zu verstehen. In einigen Fällen können dadurch auch Aussagen über zukünftige Entwicklungen gemacht werden. Eine besondere Herausforderung ist dabei das **Interdisziplinäre Arbeiten**, welches eine **ganzheitliche Sicht auf Systeme** ermöglicht.

\ System Engineering

„System Engineering versucht, die Gesamtsystemfunktionalität, unter Verwendung gewichteter Ziele und Kompromisse zu optimieren, um Gesamtsystemkompatibilität und Funktionalität zu erreichen", (Crowder et al., 2016, S. 2). Da oft solch eine Gesamtsystem-funktionalität fehlt, schlägt unsere Studie einen konkreten **Designansatz** vor, der auf System Engineering basiert, um die Koordination zwischen verschiedenen Sektoren zu stärken. System Engineering unterstützt im Vergleich zu anderen Ansätzen eine standardisierte Modellierungsmethode zur **Darstellung diverser Akteursziele** (Dahmann et al., 2009). Trade-offs zwischen diesen Zielen manifestieren sich oft in sogenannten **kritischen Bindungen**, die für das Verständnis und die Regulierung von Zielen von großer Bedeutung sind.

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Der Nexus

Der Wasser-Energie-Nahrungs Nexus (WEF-Nexus) ist ein innovatives Forschungsfeld, das multidisziplinäre Methoden zur Bewertung von Wasser-, Energie- und Nahrungsmittelproblemen aus sektorübergreifender Perspektive untersucht (Abbildung 1). Diese Art der integrierten Forschung ist besonders vielversprechend für die Fokussierung auf Kompromisse und Synergien, die sich aus einem Zusammenspiel zwischen heterogenen Sektoren und ihren Zielen ergeben (the Economic Commission for Europe, 2016). Der WEF-Nexus beschreibt das Problem der fehlenden Kooperation zwischen dem Wasser-, Energie- und Nahrungsmittelsektor.

\ Der Begriff „Nexus"
wird von uns als die komplexen Zusammenhänge zwischen Sektoren oder Systemen definiert. In der Nexus-Forschung werden typischerweise **multidisziplinäre Methoden** eingesetzt, Probleme in einem System aus einer ganzheitlichen Perspektive zu beurteilen. Wie in Pahl-Wostl (2015, S. 275f) dargelegt, könnte der Nexus eine Neuausrichtung der Problemperspektive voranbringen sowie ausgewogenere sektorale Verhandlungen und Akteursbeteiligungen unterstützen.

\ Die Komplexität von Nexus-Systemen
wird durch eine vereinfachte Abbildung der Grundwasserbelastung in Niedersachen durch Nitrat deutlich (Abbildung 3). Komplexe heterogene Elemente, Beziehungen und Funktionen in den sozialen, ökologischen und technischen Subsystemen erschweren es, das Grundwasserproblem oder andere Fragestellungen im Gesamtsystem zu verstehen und zu lösen (Bizikova et al., 2013).

\ Zusammenarbeit verschiedener wissenschaftlicher Disziplinen wird für eine effektive Nexus Analyse benötigt (El Costa, 2015). Nur durch die Bündelung von Wissen und Entscheidungskompetenzen können effektive Lösungsstrategien, wie bspw. zur Reduzierung von CO2-Emissionen entwickelt werden.

Die Agenda 2030 für nachhaltige Entwicklung

Die Überarbeitung der Nachhaltigkeitsagenda sowie die teils mangelnde Kohärenz zwischen den Indikatorensets der verschiedenen Strategien erschweren den Vergleich zwischen ihnen. Obwohl die Mehrzahl der Indikatoren der ehemaligen nationalen Nachhaltigkeitsstrategie auch in der überarbeiteten Agenda 2030 enthalten ist, werden diese Indikatoren nun in Übereinstimmung mit den 17 internationalen Entwicklungszielen der Vereinten Nationen formuliert. Die Indikatoren basieren auf verschiedenen Datenbanken, darunter vor allem Statistiken aus amtlichen Statistiken und Verwaltungsdaten. Leider haben nur sechs der 20 bevölkerungsreichsten Städte Deutschlands Indikatoren für ein regelmäßiges Monitoring der angewandten Strategie erarbeitet. Dies zeigt die Notwendigkeit eines anderen Ansatzes für den Vergleich der Strategien. Um diesen Vergleich zu erreichen, schlagen wir Kausalmodelle vor (Abbildung 3), welche den Kern jeder analysierten Strategie beschreiben. In unserem Fall konzentrieren wir uns auf energiebezogene Teile der Strategien der drei größten Städte Berlin, Hamburg und München. Dies ermöglicht es uns, die Anwendung mit unserem Framework zu demonstrieren und gleichzeitig die Komplexität bezogen auf die zur Verfügung stehenden Zeit zu minimieren.

