Development of a Sustainable Systems Engineering Framework for the Design and Assessment of Sustainability Visions

by

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ABSTRACT

The increasing severity and complexity of environmental problems require new methods and concepts to identify context-specific solution strategies. Three different types of knowledge about complex environmental issues can be generated, including systems knowledge (i.e., How did the issue emerge? What are the characteristics of the problem?), target knowledge (i.e., Which kind of sustainable system state do we want to achieve in the future?) and transformation knowledge (i.e., What measures can be taken to improve the problem and make advances towards our aspired future system state?). Various modeling methods have been developed in the past to generate systems knowledge (e.g., physical models) and transformation knowledge (e.g., explorative scenarios). Modeling methods for generating target knowledge are less developed. In scenario studies, a future system state is often represented as a number of goals, such as reduced water pollution or absence of CO_2 emissions. However, a future system state, such as a sustainable energy or food system, is much more complex. Recently, vision modeling has been introduced as a promising method to address the dynamic complexity of visions of a sustainable future system state (i.e., sustainability visions). Current challenges of vision modeling are linked to the lack of empirical data and the normativity of future visions. A lack of data particularly impedes the parametrization and validation of quantitative modeling methods. The normativity of visions requires a participatory approach to deal with the diversity of stakeholders' perceptions of a desirable future, which is based on their values, interests and worldviews.

This research has four objectives. The first objective is to identify and further develop systems modeling methods to be applicable for vision design and assessment. These methods should be able to deal with the main challenges of vision modeling, namely a lack of data and the requirement to involve diverse stakeholders. As a second objective, this research aims to develop, test and apply a methodological framework for participatory modeling, which can guide the involvement of stakeholders and an integrated analysis of the participatory process (e.g., analyzing who participated in the different steps of the process). The two remaining objectives aim to develop, test and apply a conceptual and methodological framework for vision design (Objective 3) and vision assessment (Objective 4), which builds upon the systems modeling methods (Objective 1) and a previously developed participatory modeling framework (Objective

2). Qualitative and quantitative modeling methods will be included to allow for a gradual modeling of sustainability visions. In addition, the systematic handling of uncertainties will be addressed to allow for the use of quantitative modeling methods in vision modeling.

Functional analysis is a standard method which originates in the field of systems engineering and is further developed in this research to be applicable for vision modeling. As a first step, conceptual work is required to extend the technical focus of functional analysis to include nature-based and social solutions. Based on this new conceptual framework, the functional organization analysis method is further developed to allow for the visualization of alternative system designs, i.e., alternative future system states. In addition, functional flow analysis, another systems engineering method, is also further developed to examine the dynamic complexity of alternative future visions. Fuzzy cognitive mapping is another powerful method that can deal with data scarce situations. As a third method, fuzzy cognitive mapping is further developed by highlighting system functions, requirements and ecosystem services in the model structure and analysis. Finally, system dynamics modeling is used to analyze interactions between system functions and system requirements. The methods are tested and applied in two case studies, one on sustainable food systems in Southwestern Ontario and another on water supply management in Cyprus.

The Participatory Model Building Framework is a stepwise approach to involve stakeholders in model development, starting with qualitative modeling methods (i.e., causal loop diagrams) and proceeding towards quantitative modeling (e.g., system dynamics modeling). The Participatory Model Building Framework also has a component related to process design and analysis. Thus, the involvement process can be represented as a sequence of action situations, along with participating actors as well as input and output factors. This allows for ex-ante process design (i.e., defining process steps and expected outcomes) as well as ex-post analysis (i.e., monitoring and evaluation of processed hold in the past). The process analysis can also be applied to analyze requirements for an institutionalization of participatory modeling processes, which might require the development of modeling skills of stakeholders and an institutional framework that supports stakeholder involvement in the long term. The Participatory Model Building Framework is applied to a case study on water quality management in Québec.

Based on the research presented in the previous two paragraphs, a conceptual and methodological framework for vision design and assessment was developed. The Vision Design and Assessment Framework guides vision design starting with qualitative modeling methods (i.e., functional organization analysis and causal loop diagrams) towards semi-quantitative modeling (i.e., fuzzy cognitive mapping) and quantitative modeling (i.e., system dynamics). From a systems science point of view, the Vision Design and Assessment Framework helps to specify the system organization, system structure and system processes underlying sustainability visions. The semi-quantitative and quantitative modeling methods allow for an assessment of sustainability visions by revealing the limitations and consequences of visions, including trade-offs and synergies. In addition, a systematic approach to handle uncertainties in vision modeling was developed that is comprised of integrated assessment methods, scenario analysis, sensitivity analyses, model-to-model-analysis, and expert assessment. The Vision Design and Assessment Framework is applied to case studies on sustainable food systems in Ontario and renewable energy systems in Germany.

The presented conceptual and methodological frameworks allow for a systematic design and assessment of sustainability visions, which can guide the design of sustainability strategies and policies in the future. In particular, they allow for the utilization of systems modeling methods for visioning processes and thereby complement qualitative methods, such as collages and narratives.

RESUMÉ

La gravité et la complexité croissantes des problèmes environnementaux requièrent le développement de nouvelles méthodes et de nouveaux concepts afin d'identifier des solutions adaptées au contexte spécifique de ces problèmes. Trois différents types de connaissances sur les problèmes environnementaux complexes peuvent être générés, y compris la connaissance du système (c.-à-d. Comment le problème est-il apparu? Quelles sont les caractéristiques du problème?), la connaissance cible (c.-à-d., Quel type d'état de système durable voulons-nous atteindre dans le future?) et les connaissances sur la transformation (c.-à-d., Quelles mesures peuvent être prises pour améliorer le problème et progresser vers le futur système désiré?). Diverses méthodes de modélisation ont été développées dans le passé pour générer des connaissances sur les systèmes (par exemple, des modèles physiques) et des connaissances sur la transformation (par exemple, des scénarios exploratoires). Par contre, les méthodes de modélisation pour générer des connaissances cibles sont moins développées. Dans les études de scénarios, un état futur d'un système est souvent représenté par un certain nombre d'objectifs, tels que la réduction de la pollution de l'eau ou l'absence d'émissions de CO_2. Cependant, un état futur d'un système, tel qu'un système énergétique ou alimentaire durable, est beaucoup plus complexe. Récemment, la modélisation de la vision a été introduite en tant une méthode prometteuse pour aborder la complexité dynamique des visions d'un état futur de système durable (c'est-à-dire les visions de la durabilité). Les défis actuels de la modélisation de la vision sont liés au manque de données empiriques et à la normativité des visions futures. Le manque de données entrave particulièrement la paramétrisation et la validation des méthodes de modélisation quantitative. La normativité des visions requiert une approche participative pour faire face à la diversité des perceptions des parties prenantes d'un avenir souhaitable, qui est basé sur leurs valeurs, intérêts et visions du monde.

Cette recherche a quatre objectifs. Le premier objectif est d'identifier et de développer davantage des méthodes de modélisation des systèmes applicables à la conception et à l'évaluation de la vision. Ces méthodes devraient être en mesure de faire face aux principaux défis de la modélisation de la vision, c'est-à-dire le manque de données et la nécessité d'impliquer diverses parties prenantes. Le deuxième objectif vise à développer, tester et appliquer un cadre méthodologique pour la modélisation participative pour guider la participation des parties

prenantes et une analyse intégrée du processus participatif (par exemple, analyser qui a participé aux différentes étapes du processus). Les deux autres objectifs visent à développer, tester et appliquer un cadre conceptuel et méthodologique pour la conception de la vision (objectif 3) et l'évaluation de la vision (objectif 4), qui s'appuie sur des méthodes de modélisation du système (objectif 1) et le cadre de modélisation participative (objectif 2) développé précédemment. Des méthodes de modélisation qualitative et quantitative seront incluses pour permettre une modélisation progressive des visions de la durabilité. De plus, le traitement systématique des incertitudes sera abordé pour permettre l'utilisation de méthodes de modélisation quantitative dans la modélisation de la vision.

L'analyse fonctionnelle est une méthode issue de l'ingénierie des systèmes qui est développée dans cette recherche pour être applicable à la modélisation de la vision. Dans un premier temps, un travail conceptuel est nécessaire pour étendre la portée technique de l'analyse fonctionnelle afin d'inclure des solutions sociales et basées sur la nature. En se basant sur ce nouveau cadre conceptuel, la méthode d'analyse de l'organisation fonctionnelle est développée davantage pour permettre la visualisation de conceptions alternatives du système, c'est-à-dire d'autres états futurs du système. En outre, la cartographie cognitive floue, une autre méthode d'ingénierie des systèmes, est également développée pour examiner la complexité dynamique des visions futures alternatives. Cette méthode puissante peut traiter des situations de manque de données. La cartographie cognitive floue est développée en mettant en évidence les fonctions du système, les exigences et les services écosystémiques dans la structure et l'analyse du modèle. Enfin, la modélisation de la dynamique du système est utilisée pour analyser les interactions entre les fonctions et les exigences du système. Les méthodes sont testées et appliquées dans deux études de cas, l'une sur les systèmes alimentaires durables dans le sud-ouest de l'Ontario et l'autre sur la gestion de l'approvisionnement en eau à Chypre.

Le cadre de construction de modèles participatifs est une approche par étapes pour impliquer les parties prenantes dans le développement de modèles, en commençant par des méthodes de modélisation qualitative (c'est-à-dire des diagrammes de boucles causales) et en poursuivant vers une modélisation quantitative (par exemple, la modélisation de la dynamique des systèmes). Le cadre de construction de modèles participatifs comprend également une composante liée à la conception et à l'analyse des processus. Ainsi, le processus d'implication peut être représenté comme une séquence de situations d'action, avec les acteurs participants ainsi que des facteurs d'entrée et de sortie. Cela permet la conception ex ante du processus (c'est-à-dire la définition des étapes du processus et des résultats attendus) ainsi que l'analyse ex post (c'est-à-dire le suivi et l'évaluation de la conservation traitée dans le passé). L'analyse de processus peut également être appliquée pour analyser les exigences d'une institutionnalisation des processus de modélisation participative, ce qui pourrait nécessiter le développement des compétences de modélisation des parties prenantes et un cadre institutionnel qui soutient la participation des parties prenantes à long terme. Le cadre de construction de modèles participatifs est appliqué à une étude de cas sur la gestion de la qualité de l'eau au Québec.

En se basant sur la recherche présentée dans les deux paragraphes précédents, un cadre conceptuel et méthodologique pour la conception et l'évaluation de la vision a été développé. Le cadre de conception et d'évaluation de la vision guide la conception de la vision en commençant par des méthodes de modélisation qualitative (c.-à-d. l'analyse de l'organisation fonctionnelle et les diagrammes de boucles causales) vers la modélisation semi-quantitative (c.-à-d. la cartographie cognitive floue) et la modélisation quantitative (c.-à-d. la dynamique du système). Du point de vue de la science des systèmes, le cadre de conception et d'évaluation de la vision permet de spécifier l'organisation, la structure et les processus du système qui sous-jacent les visions de la durabilité. Les méthodes de modélisation semi-quantitative et quantitative permettent d'évaluer les visions de la durabilité en révélant les limites et les conséquences des visions, y compris les compromis et les synergies. De plus, une approche systématique pour gérer les incertitudes dans la modélisation de la vision a été développée qui comprend des méthodes d'évaluation intégrées, une analyse de scénario, des analyses de sensibilité, une analyse de modèle à modèle et l’opinion d’experts. Le cadre de conception et d'évaluation de la vision est appliqué aux études de cas sur les systèmes alimentaires durables en Ontario et les systèmes d'énergie renouvelable en Allemagne.

Les cadres conceptuels et méthodologiques présentés ci-haut permettent de concevoir et d’évaluer systématiquement des visions de la durabilité, qui peuvent guider la conception de stratégies et de politiques de durabilité. En particulier, ils permettent l'utilisation de méthodes de modélisation des systèmes pour visualiser les processus et complètent ainsi les méthodes qualitatives, telles que les collages et les récits.

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"If you want to go fast, go alone. If you want to go far, go together"

(African Proverb)

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FORMAT OF THE THESIS

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the Guidelines Concerning Thesis Preparation, which are as follows (see https://www.mcgill.ca/gps/thesis/thesis-guidelines/preparation/manuscript-based-article-based-theses, retrieved: 11 November, 2020; parts that are not linked to manuscript-based theses are omitted and marked by ellipses):

"As an alternative to the traditional format, a thesis may be presented as a collection of scholarly papers of which the student is the first author or co-first author. A manuscript-based doctoral thesis must include the text of a minimum of two manuscripts published, submitted or to be submitted for publication. […] Articles must be formatted according to the requirements described below. […]

Manuscripts for publication in journals are frequently very concise documents. A thesis, however, is expected to consist of more detailed, scholarly work. A manuscript-based thesis will be evaluated by the examiners as a unified, logically coherent document in the same way a traditional thesis is evaluated. Publication of manuscripts, or acceptance for publication by a peer-reviewed journal, does not guarantee that the thesis will be found acceptable for the degree sought.

A manuscript-based thesis must:

- be presented with uniform font size, line spacing, and margin sizes […];
- conform to all other requirements listed under Thesis Components on the Preparation of a Thesis page;
- contain additional text that connects the manuscript(s) in a logical progression from one chapter to the next, producing a cohesive, unitary focus, and documenting a single program of research - the manuscript(s) alone do not constitute the thesis;
- stand as an integrated whole.

For manuscript based thesis, each individual chapter/manuscript should be identical to the published/submitted version of the paper, including the reference list. The only change is with respect to the font/size which should be the same as the one used for the rest of the thesis for consistency and homogeneity reasons. So each chapter represents a full manuscript and has its own reference list. Then at the end of the thesis, you have a master reference list which includes all the other references cited throughout the other sections of the thesis, mostly within the general introduction but also from the general discussion.

In the case of multiple-authored articles, the student must be the first author. Multiple-authored articles cannot be used in more than one thesis. In the case of students who have worked collaboratively on projects, it may be preferable for both students to write a traditional format thesis, identifying individual contributions. […]"

Further requirements listed on the Preparation of a Thesis page (see https://www.mcgill.ca/gps/thesis/thesis-guidelines/preparation, retrieved: 11 November, 2020):

"[…] the thesis must contain methodology, results and scholarly discussion. It must also contain or conform to the following requirements:

1. Title page
    - The title of the thesis
    - The student's name and Unit* followed by "McGill University, Montreal"
    - The month and year the thesis was submitted
    - The following statement: "A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of...."
    - The universal copyright notice "©" followed by the student's name and the year the thesis was submitted
2. A detailed table of contents
3. A brief abstract in both English and French.

If the language of the thesis is neither English nor French (only allowed for specific language Units) then a third abstract in the language of the thesis is required.

4. Acknowledgements
    - Among other acknowledgements, the student is required to declare the extent to which assistance (paid or unpaid) has been given by members of staff, fellow students, research

assistants, technicians, or others in the collection of materials and data, the design and construction of apparatus, the performance of experiments, the analysis of data, and the preparation of the thesis (including editorial help).

- In addition, it is appropriate to recognize the supervision and advice given by the thesis supervisor(s) and advisors.

5. Contribution to original knowledge

A doctoral thesis must clearly state the elements of the thesis that are considered original scholarship and distinct contributions to knowledge.

6. Contribution of Authors

- Contributions of the student to each chapter must be explicitly stated.
- Contributions of any co-authors to each chapter must be explicitly stated.

7. An introduction

Clearly state the rationale and objectives of the research.

8. A comprehensive review of the relevant literature

The literature review must be in line with disciplinary expectations

9. Body of the thesis

- Body of the thesis should encompass sections on:
    - Methodology
    - Research findings

10. A comprehensive scholarly discussion of all the findings

(In case of a manuscript-based thesis the comprehensive discussion should encompass all of the chapters of the thesis and should not be a repetition of the individual chapters.)

11. A final conclusion and summary

Clearly state how the objectives of the research were met and discuss implications of findings.

12. A thorough bibliography or reference list"

CONTRIBUTIONS OF AUTHORS

The chapters of this thesis have been prepared for publication in peer-reviewed journals and presented at scientific conferences. The author of this thesis was responsible for the conceptual and methodological framework development, stakeholder engagement, model development (functional analysis, fuzzy cognitive mapping and system dynamics modeling), model testing and the preparation of manuscripts for publication. Prof. Jan Adamowski is the thesis supervisor and gave advice on framework and model development, testing and evaluation. He was also involved in the editing and review of all manuscripts. Prof. Armin Grunwald (Professor of Philosophy of Technology at the Institute of Philosophy, Karlsruhe Institute of Technology, Germany) is the thesis co-supervisor and provided advice on the conceptual foundations of vision design and assessment that are laid out in the thesis as well as the mansucripts of companion articles that were submitted to the Energy Journal. Prof. Khosrow Farahbakhsh (School of Engineering, University of Guelph, Canada) gave advice on conceptual and methodological frameworks in the earlier stages of this research, supported the organization of the case study in Ontario and also aided in the editing process of one article published in the Ecological Engineering Journal. Prof. Claudia Pahl-Wostl (Institute of Environmental Systems Research, Germany) gave advice on the use of the Management and Transition Framework (as part of the manuscript published in the Journal of Hydrology) and the organization of the participatory modeling processes in Canada and Québec. Prof. Elena Bennett (McGill School of Environment and Department of Natural Resource Sciences) provided advice on the conceptual framework for integrating technical and nature-based solutions in engineering design, as part of the article on functional organization analysis published in the Ecological Engineering Journal. Stefan Gausling helped to develop the system dynamics model dealing with a fully renewable energy system in Germany that was presented in an article submitted to the Energy Journal. Dr. Peter Viebahn (Head of Research Unit 'Sectors and Technologies', Wuppertal Institute for Climate, Environment and Energy, Germany) contributed to the review and editing of companion articles on using system dynamics modeling for vision design and assessment, which have been submitted to the Energy Journal.

List of publications and scientific presentations related to the thesis:

A. Part of this thesis has been published or submitted in peer-reviewed journals:

Halbe, J., Adamowski, J., Bennett, E., Farahbakhsh, K., and Pahl-Wostl, C., 2014. Functional organization analysis for the design of sustainable engineering systems. Ecological Engineering 73, 80-91.

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Halbe, J., Pahl-Wostl, C., and Adamowski, J., 2018. A methodological framework to support the initiation, design and institutionalization of participatory modeling processes in water resources management. Journal of Hydrology 556, 701-716.

Halbe, J., and Adamowski, J., 2019. Modeling Sustainability Visions: A Case Study of Multi-Scale Food Systems in Southwestern Ontario. Journal of Environmental Management 231, 1028-1047.

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B. Part of this thesis has been presented at scientific conferences and events:

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Halbe, J., and Adamowski, J., 2018. Bridging technical, ecological and social knowledge in systems design (Oral presentation). 36th International Conference of the System Dynamics Society, August 6-10, 2018, Reykjavík, Iceland.

Halbe, J., and Adamowski, J., 2018. Vision Modeling in Sustainability Transitions Research (Oral presentation). International Sustainability Transitions Conference 2018, June 11-14, Manchester, UK.

Hakimi, R., and **Halbe, J.**, 2013. Transitioning to Sustainable Agriculture - What is your Vision and Strategy? (Poster Presentation). 32nd Guelph Organic Conference, January 31 – February 3, 2013, Guelph, ON, Canada.

Halbe, J., 2010. Potential of Group Model Building in Environmental Management (Oral presentation). 21st MIT-University at Albany-WPI System Dynamics Ph.D. Colloquium, 29 October 2010, University at Albany, State University of New York, Albany, USA.

Halbe, J., Adamowski, J., and Pahl-Wostl., C., 2010. A Participatory Model Building Framework for Integrated Water Resources Management (Poster presentation). 9th Annual Symposium presented by the Brace Centre, September 23, 2010, Montreal, QC, Canada.

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LIST OF ABBREVIATIONS

CAAF	Contrat d'Aménagement et d'Approvisionnement
CCD	Commissaire au développement durable (CCD),
CLD	Causal loop diagram
CSP	Concentrated solar power
DAC	Direct air capture
DME	Dimethyl ether
FCM	Fuzzy Cognitive Mapping
FFA	Functional Flow Analysis
FOA	Functional Organization Analysis
GEO	Global Environmental Outlook
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
LCOE	Levelized Costs of Electricity
MDDEP	Ministère du Développement durable, de l’Environnement et des Parcs
MEA	Millenium Ecosystem Assessment
MENA	Middle East & North Africa
MTF	Management and Transition Framework
MRC	Municipalité Régionale de Comté
NUSAP	Numeral Unit Spread Assessment Pedigree
OBV	Organisme de bassins versants

PAEQ	Programme d'assainissement des eaux du Québec
PMBF	Participatory Model Building Framework
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
PV	Photovoltaics
REA	Règlement sur les exploitations agricoles
ROBVQ	Regroupement des organismes de bassins versants du Québec
SAHYSMOD	Spatial Agro Hydro Salinity Model
SDGs	Sustainable Development Goals
SNG	Synthetic Natural Gas
SWAT	Soil & Water Assessment Tool
UBA	Umweltbundesamt (German Environmental Agency)
UML	Unified Modeling Language
VDAF	Vision Design and Assessment Framework
WaterGAP	Water Global Assessment and Prognosis (integrated assessment model)

“If we don’t know where we want to go,
it makes little difference that we make great progress.”

Donella H. Meadows, 1994 , p. 1

Chapter 1: Introduction

In December 1968, the first photo of the Earth from space was taken during the Apollo 8 mission, which showed the peculiarity of our blue planet in a vast universe. In fact, this photo had a tremendous impact on environmental thinking and activism and helped coin the metaphor of ‘Spaceship Earth’ (Poole, 2010). Bell (1996) suggests a complementary metaphor equally important to sustainability science namely the image of the ‘Time Machine Earth’. Thus, people on Earth are not only space travelers depending on each other, life support from ecosystems and earthly resources, but are also time travelers with a one-way ticket from the now into the future. While people can learn from the past, the future is not predetermined but shapeable through individual and collective action.

A future orientation is critical in every part of life in which effective decisions are sought. Deliberate decisions are based on expectations about the potential future effects of actions, which require an understanding of the current system stemming from past observations and experiences. The effects of actions can often be *predicted* for relatively simple and short-term decisions (e.g., opening of the outlet of a dam will increase water levels downstream) or, at least, a probability can be assigned to several outcomes (e.g., Kristensen and Rasmussen, 2002). More long-term and complex issues usually involve various *possible* outcomes, which cannot be quantified by probability (e.g., impact of climate change on migration dynamics). Another critical element of effective decision-making is having a clear idea of a *preferable* future, i.e., a specification of goals (e.g., water quality indicators) or a general vision of a desirable system state (e.g., a sustainable water supply system). Grunwald (2004) differentiates between four future-oriented notions, which have different degrees in facticity, scope and specificity: *goals* are concrete aims (e.g., the Sustainable Development Goals (SDGs), UN, 2015); *Leitbilder* are more encompassing future-oriented notions which are close to current technical developments (e.g., the paperless office); *visions* are far-reaching notions of the future that involve technical as well as social processes of change (e.g., a fully renewable energy system); *fictions* are creative and artistic pictures of the future without a serious claim of feasibility (e.g., beaming humans through space or time).

The systematic and rigorous specification, analysis and assessment of predicted, possible and preferable futures are the purposes of futures studies (e.g., Bell, 1996; Marien, 2002). Grunwald (2014) distinguishes between three modes of orientation that futures studies can provide. In mode 1, futures studies can provide orientation to decision-making by analyzing future developments for which sufficient causal and statistical knowledge is available, i.e., future projection converge and allow for a 'forecasting' approach. Simulation models are frequently applied to generate mode 1 orientation. For example, process-based models can be used for simulating physical processes, which usually requires a high availability of data (e.g., the Soil and Water Assessment Tool, Gassman et al., 2007). As another example, innovative statistical modeling approaches, such as hybrid wavelet transform and artificial neural network models, are able to deal with a lack of available data in forecasting hydrological processes (e.g., Adamowski et al., 2012). In mode 2 orientation, futures studies are not able to forecast a future system development, as uncertainties and epistemological challenges are too high. Instead, only alternative plausible 'foresights' (i.e., alternative future developments) can be identified. Scenarios are therefore located in a plausible corridor (e.g., between a best case and a worst-case scenario), which allows for the design of 'robust strategies' (Grunwald, 2014). In mode 3 orientation, futures studies are not even able to identify separate foresights, as the diversity of potential futures is too high. For example, nanotechnology or climate engineering are examples for which the model 1 and 2 approaches are hardly possible (Grunwald, 2014). Instead, knowledge about the future is sometimes so limited that it can be arbitrarily used by actors based on their values and interests (e.g., Brown and Rappert, 2017). In these cases, Grunwald (2014) proposes semantic and hermeneutic approaches to provide orientation for a reflected debate and decision-making. Thus, research providing mode 3 orientation does not offer insights about the future itself (due to the irreducible divergence of future visions), but about the present state of society including diverging values, fears and perceptions. By making the implicit process of visioning explicit, a more informed and transparent democratic debate is possible.

The solution to contemporary environmental problems, such as climate change, deforestation, water pollution and desertification (cf., UNEP, 2007), requires a clear and systematic approach to navigate towards a more sustainable future, which includes the study of probable, possible and preferable futures. Each of these purposes of futures studies has been applied to environmental assessment and management. For instance, the 5th Global Environment Outlook (UNEP, 2012) provides probable future trajectories by projecting current environment trends into the future. In addition, the report investigates possible policies and their impacts, as well as a preferable future in the form of a sustainability vision. As another example, the Intergovernmental Panel on Climate Change (IPCC) offers long-term projections of global warming given alternative policy scenarios (IPCC, 2014). The limit to growth model is another prominent example that combines a trend projection in a baseline scenario and alternative possible policies (Meadows et al., 1972). The reception of the model showed the danger of conflating forecasting and foresight approaches. By erroneously considering the model results as forecasts (i.e., an attempt to predict the future), critics termed the model a “Doomsday model” (Beckerman, 1972, p. 336), as most scenarios showed a collapse of ecological, economic and social systems. However, the study aimed at portraying the detrimental consequences of human action as well as possible pathways towards the solution of global issues. These examples underline that the analysis of desired and undesired future visions has a profound effect on current discussions and decision-making processes.

1.1 Challenges in the design and assessment of sustainability visions

This research deals with the design and assessment of sustainability visions, i.e., positive visions of a future in which economic, social and ecological wellbeing is achieved. Designing such positive future visions can have a significant effect on transitions towards sustainable development for various reasons: they can motivate people to become active, improve communication between actors and also coordinate activities (Lösch et al., 2016). Thus, future visions can be used in an instrumental way to influence discourses and expectations of actors. Meadows (1994) also highlights the motivational and inspirational character of visions by opening minds towards new possibilities. Visions also have the function of providing orientation even though they might not be reached completely due to their more idealized representation of the future. In addition to the formulation of explicit visions (e.g., through written vision statements), future visions can appear in more concealed forms, such as guidelines, media discourses or research products (e.g., computer models or scenarios) (Lösch et al., 2016). Lacking transparency about underlying future visions can spark conflict and heated debates, as the underlying cause of disagreement might remain obscured.

Environmental management shows a clear emphasis on trend projection and analysis of alternative future scenarios rather than crafting visions of preferable futures. For instance, this focus is reflected in different Global Environment Outlook reports (UNEP 2002, 2007, 2012). In the 5th Global Environment Outlook (UNEP, 2012), a preferable future state is briefly described in the form of a vision statement (i.e., a written description of a future system state). Only three pages of the report's 486 pages delineate what is meant by a 'sustainable future', which is later even qualified as preliminary work rather than an in-depth account of a future system state: "Obviously, other important global sustainable development targets exist, and the vision and goals outlined here [...] cannot provide a complete picture of a sustainable world. A vision develops through evolution and must have contributions from many people before it is mature and compelling. The vision captured here is only a start: it represents an invitation to individuals to envision the world they really want in 2050" (UNEP, 2012, p. 425). This statement points to the need for conceptual and methodological frameworks to iteratively design future visions through collaborative processes.

The SDGs, which were passed by the UN General Assembly in 2015, provide a more specific and detailed picture of a desirable future. While the preceding Millennium Development Goals defined specific targets to reduce poverty in developing countries by 2015, the SDGs have a broader scope which addresses countries in the Global North and includes sustainable consumption and production, as well as protection of the environment and natural resources (Griggs et al., 2013). The SDGs are based on an encompassing global vision of the future that covers the satisfaction of basic human needs for food, water and health, guaranteed human rights, sustainable economic growth and harmony between humanity and nature (UN, 2015, 2018). The general vision is translated into 17 goals, which are further specified into targets. Le Blanc (2015) and Nilsson et al. (2016) highlight the interrelationships between individual goals and targets, which are only implicitly acknowledged by the UN General Assembly. Trade-offs can thus appear between individual SDGs. For instance, building coal-fired power plants can improve energy access (Goal 7) and at the same time contradict goals to combat climate change (Goal 13) and air pollution (Goal 11) (Nilsson et al., 2016). Various researchers have pointed to the need to develop integrated conceptual frameworks to understand such trade-offs as well as interactions (e.g., Griggs et al., 2014; Singh et al., 2018).

From an epistemological point of view, visioning approaches produce a peculiar type of knowledge, namely target knowledge. Singer-Brodowski and Schneidewind (2014) distinguish between three types of knowledge, which are essential for implementing sustainability transitions. The implementation process is portrayed as a transition cycle starting with a problem analysis to generate *systems knowledge* (How did the problem arise? What are the different aspects of the problem?). The second phase of the transition cycle consists of the development of future visions to gain *target knowledge* (Where do we want to go? What does a sustainable society look like?). This phase is followed by the implementation of innovations in real world laboratories (see Schneidewind and Scheck, 2013) to develop *transformation knowledge*, which supports the diffusion and upscaling of innovations (How can we reach our vision? Which parts of the vision already exist?). While systems knowledge and transformation knowledge can be analyzed based on a positivist philosophy of science (cf. Geels et al., 2016), target knowledge is inherently normative, i.e., influenced by the goals, values and worldviews of the individual or group holding a future vision, which is more in a line with constructivist and relativist philosophies of science (cf. Geels et al., 2016). Nevertheless, the term ‘target knowledge’ implies a need for quality assurance, in the sense that the design process of future visions should be followed by a rigorous assessment procedure.

The previous paragraphs point to two major challenges of visioning research in the field of sustainability science. First, **conceptual and methodological frameworks are needed that guide the design of sustainability visions**. Second, further challenges are related to the **assessment of future visions in terms of internal consistency (e.g., existence of trade-offs), plausibility (Are realistic constraints considered?) and desirability (Are sustainability benefits reached?)**. These two types of challenges are analyzed more closely in the following sections.

1.1.1 Challenges linked to conceptual and methodological frameworks for designing sustainability visions

Vision design is a creative and often personal process that is guided by a person's capability of imagination and visualization. Meadows (1994) describes the beginning of the visioning process as a non-rational endeavor where she goes to a quiet place, shuts down her rational mind and develops a vision, which is subsequently refined by sharing it with other people and writing down a vision statement. Donella Meadows has been a leading systems scientist and sometimes felt uneasy for following such a seemingly irrational process (Meadows, 1994). According to her experience, visioning is a creative activity that is not based on rational analysis. Thus, visioning is about identifying genuine wants about the future rather than rational expectations that are constrained by the present. Meadows (1994) also highlights some quality criteria for visions. A vision should be judged by the clarity of values and, at first, does not require a specific plan for implementation. Even though visioning is not a rational process, it still needs to be informed by rational thought. A responsible vision acknowledges physical constraints of the world, which can be explored using a modeling approach. In addition, responsible visions should be shared with others and be based on moral values (Meadows, 1994).

By sharing her experiences of visioning, Donella Meadows brought an important topic to the field of sustainability science and built a bridge between rationalistic approaches and more intuitive and creative thinking. Her work highlights that visions are genuinely personal and normative by nature, but at the same time should be responsible by considering rational constraints and the needs of other people. The brain activities underlying the process of imagining the future is an important research topic in neuroscience (e.g., Brosch et al. 2018). The concept of the 'prospective brain' has been developed based on the finding that similar neuronal processes are active for remembering the past and imagining the future (e.g., Schacter et al., 2007, 2008). This research, however, does not further elaborate on the neuronal basis of visioning, but focuses on the development of concepts and methods that help craft responsible visions, i.e., visions that acknowledge constraints and are informed by various sources of knowledge beyond personal imagination.

Conceptual visioning frameworks can guide the development of visions by providing a blueprint for other visioning studies. For instance, general visions of a sustainable future, such as those delineated in the Brundtland report (1987), can provide a blueprint for the development of more specific visions, such as the Agenda 21 (UN, 1992). A systematic account of future visions was first provided in 1997 by the Global Scenario Group, which is an independent and interdisciplinary group of researchers that utilize a scenario approach to analyze opportunities for a sustainable future.[1] The Global Scenario Group followed a two-tier approach involving three classes of distinct futures of the world, each being further divided in two sub-classes (Gallopin et al., 1997). The first overall class of scenarios, termed 'Conventional World', assumes that no major societal transformation will be taking place. A sub-scenario was termed 'Reference Scenario' before it was later renamed 'Markets First' (Raskin et al., 2002). This sub-scenario assumes further growth of the global economy and a tendency towards dematerialization due to a stronger service sector and technological innovation. Even though dematerialization causes resource use to increase less rapidly than GDP, an overall increase of resource use and environmental pressures is expected due to continuous economic growth. In the 'Policy Reform' sub-scenario, a strong focus is set on top-down policy-making to achieve environmental, economic and social targets. The second class of scenarios is termed 'Barbarization' and describes an erosion of social and economic development. The 'Breakdown' sub-scenario involves an economic breakdown, escalating conflict and institutional disintegration. The 'Fortress World' sub-scenario is dominated by social inequality favoring rich and powerful segments of society that form protected enclaves. The third class of scenarios is termed 'Great Transitions' and provides visions of sustainable future states that follow the ideals of the Brundtland commission by pursuing a balance between environmental and socio-economic goals. Life in the 'Eco-communalism' sub-scenario is focused on the regional scale favoring local provision of goods with small technological input, such as food and energy, and face-to-face democracy. In contrast, the 'New Sustainability Paradigm' is focused on a sustainable global civilization with a higher personal and commercial mobility, and an emphasis on the utilization of modern technologies. The future scenarios developed by the Global Scenario Group inspired various further studies and policy documents, such as the fourth Global Environmental Outlook. "Snapshots of the four futures" (GEO-4; UNEP, 2007, p. 405) are provided in the form of detailed descriptions of alternative future system states in 2050 (the

[1] Website of the Global Scenario Group: www.gsg.org

scenarios are called ‘Markets First’, ‘Policy First’, ‘Security First’ and ‘Sustainability First’) along with a caricatural illustration. These global GEO-4 scenarios have been used to develop more geographical specific scenarios at continental, regional or local scales. For instance, the GEO-4 scenarios have been used in the SCENES project to examine the future of water management in Europe at European, regional and local scales (Kok et al., 2011).

Existing visioning processes build - explicitly or implicitly - on a conceptual framework that specifies aspects that are critical in developing future visions. In the case of the Global Scenario Group, driving forces and critical uncertainties have been key elements for developing distinct future visions. Driving forces are persistent and fundamental phenomena and processes that can be defined by an analysis of the current system state. The following elements are critical driving forces, which should be included in future visions, as identified by the Global Scenario Group: population numbers (Is the global population increasing in the future?), economic development (Are economies continuing to grow and is material wealth increasing?), state of the environment (Are ecosystems and natural resources protected?), equity (Are resources and services accessible for everyone?), technologies applied (Are visions based on high-tech solutions?) and conflict (How are conflicts about scarce resources handled?) (Gallopin et al., 1997). Identifying key uncertainties can be another approach to develop future visions. A key uncertainty is the scale of the vision, such as a global orientation (i.e., high interdependence through trade and mobility) or a more local orientation (i.e., more relevance of regional autonomy). Another key uncertainty relates to prevalent social values and mindsets, which can be related to a more solidary and proactive society or a more individualistic society that is based on self-interest and a reactive mindset (Hunt et al., 2012). These general key uncertainties can form a guide for the development of local scenarios that define opportunities for action given various context conditions (Falardeau et al., 2019).

From a methodological viewpoint, the aforementioned global scenarios consist of a vision of a future system state as well as a description of the pathway towards such a vision, which might reflect a more continuous development (cf. ‘Conventional World’ scenarios) or a disruptive one (cf. ‘Barbarization’ and ‘Great Transitions’ scenarios). The future system states can be visualized through collages (e.g., GEO-4), pictorial illustrations (e.g., Gallopin, 2002) or described through narratives (e.g., Gallopin and Raskin, 1998). Various quantitative approaches have been used to model the pathways of scenarios (e.g., from today to 2025, 2050 and 2100, see Electris et al., 2009). As an example, the Polestar system is a flexible and user-friendly framework used to develop and assess alternative scenarios (Raskin et al., 1999). It is a methodological framework that offers a specific accounting modeling approach to analyze the system's dynamics. The Polestar system allows for a flexible analysis at regional, national and global scales by enabling the user to add new variables, indicators and relationships. In the GEO-4 report, various integrated assessment models have been used to develop future projections, including the International Futures Models (Hughes and Hillebrand, 2006) and the Integrated Model to Assess the Global Environment (IMAGE) (Bouwman et al., 2006). The models were soft-linked by using output files from one model as an input file for another model. The Story-and-Simulation approach (Alcamo, 2001) is another methodological framework used to link qualitative story lines and quantitative models. Narrative storylines are first drafted by a stakeholder panel and iteratively revised based on model results from an expert modeler team. The framework is not specific about which models should be applied for quantification. Different models have been applied in studies such as environmental and integrated assessment models for the development of scenarios for the Millenium Ecosystem Assessment (MA) (e.g., WaterGAP, Alcamo et al. 2003a, 2003b, and IMAGE, IMAGE-Team 2001), or fuzzy cognitive mapping for analyzing the future of the Amazon forest (Kok, 2009). Finally, the integrated assessment models of the IPCC (2014) serve as an example of more expert-based quantitative modeling studies to assess future pathways.

Gallopin et al. (1997) reflect on the aim of these formal models to provide a scientifically robust basis through a disciplined and rigorous approach to understand complex systems. Nevertheless, Gallopin et al. (1997) highlight "occasionally excessive claims" (p. 7) of these formal expert models, as they implicitly embody disciplinary paradigms and usually only capture those elements from the complex system that are understood and for which empirical data are available. In addition, such models usually imply a high spatial aggregation, which does not allow insights into underlying trends at regional or local scales. Gallopin et al. (1997) argue in favor of a combined application of quantitative analysis using formal models and qualitative narratives to provide texture and richness.

The preceding overview of the literature reveals specific challenges with regard to conceptual and methodological frameworks for the design of sustainability visions, which are addressed in this research. First, current frameworks focus on the transition process through time, starting from the present towards a possible future state. The future state itself is mostly described in a qualitative way through qualitative narratives or visualizations. These narratives and visualizations are then used to develop a systems model in order to model pathways starting from the present towards a possible future state. Such a modeling approach can provide insights into the internal consistency, plausibility and desirability of visions or sensitivity to assumptions. However, due to an **unclear distinction between target knowledge (Where do we want to go?) and transformation knowledge (How can we get there?)**, it is unclear whether insights are related to the visionary future system state or the process of implementation. Second, **pathway models are** relatively **complex and data-intensive** due to the combined modeling of the target and process. Pathway model development demands large resources (e.g., time for model development), expert knowledge and an intensive literature review to parameterize the model and produce scenario runs. This can cause **problems with stakeholder engagement**, as stakeholders can become frustrated by lengthy data-gathering and modeling processes. Stakeholders often do not understand the exact functioning of complicated models and thus might question the results from the analysis. Therefore, new **systems modeling methods** are needed that allow for participatory vision modeling. Third, **conceptual visioning frameworks can foster the imagination of distinct futures, which could however impede the identification of synergies**. For instance, focusing on the scale in vision design (e.g., a regional and global sustainability vision) can obscure important synergies between scales (i.e., a synergy between regional systems based on personal contact and global, commodity-based systems).

While the aforementioned challenges are linked to the design of sustainability visions, the following section addresses challenges with regard to assessing the quality and plausibility of future visions.

1.1.2 Challenges linked to the integrated assessment of sustainability visions

Envisioning desirable futures involves unique challenges when it comes to quality assurance. Sustainability visions are inherently normative, i.e., influenced by the worldviews, experiences, interests, goals and values held by the originators, which can be an individual, a group, an organization or an epistemic community. Instead of reducing the uncertainties of future developments (e.g., through predictive models), futures studies also analyze possible futures, which has been criticized by some scholars as being unscientific or pseudo-science (Enzer, 1983). However, future visions have a profound impact on societal discussions and decision-making, which requires their systematic and rigorous analysis (Grunwald, 2007).