Conceptual map - Groundwater Quality Osnabrueck region

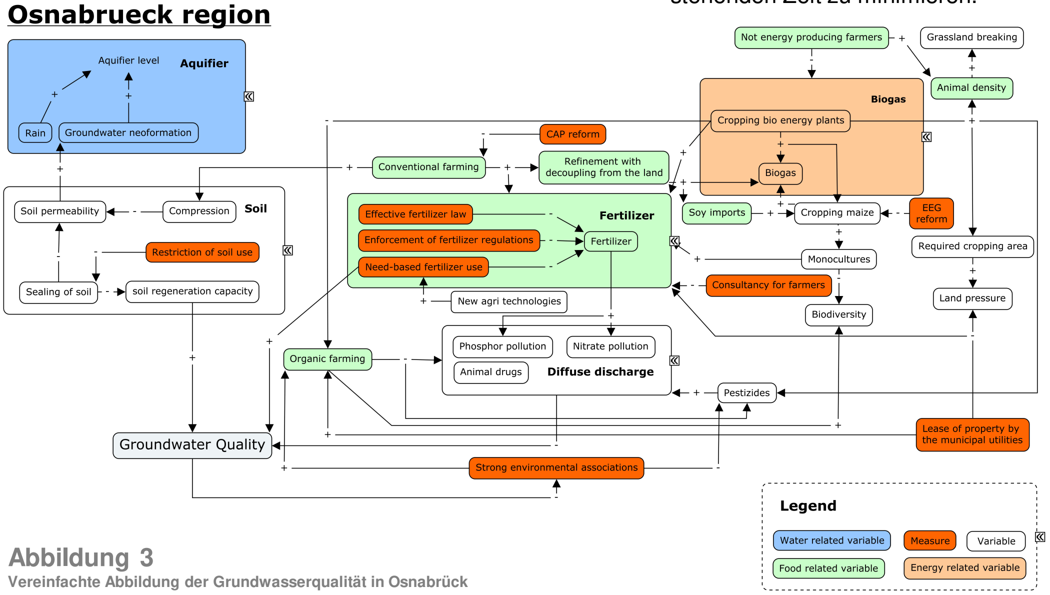

Abbildung 3
Vereinfachte Abbildung der Grundwasserqualität in Osnabrück

Konzept zur Analyse der Deutschen Nachhaltigkeitsstrategie - Agenda 2030

Eine ganzheitliche Designstudie zur Agenda 2030 für nachhaltige Entwicklung

Kurzbeschreibung
Die im Rahmen einer Doktorarbeit entwickelte Studie hat das Ziel, fundierte, gezielte und effektive Managementpläne bezüglich der Agenda 2030 für nachhaltige Entwicklung mit Experten partizipativ zu diskutieren sowie ungenutzte Potentiale aufzudecken und zu kommunizieren. Der dabei verwendete ganzheitliche Ansatz stellt die urbanen und nationalen Ziele wie sie in den Strategien formuliert sind in einen gemeinsamen Zusammenhang, und erlaubt es, Potentiale, Trade-Offs und Synergien hervorzuheben, zu diskutieren sowie nachhaltig systemische Designvorschläge zu entwickeln. Das Projekt ist in vier Phasen aufgeteilt:

1. **Konzeptualisierung und Erarbeiten eines multidisziplinären Design-Ansatzes**
2. **Durchführung von Interviews**
3. **Analyse der Interviews**
4. **Diskussion und Entwurf von Lösungsstrategien**

Hierzu wurde ein Ansatz entwickelt, der Konzepte der Systemwissenschaft und des Systemingenieurswesens verknüpft. Durch die Systemwissenschaft wird der Fokus auf die Analyse und das Verständnis der Vernetzung unterschiedlich funktionierender Teilsysteme (urbane Strategien) gelegt. Vereinfachte Systemmodelle werden hierfür zusammen mit teilnehmenden Experten erstellt. Die System Ingenieurswissenschaft (Systems Engineering) hingegen zielt auf das Design oder Re-Design von Systemen ab, welche individuell auf einzelne System-Nutzer (Akteure) ausgelegt sind. Die Interviews dienen dabei als Datengrundlage für anschließende Analysen, in denen die Schwerpunkte auf die Anforderungen der Experten an das System sowie die bestehenden Funktionen und Prozesse im System gelegt werden. So entstehen nutzbare System-Design-Vorschläge, welche anschließend partizipativ weiterentwickelt und diskutiert werden können.

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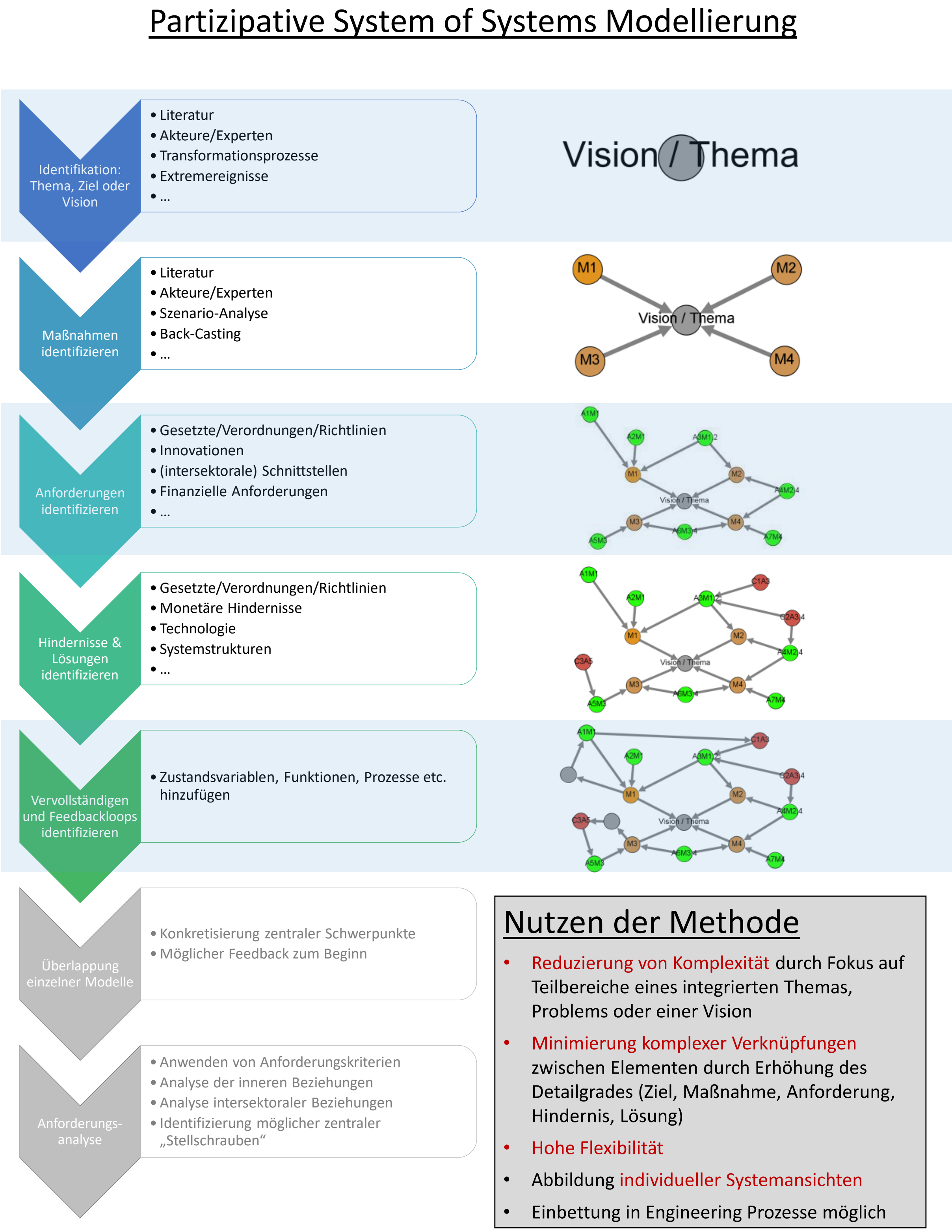