On the one hand, vision assessment is required to analyze the factual content of visions as well as underlying normative assumptions and values to allow for an informed handling of alternative visions of the future. The assessment of these visions can reveal limitations of future visions (e.g., a focus on technology without considering socio-ecological effects) and offer alternatives to predominant visions. On the other hand, vision assessment can also address the process of visioning, i.e., how visions are developed, distributed and utilized and what this says about the vision's originators as well as contemporary society (e.g., Lösch et al., 2006). The development, utilization and diffusion of ideas about the future can say much about the present, such as current desires, fears, interests and preferences (Grin, 2000; Grunwald 2016). A holistic vision assessment takes these dimensions, i.e., the vision's content, development process and socio-cultural context, into account.

The concept of post-normal science shows the difficulties in achieving quality assurance in transdisciplinary research addressing complex societal problems with high uncertainties, lack of empirical data and substantial relevance of ethical and value judgements (Funtowicz and Ravetz, 1993), as is the case for sustainability visions. Post-normal science stands in contrast to a traditional understanding of science, in which larger problems are dissected into small pieces with a lower level of complexity and inquiry is supposed to proceed without the influence of normativity. Thus, conventional science aims at reproducibility of results (i.e., the set-up of experiments is controlled so that any competent researcher should be able to reproduce it) and generation of predictive knowledge (i.e., results are identical if the same experimental design is followed), neither of which can be achieved in post-normal science. Funtowicz and Ravetz

(1993) however, highlight that post-normal science should be considered as a particular type of science that should not be conflated by regular scientific endeavor that aims at reductionism, repeatability and refutation (cf. Checkland and Holwell, 1998, who deal with quality assurance in action research). Instead, post-normal science addresses issues with high system uncertainties that cannot be fully eliminated or handled by standard statistical techniques. These high uncertainties are due to the complexity of the topic, pressure to act (e.g., identification of effective solutions to address climate change) as well as ethical aspects (e.g., preference for a particular future vision). Another element of post-normal science is the difficulty to evaluate knowledge. Peer review is a key approach in science to determine what enters the body of knowledge. However, transdisciplinary research produces knowledge that is affected by diverse worldviews and interests of stakeholders and can be interpreted in different ways.

Funtowicz and Ravetz (1993) warn against the excessive trust in quantitative simulations, similar to the words of caution by Gallopin et al. (1997). Outputs of computer models suggest accurateness even though the models might be parameterized based on expert judgment rather than profound analysis of empirical data. They differentiate between three levels of uncertainties: (1) technical uncertainties (inexactness) that can be managed through standard routines (e.g., calculating R^2 values); (2) methodological uncertainties (unreliability) which require expert judgments, as is the case, for instance, with regard to decisions in medicine or engineering; (3) epistemological uncertainties (ignorance) which cannot be reduced, as the problem boundaries are ambiguous and various plausible interpretations are possible (van der Sluijs et al., 2005).

Quality assurance for post-normal research involves epistemological uncertainties and requires unique approaches. Besides the ‘product’ and ‘process’ of research, which are key criteria in traditional science, Funtowicz and Ravetz (1993) demand that in post-normal research ‘persons’ and ‘purposes’ should also be evaluated by an extended peer community which includes all the stakeholders of an issue. For instance, the assessment of a technological risk does not only involve engineers and public bodies, but rather requires a broad societal debate about what risk level is accepted and desired. Funtowicz and Ravetz (1993) propose the NUSAP (Numeral Unit Spread Assessment Pedigree) method which complements conventional quantitative uncertainty assessment methods, such as Monte Carlo analysis, with systematic qualitative assessment methods, such as expert assessment. On the more quantitative side, the

NUSAP method evaluates quantities by its number, its unit and spread (e.g., random error or variance). On the more qualitative side, the NUSAP method draws on qualitative judgments of experts (e.g., whether a value is an optimistic or pessimistic guess) and an analysis of the pedigree, which includes an evaluation of the research process (e.g., speculative, acceptable or plausible) (van der Sluijs et al., 2005). Quality assurance in post-normal science does not imply the goal of reducing (or even eliminating) uncertainties in the analysis of future visions, which would not be possible. Instead, post-normal research requires a transparent handling of uncertainties and reflection on potential biases stemming from a stakeholder engagement process or the researcher's own expertise and professional background.

Vision modeling requires specific quality criteria as well. In general, modeling can be defined as "[…] the art of selecting those aspects of a process that are relevant to the question being asked" (Holland 1996, p. 146). Model development is not entirely determined by fixed rules, but is also guided by modeling paradigms and approaches that are established in a particular field as well as the modeler's intuition (see also Holtz, 2010). Sterman (2000) even states that "all models are wrong" (p. 521) by highlighting that models are an abstraction of reality and therefore cannot be true in a literal sense. Instead, models are useful because they provide insights into particular questions, which requires simplifications and making assumptions. A first step towards assessing a model's usefulness is to define its purpose, which can be (1) a curiosity–driven interest in a phenomenon, (2) the production of case-specific policy advice, or (3) the facilitation of social learning processes through stakeholder facilitation (Halbe et al., 2015). The visioning studies previously mentioned provide examples of all categories. The first global scenarios were more general and curiosity driven (Gallopin et al., 1997). Later scenario studies, such as the GEO-4 report (UNEP, 2007), were aimed at providing policy advice at a more specific regional level. More recent studies using visioning exercises facilitated stakeholder processes on various environmental issues (e.g., Kok et al., 2011, Falardeau et al., 2019). The modeling purpose also has important influence on the model design and evaluation (see Halbe et al., 2015). Models for policy advice tend to be more detailed and expert-driven, while models for stakeholder engagement should be simpler so as to remain understandable for stakeholders. Hence, evaluating the usefulness of models strongly depends on their primary purpose. For instance, models for policy-advice should have a high degree of facticity and specificity, whereas models for stakeholder facilitation could also reflect the false assumptions of stakeholders and thereby reveal the implausibility of a sustainability vision. The latter might therefore be excellent at fostering learning.

Despite the challenges mentioned before, modeling of sustainability visions offers various promising opportunities. Iwaniec (2013) defines vision modeling “as the process of constructing sustainability models such that the structure and function of the future desirable state is explicitly articulated as a systems model” (p. 118). Visions (desirable future states) can be understood as a subgroup of scenarios (possible future states), which are clearly different from predictions (likely future states) (Wiek and Iwaniec, 2014). Vision modeling aims at analyzing the consistency (Are there any contradictions or unintended side-effects?), plausibility (Are constraints in a given context considered?) and desirability (Which kind of sustainability benefits are achieved?) of a sustainability vision.

Quality assurance of visioning models is rarely researched. Global scenarios (e.g., UNEP, 2007; Electris et al., 2009) are supposed to gain credibility by modeling the status quo in the present or the evolution of the problem in the past. This means that the model is validated by comparing simulation results of system variables to empirical data. If the model turns out to produce accurate results for the past and/or the present, trust in the model’s results in terms of future scenarios is heightened. With regard to modeling a sustainability vision, this approach can be questioned as the model structure of today’s system might be qualitatively different to the system structure of a future sustainable system. Lack of structural continuity due to qualitatively different systems would undermine the assumption that a validation based on empirical data assures quality of the model. Another potential approach for quality assurance of sustainability visions is model-to-model analysis in which model results on similar topics are compared (Rouchier et al., 2008). For instance, a review of global scenario studies by Hunt et al. (2012) showed a surprising convergence of scenarios (i.e., the scenarios could be grouped into the original scenario classes provided by the Global Scenario Group, see Gallopin et al., 1997). This finding can also be questioned, however, as model design is often oriented towards previous studies on the same topic (cf. Chapter 1.1.1 on using visions from past studies as a blueprint).

The preceding overview of the literature reveals specific challenges with regard to the assessment of sustainability visions. First, **a systematic methodology for quality assurance of**

vision models is largely absent. This is due to a lack of studies that explicitly take a vision modeling approach, i.e., an approach that focuses on the modeling of a future system state. In particular, this is a tremendous **challenge for quantitative vision models**, as conventional model validation approaches utilize empirical data, which are usually absent with respect to future visions. On the one hand, **systems modeling methods** that can deal with such data-scarce situations need to be further developed. On the other hand, **systematic model testing approaches** need to be developed to allow for model testing and validation. Second, vision assessment requires that in addition to the product, i.e., the sustainability vision, the process (i.e., How was the process designed?), persons (i.e., Who participated in vision development?) and purposes (i.e., Why did stakeholders participate? How is the vision used?) need to be considered. Up to now, **methodological frameworks that allow for an integrated assessment of the product, process, persons and purposes of vision modeling are missing**.

The aforementioned challenges of vision design (Chapter 1.1.1) and vision assessment (Chapter 1.1.2) are translated into a number of research objectives, as described in the subsequent section.

1.2 Research objectives

Based on the aforementioned problem statements, this research has the following objectives:

- Objective 1: Further develop systems modeling methods, including functional analysis, fuzzy cognitive mapping and system dynamics modeling, to be applicable for the design and assessment of sustainability visions.
- Objective 2: Develop, test and apply a methodological framework that supports the design, implementation, evaluation and analysis of participatory modeling processes.
- Objective 3: Develop, test and apply a conceptual and methodological <u>vision design</u> framework that allows for the development of sustainability visions using participatory modeling methods.
- Objective 4: Develop, test and apply a conceptual and methodological <u>vision assessment</u> framework that allows for the systematic handling of uncertainties in modeling sustainability visions.

The first objective refers to the identification and further development of systems modeling methods to be applicable for vision design and assessment of sustainability visions. In particular, modeling methods from the fields of systems science and systems engineering show a high potential to deal with the complexity (i.e., technical, social, economic and environmental aspects need to be addressed) and normativity (i.e., stakeholder participation in vision design and assessment is required) of sustainability visions. Various conceptual and dynamic modeling methods are available that are potentially suitable for a systematic design and assessment of visions: conceptual modeling, such as functional analysis and causal loop diagrams (CLDs), can support stakeholder participation in vision design, as technical modeling skills are not required. Fuzzy cognitive mapping (FCM) is a semi-quantitative modeling that can also play an important part in vision design and assessment due to its ability to deal with a lack of empirical data. System dynamics is a quantitative modeling approach that allows for the dynamic analysis of complex systems. However, system dynamics requires further methodological development as it is a continuous modeling approach (i.e., the dynamics of systems are modeled through time), which constrains its application for analyzing a future system state.

The second objective addresses the challenges of involving stakeholders in vision modeling and assessing the context of visioning processes, including process outcomes, process steps, participating stakeholders and the process purposes. A participatory approach is required to deal with epistemological uncertainties in the development of sustainability visions. Thus, a methodological framework will be developed that allows for the stepwise involvement of stakeholders in participatory modeling processes that combine qualitative and quantative modeling methods. As laid out by Funtowicz and Ravetz (1993), research on complex topics, such as sustainability visions, requires that 'persons' and 'purposes' of research are analyzed as well as research 'products' and 'processes' of research. Dealing with high complexity and normativity of sustainability visions therefore requires consideration of the research process and its context, which will be addressed by the methodological framework.

The third objective of this research is the development, testing and application of a conceptual and methodological framework for the design of sustainability visions. The framework will have a number of characteristics that address the research challenges mentioned previously: first, the conceptual and methodological framework specifically should produce 'target knowledge' by developing models of a desirable future system state without dealing with the implementation process and potential future pathways. Second, the framework will support the design of visions specific for a regional context rather than general scenarios at a more abstract level. Furthermore, the developed framework will address key aspects of sustainable systems design, including the interlinkages between scales (i.e., multi-scale system designs), as well as the opportunities for including technical, nature-based and social solutions.

The fourth objective relates to the development, testing and application of a methodology for the integrated assessment of sustainability visions, which includes the systematic handling of uncertainties. This objective addresses a significant challenge, as conventional model testing and validation approaches usually depend on the availability of empirical data, which are often lacking for future system designs. Quantitative vision modeling studies (e.g., Iwaniec et al., 2014) often do not address the issue of model validation and testing at all, even though significant technical, methodological and epistemological uncertainties are involved. This research therefore aims at conceptualizing uncertainties involved in vision modeling and developing an approach for quality assurance of vision models.

1.3 Thesis outline

The thesis is structured as follows. In Chapter 2, a literature review is provided to introduce key concepts and the state-of-the art in research areas related to this thesis. First, general theories and concepts related to this research are presented (Chapter 2.1). In order to clarify the connections to various research strands linked to this research, state-of-the-art research with regard to highly relevant research fields is subsequently presented (Chapter 2.2), including the fields of futures studies, sustainability transitions research, sustainable systems engineering, social-ecological systems research and integrated assessment. Finally, Chapter 2.3 of the literature review addresses the research objectives mentioned before, by providing a review of systems modeling methods (Chapter 2.3.1), participatory model building frameworks (Chapter 2.3.2), vision design frameworks (Chapter 2.3.3) and vision assessment frameworks (Chapter 2.3.4).

Chapters 3 to 8 present the research articles and their links to the research objectives. In Chapter 3 and Chapter 4, the development of two systems modeling methods is presented, which will later be part of the conceptual and methodological framework for vision design and assessment. Chapter 3 presents the Functional Organization and Analysis (FOA) approach that was developed from the functional analysis method in systems engineering (Article #1). The method is applied to a case study on food systems in Southwestern Ontario. In Chapter 4, a functional flow analysis (FFA) method is developed that builds on CLDs, stock-and-flow diagrams and system dynamics modeling (Article #2). An application of this method is provided for water management in Cyprus. A key aspect of handling uncertainties in complex and normative problem situations is the participation of stakeholders in the modeling process. The design and implementation of such a participatory modeling process is described in Chapter 5, which is guided by the Participatory Model Building Framework (PMBF) (Article #3). The PMBF clarifies how to initiate a participatory modeling process, monitor its progress (including process steps and participants), and envision structures for its institutionalization. A comprehensive case study application is provided for water quality management in Québec. Chapter 6 presents the conceptual and methodological Vision Design and Assessment Framework (VDAF) and its application in a case study on sustainable food systems in Southwestern Ontario (Article #4). The VDAF is based on three methods, namely functional analysis, systems thinking and FCM. Chapter 7 provides the methodological development of the VDAF to include system dynamics modeling (Article #5). Another focus of this chapter is the development of an approach for model testing and systematic handling of uncertainties in vision modeling. Chapter 8 provides an application of the revised VDAF and the model testing approach with regard to the vision of a fully renewable energy system in Germany (Article #6).

A multi-case approach was chosen for this thesis to test the methodology for various environmental management issues in different spatial, institutional and socio-economic contexts. In this way, the potential and limitations of the different parts of the methodology were explored. Two case studies were carried out in Canada, namely in Ontario and Québec. The case study in Southwestern Ontario comprised the Bruce, Grey, Huron, Middlesex, Perth and Wellington counties and dealt with the design and assessment of sustainable food system visions. The Québec case study in the Du Chêne watershed dealt with water quality management. Another case study was organized in Germany to explore visions of a sustainable energy system that is based upon 100% renewable energy sources. Finally, a case study on water supply management in Cyprus was conducted to test and further develop the functional analysis and systems thinking methods as part of the VDAF. In summary, methods for vision assessment and design for food, energy and water systems were tested in this research in four case studies in North America and Europe. While each case study focused on a specific supply system, a nexus perspective was chosen in all case studies, i.e., synergies and trade-offs to other supply systems were explored. The geographical boundaries were adapted to the case study topic and socio-economic context. Therefore, a watershed scale was chosen for the case study on water quality management in Québec. As water supply management is predominantly conduced at a national scale in the Republic of Cyprus, the geographical boundaries of the Cyprus case study were set accordingly. A regional scale comprising several counties was chosen for the food system case in Southwestern Ontario. Finally, a national scale for the energy system case in Germany was found appropriate in order to include the challenge of geographical disparities in renewable energy potentials and energy consumption.

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Chapter 2: Literature review

The literature review is divided into three parts. Chapter 2.1 presents more general theories and concepts that are utilized in this research. Due to a strong focus on systems research, an introduction to systems science is provided (Chapter 2.1.1). Other key concepts of the conceptual framework for vision design and assessment include ecosystem services, natural infrastructure and nature-based solutions (Chapter 2.1.2). Finally, social learning is another important concept for dealing with epistemological uncertainties involved in the development of future visions (Chapter 2.1.3). Chapter 2.2 provides an overview of research fields that are linked to the design and assessment of sustainability visions. These are futures studies (Chapter 2.2.1), sustainability transitions research (Chapter 2.2.2), sustainable systems engineering (Chapter 2.2.3), social-ecological systems research (Chapter 2.2.4) and integrated assessment (Chapter 2.2.5). In Chapter 2.3, the state of the art with respect to systems modeling methods as well as conceptual and methodological frameworks that will be applied as part of this research are reviewed. Chapter 2.3.1 provides a summary of methods that will be applied and further developed in this research, including functional analysis, systems thinking, fuzzy cognitive mapping (FCM) and systems dynamics modeling (cf. Objective 1). Chapter 2.3.2 provides an overview of existing participatory modeling frameworks (cf. Objective 2). In the remaining two sub-chapters, an overview of existing conceptual and methodological frameworks for vision design (Chapter 2.3.3) and vision assessment (Chapter 2.3.4) are provided (cf. Objectives 3 and 4).

In the following sections, the state of the art with respect to general theories and concepts (Chapter 2.1), research fields (Chapter 2.2) and systems modeling methods, as well as conceptual and methodological frameworks (Chapter 2.3) are presented. After each chapter, a short paragraph is provided that clarifies the link of concepts, methodologies and methods to this research. Important terms are marked by using bold characters to allow the reader to quickly grasp key terms of this research.

2.1 General theories and concepts related to this research

This section introduces key theoretical concepts (i.e., systems science, ecosystem services, natural infrastructure, nature-based solutions and social learning) related to this research.

2.1.1 Systems science

The systems approach is not exclusively used for the inquiry of systems but also for knowledge generation in various scientific disciplines like physics, biology and engineering. An object that can be defined as a system requires certain features (Bossel 2004): First, the object must have a special purpose that can be noticed by an observer. Second, the object must consist of system elements that are connected by causal links which form the system's structure. Third, the object must have a system identity that would be destroyed if parts of the system structure were separated. Based on this definition, a chair is a system as it has a purpose (sitting), consists of a system structure (chair legs and back, sitting plate), and would lose its integrity if an element was removed. In contrast, a sand heap is not a system despite a purpose (e.g., storage of sand) and a system structure (merged grains). A removal of sand would not destroy the system identity of the sand heap, so that the third mandatory feature of a system is not met (Bossel 2004).

Bossel's definition can also be applied to technical and natural systems that deliver either direct services (i.e., ecosystem or technical services), or functions (i.e., technical or natural infrastructure). In this respect, the assigned service or function is determined by the perspective of the observer (first feature determined by Bossel). Hence, different services might be found, if the observers have different values or needs. The system structure (Bossel's 2nd feature) refers to the actual relations between components of the system (cf. Maturana and Varela 1992). The third feature of a system identity demands for simplicity of the structure that describes the organization of the system. Hence, redundant elements should be eliminated and only essential elements and their relations included.

Varela (1979) points to the distinction between the organization of a system and its structure. While the structure specifies the properties and relation of specific system elements, the organization only determines general system elements and relationships that together constitute the system. The organization is "independent of the materiality that embodies it; not the nature of the components, but their interrelations" (Maturana and Varela 1979). Varela (1979) points to the complementarity between the analysis of structure and organizations of systems: "Any explanation of a biological system must contain at least *two complementary* aspects, one referring to it as an organization, and the other referring to it as a structure, as an instance. The first must account for the specific (dynamic) configuration of components that define it; the second must account for how its particular components enter into the given interrelations that constitute it" (Varela, 1979, pp. 10-11). As for biological systems, the organization and structure can be analyzed for technical and social systems as well. Finally, the third step in the analysis of systems is the analysis of processes that underlie a specific structure of technical, environmental or social systems.

The resilience of a system is an important property for sustainability assessment. From a social-ecological system perspective, the resilience of a system represents its adaptive capacity, i.e., the property of the system to counter external forces without losing its integrity (Holling et al. 2002). The resilience concept specifies capabilities of supply systems that support sustainable development: systems have to resist and adapt to change ('sustainability'), while at the same time create and maintain opportunities ('development') (von Gleich et al., 2010). The location of a vision at a particular spatial scale (e.g., a local, regional or global scale) can have a profound impact on its resilience. In this respect, supply systems that are focused on a particular scale are not always the best ones from a resilience point of view. For example, local food systems show many sustainability benefits, such as self-reliance, ownership and awareness of environmental issues (e.g., Tripp, 2006), but at the same time are often highly vulnerable to extreme events like droughts and floods (e.g., Bryan et al., 2009). Access to global food trade can induce a higher resilience of food supply since the potential sources of supply are diversified. Scale is therefore an important aspect to be considered in the design and assessment of sustainability visions.

Building on systems science, the conceptual and methodological framework that will be developed in this research has to differentiate between the system's **organization, structure and processes** to guide the design of systems. In addition, the framework has to support an analysis of sustainability visions at different scales, and allow for a combination of visions towards **multi-scale system designs** in order to consider interactions between scales.

2.1.2 Ecosystem services, natural infrastructure and nature-based solutions

The 'ecosystem service' and 'ecosystem function' concepts address the relationship between ecological systems and human needs, and thereby can support the integrated assessment of sustainability visions. Ecosystem functions (e.g., soil retention) are ecosystem structures and processes that are used and valued by people, and therefore become ecosystem services (e.g., prevention of damage from erosion) (cf. de Groot 2006; Termorshuizen and Opdam 2009). The Millennium Ecosystem Assessment (MEA 2005a) placed ecosystem services into *provisioning, regulating, cultural,* and *supporting services* categories. Provisioning services are the most clearly recognizable services and provide direct products people can use such as clean drinking water and fertile land for agriculture and grazing. Regulating services like natural purification in wetlands and river ecosystems are often less obvious. For instance, the natural flow regime of rivers supports a variety of regulating ecosystem services, such as erosion, pollution, and flood and pest control (Poff et al. 1997). Spiritual and aesthetic services are examples of cultural services of wetlands. Water in general and rivers in particular have a special value in culture and spiritual traditions (Craig 2007). Supporting services are necessary for the provision of other ecosystem services. Their impacts on people are indirect or occur in longer time frames compared to other types of services. Examples are soil formation, nutrient cycling and climate regulation among others (MEA 2005a).

Other classifications of ecosystem services exist. Wallace (2007) criticizes the MEA (2005a) categories as being "not a coherent set of services at the same level that can be explored and traded off in a decision system" (2007, p. 238). For instance, food production (provisioning service) is at the end of an ecosystem management process, while pollination (regulating service) is a means of service delivery. Ecosystem functions can become ecosystem services, if they satisfy a need of people (e.g., a basic need like drinking water). Therefore, "one function can offer several services [..], and functions continue to exist in the absence of people" (Termoshuizen and Opdam 2009). Ecosystem functions are provided by ecosystem structures and processes. Ecosystem structures are "the physical organization or pattern of a system" (Noss 1990), while processes are the "complex interactions (events, reactions or operations) among biotic and abiotic elements of ecosystems that lead to a definite result" (Wallace 2007). Indirect functions (e.g., pest management) support the provision of primary functions (e.g., food production) that are directly related to a human need (e.g., food).

'Nature-based solutions' is an innovative concept that is increasingly considered in research (e.g., Kabisch et al., 2016; Keesstra et al., 2018) and policy (e.g., European Commission, 2015). Nature-based solutions can be defined as "[...] the use of nature in tackling challenges such as climate change, food security, water resources, or disaster risk management, encompassing a wider definition of how to conserve and use biodiversity in a sustainable manner" (Balian et al. 2014, p. 5). Natural infrastructure is a related concept, but is more in line with the definition of ecosystem services and functions. Thus, natural infrastructure comprises the ecosystem structures and processes as well as resulting ecosystem sub-functions. Natural infrastructure (e.g., a wetland that purifies water) does not satisfy a human need directly (e.g., drinking water), but provides sub-functions (i.e., generation of usable water) that indirectly support the satisfaction of needs. This definition is in line with the common usage of the term in engineering where technical infrastructure (e.g., roads) is not an end, but a means to satisfy human needs (e.g., mobility). Technical infrastructure is also composed of processes or structures (i.e., process engineering vs. structural engineering) to realize a certain sub-function (e.g., plain road). Human values will determine the choice for a specific design of technical structures and processes. For instance, the design of the technical system will be influenced depending on whether stakeholders favor long-term sustainability over short-term benefits.

The conceptual and methodological framework will build upon the concepts of **ecosystem services**, **ecosystem functions**, **natural infrastructure** and **nature-based solutions** to include complex human-environment interactions in vision design and assessment. While 'ecosystem services' and 'ecosystem functions' are established analytical concepts from ecology, 'natural infrastructure' and 'nature-based solutions' are more recent concepts that have a more applied character, i.e., aiming to utilize ecosystems to address a human need.

2.1.3 Social learning

Learning is a key concept to deal with processes of change in individuals, groups, organizations, and societies. With respect to sustainable development, all these learning levels need to be addressed including change of individual resource demands and practices, transformations of production processes in companies, and adaptation of societal institutions to challenges like climate and global change (Halbe, 2016). The engineer's role in this transformation process towards sustainable development comprises the transfer of engineering knowledge into social learning processes, and consideration of local knowledge in engineering design (cf., Koen 2003).

Social learning denotes learning of individuals in a social context (e.g., through group discussions, and joint actions), and has been variously defined in the literature. Reed et al. (2010) reviewed different notions of the concept and concluded with a comprehensive definition. Social learning is defined as "a change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks" (Reed et al., 2010, p. 6).

Stakeholders of social learning processes in resource management are users, decision-makers, implementers and experts (European Commission, 2003). Engineers might have the role of implementers (i.e., including active implementation of measures) and experts (i.e., more passive role when it comes to implementation). The participation of engineers in social learning processes constitutes a shift of the current resource management paradigm from an expert-driven top-down paradigm to an adaptive learning paradigm (cf., Halbe et al., 2013, 2018). Therefore, engineers pose a key stakeholder group to shift resource management practices at the societal level.

The Learning Alliances concept is another learning approach that reflects knowledge transfer between stakeholders. It has been applied frequently in industry facilities (e.g., Love and Gunasekaran 1999) and resource management (Verhagen et al. 2008). This concept has a focus on improvement of technical systems by bringing together workers, users, customers, management and experts. The concept aims at fostering social learning through 'multi-stakeholder learning and innovation' platforms that attempt to embed knowledge transfer within the process of innovation. This includes meaningful participation of all stakeholders and change in the operational culture as it is about incorporating new processes and technologies.

This research will build upon the concepts of social learning and Learning Alliances by embedding vision design and assessment in a **collaborative planning and management** process that implies knowledge transfers between experts (i.e., engineers) and local stakeholders.

2.2 Research fields related to this research

This research is related to different research fields, most notably to futures studies, sustainability transitions research, sustainable systems engineering, social-ecological systems research and integrated assessment. This section provides an overview of the state of the art in these five research fields.

2.2.1 Futures studies

Futures studies is the most common term used for research on alternative futures (Sardar, 2010). Bell (1996) provides a historical overview of futures studies, stating that the desire to know the future is embedded in every known society. Divination practices or rites that mark the passage into a certain societal role are examples of ancient ways to deal with the future. Thomas Moore's book 'Utopia' has been a milestone in fictional literature by describing an ideal society, which is geographically distant but exists contemporarily to the current society at that time. At the end of the 18th century, a shift from space to time took place, i.e., an ideal society was imagined at a distant point in time instead of space (Manuel and Manuel, 1979). This shift also meant that the contemporary society was considered to be shapeable towards a more perfect world (Bell, 1996).

Despite these artistic origins in utopian thought, futures studies gradually developed towards a field of research only after the Second World War. An important impetus for applied futures studies was the formation of the RAND Corporation in 1948, a think tank for the US Army, which analyzes policy alternatives, future predictions and new ideas in the scope of military applications and, by 1970, also non-military projects. The RAND Corporation applied and further developed various methodologies, including systems analysis, scenario-writing and Delphi-techniques (Bell, 1996). A helpful way to structure the vast field of futures studies constitutes the three modes of orientation by Grunwald (2014), as described in Chapter 1, which include forecasting approaches (Mode 1), foresight approaches (Mode 2) and semantic and hermeneutic approaches (Mode 3). Various research strands that form the more applied segments in the research field (see Sardar, 2010) were already presented in the introduction (see Chapter 1) and are not repeated here in detail.

Due to the field's focus on applied research, a fully developed theory of social change and the future is missing (Bell, 1996; Öner, 2010). Examples of theoretical perspectives from futures studies are the definition of principles of industrial societies by Toffler and Alvin (1980) (i.e., standardization, specialization, synchronization, concentration, maximization and centralization).

Another example is the cybernetic-decisional theory of social change by Bell and Mau (1971) that describes the influence of images of the future on individual and group action.

This research follows the **applied character of futures studies**, and does not aim to develop a general theory of sustainability visions. The purpose of such general theory development is here understood as seeking general causal relationships and "[…] designating some types of factors as especially important and others as less critical for explanatory purposes" (McGinnis 2011, p. 170). Theoretical considerations are nevertheless provided to reflect on the epistemology of vision design and assessment. This includes a differentiation between systems knowledge, transformation knowledge and target knowledge (see Chapter 1.1), and addressing the challenge of quality assurance (see Chapter 1.1.2). Instead of developing a general theory of sustainability visions, this research aims to develop a **conceptual framework of vision design and assessment.** A conceptual framework is understood in the way that it "[…] identifies, categorizes, and organizes those factors deemed most relevant to understanding some phenomenon" (McGinnis 2011, p. 170). Hence, the conceptual framework aims to systematically connect key concepts of vision design and assessment, such as ecosystem services, ecosystem functions, natural infrastructure and nature-based solutions. This research is furthermore linked to **Mode 2 and Mode 3 of futures studies** by developing alternative visions of a sustainable future (Mode 2) and analyzing the process and context of the visioning process (Mode 3).

2.2.2 Sustainability transitions research

The severity of global environment change has inspired the development of sustainability transitions research. Iterative improvement of environmental and social problems seems to be insufficient to stay within the planetary boundaries (cf. Rockström et al., 2009); instead, profound structural changes are required (e.g., Markard et al., 2012). Sustainability transition research consists mainly of four research strands related to the: (1) Multi-Level Perspective, (2) Technological Innovation Systems, (3) Strategic Niche Management and (4) Transition Management.

The Multi-Level Perspective is a conceptual framework that includes three central aspects of transitions: regime, landscape and niche (Geels, 2002, 2004, 2011, 2019). The Multi-Level

Perspective can help to explain different transition pathways, which depend on the strength of landscape pressures, the regime and niche innovations (see Geels and Schott, 2007). It has been extensively applied to explain historical transitions such as the transformation from cesspools to sewer systems (Geels, 2006a) and traditional factories to mass production (Geels 2006b). More recent work goes beyond a single regime and niche and takes a whole system perspective including multiple regimes and niche innovations (Geels, 2018).

The research strand related to Technological Innovation Systems analyses the various factors, such as institutional and organizational factors, which support the development and diffusion of innovations (e.g., Hekkert et al. 2007; Markard and Truffer 2008; Jacobsson and Bergek 2011). The 'functions approach' to Technological Innovation Systems is a prominent conceptual and methodological framework that defines specific system functions supporting innovation processes (Bergek et al., 2008). Blocking and inducing mechanisms can be further analyzed as specific intervention points, such as the development of visions and experimentation (e.g., Jacobsson and Bergek 2011).

Strategic Niche Management aims at the understanding and active facilitation of niche creation and development (Kemp et al., 1998; Schot and Geels, 2008). Historical case studies have shown that transformative innovations often initially develop in small market niches (e.g., Geels, 2002). Strategic Niche Management investigates how such niches can be purposefully created and protected to allow the development of radical sustainability innovations. This can be accomplished through setting enabling rules, the design of multiple experiments, visioning exercises and strategic network building. Strategic Niche Management has been applied to foster various innovations, such as cleaner vehicle technologies (Kemp et al., 1998; Sushandoyo and Magnusson, 2014) and community energy projects (Ruggiero et al., 2018).

Transition Management is a reflexive governance approach aiming at the pro-active facilitation of sustainability transitions (Voß and Bornemann, 2011). Visioning processes and identification of frontrunners are also central activities in a Transition Management process (Loorbach, 2010). This approach has been applied to various topics, such as sustainable waste management, energy supply and housing (e.g., Loorbach, 2007; Loorbach and Rotmans, 2010). The term 'transition governance' is a broader term than Transition Management that embraces the full complexity of multi-actor processes in societal transformations towards sustainable development (Halbe 2016).

In comparison to Transition Management, transition governance considers societal transition processes too complex and broad to be managed by a group of forerunners and transition managers. Instead, transition governance requires knowledge about intervention points and roles of multiple actors at various societal levels, such as the individual, group, organization or policy levels. Halbe (2016) developed a methodology for the analysis and design of transition governance processes, which was tested in various case studies (e.g., Halbe et al., 2015).

The importance of visions for sustainability transitions are acknowledged by all four research strands mentioned above. For example, the multi-level perspective considers the articulation of expectations and visions as a core process in niche development (Geels, 2011). In the Technological Innovation Systems, Strategic Niche Management and Transition Management approaches, vision development is seen as an instrument that actively supports innovation processes and collaboration of stakeholders. Different visualization and qualitative modeling tools have been applied in Transition Management case studies (Roorda et al., 2012). However, conceptual and methodological frameworks that support a structured and collaborative development of sustainability visions are currently lacking in the transition research field. This research will address this research gap by **providing such a conceptual and methodological framework for vision design and assessment**.

2.2.3 Sustainable Systems Engineering

The term ‘Sustainable Systems Engineering’ highlights the importance of a systems-perspective in engineering to analyze the interconnectedness of technical, environmental, social and economic systems in an integrated way. ‘Sustainable Systems Engineering’ is not a well-established concept as a Scopus literature analysis reveals: only 17 documents use this term in title, abstract, and key words (across all years and subject areas).[2]

Sustainable engineering is a broader term for which standardized approaches rarely exist. Instead, the knowledge base is still insufficient to determine the most suitable and effective methods and tools. Principles are often provided that function as a descriptive tool to frame the search space where sustainable solutions can be found. Green Engineering is an approach to sustainable engineering, and is based on nine principles for development and implementation of

[2] Search terms of the Scopus analysis (January 17, 2021): “sustainable systems engineering”

technologically and economically viable products that facilitate human and ecosystem health (e.g., use systems analysis and life cycle thinking) (see Abraham and Nguyen 2003). In addition, the Royal Academy of Engineering (Dodds and Venables 2005) determined twelve guiding principles of engineering for sustainable development (e.g., "Innovate and be creative"; "Seek a balanced solution"; "Seek engagement from all stakeholders"). Based on these and other attempts, Fenner et al. (2006) developed an eight-point framework that includes practical dimensions of sustainable engineering. The principles are: 1) Ethical foundation: explicitly consider value judgments; 2) Justice through participation: to share knowledge and achieve mutual learning; 3) Efficient provision and co-ordination of infrastructure: minimizing ecosystem impacts and consideration of interlinkages between different forms of uses and objectives; 4) Maintenance of natural capital: ecosystem functions and diversity should be maintained; 5) Holistic financial accountability: costs for the whole life cycle should be considered; 6) Systems approach that comprises technical, social, economic, and environmental systems; 7) Interlinking scales: influences of projects across temporal and spatial scales should be examined; and 8) Future vision is necessary to motivate and guide action.

Systems engineering can be defined as "a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. A "system" is a construct or collection of different elements that together produce results not obtainable by the elements alone" (NASA, 2007, p.3). This definition is in line with the definition of systems by Bossel (2004) that highlights the interconnectedness of system elements and its purpose (see Chapter 2.1.1). Systems engineering does not focus on specific technologies, but more on systemic properties that guide technological design in order to meet certain needs (Douglass, 2016). The resulting system usually has to meet various requirements, such as financial and qualitative requirements, which can potentially contradict each other (e.g., the durability of a product might require high quality materials that can be inconsistent with financial requirements). A requirement can be defined as "a statement that identifies a product or process operational, functional, or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability (by consumers or internal quality assurance guidelines)" (Dick et al., 2017, p. 7).

Given that social, economic, environmental and technical aspects need to be considered in system design, systems engineering is an inherently “interdisciplinary approach to building complex and technologically diverse systems” (Douglass, 2016, p. 2). This interdisciplinary and systemic character of systems engineering allows for the transfer of existing design methods and tools from a focus on technical solutions towards also including nature-based solutions (see Chapter 2.1.2). Various systems engineering methods and tools exist (e.g., see Chakraborty et al., 2010; Douglass, 2016; Dick et al., 2017) that can be potentially applied to the design and assessment of sustainability visions. In particular, functional analysis methods from systems engineering will play a key role in this research (see Chapter 2.3.1.1 for details). In the following, two existing approaches are introduced that can provide a bridge from a technical focus of engineering towards also considering environmental and social aspects.

The “Whole System Approach” constitutes a structured methodology for system design and assessment. The approach is defined as “a process through which the inter-connections between sub-systems and systems are actively considered, and solutions are sought that address multiple problems via one and the same solution” (Stasinopoulos et al. 2008). This approach helps to identify potential resource efficiency gains in the supply chains of products and services, and the subsequent design of solutions that harness these synergies. However, the Whole System Approach does not consider the use of ecosystem services in the design process. In contrast, Matlock and Morgan (2011) provide guidelines for ecological engineering design of ecosystem services but do not address the link to technical solutions that can complement or substitute the provision of ecosystem services, and vice versa.

While the Whole System Approach is more methodological and practical by nature, industrial ecology is a helpful conceptualization of the interface between human production systems and nature. The approach focuses on the analysis of “the flows of materials and energy in industrial and consumer activities, of the effect of these flows on the environment, and of the influence of economic, political, regulatory and social factors on the flow, use and transformation of resources” (White 1994). A central concept of industrial ecology is the metaphor of biological ecosystems in which wastes are avoided by circular material flows. Applied to industrial systems, waste should be minimized by means of optimizing the material and energy metabolism. Therefore, synergies are sought that allow for using the wastes of one industrial subsystem as raw materials in another industrial subsystem. Industrial ecology focuses on different levels of analysis by applying the concepts of "industrial symbiosis" at the inter-firm level, and "industrial metabolism" at regional and global levels (Chertow 2000).

Another important concept is the Soft Path Approach, which was initially applied to energy systems (Lovins, 1977) and later further developed towards other supply systems, including water systems (e.g., Gleick, 2003) and food systems (e.g., Ramankutty and Dowlatabadi, 2021). This approach addresses the often detrimental socio-economic and ecological side-effects of the conventional technocratic 'hard path' approach, which aims at the time and cost-effective satisfaction of users' demands (Gleick 2003). Brooks (2005) highlights that also demand management alone, including charging full-costs and conducting awareness campaigns, might not be sufficient for sustainable water management. Thus, the Soft Path Approach goes some steps further by examining the bundles of services underlying resource demands, considering decentralized solutions and following a participatory approach by including local communities in decision-making (Gleick 2003). Such a rethinking of the ways how services are delivered can open up new options for transitions towards sustainability. Brooks and Brandes (2011) highlight five characteristics of soft path solutions: (1) Focus on services; (2) Ensuring ecological sustainability; (3) Matching the quality of supply to the quality required for a specific use; (4) Using backcasting to explore paths towards a desired future state; (5) Following a participatory approach.

The vision design and assessment framework will **address the eight-point framework of Fenner et al. (2006)** in a systematic way: Points #1 and #2 (ethical and participatory dimension) of the framework are included through the linkage of the Sustainable Systems Engineering framework to the participatory model building process where values and interests are discussed by stakeholders. Point #3 (Efficient provision and co-ordination of infrastructure; minimizing ecosystem impacts; consideration of interlinkages between different forms of uses and objectives) and #4 (Maintenance of natural capital) are included by considering technical and nature-based solutions. Point #5 (Holistic financial accountability: costs for the whole life cycle) is addressed by also including economic considerations in vision design and assessment. Point #6 (Systems context: a system approach is needed) is represented through the application of systems thinking, FCM and system dynamics modeling. Point #7 (Interlinking scales) is considered through the explicit analysis of synergies and tradeoffs between scales. Point #8 (Future vision) is fulfilled by animating the visioning of sustainable supply systems. The conceptual and methodological framework developed in this research is thereby inspired by general principles for sustainable design found in the literature.

Conceptual and methodological frameworks developed in this research will also address key characteristics of the Soft Path Approach, including its focus on delivering services to satisfy human needs (i.e., considering innovative solutions to provide services), the notion of strong sustainability (i.e., ecological sustainability as the basis for socio-economic sustainability), the use of visions of a desirable future system state to guide strategy development and a strong involvement of stakeholders.