Figure A 4 The participatory SoS Modeling framework (German)

Appendix - Article 3

Table A 8 Complete variable set from the participatory stakeholder interviews

Label	Source	Actor	Type	Governance level	Betweenness-centrality
district office	Hamburg	ActorA	A	Urban_Hamburg	0.000915
environmental agency	Hamburg	ActorA	A	Urban_Hamburg	0.000915
senate chancellery	Hamburg	ActorA	A	Urban_Hamburg	0.000915
Civil engineering costs	Hamburg	ActorA	C	Urban_Hamburg	0.000039
Costs + space requirement ice storage	Hamburg	ActorA	C	Urban_Hamburg	0
difficult market situation for project developer B	Hamburg	ActorA	C	Urban_Hamburg	0
Length of heat conduction from solar collectors (cost)	Hamburg	ActorA	C	Urban_Hamburg	0.000058
Lack of National willingness to take risks on the part of project developers A	Hamburg	ActorA	C	Urban_Hamburg	0
Cooperation National transport associations	Hamburg	ActorA	I	Urban_Hamburg	0.000915
MySmartLife	Hamburg	ActorA	O	Urban_Hamburg	0
Solar thermal on the motorway embankment	Hamburg	ActorA	O	Urban_Hamburg	0.002558
MySmartLife Energy	Hamburg	ActorA	O	Urban_Hamburg	0.001088
MySmartLife Information and Communication Technologies	Hamburg	ActorA	O	Urban_Hamburg	0.000781
MySmartLife Mobility (public transport, car sharing, e-mobility)	Hamburg	ActorA	O	Urban_Hamburg	0
Broadband expansion (capacity utilization of construction companies)	Hamburg	ActorA	R	Urban_Hamburg	0
Measurement technology for energy flows	Hamburg	ActorA	R	Urban_Hamburg	0
thermal insulation of new building	Hamburg_Hamburg	ActorA_ActorE	R	Urban_Hamburg	0.001314
Smart heat pump	Hamburg_Hamburg_Hamburg	ActorA_ActorJ_ActorE	R	Urban_Hamburg	0.000117
Smart District Heating	Hamburg_Hamburg_Hamburg	ActorA_ActorJ_ActorF	F	Urban_Hamburg	0.003254
funding logic of renewables	Hamburg_National	ActorA_National	R	Urban_National	0.000019
senate level	Berlin	ActorB	A	Urban_Berlin	0
administration	Berlin	ActorB	A	Urban_Berlin	0.009989
Berlin House of Representatives	Berlin	ActorB	A	Urban_Berlin	0
Civil Society and Science	Berlin	ActorB	A	Urban_Berlin	0.014755
Climate protection administration network	Berlin	ActorB	A	Urban_Berlin	0.002551
Climate Protection Council	Berlin	ActorB	A	Urban_Berlin	0.025758
Climate Protection Network	Berlin	ActorB	A	Urban_Berlin	0

Label	Source	Actor	Type	Governance level	Betweenness-centrality
consumer associations	Berlin	ActorB	A	Urban_Berlin	0
Divisions	Berlin	ActorB	A	Urban_Berlin	0
environmental associations	Berlin	ActorB	A	Urban_Berlin	0
Federal Council and Laender	Berlin	ActorB	A	Urban_Berlin	0
financial officer	Berlin	ActorB	A	Urban_Berlin	0
Government in Berlin	Berlin	ActorB	A	Urban_Berlin	0
Offices	Berlin	ActorB	A	Urban_Berlin	0
senate	Berlin	ActorB	A	Urban_Berlin	0
Senate Department for Economics, Energy and Enterprises	Berlin	ActorB	A	Urban_Berlin	0
State Secretaries Round	Berlin	ActorB	A	Urban_Berlin	0.009014
supreme mayor	Berlin	ActorB	A	Urban_Berlin	0
tenant protection associations	Berlin	ActorB	A	Urban_Berlin	0
Low prices for fossil fuels	Berlin	ActorB	C	Urban_Berlin	0
Non-calculability of measures	Berlin	ActorB	C	Urban_Berlin	0
Restraint on the part of actors at federal and international level	Berlin	ActorB	C	Urban_Berlin	0
CO2 tax not specified in coalition agreement	Berlin	ActorB	C	Urban_Berlin	0
exclusively greening of the energy	Berlin	ActorB	C	Urban_Berlin	0
long duration of laws	Berlin	ActorB	C	Urban_Berlin	0
low frequency of law adaptation	Berlin	ActorB	C	Urban_Berlin	0
Inaction of the actors	Berlin	ActorB	C	Urban_Berlin	0
acceptance problem	Berlin	ActorB	C	Urban_Berlin	0.002886
Too little technical competence	Berlin	ActorB	C	Urban_Berlin	0
CO2 tax	Berlin	ActorB	E	Urban_Berlin	0.002244
Living	Berlin	ActorB	G	Urban_Berlin	0
Transport	Berlin	ActorB	G	Urban_Berlin	0
understaffed	Berlin	ActorB	G	Urban_Berlin	0
Majorities of voting actors	Berlin	ActorB	G	Urban_Berlin	0.001392