2.2.4 Social-ecological systems research

Research on sustainability has to deal with the complexity of social-ecological systems and precludes the application of simplistic and short-term solutions. Tipping points and non-linear dynamics limit the ability to predict system behavior through simulation models. In the face of these huge uncertainties, the scenario method is a helpful approach to analyze possible trajectories of social-ecological systems (Peterson et al., 2003; Folke 2006). An example of the application of scenarios is the linkage of ecosystem services to human well-being in the Millennium Ecosystem Assessment. The Millennium Ecosystem Assessment analysed the implications of indirect (e.g., economy) and direct (e.g., climate change) drivers of change on ecosystem services and human well-being by using qualitative storylines and quantitative integrated assessment modelling (MEA 2005b; Carpenter et al. 2006).

As the notion of a predictable world turns out to be wrong from a complex social-ecological system perspective, sophisticated simulation models cannot forecast system behaviour of social-ecological systems (cf. Mode 1 of futures studies after Grunwald, 2014), but can only examine various alternative pathways of the future (cf. Mode 2 of futures studies). A recent trend in social-ecological systems research is the development of methodological frameworks that allow for more regional and contextual positive scenarios in comparison to global scenarios developed in the scope of the Millennium Ecosystem Assessment. Raudsepp-Hearne et al. (2019) present such a scenario approach that builds on existing sustainability initiatives, so-called ‘Seeds of a

Good Anthropocene'. As this methodological framework is very relevant for vision design, more details are provided in Chapter 2.3.3.

Another approach to deal with the complexity of social-ecological systems is the development of adaptive capacity of the system to be able to react to unanticipated future changes and increase resilience towards system breakdown. In this context, the term 'sustainable development' can be understood as follows: "Sustainability is the capacity to create, test, and maintain adaptive capability. Development is the process of creating, testing, and maintaining opportunity. The phrase that combines the two, 'sustainable development', therefore refers to the goal of fostering adaptive capabilities while simultaneously creating opportunities" (Holling 2001, p. 399). In this new paradigm, "most policies are really questions masquerading as answers" (Gunderson 1999, p. 1). Success in the real world has to be monitored and compared to past expectations. In this respect, the application of participatory model building processes is a recognized approach to facilitate learning, and thereby increase adaptive capacity and resilience of communities (cf., Pahl-Wostl 2007; Sendzimir et al. 2007).

The conceptual and methodological framework for vision design and assessment will build on the experiences of social-ecological systems research. These experiences call for the **participation of stakeholders** in research and management efforts to foster social learning. In addition, this research will build upon existing research on **positive scenarios** that has been conducted in the social-ecological systems research field (see Chapter 2.3.3 for more details).

2.2.5 Integrated assessment

Integrated assessment can be defined as "the scientific 'meta-discipline' that integrates knowledge about a problem domain and makes it available for societal learning and decision-making processes" (TIAS, 2020). Various approaches exist for integrated assessment. Ness et al. (2007) established an assessment tool framework that classifies groups of tools with respect to their temporal focus, object of focus and integration of nature-society systems. The temporal nature of approaches are retrospective (i.e., indicators/indices), prospective (i.e., integrated assessment), or a combination of both (i.e., product-related assessment). In the framework of Ness et al. (2007), integrated assessment covers impact assessment approaches, such as

Environmental Impact Assessment and Strategic Environmental Assessment, as well as various, more specific methods, such as conceptual modeling, system dynamics modeling and multi-criteria analysis. System dynamics modeling is a key method in this research and will be presented in more detail in Chapter 2.3.1.4. The method is applied in various fields, such as social-ecological systems research (e.g., Cohen and Neale 2006; Croke et al. 2007) or environmental management (e.g., Stave, 2003; Winz et al., 2009). The advantages of a system dynamics approach are its flexible application to physical as well as social processes, and the opportunity to include participants in the model building process (Langsdale et al. 2007). There are other modeling approaches for integrated assessment, and a number of established simulation models. These range from massive expert models, such as the climate models of the IPCC (2014), to more flexible models such as the Polestar system (Raskin et al., 2000) and case-specific integrated assessment models on a catchment scale (e.g., Liu et al., 2008).

Numerous integrated assessment models exist, which cannot be covered exhaustively in this literature review (for an overview of integrated assessment models in climate change research see e.g., van Vuuren et al. 2011 and Weyant 2017). The Millennium Ecosystem Assessment, which has been previously mentioned in Chapter 2.2.4, serves as an example study in which different integrated assessment models, such as the IMAGE model and the IMPACT model, were applied. The IMAGE model (Integrated Model to Assess the Global Environment) integrates several sub-models through dynamic coupling and supports the analysis of the impacts of population and economic drivers on land use change, atmospheric pollution and climate change, amongst others (see Alcamo et al. 1998; IMAGE-team 2001). The IMPACT model (International Model for Policy Analysis of Agricultural Commodities and Trade) allows for the analysis of world agricultural markets of various crop and livestock commodities. The model is also able to generate regional and country-level results in terms of food supply, demand and prices (e.g., Rosegrant et al. 2012). More examples of integrated assessment models linked to this research are provided in Chapter 1.1.1 and Chapter 2.2.4.

In this research, **system dynamics is applied as an integrated assessment method** that allows for the analysis of social, environmental and economic effects of sustainability visions. In addition, system dynamics supports the involvement of stakeholders in model development, which is important to address the normativity of sustainability visions.

2.3 Systems modeling methods and frameworks related to this research

This research has the objectives of further developing systems modeling methods (Objective 1) and developing, testing and applying frameworks for participarory modeling (Objective 2), vision design (Objective 3) and vision assessment (Objective 4) (see Chapter 1.2). Chapter 2.1 and Chapter 2.2 have presented key concepts and general foundations of this research. Chapter 2.3 now presents an overview of the state-of-the-art relevant existing systems modeling methods (Chapter 2.3.1) and frameworks for participatory modeling (Chapter 2.3.2), vision design (Chapter 2.3.3) and vision assessment (Chapter 2.3.4) linked to this research.

2.3.1 Systems modeling methods

Various methods have been mentioned in the previous chapters that play a key role in this research. Functional analysis is a qualitative modeling method from systems engineering that helps to conceptualize the organization of system designs (Chapter 2.3.1.1). In this research, functional analysis will be applied to vision design. Systems thinking helps to qualitatively analyze system structures (Chapter 2.3.1.2). Systems thinking has been applied to interrogate perceptions of stakeholders on environmental issues, which makes it a promising method for vision design. FCM is a semi-quantitative modeling method (Chapter 2.3.1.3) that will be used for vision assessment. Finally, system dynamics modeling is a powerful method to quantitatively analyze the dynamics of complex systems (see Chapter 2.3.1.4), which will be utilized for the integrated assessment of sustainability visions. These methods allow for a gradual modeling of sustainability visions starting with qualitative models and going towards dynamic simulation models (cf. Chapter 2.3.2). In the following, a succinct literature review is provided for each method.

2.3.1.1 Functional analysis

Conceptual and preliminary design are important steps in the systems engineering design process, as they have a major influence on the success of engineering projects (e.g., Pahl et al., 2007). Functional analysis as part of the conceptual and preliminary system design steps of systems engineering allows one to develop alternative system designs to fulfil a specific need (i.e., the purpose of the engineering system; cf., Blanchard and Fabrycky, 2006). This method is potentially suitable to guide the design of sustainability visions, but has yet to be applied in this context.

Functional analysis in engineering design has mainly focused on functional flow analysis (FFA) (Blanchard and Fabrycky, 2006; Woldemichael and Hashim, 2011). FFA provides several benefits when used in engineering design and analysis by: (i) allowing the engineer to approach design in a logical and systematic manner, (ii) helping to reveal relationships between system elements, and (iii) supporting the design of interfaces between sub-systems (Blanchard and Fabrycky, 2006). The functional organization analysis (FOA) supports the analysis of the organization of alternative systems, along with the underlying functions invoked in the realization of the system's purpose. The lack of clarity in existing functions and the structures supporting them, along with the need for stakeholder engagement, make FOA a key preliminary step in envisioning and analyzing technical and ecosystem solutions for broader engineering problems (e.g., the design of food supply systems).

Both methods. FFA and FOA, allow for an integrated design of systems that include technical, environmental and social elements. While being a standard method in technical systems engineering and analysis, conceptual work is, however, required to extend the application of these methods to environmental and social systems. In particular, the FOA allows a focus on the system's organization, an important part of an integrated systems analysis as suggested in Chapter 2.1.1. Methods presented below are suitable for examining a system's structure (systems thinking and fuzzy cognitive mapping) and a system's processes (system dynamics modeling), such that FOA has a high complementary benefit. In addition, FOA shows a high potential to systematically conceptualize ecosystem services, ecosystem functions and natural infrastructure, as demanded in Chapter 2.1.2. This research will **further develop the FOA method** from its current focus on technical systems to include ecological and technical aspects.

Several computer-aided conceptual design and knowledge management tools exist (for an overview, see Woldemichael and Hashim, 2011). However, tools for conducting a FOA involving technical and ecological solutions are currently missing. In this respect, Cmaps is a particularly useful tool in gathering and organizing knowledge about alternative system designs.

Therefore, **Cmaps will be applied** in this research **as a graphical tool** for knowledge visualization and management (cf., Novak and Canas 2008).

2.3.1.2 Systems Thinking

Systems thinking is a methodology for the qualitative analysis of system structures and their dynamic behavior. Causal loop diagrams (CLDs) is a central systems thinking method. In CLDs, elements of the system are connected by arrows to form causal chains. A positive link indicates the parallel behavior of variables: in the case of an increase in the causing variable, the affected variable also increases, while a decrease in the causing variable implies a decrease in the affected variable. A negative link indicates an inverse relationship between variables. Another central concept in system dynamics is the elaboration of feedback loops. Two different feedback loops exist in CLDs: the self-correcting 'balancing loop' (uneven number of negative links within the loop) and the self-amplifying 'reinforcing loop' (even number of negative links) (Sterman, 2000).

There is disagreement between scholars about whether systems thinking is an independent methodology (Coyle, 2000). On the one hand, some researchers consider systems thinking to be a preparatory step of quantitative modeling (Homer and Oliva, 2001). Homer and Oliva (2001) conclude that simulation of models almost always adds value to the outcomes of research and should only be omitted if quantitative model building would be too time consuming or costly. On the other hand, several authors have shown that even qualitative models can provide plausible and useful results. Senge (1990) developed system archetypes that explain the malfunctioning of certain system structures in the business and social domains (see also Bagheri and Hjorth 2007). Hjorth and Bagheri (2006) applied systems thinking for the analysis of leverage points and process indicators for sustainable development. CLDs can also be applied in participatory modeling processes, for example in the scope of individual stakeholder interviews (Inam et al. 2015) or group modeling processes (e.g., Sendzimir et al., 2007).

The use of CLDs for vision modeling has not yet been explored in detail. Iwaniec et al. (2014) mention the use of CLDs in the participatory development of a comprehensive vision for the City of Phoenix, Arizona, USA, which were later analyzed using consistency analysis. However, details about the process of building CLDs that provide overall systems structures of sustainability visions are not provided by Iwaniec et al. (2014).

This research will develop CLDs in individual interviews that **represent system structures of sustainability visions** held by stakeholders. Based on these CLDs, dynamic models will be developed using FCM and system dynamics modeling methods to assess the consistency, plausibility and desirability of sustainability visions.

2.3.1.3 Fuzzy Cognitive Mapping

Qualitative models, such as CLDs, only allow for the analysis of dynamic system behavior to a limited extent. In particular, larger model structures impede a qualitative system analysis, as effects of feedback processes and multi-causality are difficult to trace through the model structure. On the other hand, an integrated assessment of complex issues through quantitative modeling is often constrained by data availability. This can necessitate the reduction of the model boundary to aspects for which data are available. System dynamics modeling (see Chapter 2.3.1.4) offers approaches that can handle relationships and variables that are challenging to quantify (Forrester 1980), but even with this method, substantial resources and data are required to build a reliable simulation model.

FCM is a semi-quantitative method that does not require any empirical data for quantification of causal models and allows for the dynamic analysis of feedbacks and multi-causalities. FCMs are a type of recursive neural network (Kosko, 1993) in which impulses pass through the network until a stable state or a stable limit cycle is reached. To build a FCM, causal links are weighted by assigning numerical values in the range of -1 to 1. These weights can be set during stakeholder or expert interviews by using a qualitative scale or graphical symbols (Jetter and Kok, 2014). For example, three weights for positive and negative links can be set by the interviewee (in the case of positive links: '+++' for strong positive links, '++' for moderate positive links and '+' for weak positive links).

The results of a FCM exercise are quantitative in nature, but need to be interpreted qualitatively; thus, variables usually attain values between 0 and 1 depending on the choice of a squashing function, such as a bivalent exponential function (another option is the use of a trivalent function, which involves variable values between -1 and +1). The results of FCM can also be interpreted by comparing the relative difference between variable values (i.e., variable X increases more strongly than variable Y in a certain scenario). Various FCM software tools exist, such as the FCMapper (Wildenberg et al., 2010; Olazabal and Pascual, 2016) or Mental Modeler (Gray et al., 2013; Henly-Shepard et al., 2015).

Up to now, FCM has not been applied to design and assess sustainability visions. Only Penn et al. (2013) used FCM for a similar purpose by analyzing factors to support a bio-based economy in the Humber region, UK, in the course of a participatory process. However, a clear distinction between modeling the transition process (i.e., transformation knowledge, see Chapter 1.1.1) and a future system state (i.e., target knowledge, see Chapter 1.1.1) was not conducted in the study. Nevertheless, they found the method to be suitable to engage stakeholders, but recommend analyzing the sensitivity of model outputs with regards to alternative system structures, variable values and functional relationships.

In this research, **FCM will be used to conduct a dynamic analysis of sustainability visions**, including an assessment of their consistency, plausibility and desirability. Due to the flexibility of the method, various indicators can be used to assess the desirability of sustainability visions, such as indicators linked to ecosystem services, economic development and well-being.

2.3.1.4 System Dynamics Modeling

System dynamics originated in business science (e.g., see Forrester, 1961; Sterman, 2000). Today, system dynamics is used for a variety of applications such as health (e.g., Homer and Hirsch, 2006; Macmillan et al., 2014) and environmental studies (e.g., Ford, 1999; Antunes et al., 2015). In the realm of water resource management, systems dynamics studies have been conducted for urban water supply (e.g., Bagheri and Hjorth, 2007; Bazrkar et al., 2016) as well as regional, national and global water systems (e.g., Xu et al., 2002; Simonovic and Rajasekaram, 2004; Simonovic, 2002, 2009; Prodanovic and Simonovic, 2007, 2010; Kotir et al., 2016; Sun et al., 2017).

In contrast to a FCM approach, which allows for the analysis of system states, system dynamics modeling is a continuous modeling approach that allows for a more detailed system analysis. System dynamics models support the analysis of stock-and-flow dynamics (i.e., accumulation), feedback processes and multi-causality (Sterman, 2000). The system dynamics method allows for the quantification of CLDs and modelling of system processes. To convert a qualitative systems thinking model into a quantitative system dynamics model, stock and flow variables have to be located in the CLD (Sterman, 2000). In system dynamics models, every feedback loop contains at least one stock variable that represents a state of the system, such as the inventory of a firm, or the water level of a dam. Stocks are calculated through the integration of inflows and outflows linked to the respective stock, where stocks accumulate inflows and cause a delay in the outflows.

Defining the relationships between variables is done by using mathematical functions as well as table functions. Compared to a FCM approach, system dynamics models allow for the development of more realistic models (e.g., by using physical units) and much more sophisticated analysis of system dynamics (e.g., oscillations). However, system dynamics models usually require more expertise to define auxiliary variables, parameters and functional relationships, and systematically test the model. The quantitative modeling of uncertain and qualitative linkages and variables is seen as a particular strength of the system dynamics method (Forrester 1980). Often, sensitivity testing reveals that the model behavior is not affected by high uncertainties, such that even the use of estimated data is reasonable. Furthermore, the omission of uncertain and empirically untested relationships would imply the denial of their influence, or as Forrester formulates: "To omit such variables is equivalent to saying they have zero effect - probably the only value that is known to be wrong!" (1961, p. 57).

System dynamics has the ability to take the full complexity of systems into account, including environmental, technical, economic and social aspects and is therefore also suitable for the modeling of sustainability visions. According to our best knowledge, the first explicit application of system dynamics modeling for the integrated assessment of sustainability visions was conducted in the scope of a Ph.D. thesis of David Iwaniec (2013). In a related article, Iwaniec et al. (2014) mention the suitability of system dynamics modeling to analyze complex sustainability visions. They present a simple system dynamics vision model[3] of an urban vision for the City of Phoenix, Arizona, USA. However, details about the model and simulation results are not provided by Iwaniec et al. (2014). This might be due to the broad scope of the article covering also a practical example from university education along with the case study in the City of Phoenix. While Iwaniec (2013) was the first scholar who conceptualized vision modeling,

[3] Iwaniec et al. (2014) highlight that the simple system dynamics model is only one sub-model, but do not provide details on the other sub-models.

Schmitt-Olabisi et al. (2010) provide an earlier modeling study that applied a similar approach without explicitly using the term ‘vision modeling’. Schmitt-Olabisi et al. (2010) applied system dynamics modeling in a participatory process to model different sustainability visions for the region of Minnesota, USA, in the year 2050. They aim at the moding of “a ‘snapshot’ of each scenario, meaning that the modeled relationships represented only the year 2050” (Schmitt-Olabisi et al., 2010, p. 2692), which conforms with the underlying idea of the vision modeling approach. However, the article does not provide detail on the system dynamics model, such as the chosen time steps and temporal boundaries. The modeling results provided some interesting insights, such as side-effects and trade-offs between vision elements that were not considered in the preceding process of developing qualitative future visions. For example, stakeholders underestimated the land requirements of biofuel production for the mobility sector. During their detailed and profound reflection on the participatory process, Schmitt-Olabisi et al. (2010) propose the inclusion of stakeholders in the development of CLDs or even system dynamics modeling to achieve understanding and trust in the modeling results, which was lacking for some stakeholders.

The case studies mentioned in the last paragraph underline that a **systematic conceptual and methodological framework for vision design and assessment using system dynamics** is lacking. Given the strength of system dynamics modeling to dynamically analyze and assess future visions (see Schmitt-Olabisi et al., 2010), this research will develop a conceptual and methodological framework that supports the application of system dynamics in vision design and assessment. This research will also deal with **model testing and validation**, which has not yet been addressed in other studies.

2.3.2 Participatory model building frameworks

Environmental management more and more uses participatory approaches to involve stakeholders in the investigation of problems, solution strategies and future visions. For instance, water legislation, such as the U.S. Clean Water Act, the Québec Water Policy, and the European Water Framework Directive, emphasize the need for integrated and participatory approaches for the sustainable management of water resources. Increasingly, research and practice acknowledge that current environmental problems demand the consideration of social, economic and environmental side-effects, and the creation of locally adapted solutions through the inclusion of local community stakeholders in decision-making (cf., Gleick, 2003).

Participatory model building is a suitable methodology to structure stakeholder involvement processes, conduct integrated analyses of environmental issues and design sustainability visions. By building a model, stakeholders can explicitly express their points of view, learn about other perspectives, and examine factual knowledge and subjective perceptions (Pahl-Wostl, 2007). In addition, construction of simulation models allows for the testing of the plausibility of assumptions and thereby supports learning about the system (Dörner, 1996; Sterman, 2000). Different participatory modeling approaches exist depending on the objectives of the participatory process and the specific methods applied (cf., Renger et al., 2008; Voinov and Bousquet, 2010). Modeling methods can serve several purposes, including the prediction of system behavior, exploration of alternative development pathways, communication of findings, or the facilitation of social learning processes (Brugnach et al., 2008).

Different methodological frameworks exist that guide the application of qualitative and quantitative modelling methods (e.g., Beall and Ford 2012). A prominent framework is *group model building* that has been originally developed to support organizational development in the business and public policy sectors (e.g., Andersen and Richardson, 1997; Vennix, 1996). The framework of *mediated modelling* is mainly applied for environmental management issues that involve diverse stakeholders and viewpoints (e.g., van den Belt, 2004). *Shared Vision Modeling* is another participatory model building framework using system dynamics that focuses more on technical and financial aspects of water management. Despite its name, Shared Vision Modeling does not focus on developing target knowledge, but starts with the current problem situation in order to find effective solution strategies.

All existing frameworks using system dynamics require that sufficient resources are provided and that stakeholders believe the modeling method is helpful and appropriate to their particular problem situation. Quantitative participatory modeling using system dynamics usually requires considerable time, commitment from stakeholders and financial resources, which are often limited in practice. Therefore, a stepwise process that starts with easily comprehensible methods, such as interviews and building of CLDs, can be useful, before methods are applied that require more mathematical expertise and modeling skills. The *Participatory Systems Mapping* (PSM) approach is such a participatory modeling framework that starts with preparatory interviews before stakeholders meet in a group workshop in which CLDs on environmental issues are jointly developed (Videira et al., 2012). Preparatory interviews are structured by a questionnaire to generate an overview of alternative viewpoints of stakeholders. In the following stakeholder workshop, stakeholders build CLDs in small groups to develop a shared understanding of environmental issues and identify potential leverage points. Recent research using the PSM approach has applied transition concepts (e.g., niche- regime interactions) in the development and analysis of CLDs (Tourais and Videira, 2021). After the generation of a shared understanding using CLDs, Videira et al. (2012) suggest the organization of a visioning workshop in order to define shared goals and future visions. Backcasting can be used at this stage to discuss pathways towards the vision as well as associated measures and risks (Tourais and Videira, 2021). System dynamics simulation models can be finally applied to quantitatively analyze potential pathways and suitable policies (e.g., Videira et al., 2012, 2017).

Based upon this overview of the literature on participatory model building frameworks, an interesting research topic is related to the participatory development of CLDs in the course of individual interviews. Furthermore, approaches are needed on how to develop long-term, institutionalized participatory modeling processes to iteratively revise vision models. Another research challenge is related to methodologies for context-specific design of participatory modeling processes to adapt the process to physical, environmental, socio-economic and institutional circumstances. Finally, methodologies are still needed for process design to rigorously monitor and evaluate participatory modeling processes by specifying process steps and intended outcomes (see Jones et al., 2009 and Carr et al., 2012).

This research will apply a **stepwise approach to progress from conceptual participatory modelling in the scope of individual interviews towards quantitative participatory modelling**. In addition, a process analysis approach will be developed, which allows for the **analysis of the process and its context** in order to investigate process steps and participating stakeholders, as well as the role of knowledge (e.g., factual knowledge or expertise), institutions (e.g., values, regulations or norms) and operational aspects (e.g., funding or practical interventions). The process analysis approach will allow for ex-post analysis as well as ex-ante design of participatory processes, such as visioning processes. The requirement of a long-term, continuous process to iteratively refine sustainability visions will also be addressed by developing a method for the **envisioning of supportive institutional structures for long-term participatory modeling**.

2.3.3 Frameworks for vision design

There are different approaches for the development of joint future visions in the scope of collaborative processes. First, visions of desirable future system states can be created through the use of *intuitive and non-technical methods* that tap into the creative potential of participants, such as written vision statements (e.g., Kallis et al., 2009; Auvinen et al., 2015), collages (e.g., Kok et al., 2006), or even role plays (e.g., Oels, 2002). Second, future visions can be developed in a more guided process supported by *conceptual frameworks* or *reference scenarios* (cf. Elle 1992). Such frameworks and reference scenarios assure that visions cover specific elements (e.g., different sectors or locations) and include key concepts (e.g., population dynamics and economic development). Thereby, participants are guided in the visioning process, which can imply some potential advantages, such as more structuration and comparability, as well as disadvantages, such as constrained creativity and less ownership. Third, *qualitative modeling approaches* can be applied to achieve a more systematic vision (Videira et al., 2010). These methods share similar benefits and constraints as conceptual frameworks. Qualitative modeling approaches are accessible for lay stakeholders due to their qualitative nature, but still require willingness to get involved with an unknown method. Fourth, *quantitative modeling approaches* can be applied to develop visions that are systematic and testable in quantitative terms. Quantitative models can be designed to analyze the dynamic complexity of specific visions (Iwaniec et al., 2014), or test the consequences from different visions (e.g., Trutnevyte et al., 2011, 2012). However, quantitative modeling methods usually require profound mathematical knowledge and modeling skills, which can impede the involvement of stakeholders.

Holtz et al. (2015) review several general benefits of a modeling approach that can also be related to vision modeling. First, models clarify assumptions and definitions as well as the underlying system structure. Second, modeling can reveal counterintuitive system behavior, due to feedback processes, multiple causality and delays. Third, models allow for systematic experiments through scenario analysis. Similar to Holtz et al. (2015), Iwaniec (2013) highlights that modeling can support a rigorous and systemic investigation of sustainability visions in terms of internal consistency, plausibility, desirability as well as sensitivity to assumptions.

Despite these various benefits, to date only a few studies have been published that explicitly apply a vision modeling approach. These studies can be separated into two categories: studies that use qualitative, conceptual vision modeling and those that use quantitative, dynamic vision modeling (Iwaniec et al., 2014)[4]. Conceptual modeling allows for the analysis of the system structure of a vision including the elements and their relationships. Potential methods for conceptual modeling are systems thinking (Iwaniec and Wiek, 2014) and influence matrices (Iwaniec et al., 2014). A participatory approach for developing qualitative positive scenarios of the future has been developed in the scope of the "Bright Spots: Seeds of a Good Anthropocene" project, a fast-track initiative funded by Future Earth (Bennett et al. 2016). The participatory scenario approach produces regional, context sensitive scenarios that build on existing sustainability initiatives (Raudsepp-Hearne et al., 2019). For this purpose, a database has been established to collect seeds on a global scale and analyse their characteristics (Bennett et al. 2016). The methodology comprises several activities including (1) the development of Future Wheels to examine first and second-order impacts of seeds, (2) qualitative backcasting and forecasting approaches, (3) the development of narrative storylines and (4) analysis and comparison of scenarios (Raudsepp-Hearne et al., 2019). The methodology has been applied in several case studies in South Africa (Pereira et al. 2018), Northern Europe (Raudsepp-Hearne et al., 2019) and the Arctic (Falardeau et al., 2019).

Dynamic vision models build on conceptual models and allow for quantitative analysis of the dynamics of a future vision, for instance by using a system dynamics modeling approach (Iwaniec, 2013). By specifying variables, parameters and functional relationships, dynamic models allow for a closer analysis of non-intuitive system behavior due to multi-causality or feedback processes. In particular, semi-quantitative methods, such as FCM, are suitable for dealing with a lack of data and different stakeholder perspectives, but have not yet been applied to vision modeling. Quantitative vision modeling applications are very rare. Trutnevyte et al.

[4] Iwaniec et al. (2014) introduce a third vision modeling approach termed "pathways of vision models", which is not addressed in this article as it might distract the reader.

(2011, 2012) apply resource allocation scenarios and multi-criteria analyses to analyze the consequences of stakeholder visions of a future energy system for heat and electricity. Other modeling studies test the technical feasibility of future visions; for example, UBA (2014) developed a vision for a fully renewable German energy system in the year 2050. However, these studies often do not consider the dynamics between social, economic, technical and environmental aspects of a system, and do not involve stakeholders in model development. Iwaniec et al. (2014) underline the suitability of system dynamics modeling to analyze complex visions in an integrated way. They present a simple vision model using system dynamics that was created in a participatory process designed to develop an urban vision for the City of Phoenix, Arizona, USA (see Chapter 2.3.1.4 for more details).

The literature shows that frameworks for the use of qualitative methods in participatory development of positive visions of the future (e.g., development of collages and storylines) have recently been developed. This research will address the lack of **conceptual and methodological frameworks for quantitative vision modeling**, which can provide important insights into collaborative visioning processes (e.g., analysis of feedback processes). In particular, **FCM** and **system dynamics modeling** are suitable modeling methods to deal with the complexity of sustainability visions and, therefore, will be included in the conceptual and methodological frameworks developed in this research.

2.3.4 Frameworks for vision assessment

As mentioned in Chapter 1.1.2, vision assessment can address various aspects, namely (1) the context and process of vision development, (2) the methodology used, and (3) the content of the sustainability vision.

The context and process of vision development can be analyzed by using qualitative methods, such as discourse and network analyses. Lösch et al. (2016) identifies two analytical dimensions of research on future visions. In the first dimension, the future vision is analyzed as an object by investigating which elements of the current society are expressed (e.g., analyzing why certain futures are expected to be achievable and others not). Such an analysis of sustainability visions can reveal the values, worldviews and interests of the visions' originators. Studies in the second analytical dimension analyze the effects of visions on the current society and the networks and processes in which the vision is active. This allows for a critical analysis of the development, diffusion and utilization of visions.

Wiek and Iwaniek (2014) provide quality criteria for visioning methodologies. According to Wiek and Iwaniek (2014), methods should be arranged in a meaningful sequence, i.e., they should build upon each other. The visioning process should follow an iterative procedure to continuously refine the vision. Furthermore, methods need to be applicable in a participatory setting that brings together different stakeholder groups and allows for the development of a shared vision. A participatory approach also confirms the relevance of visions to stakeholders. A vision review has to ensure that developed sustainability visions are visionary, i.e., far-sighted, holistic and suitable for a particular temporal and spatial context. Visions should include social, economic, technical and environmental aspects, rather than merely focus on a particular aspect, such as a technical innovation. A sustainability assessment is required to ensure that the vision conforms to social, environmental and economic sustainability criteria. System analysis methods and visualization approaches, such as causal diagrams, ensure that visions are systemic by exploring feedback processes and multiple causations. Methods for consistency analysis and plausibility appraisal are required to examine trade-offs, conflicting goals and the realism of visions. Furthermore, visions need to be tangible, nuanced and motivational. This can be achieved by including existing sustainability initiatives in a specific location (cf. Raudsepp-Hearne et al., 2019), such as community projects or entrepreneurial initiatives.

The quality criteria of Wiek and Iwaniek (2014) show the different ways models can be used in the development and assessment of sustainability visions (i.e., for sustainability assessment, system analysis, visualization, consistency analysis and plausibility appraisal). While the assessment of vision models has not been explicitly addressed in prior research, established conceptual and methodological frameworks for dealing with uncertainties in model development exist. Walker et al. (2003) provide a conceptual account of various types of uncertainties involved in model-based decision support. They distinguish between three different dimensions of uncertainty: the uncertainty level (comprising deterministic knowledge, statistical uncertainty, recognized ignorance and total ignorance), location in a model (e.g, paramters, model structure or model outcomes) and nature (including imperfect knowledge or natural variability). The nature of uncertainty determines whether further research is helpful in reducing uncertainties, or if uncertainty needs to be accepted. With respect to the level of uncertainty, determinism is the lowest level, which can hardly be achieved in modeling studies. Potential sources of statistical uncertainty are measurement errors (e.g., sampling errors or imprecision in the measurement process) and limitations in probability quantification. Scenario uncertainty is the next level of uncertainty in the conceptualization by Walker et al. (2003). The scenario method is a helpful approach to deal with this level of uncertainty by exploring potential trajectories of the system (for which concrete numbers of likelihood cannot be made) (see Mahmoud et al. 2009 for more details on scenario development). However, there are also processes where alternative system trajectories as well as the model variables, parameters and functional relationships are ambiguous or totally unknown. This level of uncertainty is termed recognized ignorance and is further subdivided into reducible ignorance (i.e., further research will lead to improved understanding) and irreducible ignorance (i.e., even research will not produce deeper understanding). Participatory model building can be applied to deal with a high level of uncertainty as stakeholders can bring various perspectives and assumptions can be discussed transparently (e.g., see Vennix 1996 on participatory modeling using system dynamics). Finally, the highest uncertaintly level of total ignorance takes surprises into account, as factors might become relevant that could not be anticipated during the modeling process. The embedment of the modeling process in a social learning process and the institutionalization of participatory modeling processes can help deal with this level of uncertainty. Long-term participatory processes can provide a context to adapt models continuously based upon new knowledge or policy options.

Uncertainties can also be related to various locations within the model (Walker et al., 2003): First, context uncertainties are linked to ambiguity in the selection of the system boundary and the problem to be modeled. Stakeholder values and expertise can have profound effects on how a particular problem is framed. Second, uncertainties can be located in the model structure, i.e., how relationships between variables are conceived, as well as the choice of a model technique (e.g., hidden bugs and flaws in the software). Third, model input uncertainties are linked to external forces impacting the system. As system dynamics modeling aims at the endogenous explanation of system behavior, the influence of input variables and assicated data should be minimized (Sterman 2000). Fourth, parameter uncertainty addresses the indeterminacy of model parameters and underlying data. Fifth, all uncertainties are finally accumulated in the model outcome uncertainty, as uncertainties at other locations (e.g., model structure of parameter) are propagated through simulating the model. This also underlines that uncertainties at the different locations are interlinked. For example, the determination of a model structure will also affect the model boundary, and vice versa.

The conceptual and methodological framework for vision design and assessment to be developed in this research, will **comply with the quality criteria for visioning methodologies** developed by Wiek and Iwaniek (2014). In addition, the approach by **Walker et al. (2013) will be used as the basis for vision assessment**, particularly to systematically handle uncertainties in modeling sustainability visions.

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CONNECTING TEXT TO CHAPTER 3

Chapter 3 and Chapter 4 present methods from systems engineering (i.e., functional organization analysis (FOA) and functional flow analysis (FFA)) that are further developed to be applicable for vision design (Objective 1). While systems engineering has a long history in using functional analysis in the design of technical systems, conventional functional analysis methods are not suited to deal with the complexity of sustainability visions. Sustainability visions consist of technical, environmental and social aspects, which all need to be considered in vision design and assessment. This necessitates further development of the functional analysis method, which was accomplished in this research.

Chapter 3 presents the FOA method adapted to also consider ecosystem services and nature-based solutions in system design along with technical solutions (Objective 3). The next chapter (Chapter 4) presents an additional development of the functional analysis method towards the inclusion of social solutions. Thereby, the functional analysis methods developed in this thesis allow for the analysis of the complementary and substitutional application of technical, nature-based and social solutions.

The FOA method has been applied to a case study of organic food systems in Southwestern Ontario. The research presented in this chapter provided preparatory work for the analysis of system designs in Chapter 6 of this thesis, namely urban organic gardening, a local diversified organic food system, a globalized commodity-based organic food system and a multi-scale organic food system.

This chapter was published in the Ecological Engineering Journal (Halbe et al. 2014). The format of the paper has been modified to ensure consistency with the style of this thesis. A list of references cited in this article is provided at the end of the chapter. The author of the thesis developed, tested and applied the FOA method and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided advice on all aspects of the research and contributed to the review and editing of the manuscript. Prof. Elena Bennett, McGill School of Environment and Department of Natural Resource Sciences, provided advice on all parts of the manuscript, in particular those related to the conceptual framework for integrated ecological and technical engineering design (Chapter 3.2.1). Prof. Claudia Pahl-Wostl, Institute of

Environmental Systems Research, Germany, gave advice on the organization of the participatory modeling process. Prof. Khosrow Farahbakhsh, School of Engineering, University of Guelph, Ontario, Canada, provided advice on all aspects of the research, contributed to the review and editing of the manuscript, and supported the organization of the case study in Southwestern Ontario.

Chapter 3: Functional organization analysis for the design of sustainable engineering systems

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Abstract

Sustainable engineering design requires consideration of technical and ecosystem structures and processes. Even though the concepts of ecosystem services and natural infrastructure are maturing, their application in concrete engineering design is currently lacking due to their ambiguous definitions and a lack of methods that allow for the combined consideration of ecosystem and technical approaches in engineering design. This article proposes and discusses a new Functional Organization Analysis (FOA) method for the comparative analysis and design of supply systems for basic needs (i.e., water, energy or food). This new method allows for the analysis of the organization of system functions as well as underlying technical and ecosystem structures and associated processes. On this basis the method allows one to gather data, information, and knowledge about alternative system designs, and analyze their synergies. The theoretical and conceptual background of the proposed FOA method is presented, along with a case study regarding sustainable food supply systems in Southwestern Ontario.

Keywords: Ecological engineering; ecosystem services; natural infrastructure; engineering design; food systems; agroecology

3.1 Introduction

An integrated and systems approach for the design of human-environment-technology systems is promoted by many scholars (e.g., Checkland, 1981; Pahl-Wostl, 2007; Stasinopoulos et al., 2008; Simonovic, 2009; Matlock and Morgan, 2011). Sustainable engineering comprises a life-cycle perspective and consideration of ecological, economic, and socio-cultural aspects (Maydl, 2004). Sustainable engineering includes technical approaches from structural and process engineering (e.g., Maydl, 2004), as well as ecosystem approaches from bio- and ecological engineering (e.g., Matlock and Morgan, 2011). Due to the relatively recent development of sustainable engineering, standardized methodologies for the design of sustainable engineering systems comprising both technical and ecological approaches are currently lacking.

Ecological engineering is based upon an ecosystem paradigm and forms a separate field within sustainable engineering (Mitsch, 2012). Defined as the study of "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch, 1998), ecological engineering considers the capacity of ecosystems for self-organization and self-design in engineering problem-solving (Mitsch and Jorgensen, 2004). Ecological engineering can therefore offer ecosystem solutions with the potential to complement or substitute for technical solutions. The Audubon sanctuary at Port Aransas in Texas, where the effluent from a primary and secondary treatment plant (i.e., a technical solution) flows into a freshwater marshland that functions as a tertiary treatment stage (cf., Odum and Odum, 2003), serves as an example of a complementary usage of ecosystem and technical solutions.

The principles of ecological engineering are closely related to the concept of ecosystem services, which highlights the close relationship between nature and humanity through the explicit valuation of ecosystem structures and processes based on the services they deliver (cf., Millennium Ecosystem Assessment, 2005; Mitsch, 2012). The concept of natural infrastructure has a similar meaning and refers to the indirect services that nature provides for humanity, e.g., flood protection achieved through increasing natural buffering capacity by floodplain restoration (Smith and Barchiesi, 2009; Hey and Vaughn, 2010; Wilson and Browning, 2012). The ecosystem services and natural infrastructure concepts seek to elicit an appreciation of the value of ecosystem structures and processes, while ecological engineering represents the practical implementation facet of ecosystem process and structure design for achieving human well-being and ecological balance at the same time.

The consideration of ecosystem structures and processes in the design of engineering systems is an important field of research. Even though relevant knowledge from systems science, ecology, biology and engineering is available, ambiguous definitions of concepts such as ecosystem services and natural infrastructure (cf., Wallace, 2007) and their relationship to technical approaches is a major barrier against integration of technical and ecosystem design. Other impediments are the traditional engineering paradigm that is aimed at the reduction of uncertainty (Halbe et al., 2013; Mitsch, 2014), and which lacks design methods that allow for the combined consideration of ecosystem and technical approaches. One of the more integrative design methods is the Whole System Approach, which offers ten key operational elements to find and exploit synergies between sub-systems, and design engineering systems that address multiple problems through a single solution or process (Stasinopoulos et al., 2008). However, the Whole System Approach does not consider the use of ecosystem approaches in the design process. In contrast, Matlock and Morgan (2011) provided guidelines for the design of ecosystem services, but did not provide links to technical solutions that could complement or substitute for the provision of ecosystem services, or vice versa.

To directly address the above-described issues, this article proposes a new Functional Organization Analysis (FOA) method that supports integrated engineering design of technical and ecosystem structures and processes. The FOA method is part of the preliminary system design step (cf., Blanchard and Fabrycky, 2006), and allows for knowledge integration on alternative system designs and analysis of synergies between alternative system designs, thereby identifying innovative designs as well as new areas for cooperation.

The article is structured as follows. First, the theoretical background of the proposed FOA method is explored, including the concepts of ecosystem function, structure and process, ecosystem services, and natural infrastructure, as well as how, within the conceptual framework, these might be rendered compatible with technical solutions. Based on this theoretical background, the FOA method is proposed as a new approach that allows for the analysis of alternative system designs. A case study is presented which examines various alternatives for a sustainable food supply system in Southwestern Ontario, Canada. An agroecological approach is applied by analyzing ecological structures and processes that form the basis of food systems. Finally, additional steps towards the design, assessment, and implementation of engineering system alternatives, as well as future research needs, are discussed.

3.2 Functional analysis of sustainable supply systems for basic needs

As discussed earlier, methodologies for an integrated design of ecological and technical structures and processes are currently lacking. This section develops a conceptual framework that provides a clear conceptualization of ecological and technical approaches. The lack of such a conceptual framework is a major impediment to an integrated design method (such as the FOA method). The conceptual framework builds upon system science which provides a common analytical foundation for a combined analysis and design of technical and ecological systems. In order to be classified as a system, an object must (Bossel, 2004): (i) have a special **purpose** that can be perceived by an observer, (ii) consist of **system elements** that are connected by **causal links** representing the system's structure (cf., Maturana and Varela, 2005), and (iii) have a **system identity** that would be lost if elements of the system structure were lost. This definition can be applied to either technical or ecological systems as long as their purpose is to deliver either direct services (e.g., drinking water from rivers), or indirect services (e.g., water purification through a treatment plant). As the identification of a purpose (i.e., a service or function) depends on the perspective of the observer viewing the system, different services and functions within a given system may be prioritized depending on the observer's values or needs. The system structure refers to the actual relations between system elements. As system identity demands simplicity of the structure describing system organization, redundant elements should be eliminated and only essential elements and their relationships should be included. The choice for relevant system elements is not necessarily a trivial task, and is based on systems analysis. Varela (1979) points to the distinction between the organization of a system and its structure: the **structure** specifies the properties and relationships between *specific system elements*, whereas the **organization** only specifies the *general system elements* along with the relationships that make up the system. The organization is "independent of the materiality that embodies it; not the nature of the components, but their interrelations" (Maturana and Varela, 1979). Based upon systems theory, a novel conceptual framework is developed in the following section which forms the foundation for integrated ecological/technical analysis and design using the FOA method (which will be presented in Chapter 2.2).

3.2.1 Conceptual framework for integrated ecological and technical engineering design

The **'ecosystem service'** and **'ecosystem function'** concepts address the relationship between ecological systems and human values. Ecosystem functions (e.g., soil retention) are ecosystem structures and processes that are used and valued by people (e.g., prevention of damage from erosion), and thereby become ecosystem services (cf., de Groot, 2006; Termorshuizen and Opdam, 2009). The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) placed ecosystem services into four categories: *provisioning, regulating, cultural,* and *supporting services*. Provisioning services are the most clearly recognizable services, with direct products people can physically use (*e.g*., clean drinking water, fertile land for agriculture and grazing). Regulating services, such as natural water purification in wetlands and river ecosystems are often less obvious. For instance, the natural flow regime of rivers supports a variety of regulating ecosystem services, such as erosion control, pollution management, and flood and pest control (Poff et al., 1997). Recreational, spiritual, and aesthetic services are examples of cultural services of natural bodies of water. Water in general, and rivers in particular, have a special value in certain cultural and spiritual traditions (Craig, 2007). Supporting services are those ecosystem processes or structures necessary for the provision of other ecosystem services. Their impacts on people are indirect or occur over longer time frames than other types of services. Examples include soil formation, nutrient cycling, or climate regulation (Millennium Ecosystem Assessment, 2005). The classifications provided by de Groot (2006) and the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) are not coherent and thus can cause confusion and ambiguity. For instance, water supply is a regulating function for de Groot (2006) and a provisioning service in the MA definition (Millennium Ecosystem Assessment, 2005).

Other classifications of ecosystem services exist. Wallace (2007) criticized the Millennium Ecosystem Assessment categories as "not [being] a coherent set of services at the same level that can be explored and traded off in a decision system." For instance, food production (provisioning service) is the end result of an ecosystem management process, whereas pollination (regulating service) is a means of service delivery. The following conceptualization addresses this point of criticism by explicitly differentiating between *Ecosystem Services*, *Ecosystem Function* and *Natural Infrastructure* (Figure 3.1).

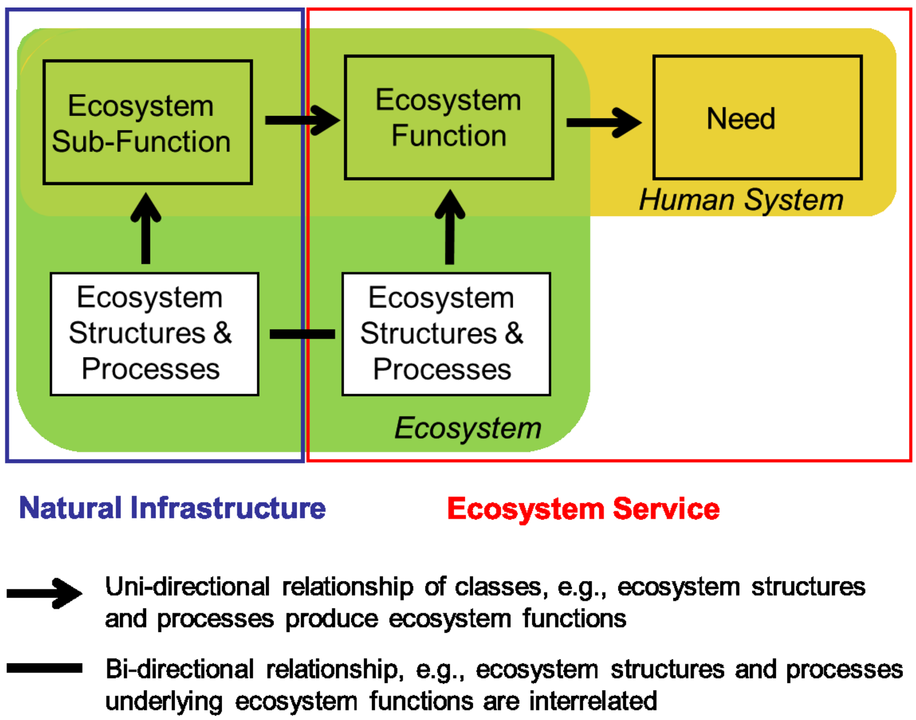

Figure 3.1: Conceptualization of Ecosystem Services and Infrastructure, adapted from Termorshuizen and Opdam (2009) – the interpretation of "natural infrastructure" has been added to Termorshuizen's and Opdam's diagram.

Ecosystem structures are "the physical organization or pattern of a system" (Noss, 1990), while processes are the "complex interactions (events, reactions or operations) among biotic and abiotic elements of ecosystems that lead to a definite result" (Wallace, 2007). Primary functions are those functions that are directly related to a human need. Thus, the human need, primary functions and underlying ecosystem structures and processes together form an ecosystem service. Sub-functions (e.g., pest management) support the provision of primary functions (e.g., food production) that are directly related to a human need (e.g., food). Thus, natural infrastructure denotes all sub-functions as well as underlying ecosystem structures and processes that together generate primary functions.

System science allows one to use the same conceptualization for both technical and ecosystem solutions (Figures 3.1 and 3.2, respectively), thus rendering feasible a comparison of their respective technical and ecosystem approaches.

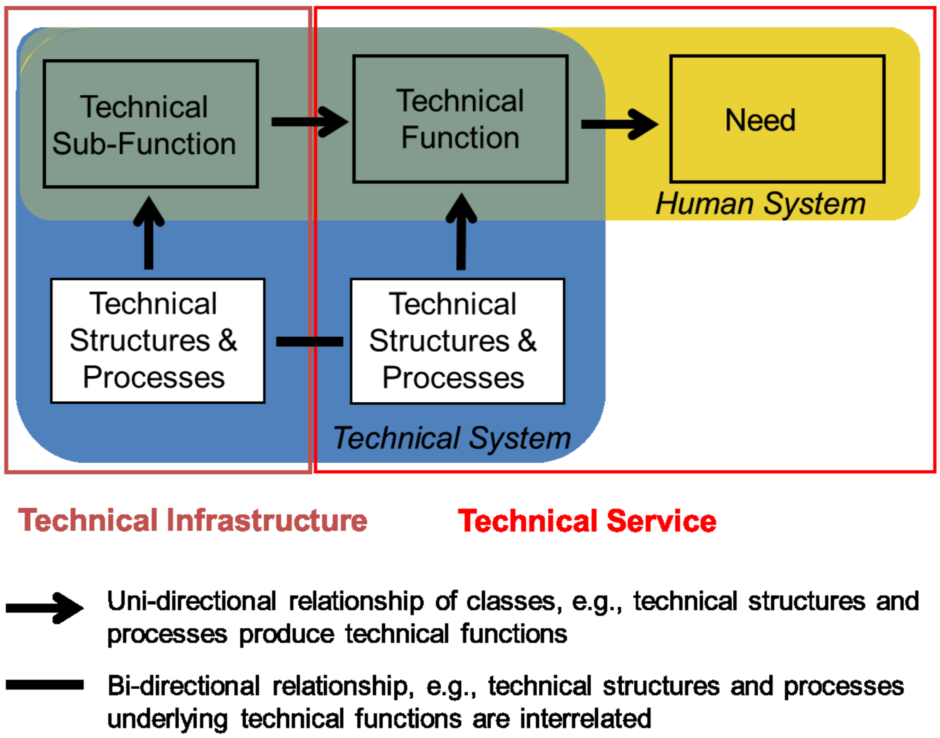

Figure 3.2: Conceptualization of Technical Services and Infrastructure as being equivalent to the conceptualization of Ecosystem Services and Infrastructure (see Figure 3.1).

Figure 3.2 shows the equivalent conceptualization for technical supply systems. A human need (e.g., mobility) is provided through a system of primary technical functions (e.g., provision of vehicles) and underlying technical sub-functions (e.g., a road network). Thus, the human need, related primary technical functions and underlying technical structures and processes form the technical service. Technical sub-functions and related technical structures and processes are understood as technical infrastructure.

Based on these concepts, the proposed FOA method for engineering supply systems (e.g., for water, energy or food) reveals the *system's organization*, comprised of basic needs (the system's purpose) and functions, which, in concert, deliver these needs. In addition, technical/ecosystem structures and the underlying functions of the processes, which represent the *system's structure*, are visualized (i.e., material specification of the respective functions), as outlined in the following section.

3.2.2 The Functional Organization Analysis method

Concepual and preliminary design are important steps in the engineering design process, and have a major influence on the success of engineering projects (e.g., Pahl et al., 2007). Functional analysis as part of the conceptual and preliminary system design steps, allows one to develop alternative system designs to fulfill a specific need (i.e., the purpose of the engineering system; cf., Blanchard and Fabrycky, 2006). Functional analysis in engineering design has mainly focused on functional flow analysis (FFA) (Blanchard and Fabrycky, 2006; Woldemichael and Hashim, 2011). While it is a standard method in technical systems engineering and analysis, FFA has yet to be implemented in design processes which include both technical and ecosystem solutions. FFA provides several benefits when employed in engineering design and analysis by: (i) allowing the engineer to approach design in a logical and systematic manner, (ii) helping to reveal relationships between system elements and, (iii) supporting the design of interfaces between sub-systems (Blanchard and Fabrycky, 2006).

The FOA method that is proposed in this study allows one to employ these benefits of FFA in the design of supply systems for basic needs (e.g., water, energy, or food) which requires a broader system boundary (e.g., a regional scale) than regular engineering projects. Instead of analysing the flow of functions, the present method supports the analysis of the organization of alternative supply systems, along with the underlying functions invoked in the realization of the system's purpose. The lack of clarity in existing functions and the structures supporting them, along with the need for joint expert-stakeholder consensus, make FOA a key preliminary step in envisioning and analyzing technical and ecosystem solutions to broader engineering problems (e.g., the design of food supply systems).

While several computer-aided conceptual design and knowledge management tools exist (for an overview, see Woldemichael and Hashim, 2011), tools for engineering design for broader societal problems that integrate technical and ecological solutions are currently missing. In this paper, Cmaps is applied as a graphical tool for knowledge visualization and management (cf., Novak and Cañas, 2008)[5]. Cmaps are used to visualize and analyze: (i) the system organization, consisting of the purpose and underlying functions, and (ii) underlying technical/ecosystem processes and structures. The relationships between concepts can be further specified by linking words that are added to connecting lines. The tool is based upon the learning psychology of Ausubel (cf., Ausubel et al., 1978) that explains learning as "assimilation of new concepts and propositions into existing concept and propositional frameworks held by the learner". Therefore, Cmaps represents a particularly useful tool in gathering and organizing knowledge about alternative system designs.

The FOA method can be employed for scientific research where it is applied by experts, as well as in the course of participatory processes to discuss alternative system designs with stakeholders. The analysis of alternative system designs and potential synergies via Cmaps occurs in five steps:

1. Defining the purpose of the engineering system, i.e., the service the system is supposed to fulfill (e.g., provision of drinking water),
2. Defining the system's primary and subsidiary functions achievable through technical/ecosystem structures and processes (e.g., water storage),
3. Defining the ecosystem/technical structures and processes underlying the functions determined in Step 2 (e.g., dams or wetlands),
4. Adding available data, information and knowledge to the determined structures and processes,
5. Identifying alternative system designs (i.e., a concerted set of functions and underlying process and structures) and assessing synergies and differences, as well as innovative system designs.

In Step 1, human needs and values expected to be supplied by the engineering system must be specified. From a resilience and sustainability perspective, basic human needs (e.g., for drinking

[5] Software for the construction of Cmaps can be downloaded for free at the following webpage: http://cmap.ihmc.us/download/

water or energy) are suitable starting points for sustainable engineering system design. The choice of a broad definition of a need (e.g., food, heating, mobility) supports creativity by integrating several perceptions that might be held by stakeholders (cf., Vennix, 1996).

In Step 2, the primary and subsidiary functions required to fulfill the system's purpose, determined in Step 1, are defined. The definition of functions and underlying structures and processes can be based on an analysis of the literature and interviews with experts and other stakeholders. Functions can be ecosystem functions (i.e., functions that are provided by ecosystems) as well as technical functions (i.e., functions that are generated by technical systems). Figure 3.3 provides a simplified example of a drinking water supply system: the need (top of graph) is connected to underlying primary functions. Together, the need and primary functions form an ecosystem or technical service, depending on whether the function is provided by an ecosystem or technical structures/processes. Sub-functions and related structures and processes together constitute the underlying technical and natural infrastructure, respectively. The need for drinking water requires *inter alia* the primary functions of *water generation*, *water storage*, and *water transport*. These functions can be interrelated as shown by the sub-function of *water purification* which increases the primary function of *water generation* when low quality water is rendered useable.

Step 3 involves the addition of structures and processes that provide these functions. Such structures can again be of either a technical or ecological nature and should reflect a diversity of solutions. For instance, water storage can be provided by dams (a technical solution) or constructed wetlands (an ecological solution) (cf., Figure 3.3). Of course, the choice of a dam *vs.* a wetland depends on various context factors, such as the scale of the area to be supplied with water. However, according to the aim of the proposed FOA method to support the analysis of alternative system designs and their synergies, the system diagrams should reflect the diversity of solutions. The choice for specific technical/ecosystem solutions requires the subsequent assessment of alternative system designs.

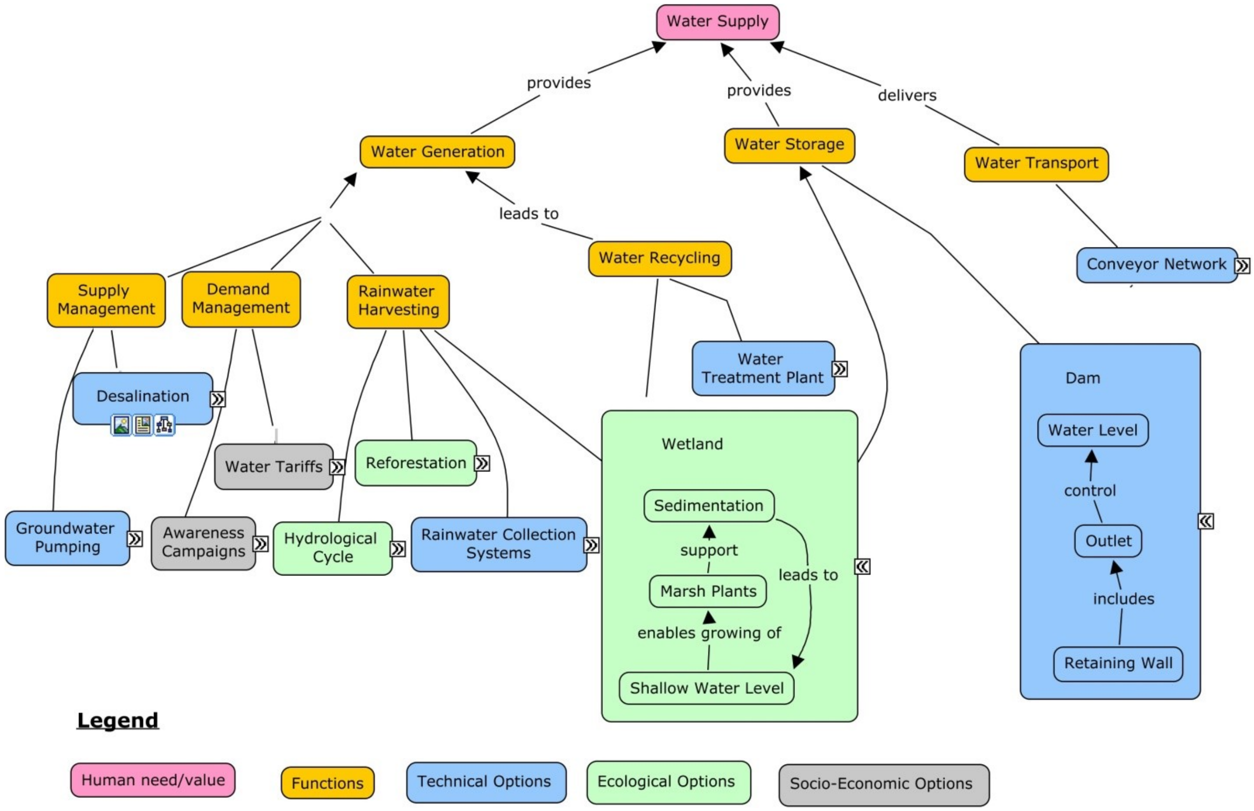

Figure 3.3: Organization of a drinking water supply system including alternative technical and ecosystem solutions for the provision of functions. Ecosystem solutions are marked in green, and technical solutions in blue.

The Cmaps software allows for the inclusion of expandable/collapsible structure or process details within a structure or process box. Figure 3.3 illustrates the structures underlying the technical solution *dam* and the feedback processes at work in the *wetland* solution — other boxes being collapsed for purposes of clarity.

In Step 4, relevant data, information, and knowledge are added to structures and concepts. Cmaps allows for adding links to documents, pictures, websites or further Cmaps to each system element. In Figure 3.3, links to further information in the form of photos, documents, and a Cmap structure have been added to the *Desalination* structure (marked through icons added to the concept box). Thus, the Cmaps tool allows for the gathering and integration of different pieces of knowledge. Cmaps can also be published online so that stakeholders can add further information.

Step 5 includes the identification of alternative system designs and the assessment of synergies and differences. The FOA of the (simplified) engineering system for drinking water supply (see Figure 3.3) integrates different system designs including a centralized/technical water supply system (that draws on massive infrastructure like dams and a conveyor network) and a more decentralized/ecosystem-based water supply system consisting of wetlands and decentralized water harvesting systems. The visualization of the system organization highlights the complementary functions that need to be realized in order to provide a specific service such as the supply of drinking water. While the system organization is often similar across different designs, a range of underlying system structures exist that can potentially produce the determined functions. A tabular presentation of the functional organization and underlying structures and processes of alternative system design can help to detect synergies (e.g., similar system structures) and differences (see Chapter 3.4). Thus, the proposed FOA method helps to analyze alternative system organizations as a part of the preliminary system design step in the engineering process. In this step, multiple alternative solutions are sought through a creative process (cf., Blanchard and Fabrycky, 2006). Such a method supports the design of innovative systems that is based upon a combination of technical and ecosystem approaches.

This kind of integrated illustration of alternative system designs is possible for relatively simple systems that include few functions and technical/ecosystem structures and processes; however, when it comes to more complex engineering systems, the construction of distinct Cmaps for each alternative system configuration has been proven to be more straightforward (see Chapter 3.3). A case study on sustainable food supply in Southwestern Ontario, Canada, is presented in the following section that illustrates the use of the FOA method.

3.3 Case study: Sustainable food supply systems in Southwestern Ontario

Agroecological engineering belongs to the spectrum of ecological engineering practices (Mitsch, 2012) and can be defined as "the science of applying ecological concepts and principles to the design and management of sustainable food systems" (Gliessman, 2007). For Francis et al. (2003), agroecology also includes "the integrative study of the ecology of the entire food system, encompassing ecological, economic and social dimensions". While our analysis focuses on a broader food system scale, agroecology can also include research at the field, or farm scale (see Wezel et al., 2009). In food systems, technological and ecological processes are intertwined with social and economic aspects (cf., Francis et al., 2003). Several practices of ecological engineering are relevant to sustainable agriculture, such as eco-hydrology (Zalewski, 2000), biological pest control (Bianchi et al., 2006), or rooftop gardens (Rowe et al., 2014).

Ontario is the province with the highest number of farms in Canada (Statistics Canada, 2011). While agriculture, forestry, fishing, and hunting account for 0.9 % of the province's overall economic output (Statistics Canada, 2006), Ontario's food processing industry contributes a slightly greater fraction (2.0%) (Ontario Ministry of Finance, 2013). The vast majority of farms in Ontario belong to the large-scale, conventional type of agriculture. Small farms (less than 10 acres / ~4 hectares) account for only 5% of the total number of farms in Ontario. Certified and non-certified organic farming remains at a niche level, representing roughly 1% and 5% of farms, respectively (Statistics Canada, 2006). Data on the relevance of subsistence agriculture (i.e., farming for personal consumption) is currently unavailable, as official statistics focus on commercial forms of agriculture. However, subsistence farming could become a significant approach for sustainable agriculture, e.g., in the form of community gardens (cf., Wakefield et al., 2007).

A case study addressing sustainable food systems was conducted in southwest Ontario's Bruce and Grey counties, along with the area around the city of Guelph, Ontario, Canada. There are several current challenges (e.g., a changing climate), as well as likely challenges in the future (e.g., depleting resources for fossil fuel and phosphate) that could pose significant challenges to the food system. A sustainable food supply system is viable in ecological, economic and social terms, and has the capacity to adapt to those challenges. An adaptation process can proceed in a reactive fashion (i.e., problems are solved when they appear), or in a proactive manner by anticipating future challenges and taking action based on expectations of future developments (Pahl-Wostl, 2008). The study aimed at supporting such an anticipatory approach by analyzing different perceptions of the term 'sustainable agriculture', and collecting and analysing visions for a sustainable food system in the study area. The proposed FOA method was chosen to *visualize* and *compare* these different system designs in terms of their synergetic potential and usage of ecosystem solutions.

In September 2012, a participatory modelling process was initiated by the authors through individual interviews with farmers, distributors, and other regional stakeholders. Over the course of 1.5 years (until March 2014), 27 stakeholder interviews have been conducted. These interviews aimed at the detection of alternative designs for a sustainable food system and related structural barriers and drivers through the construction of CLDs (a description of the method can be found in Vennix, 1996).

Further alternative visions were collected through the organization of a visioning exercise at an organic food conference in Guelph.[6] Participants at the conference were asked to complete a FOA showing their personal vision of a sustainable food system, including both the systems' purpose and underlying functions. Cmaps were used to include those technical and natural infrastructures serving to fulfil these functions according to the individual's vision. The interviews and surveys (53 surveys were completed) revealed the existence of multiple alternative visions of a sustainable food system: some participants envisioned a large-scale organic food production system, while others stressed the importance of a localized food system including small-scale organic agriculture and subsistence farming.

A clear delineation of alternative food systems' organization was the goal in implementing a FOA in the case study. Instead of becoming confined to the current problem situation and multiplicity of alternatives, the FOA served as an exercise in enhancing the stakeholders' capacity to envision a range of different system design alternatives and the potential synergies existing between them. The following sections present a FOA for the supply of vegetables from each farming system. The presentation is limited to vegetable crops for clarity. The organization of food systems for animal products and field crops would be slightly different, and should therefore be accomplished in a separate FOA.

Alternative system designs were developed based upon models built through the participatory modelling process and the visioning exercise at the Organic Food Conference in Guelph, Ontario. A supplemental review of the literature was conducted to include ecological engineering approaches relevant for sustainable food systems. System designs for the following alternative food systems are presented: (i) large scale, conventional agriculture (AG_{Conv}^{LS}), (ii) large-scale

[6] URL of the conference homepage: http://www.guelphorganicconf.ca/

organic agriculture (AG_{Org}^{LS}), (iii) small-scale, organic agriculture (AG_{Org}^{SS}), and (iv) organic subsistence agriculture (AG_{Org}^{Subs}). While the AG_{Conv}^{LS} system represents the current dominant food supply system in the study area, the AG_{Org}^{LS}, AG_{Org}^{SS}, and AG_{Org}^{Subs} systems reside more at a niche level.

3.3.1 Large-scale, conventional agriculture

Large-scale, conventional agriculture (AG_{Conv}^{LS}) is the most common farm type in Ontario in terms of vegetable production (Statistics Canada, 2006). The AG_{Conv}^{LS} system is based on the utilization of economies of scale effects which arise from the decrease of unit costs through large scale production and automation (cf., Altieri and Rosset, 1996). The diverse primary and secondary functions and underlying technical/ecosystem structures and processes required for large-scale vegetable production are outlined in Figure 3.4. This figure shows how all the features of the system come together to provide food.

The primary function of *Production* is related to the sub-functions *Provision of Water, Pollination, Provision of Seeds/Seedlings*, *Fertilization*, *Provision of Plots*, *Provision of Technical Equipment*, and *Pest Control*. Agriculture in Ontario is predominantly rain-fed so irrigation only becomes necessary during dry periods (except for greenhouses) (Statistics Canada, 2013). The *Provision of Water* thus depends upon ecological and hydrological processes which can be actively managed through an eco-hydrological approach (e.g., Zalewski, 2000). Technical approaches for water provision are mainly related to irrigation technologies to overcome dry periods and address recent climate trends (i.e., drier and warmer summers) for Southwestern Ontario (Tan and Reynolds, 2013). *Pollination* is another crucial function for agricultural production which can be provided through abiotic processes (e.g., wind pollination), natural pollinators (e.g., wild bees) or domesticated pollinators (e.g., honey bees). The demand for pollination services in Eastern Canada is increasing and has caused Ontario's beekeepers in 2012 to export about 26 % of their colonies to other provinces in Eastern Canada (Ontario Ministry of Agriculture and Food, 2013). The *Provision of Seeds and Seedlings* is the domain of specialized companies which apply sophisticated technical processes to produce high-yielding seeds (cf., Perez-Prat and van Lookeren Campagne, 2002, on hybrid seed production).

Fertilization is mainly provided by the application of mineral fertilizers and requires intensive soil studies to develop an appropriate fertilization program in terms of fertilizer materials and/or application method. Crop rotation is a more ecological approach applied by farmers to increase or sustain soil fertility and control pests. Nonetheless, the sub-function of *Pest Control* more generally draws upon the application of pesticides by mechanized methods. *Plots* are of large scale and require application of high-input technology specific to large-scale farming (cf., Altieri and Rosset, 1996). Greenhouse crops also have a high relevance in Ontario. The greenhouse area roughly doubled from 4.4 km² in 2001 to 8.0 km² in 2011 (Statistics Canada, 2011).

Another central primary function is the *Storage* function, which is relevant for the generation of all other primary functions (i.e., the storage of products is required during the production process, transport, distribution and preservation before consumption). The storage of products is accomplished by technical approaches along the supply chain including silos, storehouses, and fridges. *Transportation* is another primary function required to distribute products from producers to wholesalers and retailers. This function is mainly accomplished through professional transport companies. Transportation from the market place (e.g., supermarket chain or retailer) to the site of consumption (e.g., home) is usually accomplished through individual transport by the customer (i.e., usage of cars).

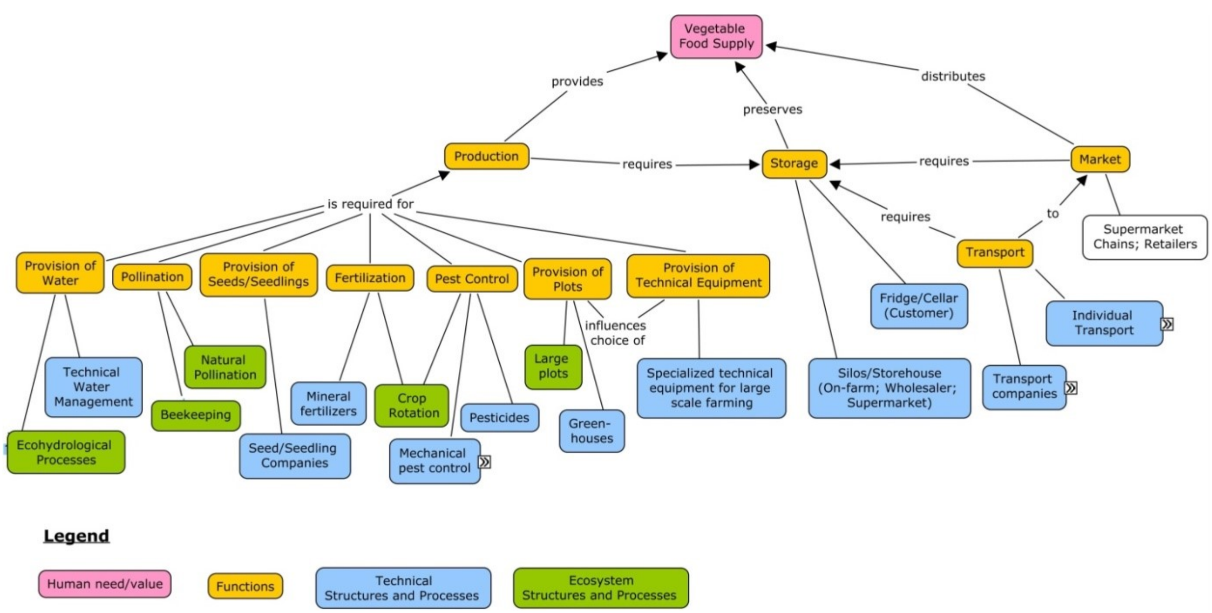

Figure 3.4: FOA of the large-scale, conventional agriculture system (AG^{LS}_{Conv}) for the production of vegetables.

3.3.2 Large-scale, organic agriculture

Compared to conventional agriculture, organic farming is considered to support biodiversity (Topping, 2011) and pollination (Gabriel and Tscharnke, 2007) in agricultural landscapes, and increases soil fertility (Mäder et al., 2002). The organization of the large-scale, organic agriculture system (AG_{Org}^{LS}) is largely the same as that of the large-scale, conventional (AG_{Conv}^{LS}) system, particularly with regard to the underlying structures and processes for the *Storage* and *Transport* primary functions. However, significant differences between the AG_{Conv}^{LS} and AG_{Org}^{LS} do exist with respect to the structures and processes underlying the sub-functions of *Provision of Seeds/Seedlings*, *Fertilization* and *Pest Control*. Organic seeds and seedlings are provided by companies which employ more natural production approaches (i.e., no chemical or genetic modification of seeds) (Forman and Silverstein, 2012); the fertilizer sub-function can also be provided by other organic fertilizers such as manure or nitrogen-fixing green crops) and crop rotation (including winter cover). Pest control is realized through physical and mechanical weed control practices, as well as through natural and biological solutions (e.g., management of natural enemies) (cf., Bianchi et al., 2006). The sub-functions of *Plots* and *Technical Equipment* are again similar to those for AG_{Conv}^{LS} systems. The *Market* function is also similar in that it includes supermarket chains and retailers, but dissimilar in that it also includes specialized organic food stores.

A comparison of Figures 3.4 and 3.5 shows that the functional organization of the AG_{Org}^{LS} food production system is compatible with the dominant AG_{Conv}^{LS} system. The food system designs AG_{Conv}^{LS} and AG_{Org}^{LS} contain the same functions, and the underlying structures and processes are the same for the transport and market functions. Thus, large-scale organic agriculture is supported through existing system elements (e.g., the distribution system) of the prevailing AG_{Conv}^{LS} system. A more detailed analysis of synergies and differences is provided in Chapter 3.4.

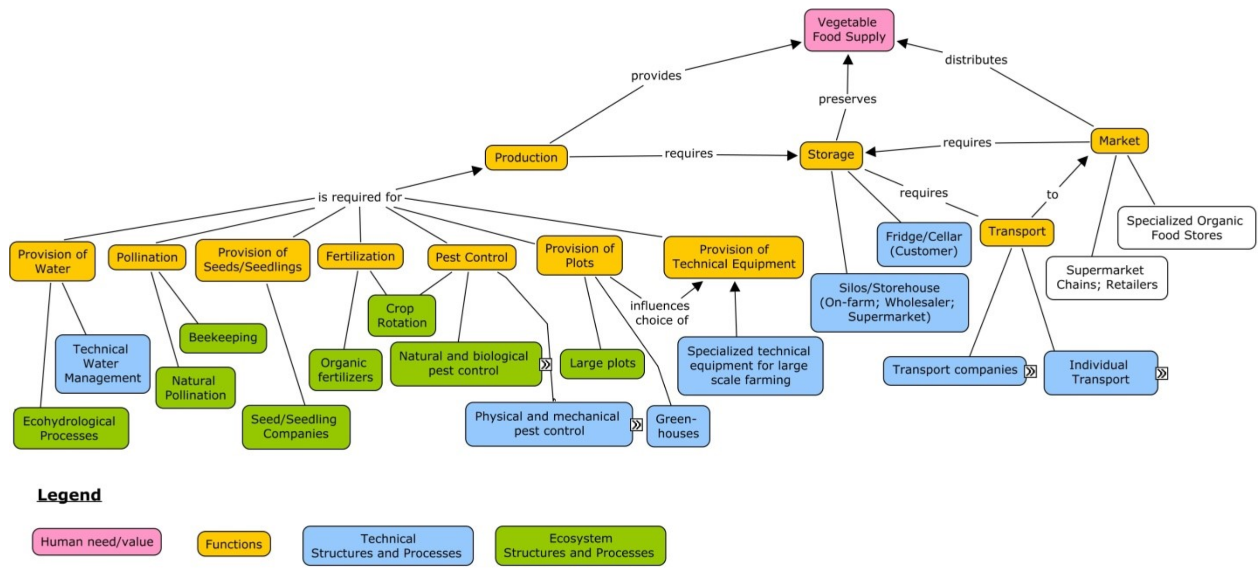

Figure 3.5: FOA for a large-scale, organic agricultural system for the production of vegetables.

3.3.3 Small-scale, diversified, organic agriculture

Small-scale, diversified, organic agriculture (AG_{Org}^{SS}) is viewed as an important part of a sustainable food system in social and ecological terms (Dalsgaard et al., 1995; De Schutter, 2010). Local food systems are expected to have positive effects on community resilience towards challenges such as globalization or scarcity of fossil fuels. Key concepts related to this approach include organic cultivation of diverse field crops, including vegetables and fruits, on a small-scale in order to minimize ecosystem impacts. Small-scale, diversified, organic farming can be done in a rural as well as urban context.

Information regarding the state of local food systems in the case study regions is sparse due to missing consideration by statistical agencies and governmental reports. In Grey/Bruce counties, only 3% of producers and 1% of processors are believed to belong to the local food system (Hammel, 2010). In any case, small scale, diversified organic agriculture in rural and urban areas can be considered as a niche solution. The result of the functional analysis of this food system is depicted in Figure 3.6.

The organization of the diversified AG_{Org}^{SS} system resembles that of the AG_{Org}^{LS} and AG_{Conv}^{LS} systems to some extent: the primary and secondary functions are the same; however, the realization of these functions is built upon different structures and processes. The implementation of the secondary function *Provision of Seeds/Seedlings* through the buy-in of seeds/seedlings from companies is complemented by self-production and preservation of seeds and seedlings. The organic orientation of this agricultural approach is reflected in the *Fertilization* function through the abandonment of chemical fertilizers, and use of organic fertilizers instead (e.g., animal manure or compost). For example, worm composting can be an ecologically friendly approach to support seedling germination and growth as well as plant fertilization (Suthar, 2010). Due to the implementation of organic principles, biological/natural and physical/mechanical pest control options are applied that are based upon a higher vegetation diversity (Bianchi et al., 2006; Xu et al., 2011). As only small scale-plots are cultivated, the use of large agricultural machinery is not necessary and can be replaced by specialized technical equipment for small-scale farming. In an urban agriculture context, plots can also be artificially developed through the installation of roof gardens (cf., Rowe et al., 2014), which support food production as well as biodiversity (Madre et al., 2013). For the storage of products, smaller technical solutions are chosen on-farm or in the distribution system (i.e., silos, storehouses, fridges) compared to the larger installations associated with large scale agricultural systems. The *Transport* function is usually accomplished by the farmers themselves, who transport their products to the market place or customers directly, or by the customers themselves (e.g., pick-up of food boxes). Other options could be a community transport system (i.e., the farming community could initiate a bottom-up transportation and distribution system) or transport by professional companies that pick up the products of small-scale farmers collectively. For the *Market* function, Community Supported Agriculture (CSA) Systems, direct marketing, and local farmers' markets are the most common approaches to distribute food (cf., Brown and Miller, 2008). Food hubs have been mentioned as another option to bring together regional supply and demand using an online marketplace (cf., Mount et al., 2013).

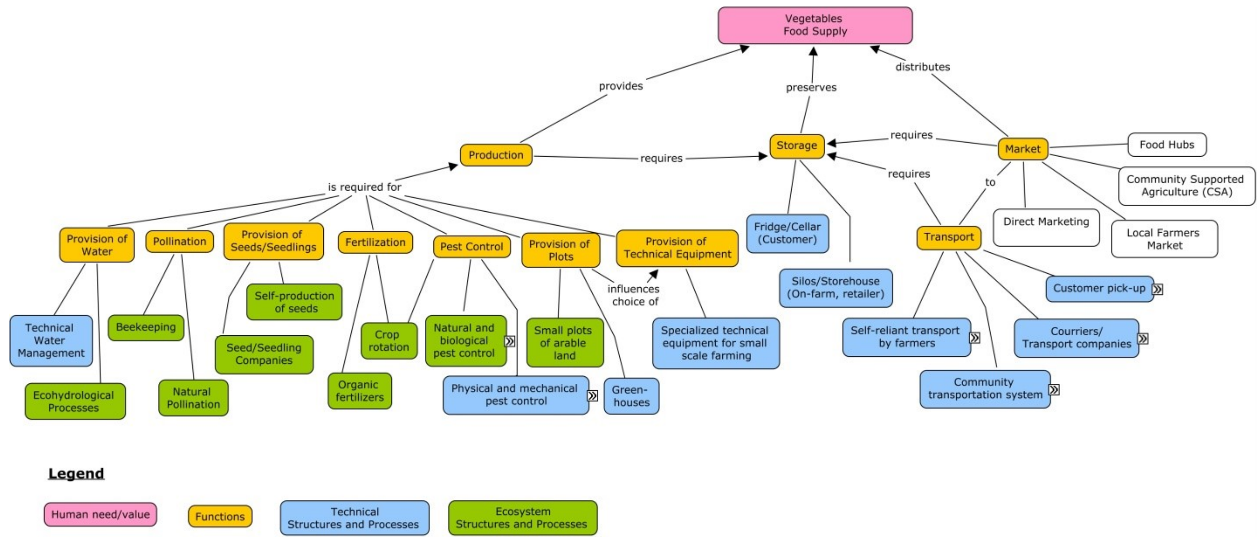

Figure 3.6: FOA of the small-scale, diversified, organic rural and urban agricultural system for the production of vegetables.

3.3.4 Organic subsistence agriculture in urban and rural areas

Organic subsistence agriculture AG_{Org}^{Subs} was stated by several stakeholders as an important element of a sustainable food system. Subsistence agriculture denotes an individual or community farming approach in which food is produced for one's own consumption. This design of food supply systems has negative connotations in the scientific literature and is mainly referred to in the context of developing and transition economies (cf., Kostov and Lingard, 2002). For instance, Todaro's definition (1995) highlights the "low productivity, risk and uncertainty" of most subsistence food systems. Data about the scale of this agricultural approach in Southwestern Ontario is currently lacking.

Most stakeholders in our analysis highlight the fact that subsistence agriculture does not necessarily imply the production of all personal food requirements. It is also a means to preserve and distribute farming knowledge and increase awareness of small-scale farming methods in general, and healthy foods in particular. While within the study area subsistence agriculture was performed predominantly in rural communities, there is an accelerating trend to also farm in such a manner in an urban context. The urban farming movement is gaining strength through city dwellers' desire to grow food by and for themselves (cf., Nasr et al., 2010). Figure 3.7 shows that the organization of a AG_{Org}^{Subs} system's *Production* and *Storage* functions resemble those of the small-scale system. However, the *Market* and *Transportation* functions are absent since the food is not sold but rather consumed by the subsistence farmers themselves. Thus, the distinction between farmers and consumers no longer exists under this system design.