Label	Source	Actor	Type	Governance level	Betweenness-centrality
economy	Berlin	ActorB	G	Urban_Berlin	0.006509
Particularly strong characteristic of the BEK	Berlin	ActorB	G	Urban_Berlin	0.000258
Conditions for public buildings	Berlin	ActorB	G	Urban_Berlin	0
policy	Berlin	ActorB	G	Urban_Berlin	0.006537
conflicting goals	Berlin	ActorB	I	Urban_Berlin	0
cooperation	Berlin	ActorB	I	Urban_Berlin	0.005981
good network capacity in the city	Berlin	ActorB	I	Urban_Berlin	0.00202
Harmonizing social goals + environmental goals	Berlin	ActorB	I	Urban_Berlin	0.003044
Inclusion of all actors in all fields of action	Berlin	ActorB	I	Urban_Berlin	0.012137
Implementation of the BEK	Berlin	ActorB	O	Urban_Berlin	0.043138
Climate neutrality in 2050	Berlin	ActorB	O	Urban_Berlin	0
Field of action Buildings	Berlin	ActorB	O	Urban_Berlin	0.004661
Field of action Economy	Berlin	ActorB	O	Urban_Berlin	0.004661
Field of action private households and consumption	Berlin	ActorB	O	Urban_Berlin	0.004661
Field of action Transport	Berlin	ActorB	O	Urban_Berlin	0.004661
resilience	Berlin	ActorB	O	Urban_Berlin	0.002181
Energy transition	Berlin	ActorB	O	Urban_Berlin	0.003505
Model effect of the public sector	Berlin	ActorB	O	Urban_Berlin	0
Increasing energy efficiency	Berlin	ActorB	O	Urban_Berlin	0
Import of renewable Gas	Berlin	ActorB	P	Urban_Berlin	0.000565
Development of implementation strategy	Berlin	ActorB	P	Urban_Berlin	0.002041
Energy efficiency requirements	Berlin	ActorB	R	Urban_Berlin	0
Administration resources	Berlin	ActorB	R	Urban_Berlin	0.00109
Distribution of measures among units + departments	Berlin	ActorB	R	Urban_Berlin	0
Development of business models	Berlin	ActorB	R	Urban_Berlin	0
small new business areas	Berlin	ActorB	R	Urban_Berlin	0.001957
High subsidies for renewable energies	Berlin	ActorB	R	Urban_Berlin	0.00001

Label	**Source**	**Actor**	**Type**	**Governance level**	**Betweenness-centrality**
Address unique selling points of actor groups	Berlin	ActorB	R	Urban_Berlin	0
Willingness of political actors to act	Berlin	ActorB	R	Urban_Berlin	0.000526
Will to prioritise measures	Berlin	ActorB	R	Urban_Berlin	0
Control + Leadership	Berlin	ActorB	R	Urban_Berlin	0
Adaptation of legal bases	Berlin	ActorB	R	Urban_Berlin	0.000506
Concentration on "soft" measures	Berlin	ActorB	R	Urban_Berlin	0.007983
Concentration on the now CO2 most effective measures	Berlin	ActorB	R	Urban_Berlin	0.001051
Decision Implementing concept	Berlin	ActorB	R	Urban_Berlin	0.00001
Development of roof area potential	Berlin	ActorB	R	Urban_Berlin	0.000029
Energy Turnaround Act (EEC)	Berlin	ActorB	R	Urban_Berlin	0.00109
Federal policy framework	Berlin	ActorB	R	Urban_Berlin	0.010113
pilot schemes	Berlin	ActorB	R	Urban_Berlin	0
Tenant flow models	Berlin	ActorB	R	Urban_Berlin	0
Installation of solar systems on public buildings	Berlin	ActorB	R	Urban_Berlin	0.000526
Self-conception and acceptance of the current role	Berlin	ActorB	R	Urban_Berlin	0
The courage of the players	Berlin	ActorB	R	Urban_Berlin	0
Impact on private actors	Berlin	ActorB	R	Urban_Berlin	0
climate education	Berlin	ActorB	R	Urban_Berlin	0.000662
educational measures	Berlin	ActorB	R	Urban_Berlin	0.001548
Long-term sustainable thinking	Berlin	ActorB	R	Urban_Berlin	0
Mainstream Topic Climate Protection	Berlin	ActorB	R	Urban_Berlin	0
direct consumption of generated electricity	Berlin	ActorB	R	Urban_Berlin	0.002906
low-cost solar and wind turbines	Berlin	ActorB	R	Urban_Berlin	0
security of energy supply	Berlin	ActorB	R	Urban_Berlin	0
Use of domestic potential renewable gas	Berlin	ActorB	R	Urban_Berlin	0.000565
Use of sealed areas in cities	Berlin	ActorB	R	Urban_Berlin	0.003237
Foreign potential renewable gas	Berlin	ActorB	RS	Urban_Berlin	0

Label	**Source**	**Actor**	**Type**	**Governance level**	**Betweenness-centrality**
Domestic potential renewable gas	Berlin	ActorB	RS	Urban_Berlin	0
Administrative nature of the implementation strategy	Berlin	ActorB	S	Urban_Berlin	0
current administrative regulations	Berlin	ActorB	S	Urban_Berlin	0
shortage of space	Berlin	ActorB	S	Urban_Berlin	0
Creation of framework conditions	Berlin	ActorB	S	Urban_Berlin	0
forms of coordination	Hamburg_Berlin	ActorB_ActorA	I	Urban_Berlin_Hamburg	0.0296
Tenant flow law	Berlin_Berlin	ActorB_ActorD	C	Urban_Berlin	0.006377
Field of action Energy	Berlin	ActorB_ActorD	O	Urban_Berlin	0.024279
Permission for indirect use of solar electricity	Berlin_Berlin	ActorB_ActorD	R	Urban_Berlin	0
legitimation	National_Berlin	ActorB_National	R	Urban_National	0.012489
Administration Urban Development and Housing	Berlin	ActorD	A	Urban_Berlin	0
Climate Protection and Adaptation office	Berlin	ActorD	A	Urban_Berlin	0
Implementation by Senate Administration Economy Energy and Enterprises	Berlin	ActorD	A	Urban_Berlin	0
Senate Department Environment, Transport and Climate Protection	Berlin	ActorD	A	Urban_Berlin	0.000266
Framework measures	Berlin	ActorD	C	Urban_Berlin	0.001412
protected areas	Berlin	ActorD	C	Urban_Berlin	0.000545
Challenge to justify from a short-term CO2 saving perspective	Berlin	ActorD	C	Urban_Berlin	0
Change in underground temperature	Berlin	ActorD	E	Urban_Berlin	0
DiBEK (Monitoring)	Berlin	ActorD	F	Urban_Berlin	0
climate adaptation	Berlin	ActorD	O	Urban_Berlin	0
climate protection	Berlin	ActorD	O	Urban_Berlin	0
Making renewables accessible to private households	Berlin	ActorD	O	Urban_Berlin	0
Production of own drinking water	Berlin	ActorD	O	Urban_Berlin	0
Utilisation of economic potential Solar energy	Berlin	ActorD	R	Urban_Berlin	0.003349
Find properties for heat storage and power to gas	Berlin	ActorD	R	Urban_Berlin	0
Adaptation of regulatory framework (Land and federal level)	Berlin	ActorD	R	Urban_Berlin	0
Adjustment of tenant flow law	Berlin	ActorD	R	Urban_Berlin	0