Community gardens can play an important role in the provision of the *Pollination* function by being a habitat for bees and other insects in urban areas (Matteson et al., 2008; Madre et al., 2013). The functions *Provision of Seeds/Seedlings* and *Fertilization* under AG_{Org}^{Subs} resemble those of the AG_{Org}^{SS} systems, where seedlings can be purchased from companies or grown by the subsistence farmers themselves, and fertilization is provided by organic fertilizers (mainly compost). Several solutions have been mentioned by stakeholders to develop sufficient plot area for subsistence farming. While in more rural areas plots can be provided by small plots of arable land, urban farming builds more on artificially-constructed plots like raised beds, small rooftop gardens, and square foot gardens. Primarily biological solutions were mentioned by the stakeholders for pest control, such as the support of biological controller species like spiders (Chatterjee et al., 2009). Fridge, cellar and traditional conservation methods were mentioned for the storage of products.

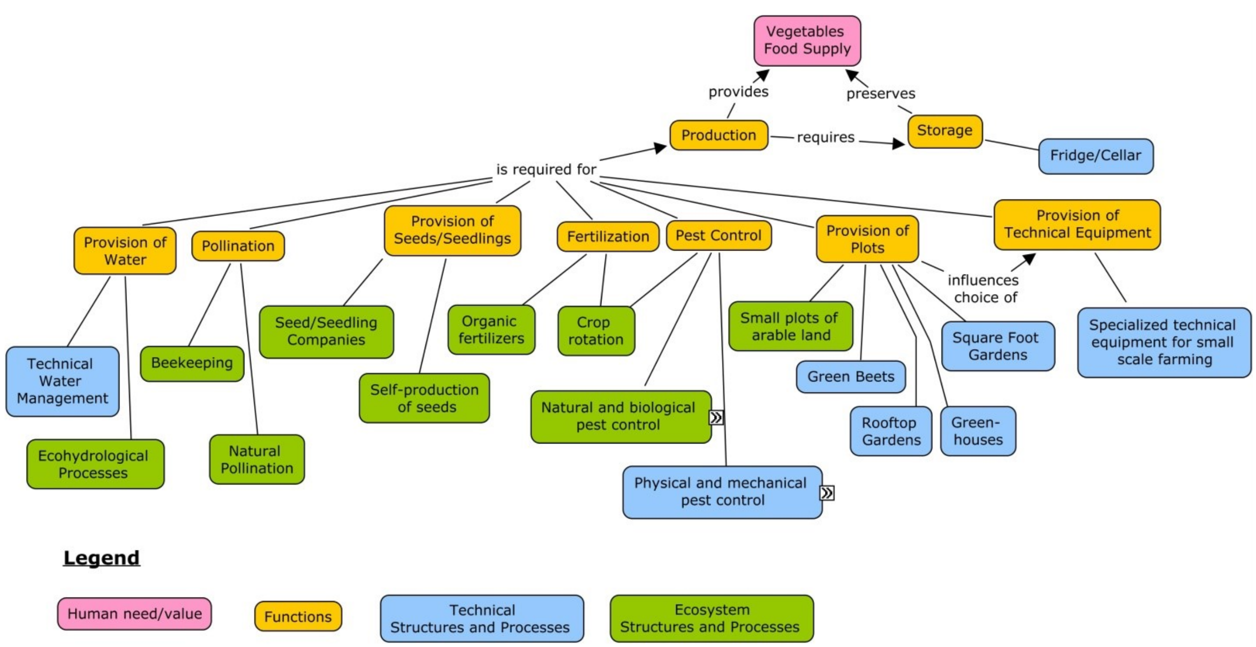

Figure 3.7: FOA of the organic subsistence agriculture ($\boldsymbol{AG_{Org}^{Subs}}$) system for the production of vegetables.

3.4 Discussion

The FOA of sustainable agriculture in Southwestern Ontario examined the organization of different alternative food supply systems. Only the organization of AG_{Org}^{Subs} systems deviates from AG_{Conv}^{LS}, AG_{Org}^{LS}, AG_{Org}^{SS} systems primarily in terms of the absence of the functions of *Transport* and *Market*. What differs between all designs of food supply systems are the specification of structures and processes that produce functions. Data, information, and knowledge were gathered from various sources including expert and stakeholder interviews, scientific publications, statistical reports, and relevant websites which were subsequently linked to associated structures and processes. In this manner, the developed Cmaps helped to integrate different kinds of knowledge.

Visualizing food supply systems' functional organization reframes one's perspective on the associated food system and reveals the interconnectedness of the food system to market processes and transportation. Instead of getting lost in the breadth and detail of structures and processes involved, the FOA reveals alternatives for the provision of needs and functions, thereby allowing the analysis to become more focused on alternative solutions that can potentially be applied in practice. In addition, the commonalities existing between different food supply systems become apparent. For instance, *Transport* and *Market* functions are similar for the AG_{Conv}^{LS} and AG_{Org}^{LS} systems. The identification of similarities can be important in revealing potential areas for cooperation between groups of stakeholders and in developing effective policies.

Table 3.1 shows an overview of similarities and differences of system designs for the four types of food systems that came out of the FOA. Clearly, all food system designs depend on a combination of technical and ecosystem approaches, in addition to the non-material structures of markets. The effectiveness of each structure and process depends on context-related factors that might vary across the case study area. Thus, the FOA method reveals the diversity of potential system designs (as a part of the preliminary systems design step) rather than determining the 'optimal' system design (cf., Blanchard and Fabrycky, 2006).

Table 3.1: Different agricultural system designs obtained by combining technical (blue), natural (green), and non-material (white) structures and processes for the provision of functions (for details on structures and processes see Chapter 3.3).

Functions \ Food system design	Large scale, conventional agriculture	Large scale, organic agriculture	Small scale, organic urban and rural agriculture	Organic subsistence agriculture
Production				
Provision of Water	Technical Water Management	Technical Water Management	Technical Water Management	Technical Water Management
	Ecohydrological Processes	Ecohydrological Processes	Ecohydrological Processes	Ecohydrological Processes
Pollination	Natural Pollination	Natural Pollination	Natural Pollination	Natural Pollination
	Beekeeping	Beekeeping	Beekeeping	Beekeeping
Provision of Seeds/Seedlings	Seed/Seedling Companies[7]	Seed/Seedling Companies	Seed/Seedling Companies	Seed/Seedling Companies
			Self-production of seeds	Self-production of seeds
Fertilization	Mineral Fertilizers	Organic Fertilizers	Organic Fertilizers	Organic Fertilizers
	Crop Rotation	Crop Rotation	Crop Rotation	Crop Rotation
Pest Control	Herbicides/ Pesticides	Natural and biological pest control	Natural and biological pest control	Natural and biological pest control
	Mechanical pest control	Physical and mechanical pest control	Physical and mechanical pest control	Physical and mechanical pest control
	Crop Rotation	Crop Rotation	Crop Rotation	Crop Rotation
Provision of Plots	Large Plots	Large Plots	Small plots of arable land	Small plots of arable land

[7] Seeds and Seedlings are heavily modified through technical processes for large-scale conventional agriculture (cf., Perez-Prat and van Lookeren Campagne, 2002). Thus, the provision of seeds and seedlings have been classified as a technical process for the conventional agriculture system while the organic agriculture systems apply more natural approaches for the production of seeds (cf., Forman and Silverstein, 2012).

				Raised Beds Rooftop Gardens
	Greenhouses	Greenhouses	Greenhouses	Square foot gardens Greenhouses
Provision of Technical Equipment	Specialized technical equipment for large scale farming	Specialized technical equipment for large scale farming	Specialized technical equipment for small scale farming	Specialized technical equipment for small scale farming
Storage	Silos/Storehouse (On-farm; Wholesaler; Supermarket)	Silos/Storehouse (On-farm; Wholesaler; Supermarket)	Silos/Storehouse (On-farm; Wholesaler; Supermarket)	Fridge/Cellar
	Fridge/Cellar (Customer)	Fridge/Cellar (Customer)	Fridge/Cellar (Customer)	Traditional conservation methods (e.g., making preserves)
	Further conservation methods (e.g., making preserves)	Further conservation methods (e.g., making preserves)	Traditional conservation methods (e.g., making preserves)	
Transport	Transport companies	Transport companies	Self-reliant transport by farmers Community transportation system Couriers/Transport companies Customer pick-up	N/A
Market	Supermarket Chains; Retailers	Supermarket Chains; Retailers Specialized Organic Food Stores	Community Supported Agriculture Local Farmers Market Direct Marketing	N/A

The application of FOA to food supply systems revealed large-scale conventional and organic systems to be similar in several respects (in particular related to transport and marketing) (cf., Table 3.1). Differences between these food systems are merely related to the sub-functions of *Provision of Seeds/Seedlings*, *Fertilization*, and *Pest Control*. Thus, a transition from AG_{Conv}^{LS} towards AG_{Org}^{LS} only requires on-farm changes, which can be more easily implemented than off-farm functions like *Transport* and *Market* which require the cooperation of several stakeholders (i.e., distributors, retailers). In contrast, small-scale agriculture faces unique challenges in off-farm functions related to the distribution of food (i.e., *Transport* and *Market*). A system transformation towards small scale agriculture would be challenging, as new structures and processes for transportation and market functions would need to be developed.

The comparison of system designs in Table 3.1 also revealed synergies between small scale organic farming and subsistence farming. In terms of production, small-scale and subsistence agriculture is based upon similar structures and processes (for instance, comparing production sub-functions of pollination, provision of seeds/seedlings, fertilization and pest control) so that cooperation on several aspects would be possible. As an example, small-scale farmers could support various inputs to subsistence farmers such as seeds, seedlings, or animal fodder. Another potential area of cooperation is the provision of expertise of small-scale farmers to subsistence farmers (for instance in urban areas). Such a close cooperation would support resilient local food systems and can also be an interesting strategy for rural development.

By clearly highlighting the diversity of technical and ecosystem approaches, the FOA method can support the envisioning and analysis of alternative system organizations and structures. For instance, Table 3.1 shows that the sub-function of pest control can be accomplished by technical approaches (i.e., application of herbicides, pesticides or mechanical pest control) or ecological solutions (i.e., natural and biological pest control, or crop rotation, cf., Bianchi et al., 2006; Chatterjee et al., 2009). Thus, options for a replacement of technical infrastructure (consisting of the pest control sub-function and underlying technical structures and processes) and natural infrastructure (consisting of the pest control sub-function and underlying ecosystem structures and processes) can be analyzed. For the *Provision of Plots* sub-function, Table 3.1 shows technical alternatives to ecosystem approaches through the construction of artificial plots (e.g., raised beds or rooftop gardens). A comparative analysis of alternative designs (as part of the preliminary system design step) can support communication and learning. For instance, some organic farming approaches could be adopted by conventional agriculture (see Pimentel et al., 2005) rather than fuel ideological disagreements between proponents of different system designs. The explicit consideration of ecosystem structures and processes supports the reframing of current system designs and highlights alternatives to technical approaches.

The proposed FOA method can make an important contribution to the conceptual and preliminary design of sustainable engineering systems. The conceptual framework integrates a range of concepts (ecosystem services, natural infrastructure, ecosystem functions, structures and processes) and renders them compatible to engineering design. In order to proceed towards detailed design and quantitative evaluation, the analysis of functional flows can follow such an organizational analysis. The assessment of alternatives and decisions for a favorable system design in a given context would require the use of assessment tools such as system dynamics modeling (Ness et al., 2007). Future research will build upon the FOA method and develop tools allowing for the quantitative simulation and assessment of system designs. Other future application areas are the participatory collection of knowledge and usage as a learning tool. For this purpose, Figures 3.4-3.7 can be presented on a website, with links providing more in-depth information for each structure (e.g., on biological solutions for pest control). Farmer communities could thereby share knowledge and learn from each other's experiences.

3.5 Conclusions

The proposed FOA method is based upon systems theory and the concepts of ecosystem services and natural infrastructure. The FOA method helps to visualize alternative system organizations (i.e., the systems of functions that fulfill a specific need) and underlying structures and processes. As part of a preliminary system design step, the method thereby reveals alternative system designs and their potential synergies. In addition, the method supports the gathering and integration of relevant data, information and knowledge on alternative designs.

The case study of Grey and Bruce counties, and the city of Guelph, situated in Southwestern Ontario in Canada, presents an example of the application of the proposed FOA method for the analysis of sustainable food systems. An agroecological perspective was applied by analyzing ecological structures and processes in each food system design. Based upon interviews and surveys, we revealed multiple alternative visions of a sustainable food system held by stakeholders, including a large-scale organic food production system, small-scale organic agriculture and subsistence farming. A FOA was undertaken for large scale conventional agriculture (AG_{Conv}^{LS}), the currently dominant agricultural system in the case study area, as well as for alternative designs such as small-scale organic agriculture in rural and urban contexts (AG_{Org}^{SS}), large scale organic agriculture (AG_{Org}^{LS}), and organic subsistence farming (AG_{Org}^{Subs}). The system organization for the AG_{Conv}^{LS}, AG_{Org}^{LS}, and AG_{Org}^{SS} agricultural systems was largely the same, whereas that of the AG_{Org}^{Subs} system differed significantly in the functions of *Transport* and *Market* being absent due to the self-consumption of products. The FOA also revealed several similarities between system structures and processes of food supply systems. For instance, AG_{Conv}^{LS} and AG_{Org}^{LS} food systems showed strong similarities in terms of distribution systems, so that a certified organic agriculture producer could draw upon established structures. Similarities also existed between production systems of small-scale and subsistence farming. There is the potential for cooperation between these food supply system designs. For example, small-scale farms can provide different kinds of inputs to urban farming (e.g., seeds or seedlings) or offer their expertise to urban farmers. The consideration of these similarities and differences supports strategic policy making, as commonalities and unique challenges can be addressed directly rather than applying a unilateral approach.

In addition, the FOA clearly highlighted alternative technical and ecological structures and processes for the provision of functions. For instance, agricultural systems applied different technical (e.g., application of herbicides and pesticides) and ecological approaches (e.g., natural and biological pest control) for pest management. The clear identification of these alternatives supports the integrated assessment of agricultural practices. Such an analysis could clarify whether ecological solutions can substitute for technical solutions, or vice versa.

Future research will apply such a method to the design of other engineering systems, e.g., for water or energy supply. While the proposed FOA method reveals a plurality of solutions, approaches are needed to assess different options and support decisions leading to an effective and sustainable system design. The application of integrated assessment approaches will be applied in future research for the assessment of sustainable engineering systems.

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CONNECTING TEXT TO CHAPTER 4

This chapter presents a further extension of the functional analysis method introduced in Chapter 3. Specifically, the functional analysis method from systems engineering has been extended from including technical functions and services towards including ecosystem functions and services (Chapter 3), and further towards including social functions and services (Chapter 4). This development of the method allows for a more holistic and interdisciplinary design and assessment of sustainability visions (Objectives 3 and 4). Besides the analysis of technical, nature-based and social structures and processes as part of the FOA, this chapter proposes to also apply functional flow analysis (FFA) in a subsequent step. FFA is more specific since it not only depicts the hierarchical relationships between functions, but also causal connections. The analysis of causal connections between system functions provides a bridge towards a systems thinking method and quantitative system dynamics modeling.

Chapter 4 presents the developed FFA method and its application to water supply management in Cyprus. As part of the method, system functions are included into causal loop and stock-and-flow diagrams and finally simulated using a system dynamics model. This approach using FFA allows for a rapid quantification of vision models. However, the resulting dynamic vision models are quite abstract and might have a lower applicability in environmental management practice compared to detailed system dynamics models (see Chapters 7 and 8).

This chapter has been submitted to the Proceedings of the Institution of Civil Engineers - Engineering Sustainability (Halbe and Adamowski, 2021). The format of the article has been modified to ensure consistency with the style of this thesis. A list of references cited in this article is provided at the end of the chapter. The author of the thesis developed, tested and applied the methods used in this article and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided valuable advice on all aspects of the research and contributed to the review and editing of the manuscript.

Chapter 4: Bridging technical, ecological and social knowledge in engineering design

Johannes Halbe and Jan Adamowski

Abstract

Sustainable engineering design requires the joint consideration of technical, environmental, economic and social aspects in the provision of societal demands, such as water and energy supply. A growing number of concepts and methods for integrated assessment and sustainable design have been developed in recent decades, and pose new challenges to the engineering profession. This article proposes the use of systems design concepts and methods to link engineering design to environmental and social-economic knowledge. This study expands the conventional functional analysis approach from systems engineering from a technical focus toward a more integrated perspective that allows for the joint consideration of technical, ecological and social-economic solutions in engineering design. Participatory systems thinking and system dynamics modelling are used for conceptual and preliminary system design by analysing the hierarchy and flows of functions to meet system requirements. The methodology consists of three steps: requirements analysis (Step 1), functional organisation analysis (Step 2) and functional flow analysis (Step 3). An example application of the methodology is provided for the topic of sustainable water management in Cyprus. The results demonstrate the synergies and trade-offs between technical, ecological and social solutions in water management that provide important information for the subsequent detailed system design phase.

Keywords: Design methods & aids; Environment; Economics & finance; Education & training; Knowledge management; Mathematical modelling; Natural resources; Social impact; Sustainability

4.1 Introduction

Methods and tools for sustainable engineering design are required to help engineers deal with the complex interactions of technical, social-economic and environmental aspects. Engineering curricula have been continuously expanded to meet new demands on the engineering profession. This includes, for example, courses in economics, chemistry and ecology to train engineers to better address the ecological and social-economic consequences of the built environment (Halbe et al., 2015a). In addition, "soft" engineering approaches, such as green infrastructure (e.g., UNEP, 2014; Mell, 2009) and nature-based solutions (e.g., Kabisch et al., 2016; Maes and Jacobs, 2017) expand the toolbox of engineers from physical materials to living systems. For example, hard measures for flood control, such as dikes, are nowadays combined with more adaptive approaches, such as retention areas or renaturation of rivers (e.g., Halbe et al., 2018a).

Further development of conventional design methodologies, from a focus on technical solutions towards a more integrated perspective, provides a promising approach to deal with new demands on engineers. Conventional technical system design follows several steps ranging from conceptual and preliminary system design (to explore different alternatives) to detailed system design and implementation. When it comes to the design of sustainable systems at a broader societal scale, conventional methods, such as functional flow analysis, have a limited applicability due to their focus on technical systems. Nevertheless, a functional perspective can be applied for technical, as well as ecological and social-economic systems, which permits further development toward an integrated functional analysis method.

In this article, we present an innovative methodology for sustainable engineering design based on the analysis of system functions using system dynamics modelling. The methodology allows for joint consideration of technical solutions (e.g., from structural engineering), ecological solutions (e.g., from ecological engineering) and social-economic solutions (e.g., from economics) for the provision of services, such as drinking water supply or housing. The methodology builds upon traditional engineering design frameworks to achieve a high compatibility with existing engineering curricula and practice. Requirements and the functional organisation of system designs are analysed, and system dynamics modelling applied to assess synergetic, exchangeable or oppositional relationships between technical, ecological and social-economic solutions. As a result, alternative system designs that combine different sets of technical, ecological and social-economic solutions to provide societal functions can be developed and quantitatively assessed.

The article begins with a description of the traditional use of the functional analysis method in engineering followed by a proposal to expand the functional analysis method from technical solutions to also consider ecological and social-economic solutions. A case study in Cyprus is presented to exemplify the application of the methodology. This article closes with a discussion and conclusion.

4.2 Functional analysis method in engineering

Functional analysis is applied for conceptual and preliminary system design steps in systems engineering (Blanchard and Fabrycky, 2006). The functional method supports a purposeful design of engineering systems by specifying: (1) the performance requirements of the system, (2) primary and secondary system functions, (3) the links between these functions and (4) technical options (i.e., technical structures and processes) that offer these functions (Halbe et al., 2014). Thereby, functional analysis provides the link between the user of an engineering system and the engineers who design the system (Cole, 1998). For sustainability issues, this might be the link between stakeholders with various (partly incompatible) demands, and engineers who offer their design skills to find solutions in a transparent and systematic way.

A requirement is “a statement that identifies a product or process operational, functional, or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability (by consumers or internal quality assurance guidelines)” (Dick et al., 2017, p. 7). A first step of requirement analysis is the systematic identification of relevant stakeholders and their needs (see Reed et al., 2009, and Stanghellini, 2010, for an overview of stakeholder analysis techniques). In the following, the process enters the problem domain in which stakeholder requirements are identified, that is, what the stakeholders want to achieve through using a system (Dick et al., 2017). Various techniques can be applied for stakeholder requirements elicitation, such as stakeholder interviews, workshops and document analysis (Dick et al., 2017). As well, a range of modelling methods are available to further analyse requirements (Nuseibeh and Easterbrook, 2000; Dick et al., 2017). In the next step, the process enters the solution domain in which engineers translate stakeholder requirements into system requirements, which are services a system provides to meet stakeholder requirements (Dick et al., 2017). A large body of work exists on system modelling methods tools that support the analysis of system requirements and their translation in system designs (see Chakraborty et al., 2010; Dick et al., 2017). Originally applied in software development, requirements analysis is presently used in various application areas, such as infrastructure planning and structural design (e.g., Zografos and Madas, 2006; de Graaf et al., 2016).

Functional analysis builds upon a requirements analysis in order to develop alternative system designs (cf., Cole, 1998; Ratchev et al., 2003; Falgarone and Chevassus, 2006). Cole (1998, p. 355) defines functions as "[…] actions a system must perform in response to its environment in order to achieve the mission or goals given to it. The objective of functional analysis is to define the set of functions that need to be included in the system design in order to satisfy the users' needs". System functions can be analysed from a hierarchical viewpoint by using functional identification diagrams that show the different abstraction levels of functions ranging from overarching primary functions to lower-tier functions (Cole, 1998). The analysis of functional flows addresses the interconnections between functions that could be material, energy or information flows (Woldenmichael and Hashim, 2011). Additional methods and tools are available to specify the order of functions and evaluate the technical feasibility and economic performance of a specific system design (Woldenmichael and Hashim, 2011). For example, functional flow block diagrams are the primary functional analysis technique that depicts sequences and relationships between functions (NASA, 2007). In these diagrams, functional events are represented by a block, which are linked according to their local arrangement, and might follow sequential or parallel pathways.

4.3 Functional analysis methodology for bridging technical, ecological and social-economic knowledge

Methods from systems science are widely applied to address the interdisciplinary character of sustainability issues (see Ness et al., 2007). Systems science provides a common analytical level encompassing technical, economic, ecological and social aspects. Concepts and methods from systems engineering can be suitable bridges between traditional technology-centred engineering, and social and ecological knowledge, which are often required to deal with the complexity of sustainability issues.

The proposed methodology for sustainable engineering design includes three steps. In the first step, a requirements analysis is conducted using causal loop diagrams that are developed in a participatory modelling process. In the second step, functional organisation analysis is applied to investigate various design options by linking technical, ecological and social-economic solutions to system functions. In the third step, a system dynamics model is developed to dynamically analyse and assess system designs. Each step of the methodology is presented in more detail in the following sections.

4.3.1 Step 1: Requirements analysis

The causal loop diagram is a powerful method that supports an integrated problem analysis by depicting causal relationships between concepts (Sterman, 2000). Its flexibility renders the method particularly suitable for participatory modelling processes in which stakeholders are asked about their perceptions on a particular problem (e.g., Inam et al., 2015). Causal loop diagrams can be developed in individual interviews with stakeholders as well as group workshops (Halbe et al., 2018b). The construction of a causal loop diagram follows a number of consecutive steps (see Inam et al., 2015; Halbe et al., 2015b, 2018b): first, a start variable is defined, which can point to a problem (e.g., water scarcity or air pollution) or a goal (e.g., water quality or energy security). Second, causes are added and connected to the start variable through causal links. Causal links can either have a positive polarity if the variables move in the same direction, or a negative polarity if variables shift in opposite directions. Third, consequences of the start variable are added to the model. Fourth, feedback loops are drawn, by adding causal linkages between consequences and influencing variables. Finally, variables representing solutions and implementation barriers are added to the model. The resulting causal loop diagrams are subsequently analysed to identify requirements and technical, ecological and social-economic solutions in the system structure (see Figure 4.2).

4.3.2 Step 2: Functional Organisation Analysis

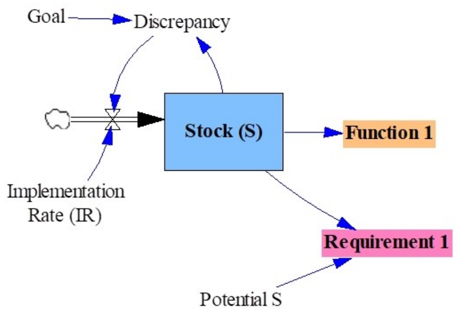
Halbe et al. (2014) present a functional organisation analysis approach for the joint design of ecological and technical systems that builds upon conventional functional analysis from systems engineering. To address the normative aspects of sustainability issues, such as different values and interests of stakeholders, this method can also be applied as part of a participatory process to examine preferred system designs including requirements, functions and underlying structures and processes (Halbe et al., 2014). Functional organisation analysis allows for the hierarchical analysis of alternative system designs using the conceptual modelling tool CMaps (Novak and Canas, 2008). A functional organisation analysis starts by defining a human need that is addressed by a system. In the next step, primary and secondary functions are identified and linked to the human need. Finally, technical, ecological and social-economic solutions from causal loop diagrams are linked to functions. With this approach, alternative system designs can be developed, such as designs that place different emphases on technical, ecological and social-economic solutions.

4.3.3 Step 3: Functional flow analysis

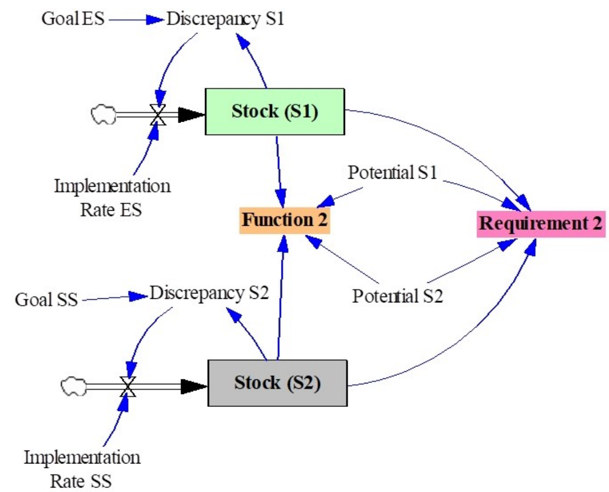
Based on results from causal loop diagrams and functional organisation analysis, a dynamic analysis of alternative system designs is needed to quantitatively assess their technical, ecological and social-economic performances. We propose the use of system dynamics modelling to dynamically analyse and assess system designs. Stock-and-flow diagrams are developed to explore the linkages between requirements, functions and underlying structures and processes in more detail. These stock-and-flow diagrams form the basis for a quantitative assessment of alternative system designs. Figure 4.1 illustrates a simple stock-and-flow structure that conceptualises the links between functions (marked in orange), technical solutions (marked in blue), ecological solutions (marked in green), social-economic solutions (marked in grey) and requirements (marked in pink). Simple stock-and-flow structures are chosen to support the practical application of the functional flow method in conceptual engineering design. Thus, each technical, ecological and social-economic solution is linked to a stock, which can reach dimensionless values between 0 (i.e., not implemented at all) and 100 (i.e., fully implemented) (see Figure 4.1a). The inflow of a stock depends upon goals set for the particular technical, ecological or social-economic solution as well as the implementation rate denoting the amount a solution can be implemented per time step (e.g., a month or a year) (see Equation 1). The stock variable follows a goal-seeking behaviour, which can be mathematically expressed by an exponential function (see Equation 2). The initial value of the stock is calculated by dividing the reference state of the solution (i.e., at the start time of the model) by the potential of the solution (i.e., a desirable capacity). In the case that only one stock variable is linked to a function, the function equals the stock value (Equation 3). The requirement is calculated by multiplying the stock variable S_t with its potential S_{Pot} (Equation 4), which can have physical units. If a function is provided by two solutions (see Figure 4.1b), the sum of the individual potentials of each solution multiplied by the stock value is divided by the additive potential (see Equation 5). The requirement is calculated by multiplying the function with the additive potential, or alternatively, adding up the stock values multiplied by individual potentials (see Equation 6). Thus, quantification of the model requires the specification of current and potential capacities of each technical, ecological and social-economic solution (e.g., the current and desired capacity of seawater desalination in mcm). In addition, further information might be required to calculate additional requirements linked to the different options (e.g., costs of desalinated water per mcm).

The definition of variables, parameters and equations should be based on the best-available data and information (Forrester, 1980), which can draw upon existing empirical data or expert advice (Ford and Sterman, 1998). System dynamics modelling is particularly powerful in dealing with uncertain variables, parameters and functional relationships, which is often the case when addressing the full complexity of societal issues (Forrester, 1961). The results of system dynamics models provide trends, rather than predictions of system behaviour, which is in accordance with the purpose of conceptual and preliminary engineering design.

1A



1B



Eq. 1: $$\frac{dS}{dt} = \frac{Goal - S_t}{IR}$$

Eq. 2: $$\mathrm{S(t)} = Goal + (S_0 - Goal) \times e^{-\frac{t}{IR}}$$

with $S_0 = \frac{S_{Reference}}{S_{Potential}}$

Eq. 3: $$Function_1(t) = \mathrm{S(t)}$$

Eq. 4: $$Requirement_1(t) = S^{Pot} \times \frac{\mathrm{S(t)}}{100}$$

Eq. 5: $$Function_2(t) = \frac{{S_1}^{Pot} \times \frac{S_1(\mathrm{t})}{100} + {S_2}^{Pot} \times \frac{S_2(\mathrm{t})}{100}}{{S_1}^{Pot} + {S_2}^{Pot}}$$

Eq. 6: $$Requirement_2(t) = {S_1}^{Pot} \times \frac{S_1(\mathrm{t})}{100} + {S_2}^{Pot} \times \frac{S_2(\mathrm{t})}{100}$$

Figure 4.1: A) Functional flow analysis using stock-and-flow diagrams; B) Calculation of further requirements, such as cost of different options.

In the following section, a case study on sustainable water management is presented to demonstrate the application of functional analysis for a complex sustainable engineering topic.

4.4 Application to sustainable water management in Cyprus

Cyprus is the third largest island in the Mediterranean Sea and covers an area of 9,251 km². Cyprus' Mediterranean climate features hot and dry summers from May to September, and rainy winters from November to March. Decreasing and unreliable precipitation is the primary source of concern of water users and authorities in Cyprus. The national mean annual precipitation shows high inter-annual variability and an overall decreasing trend of 14% from 560 mm to 480 mm over the last century. Furthermore, five periods of drought, each lasting for three consecutive years or longer, have occurred over the same time period (Katsikides et al., 2005). Total water demand amounts ranges between 250 mcm and 265 mcm (Karavokyris et al., 2010; WDD, 2020) including: about 60 % for irrigation in agriculture, 25 % for domestic use, 4 % for tourism, 3 % for livestock, 3 % for industry and 4 % for landscape irrigation (Karavokyris et al., 2010). The overexploitation of groundwater resources is a significant problem in Cyprus. Intense exploitation of aquifers began in the 1950s with the drilling of deep boreholes and the use of high-capacity pumps. In addition to decreasing amounts of water stored in the aquifers, seawater intrusion is deteriorating the quality of the water, resulting in an overall decrease in the quantity of usable water (Karavokyris et al., 2010).

During the 1980s, water policy focused on the building of dams, conveyors and irrigation networks. Increasing demands on water in conjunction with the simultaneous deterioration of natural water supplies, prompted a change in water policy toward the development of non-conventional water sources, specifically, recycled and desalinated water (Karavokyris et al., 2010). In conjunction with the maximum potential exploitation of non-conventional water resources, water conservation programs are also integral components of governmental policies (Savvides et al., 2001; WDD, 2011).

The water scarcity problem in Cyprus serves as a good example of a complex problem in which technical solutions (e.g., building of dams, exploitation of groundwater) can only solve part of the overall problem. A coordinated strategy is needed to address the continuing water scarcity problem from various angles, and through the joint action of multiple stakeholder groups. The following section outlines the results of a functional analysis aimed at broadening the technology-centred approach followed in the past decades toward a more integrated approach featuring ecological and social-economic solutions.

4.4.1 Requirements analysis

A participatory modelling process was conducted between 2009 and 2014 by the authors to investigate the mental models of stakeholders regarding the current water issue in Cyprus, including their goals and needs, as well as potential solution strategies to transform the system towards a more sustainable state. A stakeholder analysis was conducted to ensure that different types of stakeholders (e.g., experts, decision-makers, users, innovators) were represented in the participatory process. The stakeholder analysis showed the importance of several government agencies (e.g., Water Development Department, Department of Agriculture, Department of

Environment, Cyprus Energy Agency), water boards, farmer unions, and research institutes (e.g., Agriculture Research Institute, Cyprus Institute, University of Cyprus) (Halbe et al., 2015b). In total, 16 causal loop diagrams[8] were subsequently constructed in individual interviews that represent the stakeholders' mental models on the water scarcity issue (see Halbe et al., 2015b for more details on the participatory modelling process). Figure 4.2 provides an example of a causal loop diagram from a stakeholder interview.

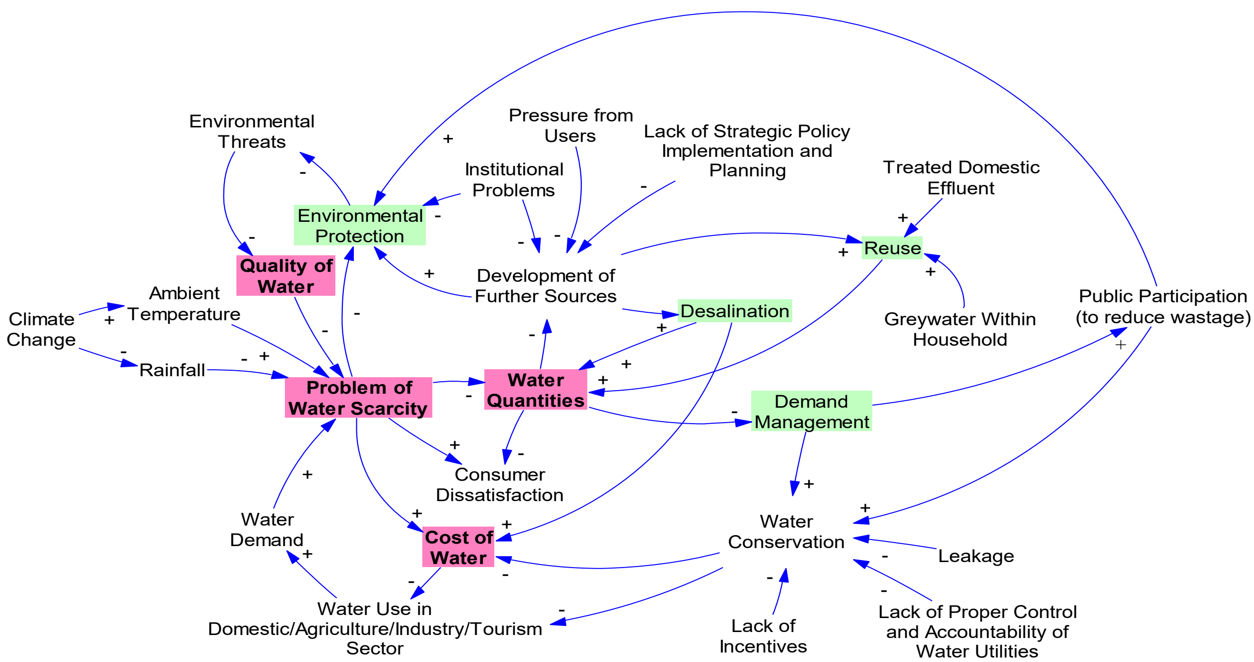


Figure 4.2: Causal loop diagram constructed by a stakeholder in Cyprus. Requirements are marked in pink, and proposed solution strategies are marked in green.

The causal loop diagram in Figure 4.2 depicts the perceived requirements for a sustainable water system in Cyprus (marked in pink), including the cost and quality of water as well as the reliability of supply (represented through the variables "Problem of Water Scarcity" and "Water Quantities"). Different solution strategies, marked in green, were proposed by the stakeholder,

[8] In addition, 11 causal loop diagrams were built in interviews with innovators in which a particular innovation served as the start variable. These interviews were conducted by using a slightly different methodology and results were analyzed from a governance perspective (see Halbe et al., 2015b). We do not provide details on the methodology to conduct individual interviews with innovators, as we do not want to confuse the reader.

comprising technical solutions (i.e., desalination and water reuse), ecological solutions (i.e., environmental protection) and more socio-economic solutions (i.e., water demand management).

4.4.2 Functional Organisation Analysis

In the next step, a hierarchical analysis of system functions was completed by the first author of this article. The functional organisation analysis approach was used to link primary and secondary functions to underlying technical, ecological and social-economic solution strategies (cf., Halbe et al., 2014). Figure 4.3 shows the resulting diagram, comprising the primary functions of "Water Generation" (i.e., generation of usable water), "Water Storage" and "Water Transport". Several options have been identified to implement functions. For clarity, Figure 4.3 contains only a subset of potential options to demonstrate the ability of the methodology to jointly consider a mix of technical, ecological and social-economic solutions. While the function of supply management can be accomplished by technical options (e.g., desalination and groundwater pumping), demand management builds more upon social-economic processes (e.g., awareness campaigns and water pricing). Rainwater harvesting (in its wider sense) can be accomplished through rainwater collection systems (a technical option), but can also be realised by ecological structures and processes, such as constructed wetlands or reforestation which minimises evaporation. Water storage is another example of a function that can be addressed with technical structures (e.g., a dam) or ecological structures (e.g., a constructed wetland).

In a next step, different system designs can be derived from the functional organisation analysis. For instance, one system design could integrate all technical solutions, while another design integrates ecological and social-economic solutions as well. In order to quantitatively test and assess the ability of different designs to accomplish system requirements (e.g., reliability of supply), functional flow analysis is required as described in the following section.

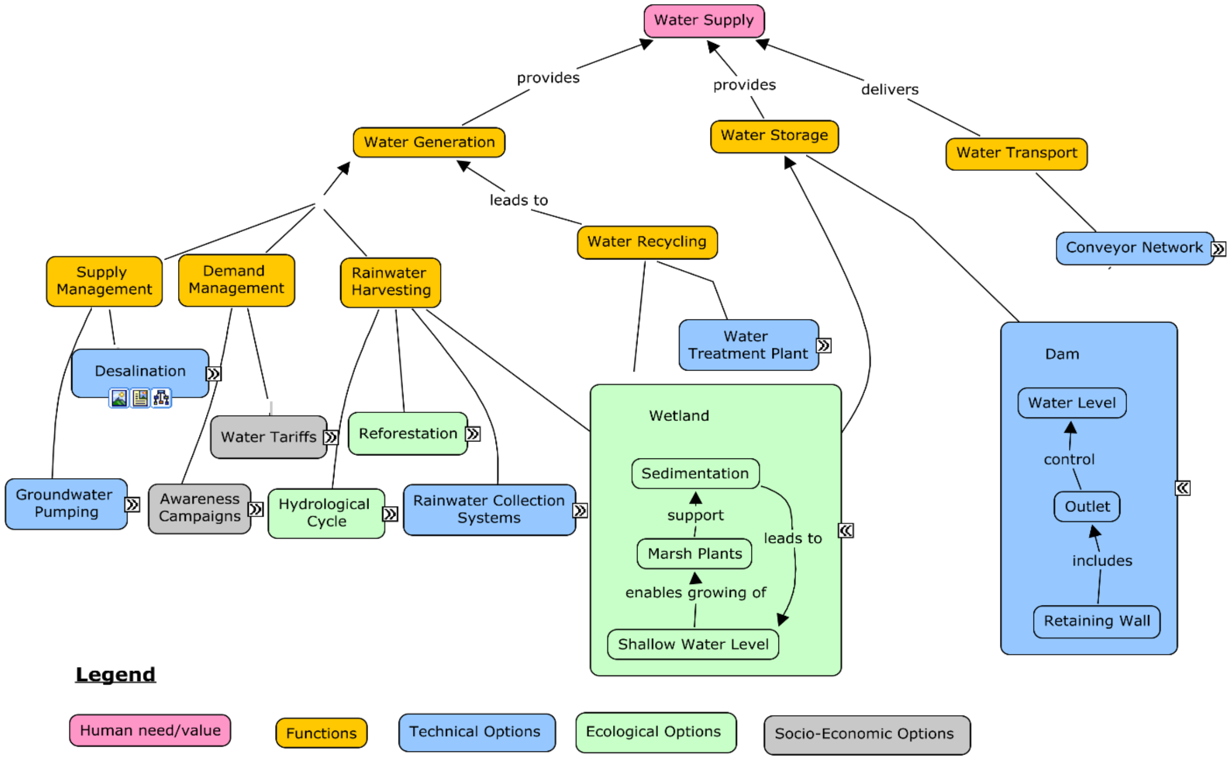


Figure 4.3: Functional organisation analysis for a water supply system.

4.4.3 Functional Flow Analysis

Figure 4.4 illustrates a simplified stock-and-flow model developed by the first author of this article that defines how the technical solutions (marked in blue), ecological solutions (marked in green) and social-economic solutions (marked in grey) are linked to functions (marked in orange), identified through the functional organisation analysis, and requirements (marked in pink) in the Cyprus case study (a detailed picture of the model structure is provided in Appendix 4.1). Conscious consumption (a social-economic solution) and water-saving technology (a technical solution) are linked to water demand, which has an impact on water scarcity. Water supply is provided through desalination, groundwater pumping, stored water in dams (technical solutions) and rainwater harvested through wetlands (an ecological solution) and a rainwater collection system (a technical solution). Wetlands have a positive effect on water storage and groundwater recharge. The effect of wetlands on groundwater recharge is a complicated hydrological process, which was simplified in the model by adding a factor (>1) that is multiplied by the potential of groundwater pumping. A comparison of water supply and water demand determines the water scarcity indicator, which is calculated by dividing water demand by water supply. Water security is included by assuming an overcapacity of 50% in order to be able to buffer shortfalls and inter-annual variation of water supply (e.g., low water levels in dams due to long-lasting droughts; disruptions in seawater desalination due to maintenance or failures).

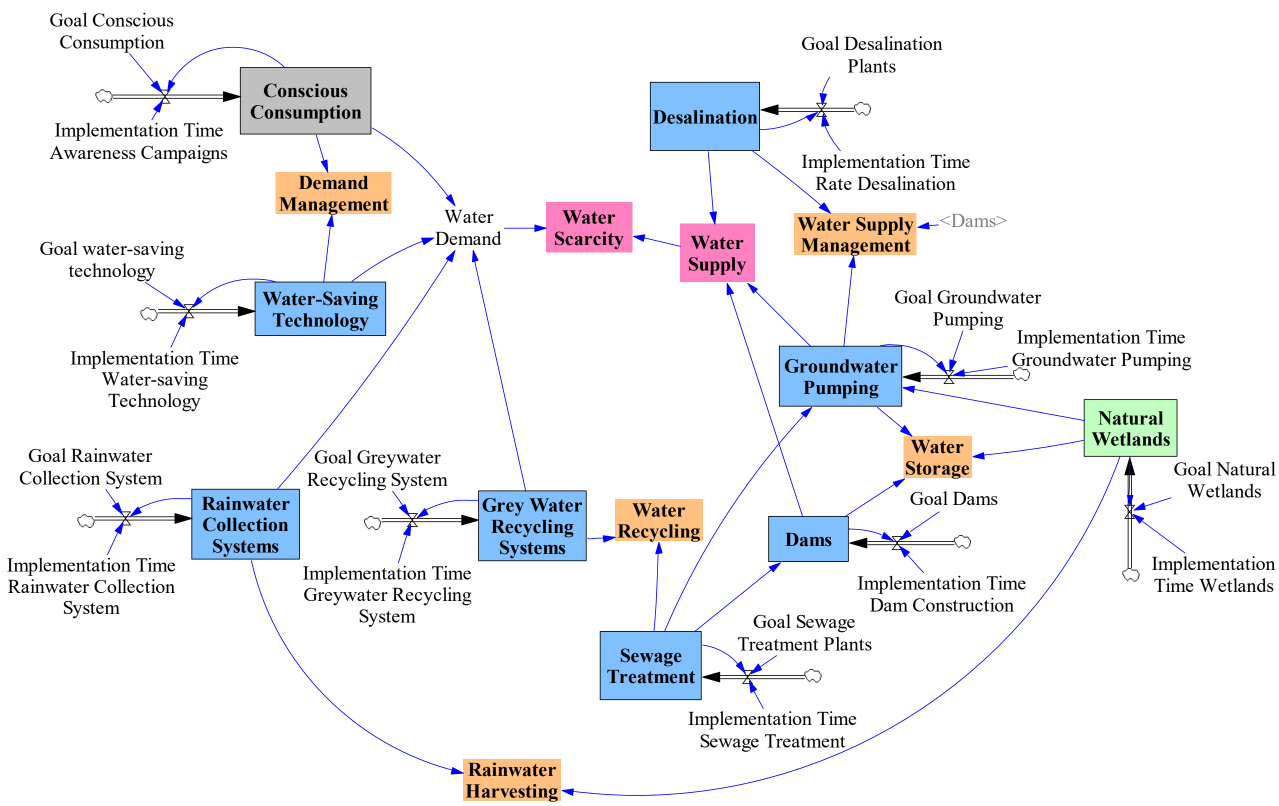


Figure 4.4: Simple stock-and-flow structure for quantitative modelling of design approaches.

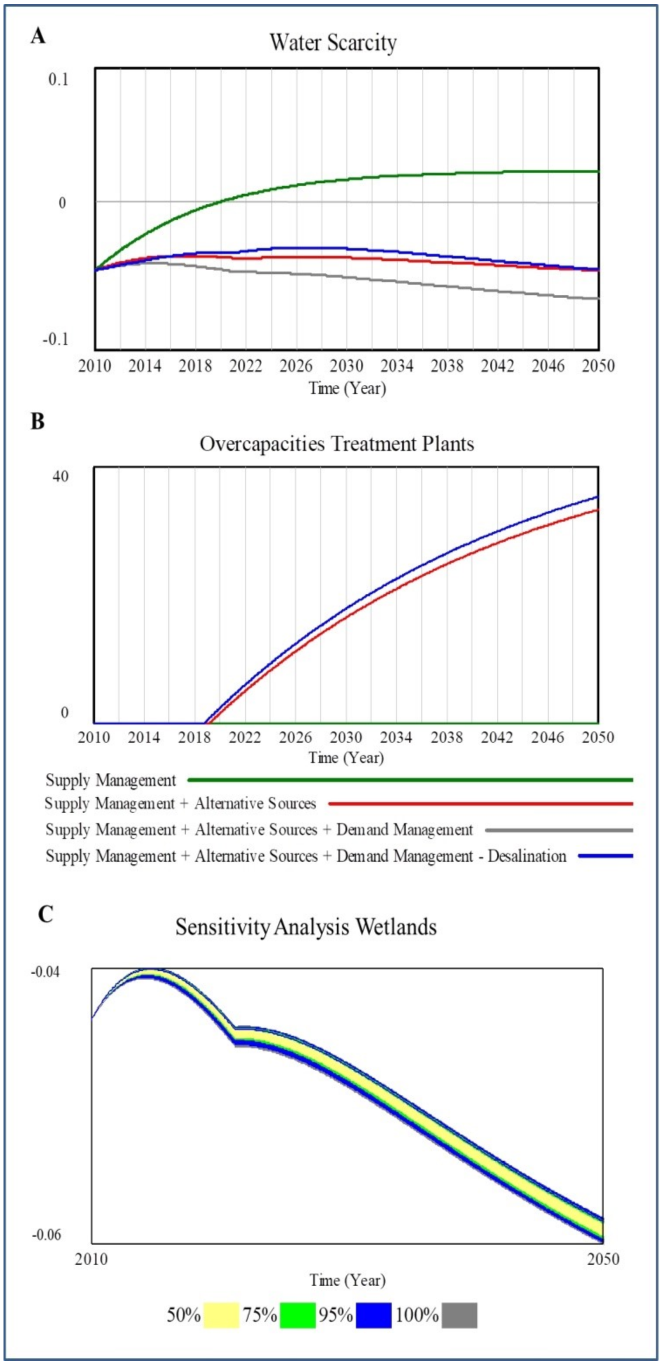


Figure 4.5: Figure 4.5A shows the water scarcity indicator through time for all four scenarios. Figure 4.5B points to overcapacities of wastewater treatment plants following a reduction of water demand (curves for Sc. 3 and 4 overlap). Figure 4.5C presents the results of a sensitivity analysis for the effects of parameter uncertainties related to natural wetlands on the water scarcity indicator.

Model parameterisation requires knowledge and empirical data from different disciplines. For instance, ecological knowledge is needed to assess the capacity of wetlands to store water in Cyprus. Empirical data on water demand is required to assume reduction potentials due to more conscious water consumption, which might be affected by water pricing or awareness campaigns. The processes included in the model are highly complex and data are partly missing. For instance, data on the capacity of wetlands to store water and the amount of water percolating to the groundwater are not available. By using functional analysis at a more abstract level, engineers can, however, make an estimate of the capacity of technical, ecological and social-economic solutions without entering into the details of disciplinary debates. The effect of data gaps can be analysed through sensitivity analysis, which can ultimately point to research needs, another important result of functional analysis. Parameter values and assumptions are listed in Appendix 4.2 along with a specification of data sources (e.g., from governmental reports or scientific publications) and assumptions.

As previously noted in section 4.4.2, system designs can be tested by computing requirements for different combination of technical, ecological and social-economic solutions. Four different system designs were tested in this study using scenario analysis: (1) a design solely based on technical supply-side solutions (i.e., desalination, groundwater pumping and dam construction); (2) a design based on technical and alternative sources, including wastewater recycling, rainwater harvesting and construction of wetlands; (3) a design based on a combination of technical, ecological and social-economic solutions, i.e., the previous scenario is complemented by demand-side measures including awareness campaigns and water-efficient fittings; (4) a design based on technical, ecological and social-economic solutions, in which water supply from desalination is reduced by the amount of water savings through demand-side measures (i.e., the substitution of water demand and supply management is tested).

Figure 4.5A shows the results of the scenario runs. The highest water scarcity indicator is related to Scenario 1 (i.e., water supply management), followed by Scenario 2 (additional use of water recycling, rainwater harvesting and natural wetlands) and Scenario 3 (additional use of water demand management). The significant reduction of water scarcity through alternative water sources (Scenario 2) supports the current water policies in Cyprus, which promotes such measures. Demand management allows a reduction of desalination capacities by 30% in Scenario 4 to match the water scarcity indicator in Scenario 2. Figure 4.5B points to a trade-off between water demand management and wastewater treatment.

Overcapacities arise in all scenarios in which water recycling is considered (i.e., except Scenario 1 as wastewater treatment is not considered in this scenario; the curves for Scenarios 3 and 4 overlap in Figure 4.5B). Due to the lack of data linked to the nature-based solution of wetlands for water storage and rainwater harvesting, a sensitivity analysis was performed for two parameters using a Monte-Carlo approach (Latin Hypercube distribution): (1) the wetland capacity was varied between 5 mcm and 30 mcm; (2) the percolation rate was varied between 0.05 and 0.4. Figure 4.5C shows an only slight impact of parameter uncertainties on the water scarcity indicator in Scenario 2 (median: -0.049; standard deviation: 0.008).

4.5 Discussions

The case study in Cyprus demonstrates the potential of a systems engineering approach for an integrated design and assessment of engineering systems. Systems engineering concepts and methods that were originally intended for the design of technical systems can also be applied for the analysis of requirements and functions of combined technical, ecological and social-economic systems. As described above, quantitative functional analysis requires parameters that define the potential for technical, ecological or social-economic solutions. For instance, landscape ecologists have to define opportunities for constructed wetlands based on environmental factors (e.g., soil properties or climatic conditions). Functional analysis specifies those parameters that are required for integrated engineering design, and thus, could function as a link between disciplines.

Instead of providing definitive answers on the selection of a particular design, which would be part of the detailed engineering design phase, the presented methodology provides trends of the advantages/disadvantages and synergies/trade-offs of various design options as part of the conceptual and preliminary design phase. The exemplary case study about water management in Cyprus highlighted the advantages of a combined application of technical, ecological and social-economic solutions with regard to water scarcity. In addition, a potential trade-off was identified between water demand management and wastewater recycling, as a decreasing water demand could imply overcapacities in sewage treatment. A more detailed analysis of effluent volumes is required to clarify this issue. The sensitivity analysis regarding the storage capacity of wetlands and percolation rates showed only a minimal effect on the water scarcity indicator.

Further research is required to quantitatively test different system designs and assess the synergies between technical, ecological and social-economic solutions. For instance, costs associated with technical, ecological and social-economic options could be added to the model. Due to the explorative character of this research, we applied systems thinking and system dynamics, which are flexible and transparent modelling methods. However, future research should test the applicability of existing modelling tools for technology-centred functional analysis (e.g., Hull et al., 2005; Falgarone and Chevassus, 2006). Building upon the conceptual work in this article, it might be possible to expand the use of these modelling tools towards ecological and social-economic aspects, which would support the integration of sustainability topics in the engineering profession.

4.6 Conclusions

This article presents a methodology to allow for the inclusion of ecological and social-economic aspects in engineering design for sustainable development. Concepts and methods from systems engineering are proposed as key approaches to bridge the traditional technology-centred expertise of engineers with knowledge from ecology, economics and behavioural sciences, amongst others. The case study on sustainable water management in Cyprus illustrated the potential of the methodology to provide a common analytical level and to make knowledge from other disciplines applicable in engineering design. Synergies and trade-offs between technical, ecological and social-economic solutions were identified in the case study application. While systems thinking and system dynamics modelling were found to be suitable methods for conceptual and preliminary system design, existing tools for functional analysis should be tested in future research, whether they allow for an integrated assessment of technical, ecological and social-economic options in the detailed system design phase.

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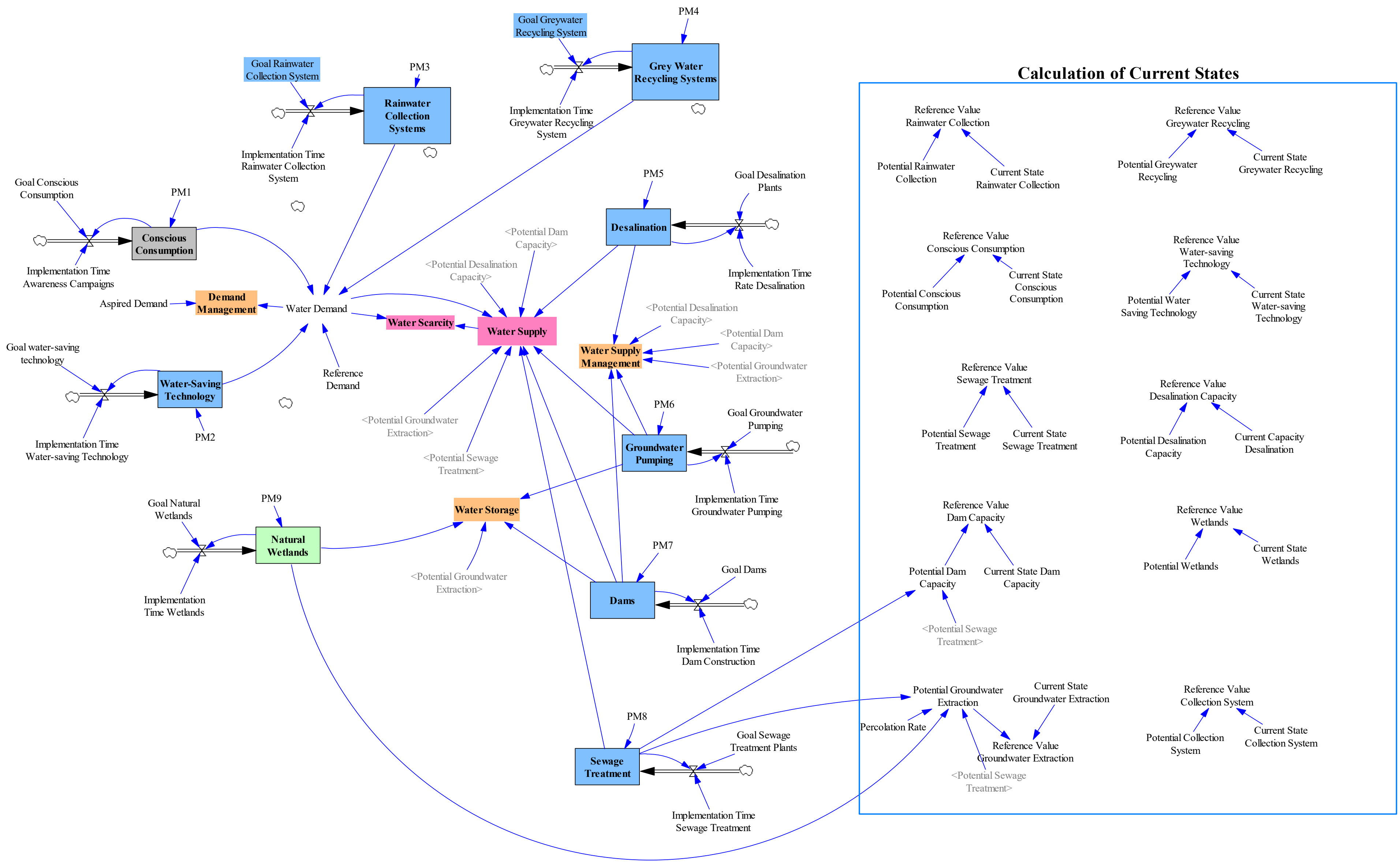
Appendix 4.1: Detailed model structure



Appendix 4.2: List of parameters linked to stock variables

Stock variable	Parameter Value Current State	Parameter Value Potential
Conscious Consumption	The total water demand is estimated to amount to 252 mcm in the year 2011 (Karavokyris et al., 2010), including 73.5 mcm for domestic (63.8 mcm) and tourism (9.7 mcm) sectors (Karavokyris et al., 2010). The average daily consumption of households amounts accordingly to **608 l** (see Statistical Service, 2012a for population numbers). The average daily consumption of tourists amounts to **450 l** (see Statistical Service, 2012b for tourism numbers). The annual water demand of agriculture amounts to **170.5 mcm**. More recent data shows a slightly increasing trend of total water demand to 265 mcm in 2018 (WDD, 2020).	Specific numbers on the potential effect of conscious consumption on water demand are currently not available. Halbe (2009) calculates saving potentials based on data from Savvides et al. (2001) and Ecologic (2007). Conscious Consumption can reduce average daily consumption of households to **473.2 l**. The tourist water demand can be reduced through a more conscious consumption to **402 l**. Behaviour changes in the agriculture sector (e.g., through changes of cropping patterns) are assumed to decrease the water demand by about 10% (see Halbe 2009 for details on the calculation).
Water-saving technology	The total water demand is estimated to amount to 252 mcm in the 2011 (Karavokyris et al., 2010), including 73.5 mcm for domestic (63.8 mcm) and tourism (9.7 mcm) sectors (Karavokyris et al., 2010). The average daily consumption of households amounts accordingly to **608 l** (see Statistical Service, 2012a for population numbers). The average daily consumption of tourists amounts to **450** l (see Statistical Service, 2012b for tourism numbers). The annual water demand of agriculture amounts to **170.5 mcm**.	Specific numbers on the potential effect of more efficient technology on water demand are currently not available. Halbe (2009) calculates saving potentials based on data from Savvides et al. (2001) and Ecologic (2007). Water-saving technology can reduce the average daily consumption of households to **419.2 l** (see Halbe 2009 for details on the calculation). The tourist water demand can be reduced through more efficient technology by 147 l to **318 l** (see Halbe 2009 for details on the calculation). Irrigation efficiency is already high in Cyprus. Conveyance efficiency in Cyprus amounts to 90-95% and the field application efficiency to 80-90% (EEA 2001).
Desalination	The capacity of desalination plants	The capacity of desalination could be

	amounts to 220,000 m^3/day. The minimum yearly production amounts to 70.53 mcm (Neocleous and Charalambous, 2016), which is sufficient to meet the full portable water demand (Water Development Department, 2011, 2014).	increased further in case that the potable water demand shows a rising tendency. The use of desalinated water for irrigation purposes is a technically and economically viable option for high value crops (see Martinez-Alvarez et al., 2016), but is not considered to be an option in Cyprus due to adverse environmental effects. Thus, the capacity of desalination plants is considered to be stable in the model.
Groundwater Pumping	Karavokyris et al. (2010) calculate an average yearly extraction of 135 mcm for the period between 2000 and 2009.	As 16 out of 19 groundwater bodies are overpumped, Karavokyris et al. (2010) propose a reduction of extraction to 104.1 mcm per year.
Dams	Since 1960, the dam capacity has been increased from 6 mcm to 300 mcm (Iacovides, 2011). However, the actual inflows to the dams are mostly lower (up to 84%) than anticipated in the initial dam design (Karavokyris et al., 2010). Thus, only 60 % of the actual installed dam capacity is included in the model.	As the most economically efficient dams are already in place (Iacovides, 2011), the dam capacity is assumed to stay stable in the model.
Water Treatment Plants	In 2012, the volume of treated wastewater amounted to 22.2 mcm (Hadjigeorgiou, 2014). About 72% on average of treated water has been used for irrigation, 15 % for aquifer recharge and 3 % for discharge into dams.	In 2025, it is expected that the volume of treated effluent will be significantly increased to 86 mcm (Hadjigeorgiou, 2014).
Wetlands	Data on the capacity of wetlands in Cyprus to store water and recharge aquifers could not be found. Calculation of these parameters requires knowledge about soil properties and various further hydrological parameters. In particular, the interaction with groundwater is unique to each wetland and precludes generalised relationships (Acreman, 2010). The total area of natural wetlands	More than 60% of natural wetlands have been lost in Mediterranean Europe in the last century (Acreman, 2010; Mediterranean Wetlands Observatory, 2014). Thus, the potential for wetlands to store water is calculated by dividing the estimated storage capacity by 0.6.

	in Cyprus amount to 57.05 km^2 (Terra Cypria, 2018). Due to the lack of data, the environmental water demand is taken as a proxy for the storage capacity of wetlands, which is estimated by Savvides et al. (2001) to be 5 mcm. It is furthermore assumed that about 10 % of the water percolates to the groundwater.	
Rainwater Collection Systems	Rainwater can be stored and collected for non-potable water uses in households, industry and agriculture (Campling et al., 2008). In Cyprus, water use for toilet flushing, garden irrigation, car washing and outdoor cleaning, amounting to 51% of the domestic water demand (WDD, 2002) (~32.5 mcm; ~ 37.7 m^3/capita), could be provided by rainwater.	Low annual precipitation rates and availability of suitable roof surfaces are major constraining factors for rainwater harvesting (Campling et al., 2008). The potential for water saving through rainwater harvesting in the domestic and tourism sectors are assumed to amount to 10 %.
Greywater recycling systems	Greywater from bath, washbasins and the kitchen amount to 42% of the domestic water demand (WDD, 2002) (~26.8 mcm), which could be re-used for toilet flushing, outdoor cleaning and car washing.	The potential for water saving through greywater recycling technologies in the domestic and tourism sectors are assumed to amount to 30 % and 15 % respectively.

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CONNECTING TEXT TO CHAPTER 5

Chapter 5 presents a methodological Participatory Model Building Framework (PMBF) for the context-sensitive initiation, design and institutionalization of participatory modeling processes (Objective 2). Institutional and process analysis is included as part of the framework, which allows for the ex-post analysis as well as the ex-ante design of participatory modeling processes. This involves the analysis of participating actors, process steps and the socio-economic context of the modeling process (cf. Objective 2). Systems thinking (i.e., CLDs) are proposed for initiating participatory modeling processes. At a later step in the process, other modeling methods are proposed that allow for quantitative analysis, such as fuzzy cognitive mapping and system dynamics modeling (Objective 1). The PMBF supports the iterative development of models in the course of participatory processes. In particular, group model building is proposed to facilitate social learning between stakeholders. In addition, the Management and Transition Framework is included for process analysis and design, which has a strong conceptual foundation in the social learning concept.

The methodological framework is applied to a case study on water quality management in Québec. Each step of the PMBF has been applied in the case study ranging from problem and stakeholder analysis to process design, individual and group modeling and analysis of requirements for institutionalized participatory modeling.

This chapter was published in the Journal of Hydrology (Halbe et al. 2018). The format of the article has been modified to ensure consistency with the style of this thesis. A list of references cited in this article is provided at the end of the chapter. The author of the thesis developed, tested and applied the conceptual and methodological framework and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, gave advice on all aspects of the research and contributed to the review and editing of the manuscript. Prof. Claudia Pahl-Wostl, Institute of Environmental Systems Research, Germany, contributed to the review of the manuscript and provided advice on the organization of the participatory modeling process and the use of the Management and Transition Framework for process design and analysis.

Chapter 5: A methodological framework to support the initiation, design and institutionalization of participatory modeling processes in water resources management

Johannes Halbe, Claudia Pahl-Wostl and Jan Adamowski

Abstract

Multiple barriers constrain the widespread application of participatory methods in water management, including the more technical focus of most water agencies, additional cost and time requirements for stakeholder involvement, as well as institutional structures that impede collaborative management. This paper presents a stepwise methodological framework that addresses the challenges of context-sensitive initiation, design and institutionalization of participatory modeling processes. The methodological framework consists of five successive stages: (1) problem framing and stakeholder analysis, (2) process design, (3) individual modeling, (4) group model building, and (5) institutionalized participatory modeling. The Management and Transition Framework is used for problem diagnosis (Stage One), context-sensitive process design (Stage Two) and analysis of requirements for the institutionalization of participatory water management (Stage Five). Conceptual modeling is used to initiate participatory modeling processes (Stage Three) and assure a high compatibility with quantitative modeling approaches (Stage Four). This paper describes the proposed Participatory Model Building framework (PMBF) and provides a case study of its application in Québec, Canada. The results of the Québec study demonstrate the applicability of the PMBF for initiating and designing participatory model building processes and analyzing barriers towards institutionalization.

Keywords: water management; participatory modeling; stakeholder participation; systems thinking; policy analysis; process design

5.1 Introduction

Water legislation such as the U.S. Clean Water Act, the Québec Water Policy and the European Water Framework Directive emphasize the need for integrated and participatory approaches for the sustainable management of water resources. Participatory modeling has been found to be a useful methodology to support stakeholder involvement and integrated analysis of water resources issues (e.g., Pahl-Wost et al., 2007; Serrat-Capdevila et al., 2011; Inam et al., 2015). Stakeholders can be an individual or group who can (indirectly or directly) affect or be affected by a topic of interest (cf. Glicken, 2000), such as a water quality issue. By building a model, stakeholders can express their points of view, learn about other perspectives, and examine factual knowledge and subjective perceptions (Pahl-Wostl, 2007). The construction of simulation models allows for the testing of assumptions and thereby supports learning about the system (Dörner, 1996; Sterman, 2000).

There are profound barriers to the implementation of participatory modeling in water resources management. First, the initiation of participatory modeling processes is often hampered due to the limited modeling and facilitation skills of practitioners (e.g., water agencies) (Hare, 2011), and the widespread perception that stakeholder involvement is a time-consuming and costly process, while the benefits remain obscure (Morrison, 2003; Winz et al., 2009; Hare, 2011). Second, context-specific design of participatory modeling processes is a challenging task and requires methodological development to adapt the process to physical, environmental, socio-economic and institutional circumstances (Hatzilacou et al., 2007; Winz et al., 2009: Metcalf et al., 2010). Besides a context-specific customization, an explicit process design also allows for a rigorous monitoring and evaluation of participatory modeling processes by specifying process steps and intended outcomes (see Jones et al., 2009 and Carr et al., 2012). Third, participatory modeling processes are often constrained to short and mid-term 'interventions' during research projects led by modeling experts (Voinov and Bousquet, 2010), even though significant improvement of water issues usually requires long-term engagement (Pahl-Wostl et al., 2007). Thus, approaches are needed that support an analysis of requirements for long-term participatory modeling processes which involve envisioning of supportive institutional structures and mechanisms for capacity building.

This paper proposes a Participatory Model Building Framework (PMBF) that addresses the aforementioned challenges by proposing an innovative stepwise approach for the *initiation,* *design* and *institutionalization* of participatory modeling processes. The methodological framework consists of five successive stages: (1) problem framing and stakeholder analysis, (2) process design, (3) individual modeling, (4) group model building, and (5) institutionalized participatory modeling. The PMBF combines context-sensitive process design (Stages One and Two), a focus on process initiation through a low-threshold modeling approach (Stage Three), a high compatibility with quantitative modeling approaches (in Stage Four), and an analysis of requirements for institutionalized participatory modeling (Stage Five).

The structure of the paper is as follows. First, the methodological foundations of the PMBF are introduced including the Management and Transition Framework, as well as conceptual participatory modeling. Second, the five steps of the PMBF and their links to other participatory modeling frameworks are presented. Third, a case study in Québec, Canada, on water quality management is provided, in which the application of the PMBF is tested and assessed. Our experiences from the case study in Québec and further participatory modeling processes in Ontario (Canada), Cyprus, Guatemala and Pakistan are discussed, before we conclude with suggestions for future research.

5.2 Methodological background

The MTF and conceptual participatory modeling are the methodological foundations of the PMBF. The MTF is used for problem and stakeholder analysis (Stage One), context-sensitive process design (Stage Two) and analysis of requirements for institutionalized participatory modeling (Stage Five). Conceptual modeling is used to initiate participatory modeling processes (Stage Three) and assure a high compatibility with quantitative modeling approaches (Stage Four).

5.2.1 Management and Transition Framework

The MTF was developed by Pahl-Wostl et al. (Pahl-Wostl et al., 2010; Knieper et al., 2010; Pahl-Wostl, 2015; Knüppe and Knieper 2016) as a diagnostic tool for water resources governance and management problems. The MTF is based upon the three conceptual pillars of adaptive management (e.g., Holling, 1978), social learning and transformation processes (Pahl-Wostl et al., 2007), as well as the Institutional Analysis and Development Framework (Ostrom, 2005).

Key concepts and their relationships are specified through a class diagram that defines the general structure of a water system (Figure 5.1a). Each class (e.g., 'technical infrastructure' or 'actor') is characterized by certain attributes that allow for a detailed description of case-specific conditions (for instance, actors can be characterized by sectors (or sectoral affiliation) and the spatial scale at which they typically operate). Relational databases are used to support formalization and standardization of data collection and representation (Knieper et al., 2010).

The overarching problem boundaries are given by the 'Water System', which comprises all environmental and human components (Figure 5.1a). The 'Ecological System' class comprises abiotic and biotic components of the water system, which provide different services for human activities. The 'Societal System' embeds multiple 'Action Arenas', which are issue-specific political arenas focused on a societal function such as flood protection or water supply, and characterized by 'Strategic Management Goals', 'Actors' and 'Action Situations'. An 'Action Situation' is a key concept of the MTF that allows for the analysis of the water management process and is defined as a structured social interaction context that leads to specific outcomes (see Figure 5.1b). Results of an action situation can be, for example, institutions or knowledge which can affect social interactions in other action situations, or direct physical interventions in the system such as implementation of infrastructure or distribution of water to different uses.

Thus, the MTF is able to specify (a) water management processes as a sequence of action situations including influencing factors and outputs (Figure 5.1b), as well as (b) the overall structure of the water system which forms the context in which management processes take place (Figure 5.1a). As depicted in Figure 5.1a, the MTF has a number of other classes (e.g., institution, knowledge, role), which are explained in detail in Pahl-Wostl et al. (2010) and Pahl-Wostl (2015).

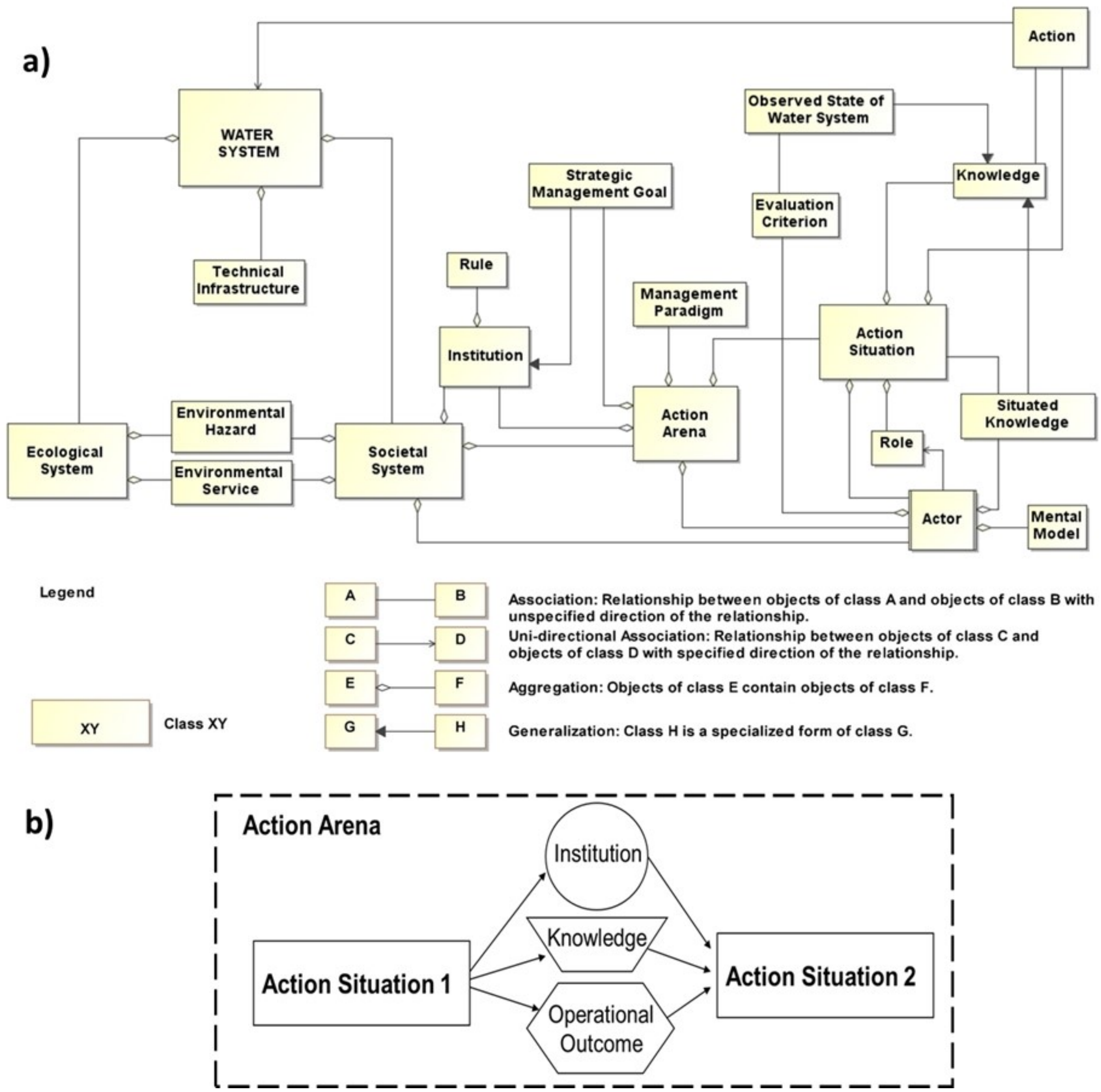


Figure 5.1: a) Class diagram in Unified Modeling Language (UML), which is part of the Management and Transition Framework, for the analysis of structural elements of the water system (Pahl-Wostl et al., 2010); b) Representation of policy and learning processes as a sequence of action situations that are embedded in an action arena and connected by institutions, knowledge and operational outcomes.

The application of the MTF as a diagnostic, ex-post analysis tool has been extended in the PMBF towards a planning, ex-ante analysis tool (see Chapters 5.3.2 and 5.3.5 for a detailed explanation). The MTF allows for the systematic examination and graphical representation of the process steps, as well as interactions between context and process, which includes the definition of action situations, participating actors, and aspired outcomes (Halbe et al., 2013). In addition to its application for problem diagnosis and process design, the MTF is also applied for the analysis of requirements for institutionalizing participatory modeling. Here, institutionalization is understood as in Scott (1995, p. 33) as "cognitive, normative, and regulative structures and activities that provide stability and meaning to social behavior" (Scott, 1995, p. 33). The institutionalization of the participatory model building process comprises the development of the capacity of stakeholders (e.g., water agencies) to continue the participatory modeling process in the long-term (i.e., *cognitive activities* such as the development of modeling skills), awareness raising for the relevance of stakeholder involvement in civic, professional and political networks (i.e., *normative activities* such as curriculum or guideline development), and the establishment of formal rules to organize the process and specify its mandate (i.e., *regulative activities/structures* such as mechanisms for conflict resolution and implementation).

5.2.2 Conceptual participatory modeling

Participatory modeling involves the engagement of stakeholder in the modeling process, which can be accomplished in various forms, ranging from direct participation in model construction to consultation on model validity and testing of a completed simulation model (Hare, 2011). Beall and Ford (2010) define three continuums that illustrate the diversity in participatory environmental modeling: (1) The "hands on continuum" that ranges from models built by experts with some input of participants to joint problem mapping with participants; (2) the "problem definition to solution producing continuum" that points to the complexity that is addressed in the modeling process ranging from well-defined problems and options for solutions to poorly defined "messy" problems; and (3) the "quantitative to qualitative data" continuum that expresses the various types of data that is relevant for a specific problem and thus needs to be included in the model, ranging from hard, quantitative data (e.g., water quality indicators) to soft, qualitative data requirements (e.g., environmental awareness).

Various participatory modeling frameworks exist that propose specific process steps and combinations of qualitative and quantitative modeling methods. Voinov and Bousquet (2010) provide an overview of different stakeholder-based modeling frameworks and criticize the proliferation of participatory modeling frameworks, which in many cases only differ slightly. Major differences among existing participatory modeling frameworks relate to the modeling methods included in the frameworks, such as agent-based modeling (e.g., Gurung et al., 2006) or system dynamics modeling (e.g., Langsdale et al., 2006). For example, companion modeling is a well-known participatory modeling framework that integrates the application of role-playing games and agent-based models (e.g., Barreteau et al., 2003; Gurung et al., 2006; Campo et al., 2010). System dynamics is applied in various modeling frameworks including group model building (Vennix, 1996), mediated modeling (van den Belt, 2004) and Shared Vision Planning (SVP) (Palmer et al., 2013).

Conceptual modeling is an important step in any model building process (Gupta et al., 2012), and is particularly suitable for the initiation of participatory modeling processes (Inam et al., 2015). In contrast to quantitative models, conceptual models describe system elements and their interactions in a verbal or pictorial form without rigorously specifying the relationships between system elements (Gupta et al., 2012). In this respect, systems thinking using causal loop diagrams (CLDs) allows for user-friendly and participatory conceptual modeling (Mirchi et al., 2012). In CLDs, elements of the system are connected by arrows and together form causal chains (for an example see Figure 5.4). A positive link indicates the parallel behavior of variables: in the case of an increase in the causing variable, the variable that is affected also increases, while a decrease in the causing variable implies a decrease in the affected variable. A negative link indicates an inverse relation between variables. A further central concept in system dynamics is the elaboration of feedback loops. Two different feedback loops exist that can be detected in CLDs: the self-correcting 'balancing loop' (uneven number of negative links within the loop) and the self-amplifying 'reinforcing loop' (even number of negative links) (Sterman, 2000). CLDs built by individuals or groups represent individual or collective cognitive maps regarding a problem (e.g., water pollution or flooding). Such “a cognitive map can provide the basis for any type of advanced modelling” (van Kouwen et al., 2008, p. 1143), such as system dynamics simulation models (e.g., Langsdale et al., 2006), agent-based models (e.g., Scholz, 2016), Bayesian networks (e.g., Giordano et al., 2013) or fuzzy cognitive maps (e.g., Gray et al., 2014) (see Chapter 5.3.4 for more details).

The choice for a specific modeling method or framework should be based on the purpose of the modeling process, which can be decision-support, social learning or model improvement

(Hare, 2011). Various context-factors can furthermore influence method selection and process design, such as the availability of data, the level of conflict or the size of the stakeholder group (Beall and Ford, 2010; Beall King and Thornton, 2016). The coupling of stakeholder-built models with expert models, such as SAHYSMOD (Inam et al., 2017a, b), or combination with other tools, such as spreadsheet software (Lorie and Cardwell, 2006) or individual audience response technologies (Beall King and Thornton, 2016), constitute further options to tailor the participatory process to case-specific demands, opportunities and constrains. There is also an increasing relevance of social media and web applications in participatory modeling that allow for new contexts and scales of stakeholder participation (Voinov et al., 2016). The PMBF developed in the current study focuses on conceptual modeling using CLDs to provide a low-threshold approach to systematically engage stakeholders (see Chapter 5.3.3 for a detailed description of the modeling approach). In addition, the PMBF allows for compatibility with other participatory modeling frameworks that use quantitative modeling and further engagement tools (see Chapter 5.3.4).