Label	Source	Actor	Type	Governance level	Betweenness-centrality
technical potential solar energy	Berlin	ActorD	R	Urban_Berlin	0.002151
Expansion of gas-based (bio and natural gas) flexible cogeneration	Berlin	ActorD	R	Urban_Berlin	0
Exploitation of the existing solar energy potential	Berlin	ActorD	R	Urban_Berlin	0
Improvement of economic efficiency of solar plants	Berlin	ActorD	R	Urban_Berlin	0
power storage	Berlin	ActorD	R	Urban_Berlin	0
Power to Gas Applications	Berlin	ActorD	R	Urban_Berlin	0.000526
Power to heat	Berlin	ActorD	R	Urban_Berlin	0
Reduction of the operating temperature	Berlin	ActorD	R	Urban_Berlin	0
Use of heat grids	Berlin	ActorD	R	Urban_Berlin	0.001051
Use of heat pumps and geothermal energy	Berlin	ActorD	R	Urban_Berlin	0.001071
Use of renewable energies on land owned by the state	Berlin	ActorD	R	Urban_Berlin	0
Use of surplus electricity	Berlin	ActorD	R	Urban_Berlin	0.000058
Structure of heat storage structure	Berlin	ActorD	S	Urban_Berlin	0.00001
Vattenfall/Moorburg	Hamburg	ActorE	A	Urban_Hamburg	0
Legislative assembly	Hamburg	ActorE	A	Urban_Hamburg	0
Coal Goodbye Initiative	Hamburg	ActorE	A	Urban_Hamburg	0.000088
Municipal companies	Hamburg	ActorE	A	Urban_Hamburg	0
Net buyback initiative	Hamburg	ActorE	A	Urban_Hamburg	0.000029
Regional Projects	Hamburg	ActorE	A	Urban_Hamburg	0.000662
The craft	Hamburg	ActorE	A	Urban_Hamburg	0
investment cost	Hamburg	ActorE	C	Urban_Hamburg	0
Room for manoeuvre (contradictions to other regulations and laws)	Hamburg	ActorE	C	Urban_Hamburg	0
CO2 price	Hamburg	ActorE	E	Urban_Hamburg	0.000681
legislation	Hamburg	ActorE	G	Urban_Hamburg	0.000214
Goals and steering options	Hamburg	ActorE	O	Urban_Hamburg	0.000088
Difficult purchase price negotiations	Hamburg	ActorE	P	Urban_Hamburg	0
price security	Hamburg	ActorE	R	Urban_Hamburg	0

Label	Source	Actor	Type	Governance level	Betweenness-centrality
Request to the Senate	Hamburg	ActorE	R	Urban_Hamburg	0.000019
Amendment of Climate Protection Act in Hamburg	Hamburg	ActorE	R	Urban_Hamburg	0.000277
Building regulations (administration)	Hamburg	ActorE	R	Urban_Hamburg	0
industrial waste heat	Hamburg	ActorE	R	Urban_Hamburg	0
More efficient heating	Hamburg	ActorE	R	Urban_Hamburg	0
New heat sources	Hamburg	ActorE	R	Urban_Hamburg	0.002536
New windows	Hamburg	ActorE	R	Urban_Hamburg	0
Waste incineration (expansion)	Hamburg	ActorE	R	Urban_Hamburg	0
Lack of space/competition for space	Hamburg	ActorE	S	Urban_Hamburg	0
aquifer tank	Hamburg	ActorE	S	Urban_Hamburg	0
coal phase-out	Hamburg_Hamburg_National	ActorE_ActorJ_National	O	Urban_National	0.005742
Reduction of final energy demand	Hamburg_National	ActorE_National	O	Urban_National	0.003042
Expansion of solar energy use	Hamburg_Berlin_National	ActorE_National_ActorD	R	Urban_National	0.015509
An umbrella capable of operational action: The Environmental Partnership Hamburg	Hamburg	ActorF	A	Urban_Hamburg	0
Halving the value of the company	Hamburg	ActorF	C	Urban_Hamburg	0
Complexity of the LHO	Hamburg	ActorF	C	Urban_Hamburg	0
1 Environmental checks for crafts and other small businesses	Hamburg	ActorF	F	Urban_Hamburg	0
1 Support of the independent analysis of the actual state of the business in an initial consultation with little bureaucracy in the vicinity of the business	Hamburg	ActorF	F	Urban_Hamburg	0.000107
2 Support for the implementation of priority measures	Hamburg	ActorF	F	Urban_Hamburg	0
2 Use of the Energy Book	Hamburg	ActorF	F	Urban_Hamburg	0
3 Certification according to the Quality Association of Environmentally Conscious Companies (QuB) / Participation in the ÖKOPROFIT(R) beginner programme	Hamburg	ActorF	F	Urban_Hamburg	0
4 Certification according to DIN14001 / EMAS (environmental management standard)	Hamburg	ActorF	F	Urban_Hamburg	0
4 Further cultivation of contacts and implementation of measures	Hamburg	ActorF	F	Urban_Hamburg	0
5 Certification according to DIN 50001 (energy management standard)	Hamburg	ActorF	F	Urban_Hamburg	0
Consulting and promotion for the efficient use of resources	Hamburg	ActorF	F	Urban_Hamburg	0
Support for the introduction of energy and environmental management systems	Hamburg	ActorF	F	Urban_Hamburg	0.000049