5.3 Participatory Model Building Framework

The PMBF has been iteratively developed and applied in several study sites over six years by our research team. Several of our publications previously focused on specific parts of the framework, such as individual interviews (Halbe, 2009; Halbe et al., 2014; Inam et al., 2015), process design and analysis of institutional structures (Halbe et al., 2013; Halbe, 2016), as well as quantitative modeling using system dynamics (Halbe, 2009; Inam, 2016; Inam et al., 2017a, b). The framework was applied in several case studies, including Cyprus (water scarcity management; Halbe, 2009, Halbe et al., 2015), Pakistan (soil salinity management, Inam et al., 2015, 2017a,b), Guatemala (food security, Malard et al., 2015), Ontario, Canada (sustainable agriculture; Halbe et al., 2014) and Québec, Canada (water quality management; Halbe and Adamowski, 2012). While individual modeling was found to be sufficient in the Cyprus case study, stakeholders in the Québec and Guatemala cases explicitly requested a group modeling process as a result of their positive experiences with individual modeling. This inspired the development and testing of the 'Group Model Building' stage (Stage Four) in the PMBF. The Cyprus and Québec case studies furthermore underlined the importance of process design to consider potential linkages between the participatory process and formal water management.

Both cases also showed several barriers towards a long-term continuation of the process, such as the availability of modeling skills and financial resources, which required structural changes in the water governance framework. This experience resulted in the usage of the MTF as an integrated planning and analysis tool in the “Process Design” stage (Stage Two) and inclusion of the “Institutionalized Participatory Modeling” stage (Stage Five) in the framework. The different stages of the PMBF are presented in Figure 5.2.

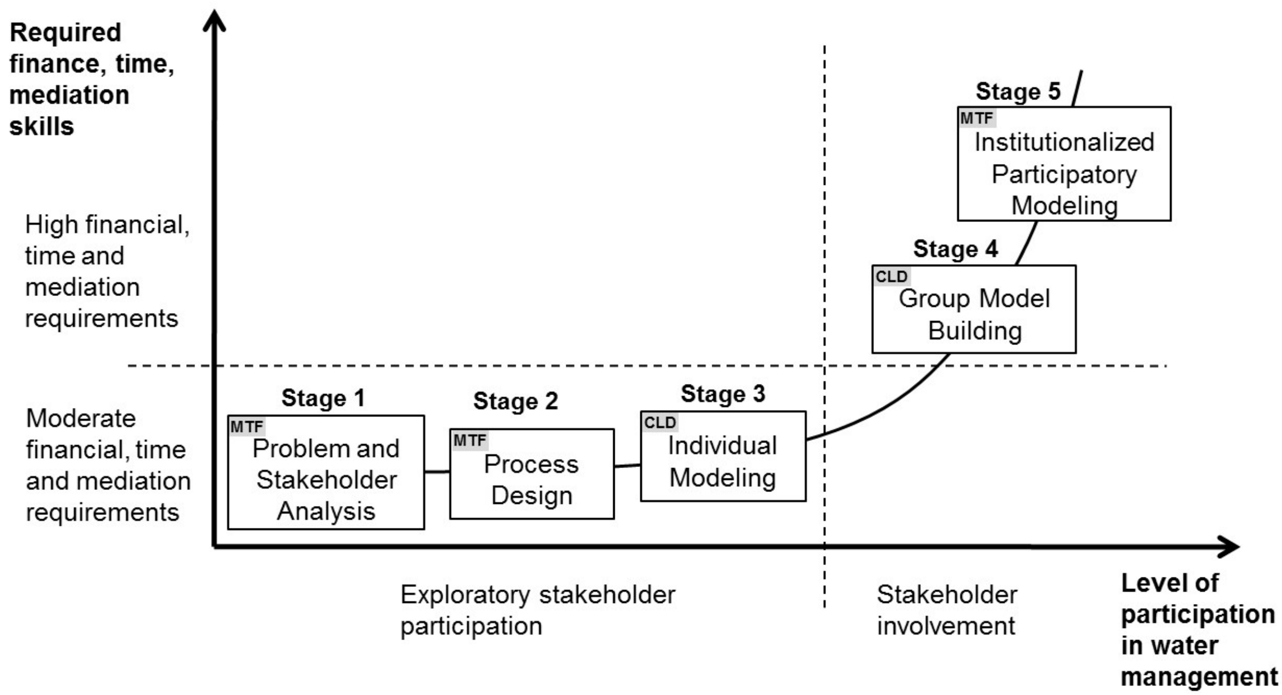


Figure 5.2: The Participatory Model Building Framework (PMBF) - a stepwise approach towards collaborative water management. The grey boxes show the methodological focus of the respective stage including the Management and Transition Framework (MTF) and causal loop diagrams (CLD).

Stakeholders such as water managers can test qualitative participatory model building in the exploratory phase (Stages One to Three) even in the context of limited funding, time and expertise, and decide after these practical experiences whether a continuation of the process is useful for the specific problem situation. More resource-intensive (quantitative) participatory modeling approaches can be applied in Stage Four, which allows the PMBF to be highly compatible with other modeling frameworks, such as Mediated modeling, Shared Vision Planning or Group Model Building. Institutionalized participation requires that water authorities (e.g., water boards, watershed organizations) are able to organize and implement participatory processes independently from external process facilitation experts in the long-term. In Stage Five, the PMBF therefore offers a methodology for detecting barriers to participatory management, and envisioning pathways towards capacity building in water agencies and institutional change for the realization of collaborative water management. The five stages of the proposed PMBF are described in detail below.

5.3.1 Stage One: Problem and stakeholder analysis

In Stage One of the PMBF, the MTF database is used as a diagnostic tool that supports a systematic collection and analysis of information for the development of a preliminary problem definition and selection of key stakeholders. All available data and information regarding the water system structure is added to the MTF database by the process organizers, such as attributes of the water system (e.g., basin area, average annual discharge, population density) and technical infrastructure (e.g., scale, ownership, state of maintenance). The evolution of the water issue is defined through a sequence of action situations in the MTF (see Chapter 5.2.1). Actors involved in the history of the water issue should be included in the database as well as information on their roles (e.g., decision-maker, expert) and sectoral affiliation (e.g., agriculture, water supply). In this first stage, the main sources of information are the scientific literature dealing with the problem and other documents that reflect the opinions and interests involved (e.g., newspaper articles, reports from interest groups). In addition, informal interviews with experts and other stakeholders can provide first impressions regarding hidden conflicts and perspectives.

Based upon data and information from the problem analysis, stakeholders relevant to finding a solution to the water issue are selected. The MTF allows for the specification of several stakeholder attributes, such as their associated spatial unit (e.g., local, regional, national), interest in the resource issue, and perceived urgency. Different methods of stakeholder analysis exist (e.g., Reed et al., 2009; Stanghellini, 2010) that can be applied based upon the data in the MTF. Halbe (2009) and Inam et al. (2015) propose a systematic stakeholder analysis approach that is applied in Stage One of the PMBF. First, stakeholders are sorted according to their roles, such as decision makers, users, implementers/executives and experts/suppliers (European Commission, 2003), to examine any gaps in the composition. Second, stakeholders are prioritized using three attributes (power to influence the process; legitimacy to influence; and the perceived urgency for action) in order to detect those stakeholder groups that are of critical importance for an effective stakeholder process (Mitchell et al., 1997).

5.3.2 Stage Two: Process design

Transparent process design, a relatively young field of research (von Korff et al., 2010; Forrest and Wieck, 2015), is another important step in participatory modeling as it can prevent possible negative effects of stakeholder involvement (such as stakeholder disillusionment (Barreteau et al., 2010), lopsided decisions and increased conflict and wasted resources (von Korff et al., 2010) by clearly defining process steps and expected outcomes in advance. Process design can be guided by conceptual and methodological frameworks that define key processes and mechanisms in participatory processes (e.g., Rowe and Frewer, 2005; Barreteau et al., 2010), criteria for effective participatory modeling processes (e.g., Rouwette et al, 2002; Rowe and Frewer, 2000), and principles based upon experience from practice (e.g., von Korff et al., 2010; Argent et al., 2016).

Consideration of the context in the design of participatory processes is a critical factor (Carr et al., 2012) as institutional, socio-economic or environmental context factors can influence the outcome. Forrest and Wieck (2014) point to the need for analytical-evaluative frameworks to identify context-sensitive success factors for societal transitions towards sustainability. The MTF is such a framework (e.g., Sendzimir et al., 2010; Schlüter et al., 2010; Knueppe and Pahl-Wostl, 2012), and which has been widely applied to analyze the embedment of water management processes in case-specific contexts.

Process representation through action situations (see Figure 5.1b, Chapter 5.2.1) is used for historical analysis of the water management processes in Stage One and the same scheme is used to plan for the organization of a future participatory process in Stage Two. Thus, each step in the participatory process is defined by an action situation (e.g., contacting potential stakeholders, organization of individual interviews) and related influencing factors and expected results (Halbe et al., 2013). The analysis of the historical process (completed in Stage One) can be used to define possible influential factors from past management efforts (e.g., a piece of legislation) as well as potential ways in which the participatory process can induce change in the water system (e.g., have a positive impact on water quality). The process planning approach using sequences of action situations allows for inclusion of stakeholders (e.g., water agencies) in the design process through a graphical representation of the process evolution over time (see Halbe et al., 2013; Halbe, 2016).

The identification of consecutive process steps allows for the definition of specific and practical process indicators (Halbe and Ruutu, 2015), which can point to resource management outcomes (e.g., improved water quality or reduction of conflict between water users), intermediary outcomes (e.g., trust or knowledge), or process quality indicators (e.g., legitimacy of participants) (Carr et al., 2012). The continuous comparison of expected process results to actual experienced results stimulates a questioning of the applicability and suitability of the methods applied as well as underlying theories. If expectations are not met, process organizers have to rethink their understanding of the system and, based upon this, revise the organization of the participatory process (e.g., through the application of new methods and tools). Thus, the application of the MTF constitutes an important step towards effective participatory process design and evaluation (see Halbe and Ruutu, 2015).

5.3.3 Stage Three: Individual modeling

The building of individual CLDs by each key stakeholder constitutes the third stage of the proposed PMBF. Compared to the group modeling of Stage Four, individual interviews usually require minimal resources (i.e., only the travel costs of the facilitators) and provide an opportunity for stakeholders to express their points of view more freely, due to a personal atmosphere (i.e., only the interviewee and facilitators meet) and the absence of potential influence from other stakeholders (i.e., facilitators take a neutral position).

Three steps are proposed for the individual modeling stage of the PMBF (Halbe, 2009; Inam et al., 2015): In the first step, facilitators visit each stakeholder that were identified in Stage One. Each stakeholder builds their CLD independently by choosing variables and drawing causal linkages. The facilitator provides only methodological support without influencing the content of the model. Variables are written on sticky notes that are put on a large sheet of paper, and causal linkages are drawn in by the stakeholders (see example model in Figure 5.4). The individual modeling process begins with a discussion of the preliminary problem definition and the identification of the causes of the defined problem as well as the polarity of causal links. The consequences of the problem are then studied, and the interviewee is encouraged to find feedback loops (Vennix, 1996). Finally, solution strategies are added to the model, as well as barriers towards their implementation. In summary, this approach encourages the structured construction of a holistic system that includes a representation of the participants' mental models of the status quo as well as preferred strategies and challenges related to the problem being explored. Due to its structured nature, the system thinking approach allows for the comparison of CLDs as all participants follow the same methodology. The analysis of the causal structures furthermore supports a deep understanding of the causes, consequences and possible intervention points (Sterman 2000).

In the second step, individual CLDs are merged into an overall CLD by the facilitator to provide all stakeholders with a holistic picture of the water issues based on the different mental models of the stakeholders. Conflicts and diverging points of views are elicited by comparing and merging CLDs built by individual stakeholders (see Inam et al. (2015) for more details on comparing and merging CLDs). The CLDs from different stakeholders may consist of redundant, complementary, or oppositional elements. Oppositional system representations should be highlighted (e.g., by an exclamation mark) since these aspects may create potential conflicts between stakeholder groups. If complementary system elements are available, the merging of these aspects will result in a more detailed model structure (Inam et al., 2015). To avoid the preparation of an unwieldy merged model (with a large number of variable names and crossing causal links), it can be useful to develop thematic models. Thematic models are clearly arranged sub-models that represent the collective viewpoint on a certain topic, such as environmental or socio-economic aspects (see Appendix 5.1 for examples of thematic models). Merging individual CLDs can be a challenging task "as interviewees may use different words for the same concept, may refer to different concepts with the same words, or use concepts that overlap but do not match exactly" (Halbe et al., 2015, p. 6). Thus, some interpretation is needed to develop a comprehensive overall CLD model and subdivide it into thematic models. In the end, the merged model should be regarded as a preliminary group model that includes diverging stakeholder perspectives. Such a model can allow water authorities to see the potential benefits of group model building processes that will be organized in Stage Four of the PMBF.

In the third step, the presentation of the merged CLD model to the participants can be a learning process as stakeholders examine different perspectives and ideas. A workbook can be designed that includes the merged model and a questionnaire to ask for stakeholder opinions regarding the merged model (Halbe, 2009) (see Appendix 5.1 for a workbook designed for the Québec case study).

Based upon the experiences and findings in Stages One to Three, water managers and other stakeholders can decide whether investment in more intensive stakeholder involvement (Stage Four) is sufficiently promising to address the case-specific water issues.

5.3.4 Stage Four: Group model building

The group model building stage of the PMBF involves the organization of group workshops in which stakeholders meet face-to-face. Such personal interactions are critical for effective social learning processes (Pahl-Wostl, 2007), and require professional conflict mediation skills (van den Belt, 2004). Compared to the individual modeling of Stage Three, group processes usually require substantial resources for renting an appropriate meeting place, supplementary material, catering and travel of stakeholders. In an acute problem situation, stakeholders might have a high motivation to participate and might bring in some of their own resources. Stakeholders with a low interest in a change of the status quo might however refuse to make an effort. The limited motivation of some stakeholders is particularly problematic for the organization of multiple workshops, which can result in low attendance and discontinuity (e.g., Videira et al., 2009; Burgin et al., 2013).

Conceptual modeling helps to develop a common understanding of how a system works, and thus supports communication and learning between modelers, decision makers and other stakeholders (e.g., Liu et al., 2008; Serrat-Capdevila et al. 2011). The conceptual group modeling process builds upon the results of Stage Three: stakeholders have gained experience in the application of conceptual modeling (i.e., CLDs) and the preliminary comprehensive model (i.e., the 'merged model') provides an indication of the scope of the issue, potential conflicts, alternative problem perspectives and solution strategies. The actual (conceptual) group modeling process can begin rapidly, as stakeholders are already acquainted with the method through the construction of individual CLDs. The merged model and the results of the questionnaires can function as an entry point for discussion. The group has to decide whether to use or revise the merged model that was built in the previous stages, or whether to start from scratch (i.e., a new model is jointly developed by the group from the beginning) (Vennix, 1996).

Quantitative participatory modeling can further build upon the conceptual modeling efforts proposed in the PMBF and provide insights into complex system dynamics and potential solution strategies. Quantitative modeling involves the specifications of equations and model parametrization based upon available data and information. Various quantitative modeling methods exist that allow for stakeholder involvement, each having different application contexts and requirements, such as expertise of stakeholders and the facilitators, time requirements and the nature of the problem (e.g., lack of knowledge or conflicting interests). The most frequently used participatory modeling methods are system dynamics and agent-based modeling, fuzzy cognitive mapping (FCM) and Bayesian networks (Voinov and Bousquet, 2010). Quantitative *system dynamics* modeling requires the conversion of the group-built CLD into a stock-and-flow diagram, to which parameters and equations are subsequently added (Vennix, 1996; Sterman, 2000; van den Belt, 2004). For an *agent-based modeling* approach, the individual and group-built CLDs can be interpreted as individual and collective mental models and thus can support the design of agents (Etienne et al., 2011; Scholz, 2016). *FCM* allows for assessing the plausibility of cognitive maps and generating scenarios (e.g., van Vliet et al., 2010; Jetter and Kok, 2014). CLDs can also be used in the design of qualitative and quantitative *Bayesian networks* (van Kouwen et al., 2008; Giordano et al., 2013).

The modeling process usually proceeds in an iterative manner. For example, findings from quantitative analyses can necessitate a revision of the group-built CLD. In all model stages, the outcomes and proceedings of the model building need to be documented in a transparent way in order to inform non-participating stakeholders (for example through reports or action plans).

5.3.5 Stage Five: Institutionalized participatory modeling

While project-oriented and short-term group model building research has yielded remarkable outcomes (see Rouwette et al. (2002)), there has been little implementation of long-term participatory processes (Voinov and Bousquet (2010)), even though overcoming barriers towards stakeholder involvement and implementing adaptive management requires long-term engagement (e.g., Hatzilacou et al. 2007; Camacho et al., 2010; Allen and Gunderson, 2011) to adapt the strategies, values and institutions to current challenges and achieve social learning (Pahl-Wostl et al., 2007).

Social learning requires informal discourse in which water management problems are discussed, and the stakeholder group strives to develop the capacity to solve problems collectively (Pahl-Wostl et al., 2007). This does not imply consensus but at least the ability to deal constructively with controversial perspectives. These informal learning processes need to be linked to formal policy making in order to effectively facilitate new routines or practices (Sendzimir et al., 2010). Such linkages might be a formal mandate for participatory processes, legal obligations that result from participatory processes, representation of stakeholders in committees, or clearly defined governmental involvement in stakeholder processes. With respect to participatory model building, water agencies can function as a link between formal water management and informal learning processes. Water agencies (e.g., water boards or watershed organizations) are often located at the interface between policy development and implementation where close collaboration with stakeholder groups is particularly important. To function as such a link, water agencies require adequate funds, skills and mandates to ensure long-term financing and organization of collaborative management processes.

The MTF is applied as an analytical tool in the “institutionalized participatory modeling” stage of the proposed PMBF (Stage Five). The analysis of institutionalization requirements includes financial instruments, dissemination of information and knowledge, as well as the roles of stakeholders in the learning process and rules for decision making. For example, a facilitator may be required for the group discussion and to elicit knowledge and insights from stakeholders. In addition, a process coach can examine the group-internal social processes and provide skills for mediation of conflicts (Richardson and Andersen, 1995). Importance can also be attributed to emergent leadership, which may be essential for facilitating the implementation of solution strategies (e.g., Möllenkamp et al., 2008).

The ex-ante analysis bases upon previously gathered information about systemic barriers and drivers of institutionalization from the problem diagnosis in Stage 1, as well as individual interviews and group processes in Stages 3 and 4 (further expert interviews can be conducted as well). Specific process steps towards institutionalized participatory modeling are defined in the form of action situations that aims at overcoming an institutionalization barrier (e.g., lack of modeling skills) or support a driver (e.g., existing cooperation between stakeholders). Again, each action situation is further specified by expected influencing factors, aspired outcomes (see Chapter 5.3.3) as well as stakeholders that need to be involved. A pathway towards institutionalized participatory modeling is developed by linking action situations through time. This pathway can provide orientation to stakeholders in their efforts to achieve transformative change and long-term continuation of the process by identifying suitable measures to develop skills and capacities. The pathway should be revised in case that new barriers, drivers or implementation challenges (e.g., stakeholder who refuse to cooperate) are identified.

5.4 Application of the PMBF in Québec

The research team explored the use of the PMBF in the du Chêne watershed in Québec in cooperation with the local watershed organization (L'Organisme de bassins versants de la zone du Chêne: "OBV du Chêne"). The OBV du Chêne is located in Southern Québec, Canada, about 40 km south of Québec City, and manages one of the 40 priority integrated watershed management zones in the province. The OBV du Chêne was formed in 2007 through a joint effort of the Union of Agricultural Producers and the Municipalité Régionale de Comté (MRC) Lotbinière. The du Chêne is the major watershed in the Zone du Chêne and along with a number of smaller adjacent watersheds, directly discharges into the Saint Lawrence River. The du Chêne watershed covers 800 km^2 with intensive agricultural and forestry production, which has resulted in pollution problems and soil erosion.

The participatory process started in 2010 with a meeting of McGill researchers and the OBV staff to consider the participatory modeling process as a potentially useful tool to improve relations between stakeholders in the du Chêne watershed, and to learn about different perspectives of the causes, consequences and solutions regarding the water quality problem in the watershed.

5.4.1 Problem framing and stakeholder analysis (Stage One)

The problem and stakeholder analysis was accomplished in close cooperation with the OBV du Chêne. At the beginning of the participatory modeling process, a thorough literature review and interviews with staff of the du Chêne watershed organization were conducted. The OBV du

Chêne determined that the major issue in the watershed was declining water quality mainly due to eutrophication and chemical contamination. The sources of water pollution were thought to originate from the agriculture, forestry, and municipal sectors. However, the exact pathways and quantities were unclear, and further research was required to identify solution strategies. The research project adopted this initial problem frame from the OBV du Chêne, as it was broad enough to motivate many stakeholders to participate. In addition, this broad problem definition was expected to include different, more specific problem perspectives from other stakeholders.

Available information was included in a MTF database to analyze the complexity of the water quality issue and associated stakeholders in an integrated and systematic manner. The problem analysis starts in 1960 to consider long-term impacts from the agricultural, municipal and forestry sectors. The level of detail of the problem analysis increased with time due to greater information and data (e.g., systematic monitoring of water quality data in the du Chêne watershed was not started until 2005). Important historical events for water quality management include the Programme d'assainissement des eaux du Québec (PAEQ) initiated in 1978 by the provincial government to foster water treatment in the municipal and industrial sectors as well as improved manure practices in agriculture (Gravel, 2006). The Règlement sur les exploitations agricoles (REA), implemented in 2002, includes important regulations regarding diffuse pollution from agriculture (including the development of fertilizer management plans, and the limitation of agricultural expansion in degraded watersheds).

Before the new Québec Water Policy in 2002, local and regional county municipalities were responsible for enforcing environmental law and managing rivers and adjacent areas. The Québec Water Policy introduced a participatory integrated watershed-based management approach. Beginning in 2002, watershed agencies were formed at local and regional levels to develop and implement a master plan for water to comply with priorities, guidelines, regulations and legislation at the national, provincial and municipal levels. Plans have to be submitted for evaluation and approval by the Minister of State for the Environment and Water. The watershed organizations are composed of representatives of stakeholder groups comprising citizens, elected officials of municipalities or regional county municipalities, and water-user representatives, such as the agricultural or industrial sectors. Provincial government representatives act as facilitators and provide scientific and technical support but do not have voting or decision rights (Baril et al., 2005). Watershed-based management is synchronized at the provincial levels through a general reference framework established by the Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP, 2002). The Le Regroupement des organismes de bassins versants du Québec (ROBVQ) represents local watershed agencies (i.e., OBVs) and is another central actor that fosters integration of local water management in Québec. Thus, the OBVs are embedded in a multi-level water governance framework. Due to the central importance of the OBVs, the du Chêne watershed was chosen as an appropriate boundary for the participatory process.

The Board of Directors of the OBV du Chêne aims to represent all water-related stakeholders in the Zone du Chêne. Through the analysis of stakeholder roles, attributes and dynamics, it was determined that crucial participants were the staff of the OBV du Chêne and representatives from the agriculture, municipal, forestry, tourism, environmental, and civil society sectors. The analysis of stakeholder dynamics highlighted the possibility of future participation by representatives of the industrial sectors. In particular, the shale gas industry was emerging as a new stakeholder in the watershed at that time, due to exploratory drilling activities. However, the development of the industry was stopped in 2013 through a moratorium by the provincial government that prohibits drilling, fracturing and injective testing in the area (OBV du Chêne, 2014a).

5.4.2 Process design (Stage Two)

During the preparatory meeting, the staff of the OBV du Chêne emphasized the importance of linking the participatory modeling process to the formal water management framework in Québec. A tangible outcome was expected from the participatory process to support the OBV du Chêne in fulfilling their formal obligations (e.g., develop a master plan for water, foster knowledge dissemination, and raise awareness). The outcomes from each step in the participatory modeling process and its linkage to the formal mandate of the OBV du Chêne were thus discussed in detail by the research team and the staff of the OBV.

Figure 5.3 shows a simplified conceptualization of the modeling process (blue elements) and the formal water management process (white elements) in the du Chêne watershed. The OBV du Chêne was established in 2007 on the basis of the Québec Water Policy. By 2010, knowledge regarding water quality and other attributes of the watershed was gathered, and a technical committee was formed consisting of all major stakeholder groups (agriculture, economic, municipal and civic sectors). From 2010 to 2014, a participatory analysis of the basin was conducted by the staff of the OBV to produce a portrait (OBV du Chêne, 2014a) and a diagnostic report (OBV du Chêne, 2014b) of the watershed. Based on these findings, the watershed organization defined specific problems and objectives (OBV du Chêne, 2014c). This work resulted in a master plan for the watershed specifying concrete actions and responsibilities (OBV du Chêne, 2014d).

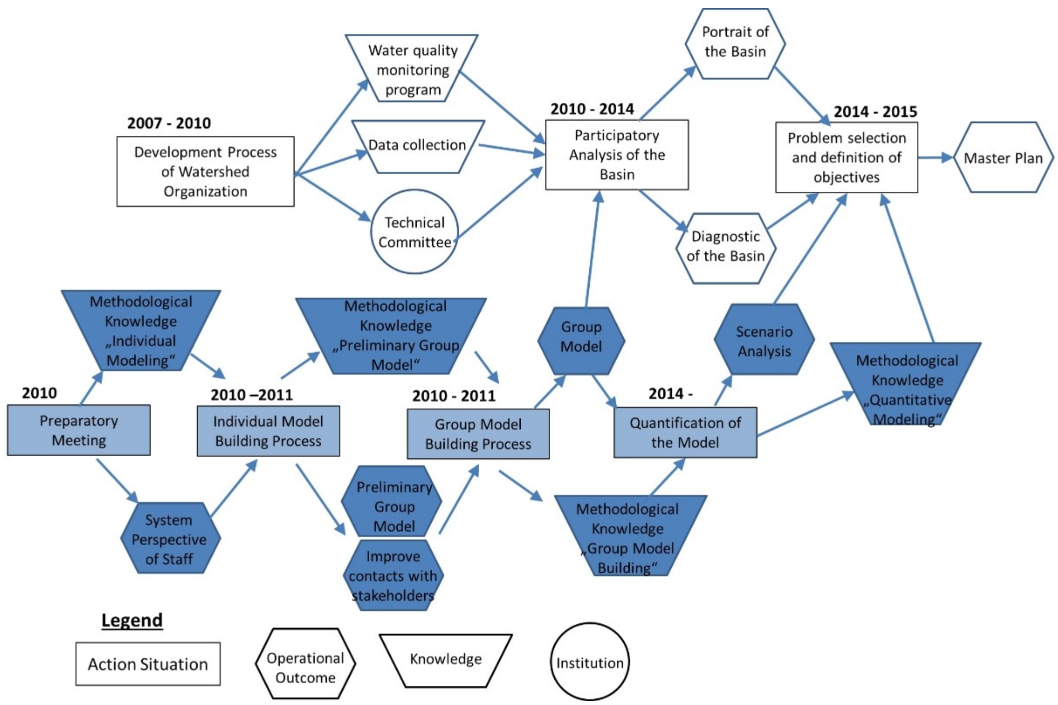


Figure 5.3: Analysis of the linkages of the group model (blue) building process to the water management (white) process in the du Chêne watershed (using the MTF).

The participatory modeling process entered the official water management process at different points in time. The involvement of the researchers started in 2010 with a preparatory meeting in which a CLD was constructed with the OBV staff. The members of the OBV du Chêne learned about the method and decided to initiate an individual modeling process in October 2010. The low time and resource requirements of the individual modeling stage allowed water managers to commit to the process, since separate funds for the testing of new facilitation methods were not available. The outcomes of this process were intended to be a collection of individual CLDs developed by each stakeholder and a merged overall CLD of all perspectives (as described in Chapter 5.3.3). The individual modeling process was aimed at improving contacts and communication between the watershed organization and stakeholders to support the participatory analysis of the basin. Based on positive experiences with the individual modeling stage, the watershed organization decided to proceed towards the group model building stage to support group discussions in an upcoming stakeholder meeting (see Chapter 5.3.4). Thus, the development of a group model was planned to improve the understanding of problems in the watershed and allow staff and stakeholders of the OBV to gain new methodological knowledge. In a next step, the development of a quantitative system dynamics model was discussed with the staff of the OBV based upon the previously developed individual and group-built CLDs. A system dynamics model was considered helpful to test different solution strategies for the water quality problem (e.g., alternative farming methods, planting of riparian vegetation) under varying conditions (e.g., changing precipitation patterns due to climate change, population dynamics), which could inform the choice of objectives and the preparation and revision of the watershed master plan. As the pathways of nutrients and suspended solids are a central concern in the watershed, a model coupling approach was discussed that would dynamically couple a physically based model (i.e., the SWAT model) to the group-built system dynamics model in order to assess the effects of policies (e.g., on soil erosion) in detail (see Inam (2016) and Inam et al. (2017a, b) for more details on this model coupling approach).

The application of the MTF was considered to be useful for process design and evaluation. The analysis of the linkages of the modeling process demonstrated how the participatory process fed into the formal decision-making process (see Figure 5.3), and thereby helped to fulfill the formal mandate of the OBV. This assisted staff members in clearly communicating the purpose of the process to stakeholders and government agencies.

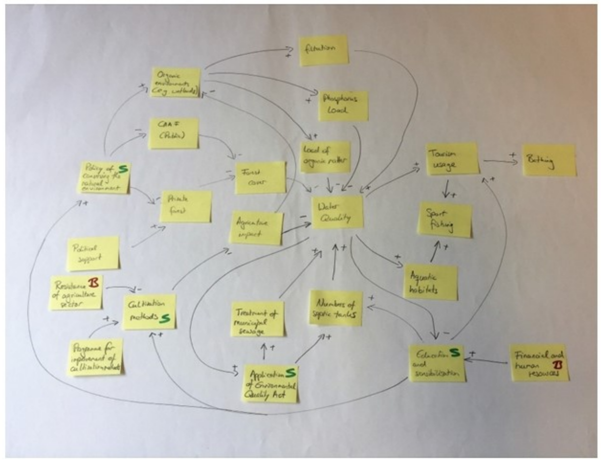
5.4.3 Individual modeling (Stage Three)

Individual models were built in eight stakeholder interviews. The stakeholders were visited by two facilitators (i.e., one staff member and one researcher) at their home or office to minimize efforts required by stakeholders, such as time requirements for traveling. The choice for interviewees represented the composition of the du Chêne Watershed Organization, and included two representatives of civil society (environmental NGO and citizen’s group), three representatives from different municipalities and three representatives from the economic sector (tourism, agriculture and forestry). These stakeholders brought a broad range of expertise to the participatory process, including training in environmental management, biology, ecology, and economics. CLDs were built by each interviewee individually while methodological support was jointly provided by two staff members of the du Chêne Watershed Organization and one of the authors. The staff members received training through a two-hour preparatory meeting in which the systems thinking method was presented and an individual CLD built. The stakeholder interviews took approximately 1.5 hours each and the entire individual interview process was accomplished in three days.

According to the guideline in Chapter 5.2.3 (i.e., *problem, causes, consequences, feedback, solutions, barriers*), the construction of the individual stakeholder CLDs began with the definition of the problem variable. All participants agreed that water quality was the major *problem* in the du Chêne watershed. While emissions from agriculture and municipal sectors were seen as *causes* by all participants, the role of forestry was not seen uniformly by stakeholders (i.e., a number of models did not include impacts from forestry). The main suggested impacts from agriculture stemmed from soil erosion and the use of pesticides and fertilizers that entered the river through the agricultural drainage system. River dredging and drainage systems were also seen as having major impacts on water quality by some stakeholders as they increase the velocity of river flow and disturb natural filtration processes. The impact of the municipal sector was related to deficient wastewater infrastructure in urban areas and septic tanks at isolated residences. Emissions from the road network were also seen as a relevant source of emissions by some participants. Forestry contributed to the water quality issue through deforestation, which caused higher water temperatures and soil erosion. Natural emissions (e.g., from wetlands) were mentioned as an important factor by some stakeholders. Participants considered the *consequences* of the water quality issue on the environment (e.g., aquatic flora and fauna), tourism and recreation (e.g., swimming and fishing), and potable water supply (e.g., higher treatment costs). Several reinforcing *feedback loops* were identified (see Appendix 5.2); for example, in the case of a declining standard of living in the du Chêne watershed, this would be expected to lower the willingness of citizens to protect the aquatic environment as socio-economic issues become a priority. As a consequence, water quality could deteriorate and the standard of living might be reduced even more. Balancing feedback loops to improve water quality included *solutions* proposed by stakeholders such as stricter legislation and implementation of regulations (e.g., REA), installment of riparian vegetation strips, reforestation, investment in wastewater infrastructure and education campaigns. For example, a famer proposed more hands-on measures such as "placing stones in the riverbed" to reduce erosion while representatives from the municipalities included more policy-oriented approaches such as "application of the Environmental Quality Act". Responsibilities for the implementation of these measures were seen on a broad societal scale, including provincial ministries, municipal administration, OBVs, agriculture clubs, foresters and civic society. *Barriers* were related to the costs of solution strategies and a lack of environmental consciousness by several stakeholder groups.

The outcomes of these individual model building sessions consisted of a number of multi-faceted CLDs. The participants were generally satisfied with their models and believed that they reflected their point of view in a comprehensive way. Figure 5.4 presents a translated CLD model (upper part of Figure 5.4) developed by a stakeholder during a 1.5-hour interview, and which was later digitized by the facilitators using the Vensim software (lower part of Figure 5.4).

Translated CLD built by a stakeholder



CLD converted into a Vensim model; marking of feedback loops and problem /solution variables

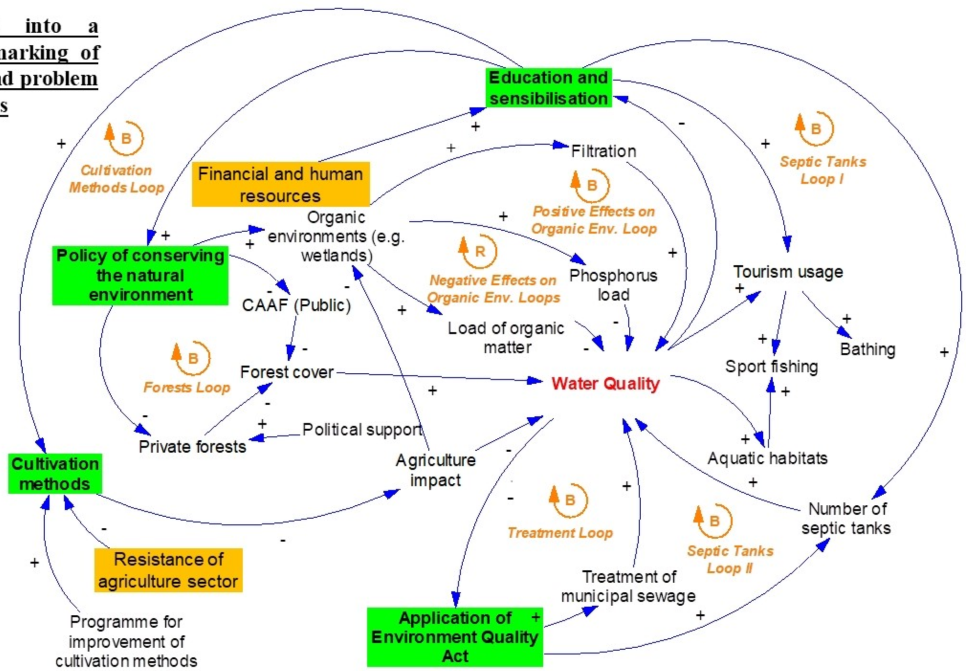


Figure 5.4: Example of a CLD from a 1.5-hour interview (translated model above; digitized and analyzed model below). The red variable represents the problem variable. Green variables are proposed solutions; orange variables are perceived implementation barriers. A '+' sign denotes a parallel behavior between linked variables, while a '-' sign indicates an inverse behavior. Balancing ('B') and reinforcing ('R') feedback loops are marked in orange symbols (see Chapter 5.2.3.1 for more details). CAAF stands for "Contrat d'Aménagement et d'Approvisionnement Forestier" (supply and management agreement for forests)

The model in Figure 5.4 shows the perceived causes and consequences of the water quality problem in the du Chêne watershed as well as preferred solution strategies and implementation barriers from the perspective of a single stakeholder. Apart from the “Treatment Loop”, all feedback loops include the variable “Education and sensibilization” (see Appendix 5.1 for a detailed description of all loops). There are various balancing feedback processes that include solution strategies that are expected to balance the water quality problem, e.g., new cultural practices, implementation of environmental regulations, or natural conservation. Two implementation barriers point to limited resources and opposition of stakeholders from the agricultural sector. In Figure 5.4, only one reinforcing feedback loop is included, which refers to loads of organic environments, such as wetlands, that contribute to natural emissions of organic materials. In summary, the CLD depicts the stakeholder’s mental model of the water quality issue including environmental (e.g., wetlands, forest cover), economic (e.g., financial resources), technical (e.g., sewage treatment, septic tanks), and social (e.g., education, sensitization) aspects.

Subsequent to the individual interviews, a merged model from all stakeholder-built CLDs and a related workbook were prepared by one of the authors (see Appendix 5.1). In the workbook, the merged model was presented successively by using thematic models, each highlighting a specific thematic aspect of the overall model: erosion and deforestation problems; water pollution and economic impacts; impacts of water quality on tourism and quality of life. These models are not independent from each other and it was underlined that the three models are intertwined and only presented this way for clarity. The staff members of the OBV du Chêne decided to directly enter the “involvement phase” (Stages Four and Five) of the PMB without sending the workbook out to stakeholders. Nevertheless, the workbook demonstrated the ability of the method to provide an integrated picture of the water quality issues in the watershed.

5.4.4 Group model building (Stage Four)

Based upon the positive experiences and the methodological knowledge that was acquired, a group modeling exercise was integrated into a regular meeting of the OBV du Chêne. The group exercise was attended by ten stakeholders who represented all sectors involved in the water quality issue. Two researchers supported the staff members to structure the group exercise. Instead of discussing the general problem of “water quality”, the group decided to concentrate on the more focused problem of soil erosion as they perceived it to be the major reason for water quality problems in the du Chêne watershed.

The discussion of causes and consequences of soil erosion affirmed the diversity in stakeholder perceptions that had been revealed through the individual modeling process. The group exercise took approximately 1.5 hours and helped to clarify differing definitions of terms and levels of abstraction with respect to causes and consequences. Each model variable was discussed by the group, and only added to the model if all participants agreed upon its meaning and validity. This approach resulted in a structured and in-depth discussion. The model building process was considerably slower than the individual model building given all the discussion. However, this provided the stakeholders with a unique opportunity to discuss points of contention in a productive way, learn about the perspectives of others, and discover the interconnected system structure of soil erosion and its link to water quality. As considerable time was needed to clarify stakeholder contributions to the discussion, the resulting model (Figure 5.5) contains a lower number of variables and connections than the individual models (cf. Figure 5.4). The process of detailed explanation and rephrasing of statements is an important step towards social learning.

Original CLD built by the stakeholder group in the Québec case study

Digitized and translated group model

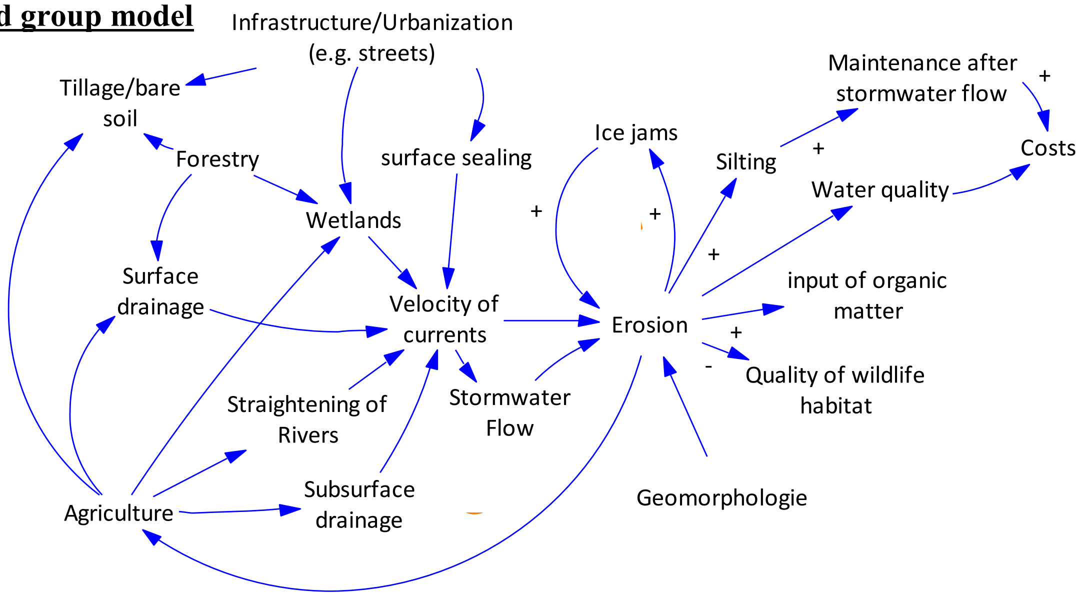


Figure 5.5: Group model of soil erosion management in the du Chêne watershed in Québec (original model, above, and digitized model below). The digitized model does not contain separate variables that were not connected to the model: "riparian vegetation strips"; "soil conservation practices"; "profit".