Label	Source	Actor	Type	Governance level	Betweenness-centrality
Target group-oriented consulting of SMEs in Hamburg on energy efficiency and resource protection	Hamburg	ActorF	F	Urban_Hamburg	0
lack of knowledge of the senators and government faction about the LHO	Hamburg	ActorF	G	Urban_Hamburg	0.001285
Clarification: What stands really in the LHO?	Hamburg	ActorF	G	Urban_Hamburg	0.001139
External expert opinion on the LHO	Hamburg	ActorF	G	Urban_Hamburg	0
Building and expanding trust in business relations	Hamburg	ActorF	I	Urban_Hamburg	0
Making energy requirements in companies more flexible	Hamburg	ActorF	I	Urban_Hamburg	0
Own events (Hamburger Waermedialog)	Hamburg	ActorF	I	Urban_Hamburg	0
Synergy effects with other municipal network companies	Hamburg	ActorF	I	Urban_Hamburg	0.000078
Climate protection targets in Hamburg	Hamburg	ActorF	O	Urban_Hamburg	0
Buyback of Vattenfall's district heating network	Hamburg	ActorF	O	Urban_Hamburg	0
Coal phase-out in Hamburg	Hamburg	ActorF	O	Urban_Hamburg	0.000299
common and binding agreed credible target system	Hamburg	ActorF	O	Urban_Hamburg	0
Focus on resource efficiency and life-cycle economy	Hamburg	ActorF	O	Urban_Hamburg	0
Using renewable energies in industry and commerce	Hamburg	ActorF	O	Urban_Hamburg	0
Intensify climate adaptation	Hamburg	ActorF	O	Urban_Hamburg	0
Green the roofs of Hamburg	Hamburg	ActorF	O	Urban_Hamburg	0
Option right until 30.11.2018	Hamburg	ActorF	P	Urban_Hamburg	0
Referendum from September 2013	Hamburg	ActorF	P	Urban_Hamburg	0
Voluntary commitment of Hamburg industry to climate protection	Hamburg	ActorF	R	Urban_Hamburg	0
sufficient human and material resources	Hamburg	ActorF	R	Urban_Hamburg	0
3 Subsidy consultancy to increase the economic efficiency of sensible measures (KfW, BAFA, IFB Hamburg)	Hamburg	ActorF	R	Urban_Hamburg	0
Increase in regional value added	Hamburg	ActorF	R	Urban_Hamburg	0.000078
Reduction of the climate impact costs of CO2 emissions	Hamburg	ActorF	R	Urban_Hamburg	0
Relief for the Hamburg state budget	Hamburg	ActorF	R	Urban_Hamburg	0
Reduction of the medical follow-up costs of toxic emissions	Hamburg	ActorF	R	Urban_Hamburg	0
Thematization in the Netzbeirat and invitation HGU	Hamburg	ActorF	R	Urban_Hamburg	0
Senate decision at the agreed minimum price	Hamburg	ActorF	R	Urban_Hamburg	0.001606

Label	**Source**	**Actor**	**Type**	**Governance level**	**Betweenness-centrality**
policy credibility	Hamburg	ActorF	R	Urban_Hamburg	0
Meeting of all actors at eye level (government employees, employees of development banks, independent energy consultants, interest representatives and company owners)	Hamburg	ActorF	R	Urban_Hamburg	0.000083
Discussions with Finance Senator, BM, Environment Senator, Party Leaders on LHO	Hamburg	ActorF	R	Urban_Hamburg	0
Avoidance and reuse before recycling	Hamburg	ActorF	R	Urban_Hamburg	0
Remind population from 2013 referendum and danger of final privatisation	Hamburg	ActorF	R	Urban_Hamburg	0
Develop operational mobility concepts	Hamburg	ActorF	R	Urban_Hamburg	0
Efficient design of operational heat generation	Hamburg	ActorF	R	Urban_Hamburg	0
Optimising the energy efficiency of commercial buildings	Hamburg	ActorF	R	Urban_Hamburg	0
Raise the potentials of heat recovery	Hamburg	ActorF	R	Urban_Hamburg	0
online article	Hamburg	ActorF	S	Urban_Hamburg	0
Own press releases	Hamburg	ActorF	S	Urban_Hamburg	0
Own statement on the LHO by NGO representatives	Hamburg	ActorF	S	Urban_Hamburg	0
Social media	Hamburg	ActorF	S	Urban_Hamburg	0
Change the order of operation and number of operating hours of the dirtiest power plants	Hamburg	ActorF	S	Urban_Hamburg	0.000104
Functioning network structure related to climate protection and capable of further development	Hamburg	ActorF	S	Urban_Hamburg	0.000005
Use of renewables in heating grids	Hamburg_Berlin	ActorF_ActorD	R	Urban_Berlin_Hamburg	0.000221
NEW 4.0	Hamburg_Hamburg	ActorF_ActorE	O	Urban_Hamburg	0
Financial interests of house owners (private and commercial)	Hamburg	ActorJ	C	Urban_Hamburg	0
Economic framework conditions for energy companies	Hamburg	ActorJ	C	Urban_Hamburg	0
Shifting policy priorities	Hamburg	ActorJ	C	Urban_Hamburg	0
To be achieved through existing measures max. 25%.	Hamburg	ActorJ	C	Urban_Hamburg	0
CO2 reduction	Hamburg	ActorJ	O	Urban_Hamburg	0.000146
Heat turnaround in Hamburg	Hamburg	ActorJ	O	Urban_Hamburg	0
Focus on electrical heat generation systems	Hamburg	ActorJ	O	Urban_Hamburg	0.000078
Reduction of heating requirement (required at least 50%)	Hamburg	ActorJ	O	Urban_Hamburg	0.000058
environmental awareness	Hamburg	ActorJ	R	Urban_Hamburg	0.00001

Label	Source	Actor	Type	Governance level	Betweenness-centrality
Electric direct heating	Hamburg	ActorJ	R	Urban_Hamburg	0
Low CO2 fuels	Hamburg	ActorJ	R	Urban_Hamburg	0.003857
Low CO2 heat supply (not district heating)	Hamburg	ActorJ	R	Urban_Hamburg	0.000058
synthetic natural gas (power-to-gas)	Hamburg	ActorJ	R	Urban_Hamburg	0
Biomass (only from sustainable sources)	Hamburg	ActorJ	RS	Urban_Hamburg	0
natural gas	Hamburg	ActorJ	RS	Urban_Hamburg	0
Structure of electricity prices	Hamburg	ActorJ	S	Urban_Hamburg	0
veto player	National	National	A	National	0
Regional dependency	National	National	C	National	0
Increasing renewable levy	National	National	C	National	0
No targeted investments (Paris + SDGs)	National	National	C	National	0
lack of political agreement	National	National	C	National	0
One-sided focus (climate)	National	National	C	National	0
One-sided focus (structural change)	National	National	C	National	0
Problems in the derivation of suitable, realistic and at the same time ambitious target statements	National	National	C	National	0.000049
Historical experience with structural change	National	National	C	National	0
landscape	National	National	C	National	0
Risk Unemployment (Workers)	National	National	C	National	0
Understanding structural change (negative)	National	National	C	National	0
Exemption energy-intensive industry	National	National	C	National	0
old inefficient power plants	National	National	C	National	0.000011
Storage (dark doldrum)	National	National	E	National	0
Monitoring and evaluation	National	National	F	National	0.000837
government accountability	National	National	G	National	0
lack of verifiability	National	National	G	National	0
Differentiation: target and report indicators	National	National	G	National	0
Stakeholder knowledge	National	National	G	National	0.000125

Label	Source	Actor	Type	Governance level	Betweenness-centrality
Same unit of measurement of indicators	National	National	G	National	0
Transparent and binding definition and operationalisation of indicators	National	National	G	National	0.000273
Training + Narrative	National	National	G	National	0
lack of political communication	National	National	I	National	0
Clear designation of the indicator (narrative and wording)	National	National	I	National	0
communicability	National	National	I	National	0
comparability	National	National	I	National	0
Cross-resort communication and cooperation (horizontal integration)	National	National	I	National	0
Exchange with Peers	National	National	I	National	0
Implementation mechanisms (e.g. measures) + capacity building to achieve objectives	National	National	I	National	0
International agreement on CO2 price	National	National	I	National	0
Link of climate targets and structural change	National	National	I	National	0.000078
sector coupling	National	National	I	National	0.000969
Transparent calculation paths for indicators	National	National	I	National	0
Withdrawal from hard coal production (Completed)	National	National	O	National	0
Target of the government	National	National	O	National	0
Trend and direction of the status quo in relation to the achievement of objectives	National	National	O	National	0
Many "win"	National	National	O	National	0.000068
Scheduled and quantified objectives (SMART criteria)	National	National	O	National	0.001548
Vertical integration and coherence of indicators and objectives	National	National	O	National	0.001236
Beyond SDGs	National	National	O	National	0
transformation process	National	National	O	National	0.000487
Change is uncomfortable	National	National	P	National	0
grid extension	National	National	P	National	0
Concrete path for lignite mining	National	National	P	National	0.00001
Concrete path for the power plants	National	National	P	National	0.000097
benchmarking	National	National	P	National	0

Label	Source	Actor	Type	Governance level	Betweenness-centrality
Feed-in order according to emissions + flexibility	National	National	R	National	0
Perspectives for employers and the region	National	National	R	National	0
concrete perspective workplace	National	National	R	National	0
Clear investment plan (low carbon)	National	National	R	National	0.001816
Decreasing electricity costs	National	National	R	National	0
Fair distribution of expansion costs	National	National	R	National	0
Feasibility of coal exit	National	National	R	National	0.003704
Financing expansion of renewables	National	National	R	National	0
Financing of the energy system in line with the Paris objectives	National	National	R	National	0.001071
private-sector investments	National	National	R	National	0
Definition of scheduled target corridors	National	National	R	National	0
Clear mandate for the Coal Commission	National	National	R	National	0.000487
Use of the German pioneering role	National	National	R	National	0.000049
Further development of sustainability strategies (international, national, regional, municipal)	National	National	R	National	0.000438
professional communication	National	National	R	National	0.000127
consensus orientation	National	National	R	National	0.000594
Fair structural change	National	National	R	National	0.004629
Acceptance of the renewable expansion	National	National	R	National	0.002473
Confidence in the positive outcome of the transformation process	National	National	R	National	0.000107
success stories	National	National	R	National	0
Understanding structural change (positive)	National	National	R	National	0
Promoting future technologies	National	National	R	National	0
efficient flexible gas power plants	National	National	R	National	0.000006
innovativeness	National_Berlin_Hamburg	National_ActorD_ActorE	R	Urban_National	0.002015
Decentralisation (SMEs + cooperatives)	National_National	National_National	A	National	0
95% CO2 reduction	National_National	National_National	O	National	0
Participation at eye level	National_National	National_National	R	National	0.004508

Table A 9 Code relations matrix - Berlin Energy and Climate Protection Program 2030

Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	Sum
1 Framework measures	0	0	0	0	0	0	7	0	4	2	0	2	1	0	0	0	0	0	0	0	0	0	1	6	0	0	1	1	1	0	0	0	0	2	0	1	5	0	1	0	3	0	2	2	1	0	0	0	0	0	43
2 Majorities of voting actors	0	0	0	0	0	0	2	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	10
3 protected areas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
4 Tenant flow law	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	5
5 Import of renewable Gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
6 acceptance problem	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	9	0	0	1	0	0	0	0	0	0	0	0	0	12
7 economy	7	2	0	1	0	1	0	0	7	5	0	9	4	0	3	13	3	4	5	0	2	1	0	3	2	2	0	3	3	0	0	0	0	0	0	1	1	1	7	0	4	0	1	2	0	0	0	1	0	0	98
8 technical potential solar energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	8
9 Implementation of the BEK	4	0	0	0	0	0	7	0	0	1	0	6	1	0	1	0	2	2	0	0	3	0	0	0	0	0	0	1	2	1	0	1	0	0	0	5	1	1	5	0	5	0	3	5	0	0	0	2	0	0	59
10 administration	2	0	0	0	0	0	5	0	1	0	2	3	6	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	0	2	0	0	3	0	2	0	2	2	0	0	0	0	0	0	34
11 Administration resources	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
12 Civil Society and Science	2	3	0	1	0	0	9	0	6	3	0	0	2	0	0	1	0	0	0	0	0	0	0	1	0	0	0	2	4	1	0	0	0	0	0	1	0	0	1	0	6	0	2	5	0	0	0	0	0	0	50
13 Climate protection administration network	1	0	0	0	0	0	4	0	1	6	0	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	1	0	0	0	1	0	0	0	1	0	0	2	0	1	0	4	4	0	0	0	0	0	0	31
14 Climate Protection Council	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 Field of action Buildings	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	3	3	2	5	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	22
16 Field of action Economy	0	1	0	0	0	0	13	0	0	0	0	1	0	0	3	0	3	2	3	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	29
17 Field of action Energy	0	0	0	0	1	0	3	0	2	0	0	0	0	0	3	3	0	2	3	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	21
18 Field of action private households and consumption	0	0	0	0	0	0	4	0	2	0	0	0	0	0	2	2	2	0	2	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	21
19 Field of action Transport	0	0	0	0	0	0	5	0	0	0	0	0	0	0	5	3	3	2	0	0	3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	24
20 State Secretaries Round	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 Willingness of political actors to act	0	0	0	0	0	0	2	0	3	0	0	0	0	0	2	1	1	2	3	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	5	0	1	0	0	0	0	0	0	0	0	0	23
22 small new business areas	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	6
23 Utilisation of economic potential Solar energy	1	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	1	0	0	0	1	0	13
24 cooperation	6	1	0	0	0	0	3	0	0	1	0	1	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	2	2	0	0	0	1	0	0	23
25 forms of coordination	0	0	0	1	0	0	2	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	1	0	1	2	1	0	0	0	0	0	14
26 good network capacity in the city	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	4

Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	Sum
27 Harmonizing social goals + environmental goals	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
28 Inclusion of all actors in all fields of action	1	2	0	0	0	0	3	0	1	1	0	2	1	0	1	1	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	19
29 innovativeness	1	0	0	0	0	0	3	0	2	0	0	4	0	0	0	0	0	0	1	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	1	0	0	0	1	0	0	25
30 Development of implementation strategy	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	4
31 resilience	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
32 Adaptation of legal bases	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	4	0	0	1	0	4	0	1	1	0	0	0	0	0	0	16
33 CO2 tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
34 Concentration on soft measures	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
35 Concentration on the now CO2 most effective measures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36 Energy Turnaround Act (EEC)	1	0	0	0	0	0	1	0	5	2	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	4	0	0	0	0	0	0	2	0	23	0	2	3	0	0	0	0	0	0	48
37 Federal policy framework	5	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	14
38 legitimation	0	0	0	0	0	9	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	13
39 policy	1	0	0	0	0	0	7	0	5	3	0	1	2	0	1	1	1	0	1	0	5	1	0	1	0	0	0	0	0	0	0	1	0	0	0	2	3	0	0	0	3	0	1	1	0	0	0	0	0	0	41
40 direct consumption of generated electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
41 Energy transition	3	1	0	1	0	1	4	0	5	2	0	6	1	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	8	0	0	4	0	0	0	23	3	1	3	0	0	0	2	4	0	0	0	0	0	0	77
42 Expansion of solar energy use	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	7
43 climate education	2	0	0	0	0	0	1	0	3	2	0	2	4	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	1	0	0	0	2	0	0	1	0	2	0	0	19	0	0	0	0	0	0	42
44 educational measures	2	0	0	0	0	0	2	0	5	2	0	5	4	0	0	0	0	2	0	0	0	0	0	2	2	0	0	0	1	0	0	1	0	0	0	3	0	0	1	0	4	0	19	0	0	0	0	0	0	0	55
45 Installation of solar systems on public buildings	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
46 Power to Gas Applications	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	5
47 Use of domestic potential renewable gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48 Use of heat grids	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	2	0	11
49 Use of heat pumps and geothermal energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	0	0	5
50 Use of sealed areas in cities	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A 10 Code relations matrix - German Strategy for Sustainable Development

Code	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Sum**
1 Financing of the energy system in line with Paris objectives	0	0	16	0	0	3	1	0	6	0	0	0	6	4	0	0	18	3	5	62
2 Expansion of solar energy use	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2
3 innovativeness	16	0	0	0	0	4	0	0	3	0	1	0	3	4	0	0	39	4	12	86
4 legitimation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	2
5 Clear mandate for the Coal Commission	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6 Clear investment plan (low carbon)	3	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	2	18
7 Feasibility of coal exit	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2
8 Participation at eye level	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9 sector coupling	6	0	3	0	0	0	0	0	0	0	0	0	1	0	0	0	4	1	2	17
10 coal phase-out	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
11 Reduction of final energy demand	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	5
12 Scheduled and quantified objectives (SMART criteria)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 Vertical integration and coherence of indicators and objectives	6	1	3	0	0	0	0	0	1	0	0	0	0	2	0	0	16	1	3	33
14 consensus orientation	4	0	4	0	0	0	1	0	0	0	0	0	2	0	0	0	4	0	0	15
15 Fair structural change	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3
16 Further development of sustainability strategies (international	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 Monitoring and evaluation	18	1	39	1	0	6	0	0	4	2	3	0	16	4	2	0	0	2	12	110
18 transformation process	3	0	4	0	0	3	0	0	1	0	0	0	1	0	0	0	2	0	1	15
19 Acceptance of the renewable expansion	5	0	12	0	0	2	0	0	2	0	1	0	3	0	0	0	12	1	0	38