The OBV Du Chêne was satisfied with the group process, as the modeling exercise was the first time that stakeholders had discussed water issues in the du Chêne watershed in an active manner. Despite previous repeated attempts of staff members to stimulate an open discussion, stakeholder meetings had merely been one-way ‘information’ meetings. The structured modeling process helped the stakeholders to discuss the causes and consequences of poor water quality including socio-economic, technical and environmental aspects.

The modeling process was evaluated through a questionnaire that was handed out to all participants. All respondents agreed that the group model building method supported discussion and development of a deeper understanding of the water quality issue in the du Chêne watershed. The majority of participants suggested that the group modeling process continue in the future in order to explore the soil erosion problem and other issues related to soil erosion and water quality in more depth. In addition, some respondents explicitly asked that the PMB process move towards quantification of the model and subsequent scenario analysis. Criticism was mainly related to the differing involvement of participants (i.e., some participants chose to contribute more to the discussion than others). A continuation of the participatory modeling process could address these demands by offering more time for discussion and additional opportunities for participants to express their points of view.

Following the group model building process, the development of a quantitative system dynamics model based upon the qualitative models from the individual and group model building process was planned in a follow-up meeting of McGill researchers and OBV staff. Due to the prioritization of the soil erosion problem, the model was intended to initially focus on the simulation of erosion pathways and the effectiveness of measures, such as the improvement of riparian vegetation strips. The simulation model was expected to help the OBV in choosing management actions to improve water quality in the du Chêne watershed. Therefore, a model coupling approach was designed to dynamically couple a system dynamics model (addressing socio-economic aspects of the water quality issue) to a SWAT model (simulating physical and environmental processes) (cf. Inam, 2016, Inam et al., 2017a, b). However, missing streamflow data for the du Chêne created a barrier to quantitative modeling. The installation of streamflow gauging stations in the watershed is an example of a long-term measure, which requires substantial investment. Such broader requirements for systemic change towards participatory and sustainable water management (further examples are the development of facilitation skills or the implementation of new legal frameworks and funding structures) are prevalent in water resources management practice. This motivated the development of Stage Five of the PMBF, which allows for the systematic analysis of long-term solution strategies and opportunities for institutionalized participatory modeling.

5.4.5 Institutionalized participatory modeling (Stage Five)

Up to this point, the participatory modeling process was jointly facilitated by the research group and staff members from the OBV du Chêne. Throughout the process, the staff members were included as much as possible in the application of the participatory methods to develop their capacity to independently continue the process. Legislative conditions for the initiation of the participatory modeling process are supportive given that the OBVs have flexibility in their choice of approaches for stakeholder participation. However, several challenges for the long-term continuation and institutionalization of the modeling process were revealed during the participatory process, including the availability of modeling skills, financial resources, decision-making power, broader experiences in participatory modeling, and a coherent water governance framework. Figure 5.6 shows a simplified pathway to overcome the detected barriers of long-term participatory modeling processes in the du Chêne watershed. This is explained in more detail below.

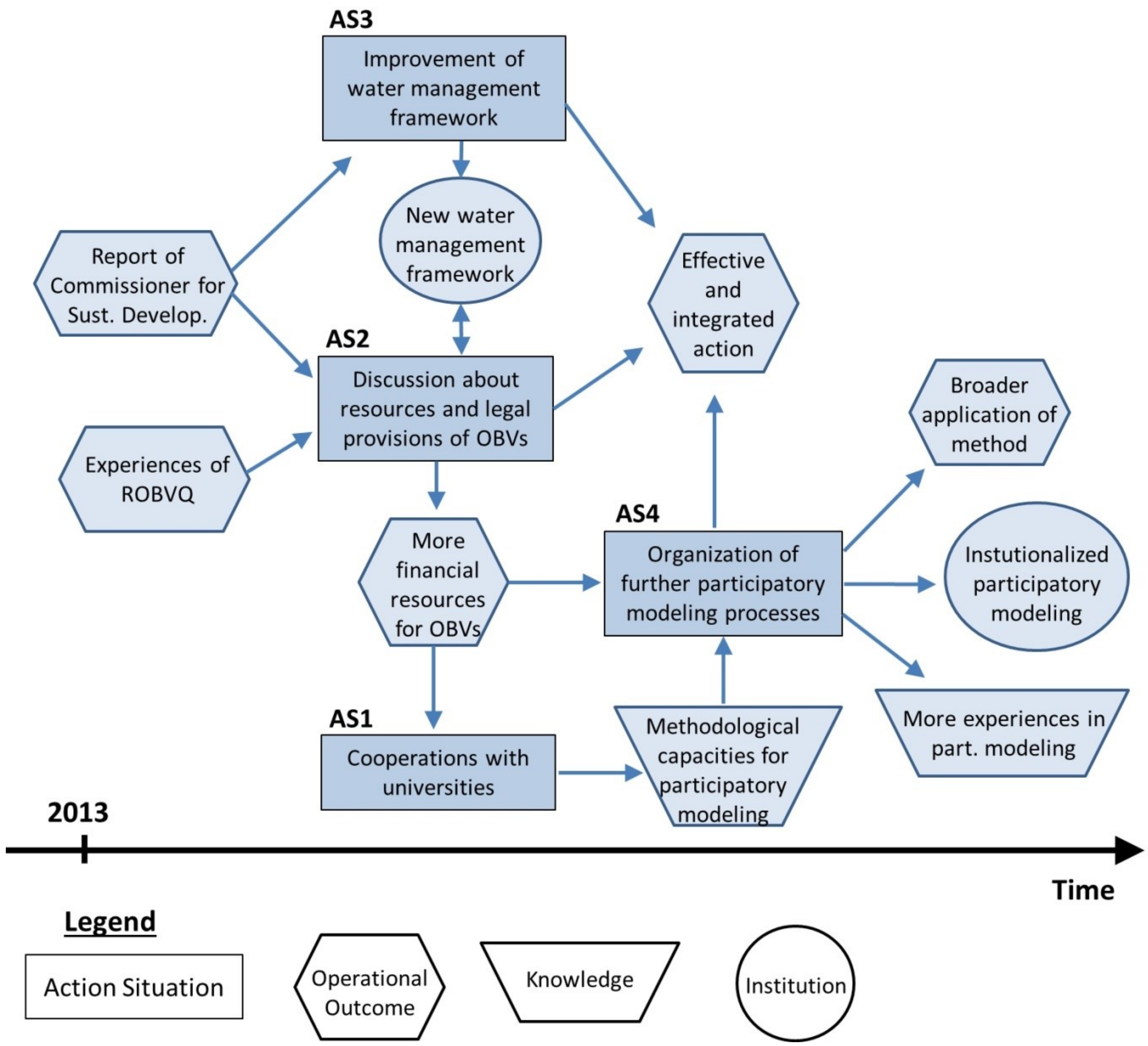


Figure 5.6: Potential pathway towards institutionalized participatory model building in the du Chêne watershed. The pathway includes required action situations (AS) and related inputs and outputs. Further information about the pathways (e.g., stakeholders participating in action situations) can be included in the MTF database.

First, while qualitative system analysis with the help of CLDs turned out to be quite intuitive, the development of a quantitative system dynamics model requires significant modeling skills. OBV staff would need further training in modeling to autonomously continue the process in the future. Long-term cooperation between universities (AS1) in the region and OBVs is a promising approach to ensure methodological support and modeling skill development.

Second, the long-term involvement of scientists in the process as well as the establishment of a streamflow gauging network in the du Chêne requires financial resources and decision-making power (AS2). Until now, the OBVs have not had sufficient funding for a strategic partnership with universities, but mainly depended upon resources from stakeholders (e.g., municipalities). This lack of funding and dependence upon the goodwill of stakeholders influences the OBV's ability to implement measures and strategies laid down in their master plans (ROBQV 2013; CCD, 2013; Medema et al., 2015).

Third, there is further potential for improvement of water management in Québec (AS3). For instance, an action plan for water has been requested by the Sustainable Development Commissioner (from the Ministère du Développement durable, de l'Environnement et des Parcs) and the ROBVQ that involves all governmental agencies and supplements water master plans in the watershed (ROBQV 2013; CCD 2013). Another request by the Sustainable Development Commissioner and the ROBVQ relates to a management framework that specifies responsibilities between different entities of the water system, including OBVs, ministers, and municipalities (CCD, 2013). Such a framework would support vertical integration (i.e., across management levels) as well as horizontal integration (i.e., across sectors such as water management and land planning) within the water governance system in Québec.

Finally, the initiation of further participatory modeling processes in Québec is needed (AS4) for experience to be acquired and the potential of participatory model building to be demonstrated to a wider audience (i.e., other OBVs, the ROBVQ and provincial ministries). As participatory modeling is increasingly applied in research and teaching at universities in Québec (e.g., at McGill University, see Halbe et al., 2015; Inam et al., 2015), more students, scientists and practitioners have the required methodological expertise that is necessary for a broader application of participatory modeling approaches.

5.5 Discussion

The case study in Québec demonstrates the usefulness of the PMBF for initiating participatory modeling processes in unfavorable contexts (i.e., limited time, financial resources and methodological knowledge). While the time requirements for the researcher were considerable (about 3-4 months for problem and stakeholder analysis and individual modeling), the time requirements for other stakeholders, such as the du Chêne watershed organization (about 3-4 weeks of involvement) and interviewees (about 1 - 1.5 hours each) were lower. The intensive involvement of a researcher was needed to test, evaluate and refine the new PMBF. In the future, we anticipate that Stages One to Three of the PMBF can be accomplished with less involvement of researchers through the preparation of a website that contains guidance documents and further case study examples. The results of the exploratory phase in the case study comprise a systematic analysis of stakeholder perspectives on the water quality issue and the development of a holistic system understanding, which were explicitly mentioned in an official report of the watershed organization (OBV du Chêne, 2014b). The study revealed that further research and action is needed on economic and institutional aspects of the problem (e.g., effective policies to foster reforestation), as well as streamflow monitoring in the watershed to allow for more detailed analyses of emission pathways. Besides these more problem-related outcomes, the modeling process significantly improved the discussion process and relationships between stakeholders.

Without the exploratory stakeholder participation phase of the PMBF (Stages One to Three), it is likely that participatory modeling would not have been applied in the case studies in Canada, Pakistan, Guatemala and Cyprus, due to minimal funding, time and expertise. Stakeholders were not aware of participatory modeling even though participatory water management was desired in the study areas. The PMBF is thus a promising approach to support the widespread initiation and application of the participatory modeling method in water management practice. Watershed agencies can test the appropriateness of participatory modeling step-by-step during the exploratory phase of the PMBF, and decide from the insights gained whether more intensive involvement is appropriate in the specific case study. The PMBF needs to be used in an iterative way to deal with the complexity of water resources issues. For instance, findings from individual interviews (Stage Three) can require a revision of the initial problem and stakeholder analysis (Stage One) and process design (Stage Two).

The use of the MTF for process design (Stage Three) allows for a systematic analysis of the participatory process and its context. Such a systematic process design supports process monitoring and assessment, and based upon this, an iterative adaptation of the process design to any challenges and opportunities (such as a change in stakeholder composition or funding options). More systemic case-specific challenges of stakeholder participation and requirements of institutionalized participatory modeling are addressed in Stage Five of the PMBF. Of course, the use of the MTF alone does not dissolve barriers to institutionalized participatory modeling, such as inadequate funds or limited capacities. However, analyzing requirements for institutionalizing participatory modeling allows for a more strategic stakeholder selection (Stage One) and process design (Stage Two), for instance by including stakeholders who can support capacity building or even act as process facilitators in the long term. In addition, the MTF can be used to systematically compare and to facilitate exchange of experiences between cases (Knieper et al., 2010; Pahl-Wostl et al., 2012), for instance regarding barriers and drivers of participatory processes (e.g., Sendzimir et al., 2010; Schlüter et al., 2010), and to help envision a more supportive institutional structure for participation (e.g., Halbe et al., 2013). In this way, challenges that were faced during the participatory modeling process can point to the need for broader changes in water governance systems. Further research is needed to gather more case-specific data on barriers and drivers of participatory modeling processes as well as systematically reviewing and synthesizing such context-specific factors into general findings.

5.6 Conclusions

The proposed PMBF addresses the challenges of initiating, designing and institutionalizing participatory model building processes in water resources management. To date, participatory modeling has resulted in promising outcomes under favorable contexts (e.g., available funds) such as research projects, but widespread implementation is limited given the "unfavorable contexts" which often exist in practice (e.g., insufficient time, financial resources and facilitation skills).

The PMBF provides a stepwise approach for water managers to move towards stakeholder involvement and integrated water resources planning and management. Starting with approaches that require little investment of finances and time as well as low levels of mediation skills (Stages One to Three), water managers and agencies can obtain insights on the need and applicability of a participatory approach. In the event of positive experiences, the process can proceed to the involvement stage (Stages Four and Five), where stakeholders meet and discuss the causes and consequences of a water resource problem, as well as policies and strategies for its solution. The PMBF highlights the importance of capacity building in the water sector to allow for independent implementation of participatory model building processes (which is an important requirement for institutionalized participation). Case specific requirements for continuous and effective collaborative management processes can be analyzed using the Management and Transition Framework (MTF), an analytical tool that allows for the integrated analysis and planning of water management processes.

The proposed PMBF was tested in multiple case studies in Canada (Québec and Ontario), Cyprus, Pakistan and Guatemala. The results from the case study in Québec were presented in detail in this paper and highlight the heterogeneity of stakeholder perspectives, which in turn underline the need for participatory and interdisciplinary approaches in water management.

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Appendix 5.1: Detailed description of feedback loops in Figure 5.4

Balancing Loops (uneven number of negative links).

- **Treatment Loop**: Water Quality $\xrightarrow{-}$ Application of Environmental Quality Act $\xrightarrow{+}$ Treatment of municipal sewage $\xrightarrow{+}$ Water Quality

- **Septic Tanks Loop I**: Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Number of septic tanks $\xrightarrow{+}$ Water Quality

- **Septic Tanks Loop II**: Water Quality $\xrightarrow{-}$ Application of Environmental Quality Act $\xrightarrow{+}$ Treatment of municipal sewage $\xrightarrow{+}$ septic tanks $\xrightarrow{+}$ Water Quality

- **Cultivation Methods Loop**: Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Cultivation Methods $\xrightarrow{-}$ Agriculture Impact $\xrightarrow{-}$ Water Quality

- **Forests Loop**: Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Policy of conserving the natural environment $\xrightarrow{-}$ CAAF/Private Forests $\xrightarrow{-}$ Forest Cover $\xrightarrow{+}$ Water Quality

- **Positive Effects of Organic Environment Loop**: Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Policy of conserving the natural environment $\xrightarrow{+}$ Organic environments (e.g. wetlands) $\xrightarrow{+}$ Filtration $\xrightarrow{+}$ Water Quality

Reinforcing Loop (even number of negative links):

- **Positive Effects of Organic Environment Loop:** Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Policy of conserving the natural environment $\xrightarrow{+}$ Organic environments (e.g., wetlands) $\xrightarrow{+}$ Phosphorus Load / Load of organic matter $\xrightarrow{-}$ Water Quality

Appendix 5.2: Stakeholder questionnaire**.**

Questionnaire

Le portrait et diagnostic du bassin versant de la rivière du Chêne - Examiner les causes et effets de l'enjeu de la qualité d'eau

McGill

OBV du Chêne Organisme de bassins versants DE LA ZONE DU CHÊNE

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Ce questionnaire présente les résultats d'un processus d'entrevues qui a eu lieu en Novembre 2010. Huit membres d'administration ont été interrogés sur leur perception du problème de la qualité de l'eau dans la zone du Chêne. Lors de ces entrevues, la méthode de la « modélisation participative » a été appliquée dans le but d'identifier et d'analyser les enjeux de la qualité de l'eau avec une approche structurée. Une modélisation participative est efficace pour dégager les principaux enjeux de l'eau et amorcer le diagnostic de la zone du Chêne. Les 8 modèles qui ont été construits à l'issue des entrevues ont été regroupés dans la mesure où les aspects particuliers de chaque modèle ont été fusionnés pour ne former qu'un modèle global. Nous vous invitons donc à donner votre opinion sur les différents points abordés ci-dessous. Basé sur les résultats de ce questionnaire, une modélisation participative sera organisée dans la prochaine assemblée générale en Septembre 2011.

Brève description de la méthode de la modélisation participative

La modélisation participative peut être appliquée au cours d'une entrevue individuelle ou de groupe. Les entrevues individuelles permettent la description et la comparaison des différentes perspectives des intervenants municipaux, agricoles, forestiers et communautaires. Afin de compléter les entrevues individuelles, une modélisation au sein d'un groupe permet d'expliquer les différentes suppositions concernant le système de l'eau. Les entrevues ont été effectuées à l'automne 2010. Les résultats obtenus constitueront la base de la modélisation par le groupe des intervenants en automne 2011.

Les résultats de la modélisation participative comprennent un «Diagramme de Boucles Causales» (DBC) qui expose les éléments et les connexions causales qui sont considérées comme importantes à l'enjeu de la qualité de l'eau.

La figure ci-dessous présente un DBC relatif à la mesure du prix de l'eau dans le but de corriger un problème de pénurie.

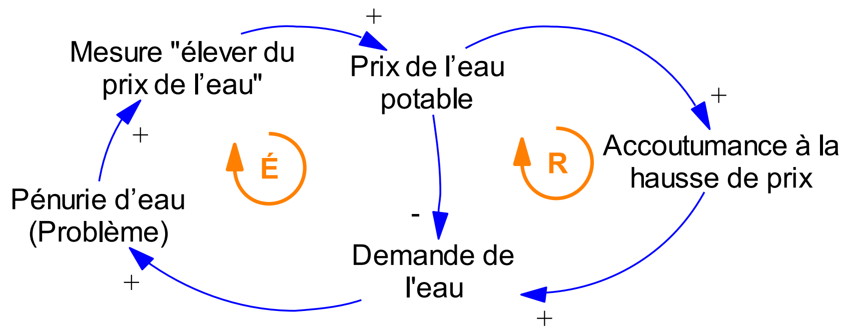


Figure A.5.2.1: DBC sur la mesure de prix de l'eau en vue de corriger une pénurie d'eau.

Le modèle en figure 1 illustre la structure d'une solution économique au problème de pénurie d'eau. Cette problématique cause l'implantation d'une mesure du prix de l'eau qui a pour conséquence une hausse de prix de l'eau. Cela provoque une baisse de la demande de l'eau, ce va résorber la situation de pénurie initiale. Par contre, une hausse de prix de l'eau causera une accommodation de la demande à la hausse de prix, de sorte que cette dernière continuera à augmenter progressivement. La dynamique du système et l'efficacité de la solution varie en fonction des différents impacts sur la demande de l'eau.

Une flèche peut avoir une polarité positive ou négative. Une flèche positive indique que les variables se déplacent dans la même direction (par exemple, tel qu'illustré sur la figure 1, plus la demande de l'eau augmente, plus la pénurie d'eau augmente également). Une flèche négative implique que les variables se déplacent dans la direction opposée (par exemple, une hausse du prix de l'eau cause une baisse de la demande en eau - voir la figure 1).

Deux types de boucles de rétroaction existent. Elles sont des réactions circulaires qui relient les causes et les effets. La boucle du renforcement est représentée par le symbole : R alors que la boucle de l'équilibrage est représentée par le symbole : É. Le modèle en figure 1 contient les deux types de boucles de rétroaction. Le résultat de la boucle d'équilibrage est que le problème de pénurie d'eau est tempéré (au cas où le prix est élevé). Par contre, la boucle du renforcement provoque une aggravation du problème. L'analyse de l'interaction des deux types de boucles permet le diagnostic intégré du système de ressources.

Le cours d'une interview:

Le modèle est construit en utilisant des moyens simples: une grande feuille de papier, des feuillets adhésifs (notes « post-it ») et un crayon. Au cours de la première étape, la problématique est inscrite sur un feuillet adhésif (par exemple : l'enjeu de la qualité d'eau) et ensuite, collé à la feuille de papier (voir la figure 2). Lors de la deuxième étape, les causes du problème sont ajoutées en commençant par les causes directes et ensuite, les causes indirectes. Durant la troisième étape, les retombées du problème sont ajoutées et, finalement c'est dans la dernière étape que sont identifiées les réactions circulaires qui connectent les les causes avec les effets.

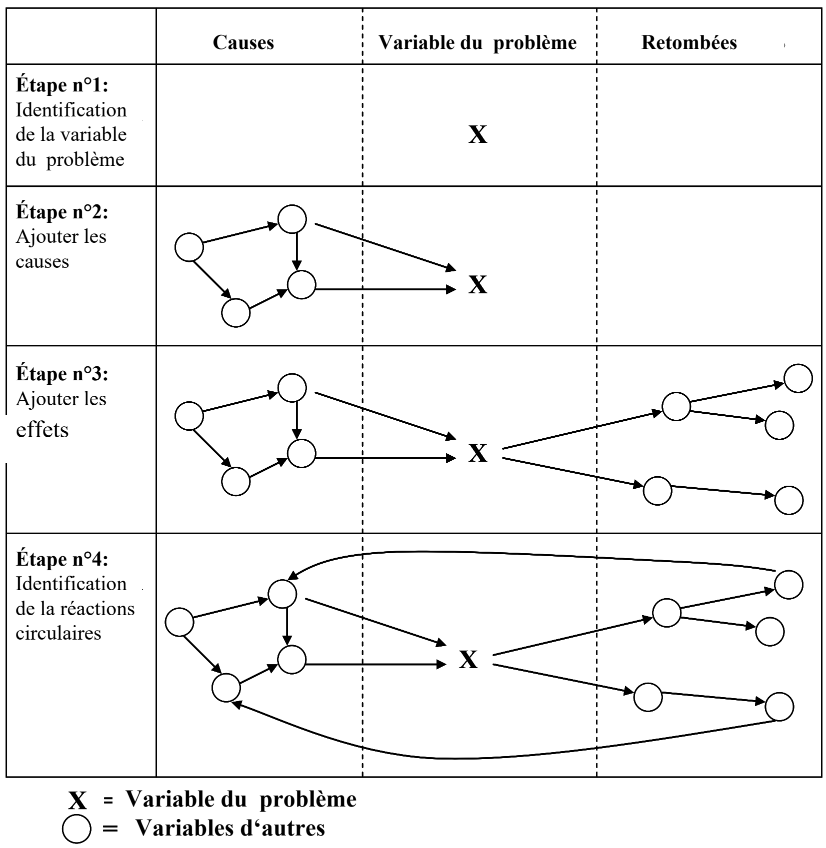


Figure A.5.2.2: Étape par étape pour créer un DBC.

Le résultat:

Le résultat d'une modélisation participative est un DBC qui représente la perspective de l'individu ou du groupe rencontré. Un exemple du modèle est montré dans la figure 3.

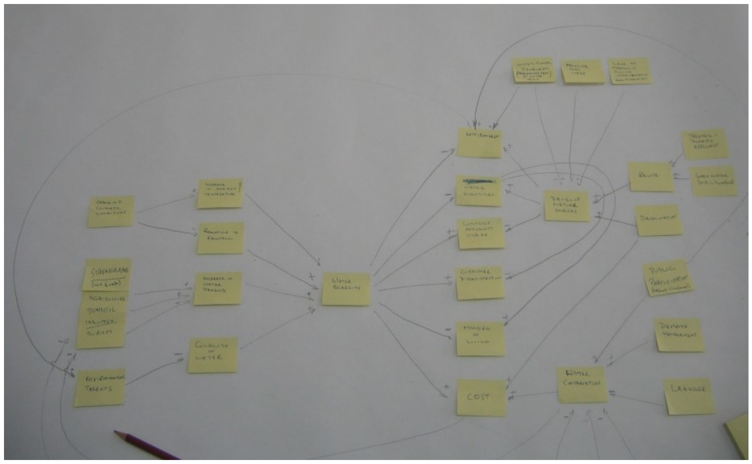


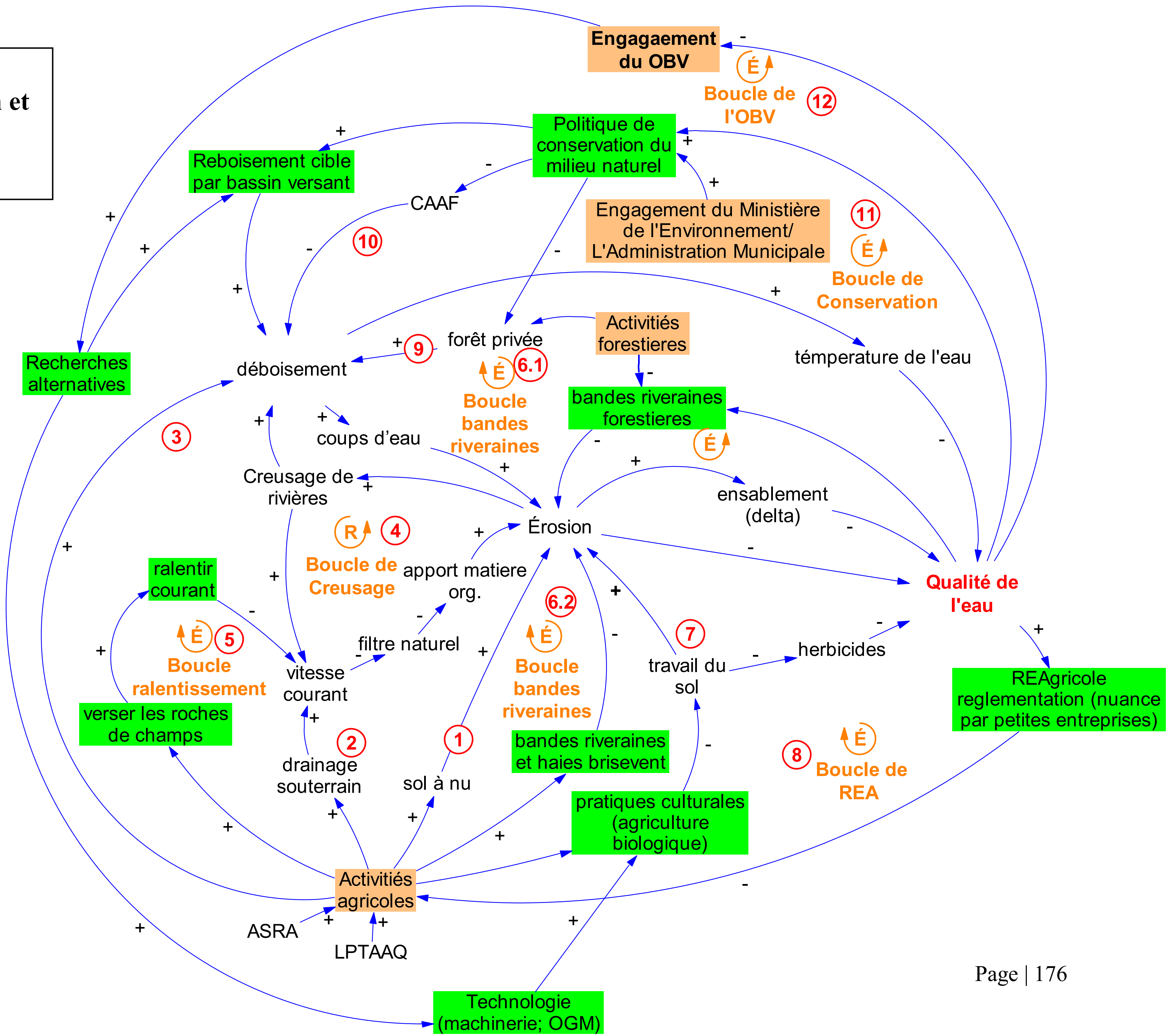
Figure A.5.2.3: Exemple d'un modèle qui composé de variables et de flèches de causalité.

L'enjeu de la qualité d'eau de la rivière du Chêne

Tous les aspects des huit modèles qui ont été construits au cours des entretiens sont présentés ci-dessous. Au lieu de présenter tous les modèles, les «Diagrammes de Boucles Causales» ont été fusionnés pour construire un modèle réunissant les DBC. Le modèle sera présenté pendant la prochaine assemblée générale réunion des intervenants en Septembre. Dans ce questionnaire, le modèle est découpé en trois sous-modèles pour des soucis de clarté. Le premier modèle (page 7 et suivantes) présente les aspects «Du problème de l'érosion et de la déforestation » ; Le deuxième sous-modèle (page 17 et suivantes) contient des aspects de « la pollution de l'eau et des conséquences économiques » ; Le troisième sous-modèle (page 26 et suivantes) présente « les conséquences de la qualité de l'eau pour le tourisme et la qualité de vie ».

Les «Diagrammes de Boucles Causales» contiennent des nombres qui sont liées à une structure causale. Dans les modèles présentés, les variables de solution sont marquées en vert (les variables qui ont été proposées comme solution pour le problème de la pollution de l'eau), et les groupes d'acteurs sont marqués en orange. Chaque structure est décrite de façon concise et il vous est demandé de donner votre avis, que ce soit pour approuver le modèle ou critiquer ce dernier (le nom de variables est indiqué en gras). De plus, il vous est demandé d'évaluer l'importance actuelle de chaque structure ainsi que son développement dans le futur. Il est préférable de prendre le tableau à partir du questionnaire et de répondre aux questions qui l'accompagnent. S'il-vous-plaît, n'hésitez pas à exprimer vos critiques et commentaires directement dans le «Diagramme de Boucles Causales», par exemple en dessinant ou en biffant les liens, en renommant des variables, ou même en écrivant des notes!

1ère sous-modèle
« Le problème de l'érosion et la déforestation »



Le premier sous-modèle

Le problème de l'érosion et de la déforestation

Ci-dessous, les structures causales qui expliquent les effets de l'érosion et de la déforestation sur la qualité de l'eau sont présentés étape par étape.

n ° 1 : Le **sol à nu**

À cause des **activités agricoles**, les terres en jachère (**sol à nu**) provoquent de l'**érosion** et la **qualité de l'eau** diminue.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 2 : Le drainage souterrain

Entre autres, les **activités agricoles** causent du **drainage souterrain** qui accélère la **vitesse du courant**. Cela provoque la dégradation du **filtre naturel qui assure** l'augmentation de l'**apport de la matière organique** dans l'eau.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance

☐ Peu d'importance

☐ Une importance considérable

☐ Une grande importance

☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 3 : Déboisement - secteur de l'agriculture

Un autre impact de l'agriculture (**activités agricoles**) est le **déboisement** (c'est–à-dire des terres forestières sont converties en terres agricoles). Une des causes de la déforestation est l’augmentation de **vitesse du courant** qui cause l'**érosion**. D'autre part, la **température de l'eau** augmente ce qui détériore la **qualité de l'eau**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- [ ] Aucune importance
- [ ] Peu d'importance
- [ ] Une importance considérable
- [ ] Une grande importance
- [ ] Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 4 : Boucle de creusage (boucle de renforcement)

La vitesse du courant est augmentée par le **creusage** de la rivière: Le creusage augmente la vitesse du courant qui provoque plus d'**érosion** étant donné que le **filtre naturel** diminue, plus de **matières organiques** sont apportées. Donc, comme il y a plus d'**érosion**, la rivière doit être **creusée** plus fréquemment.

Pensez-vous que cet énoncé est correct?

Oui [ ]

Non [ ]

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- [ ] Aucune importance
- [ ] Peu d'importance
- [ ] Une importance considérable
- [ ] Une grande importance
- [ ] Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 5 : Boucle de ralentissement (boucle d'équilibrage)

Afin de **ralentir** la **vitesse du courant** et l'**érosion** potentielle, les agriculteurs (**activités agricole**) pourraient **déposer des roches** dans les rivières.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 6.1 et 6.2 : Boucle des bandes riveraines (boucle d'équilibrage)

Une autre solution pour le problème de l'**érosion** pourrait être la formation des **bandes riveraines forestières** (6.1) d'**agriculture** (6.2) et des **haies brise-vent**.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- [ ] Aucune importance
- [ ] Peu d'importance
- [ ] Une importance considérable
- [ ] Une grande importance
- [ ] Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 7 : Travail du sol

Le changement des **pratiques de culturales agricoles** a été proposé par certaines personnes interrogées (par exemple, l'agriculture biologique). Cela causerait une diminution de **travail du sol**. D'une part, cela implique une réduction de l'**érosion** et une meilleure **qualité de l'eau**. D'autre part, plusieurs **herbicides** doivent être utilisés qui réduisent la **qualité de l'eau**.

Pensez-vous que cet énoncé est correct?

Oui [ ]

Non [ ]

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- [ ] Aucune importance
- [ ] Peu d'importance
- [ ] Une importance considérable
- [ ] Une grande importance
- [ ] Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 8 : Boucle de REA (Agricultural Operations Regulation) (boucle d'équilibrage)

Si la **qualité de l'eau** diminue et descend en dessous d'un seuil limite, le **REA** doit limiter les **activités agricoles** (la récupération des terres est interrompue). Ainsi, les impacts de l'agriculture (l'**érosion**, par exemple) s'amoindrissent et la **qualité de l'eau** s'améliore.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance

☐ Peu d'importance

☐ Une importance considérable

☐ Une grande importance

☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 9: Déboisement - le secteur forestier

Le **déboisement** est aussi causé par les **activités forestières**, particulièrement dans les **forêts privées**. Les conséquences sont les mêmes que dans n ° 5: augmentation de l'**érosion** et la **température**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 10: Déboisement – le CAAF

Le **CAAF** (Le contrat d'aménagement et d'approvisionnement forestier) a aussi un impact négatif sur le couvert forestier et il soutient le **déboisement**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- [ ] Aucune importance
- [ ] Peu d'importance
- [ ] Une importance considérable
- [ ] Une grande importance
- [ ] Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 11 : Boucle de conservation (boucle d'équilibrage)

Une solution pourrait être un resserrement de la **politique de conservation du milieu naturel** (initié par le **ministère de l'environnement et l'administration municipale**). Cette politique devrait permettre de réduire l'impact des **forêts privées** et le **CAAF**. Entre autre, le **reboisement cible par basin versant** devrait être réalisé dans le bassin afin d'augmenter la couverture forestière (donc, de réduire le **déboisement**).

Pensez-vous que cet énoncé est correct?

Oui [ ]

Non [ ]

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- [ ] Aucune importance
- [ ] Peu d'importance
- [ ] Une importance considérable
- [ ] Une grande importance
- [ ] Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 12 : Boucle de l'OBV (boucle d'équilibrage)

Une qualité de l'eau diminuée va augmenter l'**engagement de l'OBV** qui ira **chercher des solutions alternatives**. Cela permettra d'accroître les activités de **reboisement** et l'application de **technologies** novatrices qui permettront d'améliorer les **pratiques culturales agricoles**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance

☐ Peu d'importance

☐ Une importance considérable

☐ Une grande importance

☐ Très grande importance

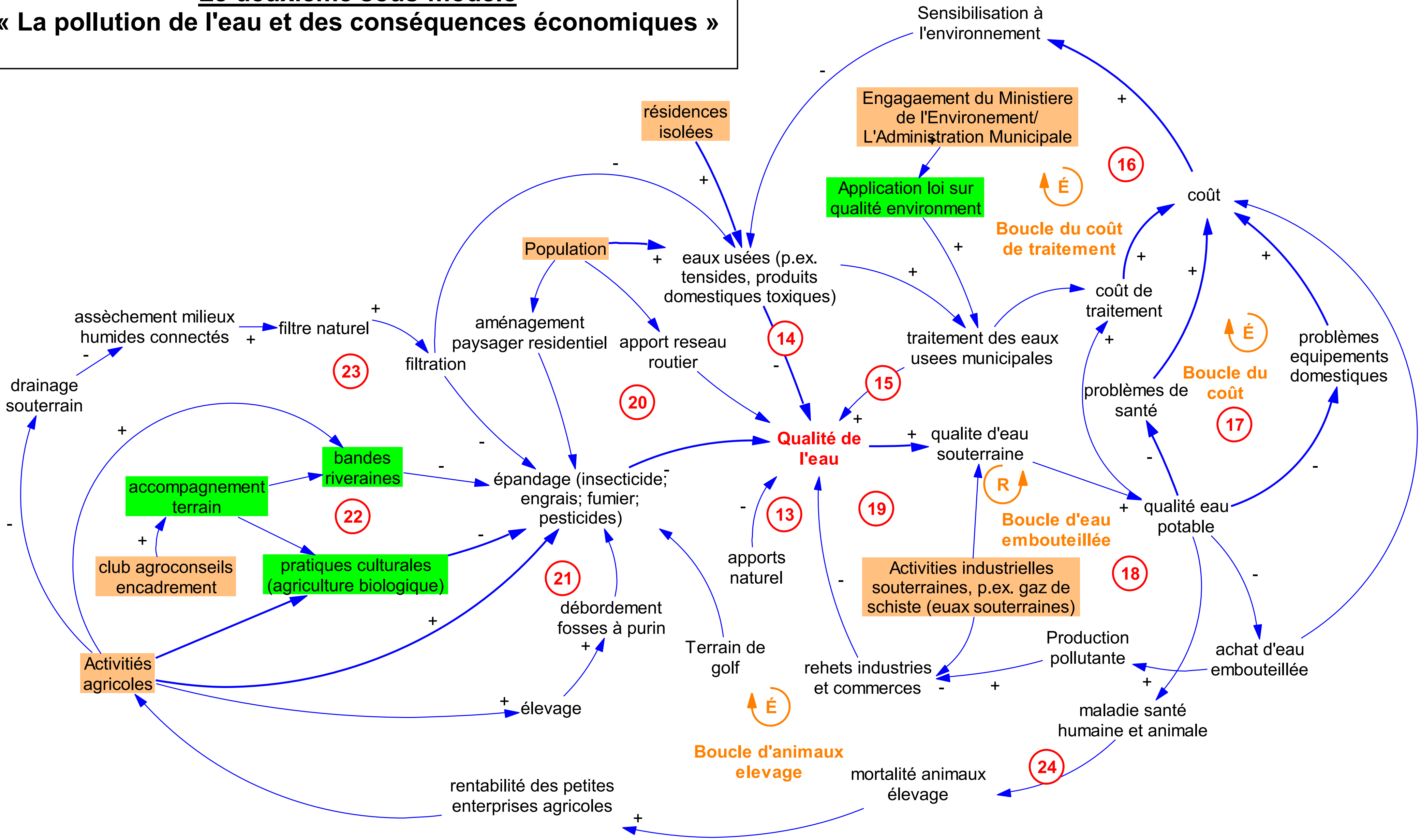
Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

Le deuxième sous-modèle
« La pollution de l'eau et des conséquences économiques »



Le deuxième sous-modèle

La pollution de l'eau et les conséquences économiques

Le deuxième sous-modèle traite le problème de la pollution de l'eau provenant des secteurs agricoles, industriels et municipaux. Il met l'accent sur les conséquences économiques.

n ° 13 : Apports naturels

Une partie des problèmes de la **qualité de l'eau** est due aux **apports naturels** (p. ex phosphore, matières organiques, chimiques et par éluviation).

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 14 et n °15: Eaux usées municipales

Une autre cause du problème de **qualité de l'eau** sont les effluents provenant des municipalités et des résidences isolées. **Les eaux usées** non traitées ont un effet négatif sur la **qualité de l'eau** (n ° 15), tandis que les **eaux usées traitées** ont un effet plus positif (n ° 16).

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 16 : Boucle du coût de traitement (boucle d'équilibrage)

La hausse des **coûts** pour le **traitement des eaux usées** pourrait conduire à une prise de conscience généralisée (**sensibilisation) à l'environnement**. Cela pourrait provoquer une réduction de la charge des **eaux usées** et faire en sorte que les gens utilisent l'eau plus efficacement ou en de minimisant la pollution de l'eau (par exemple en utilisant moins de détergents nocifs).

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 17 : Boucle du coût (boucle d'équilibrage)

Une mauvaise **qualité de l'eau** en général implique une mauvaise **qualité de l'eau potable** en particulier. Cela peut provoquer des **problèmes de santé**, des **coûts** plus élevés pour **le traitement de l'eau**, et **problèmes avec les équipements domestiques** (les raccordements, par exemple). Tout cela se traduit par des **coûts** plus élevés qui pourraient initier une meilleure **sensibilisation à l'environnement**, moins d'**eaux usées** et l'obtention d'une **qualité de l'eau**, enfin supérieure.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 18 : Boucle d'eau embouteillée (boucle de renforcement)

Une autre conséquence d'une eau de mauvaise **qualité**, c'est que les gens augmentent leur consommation **d'eau embouteillée**. Cela provoque des **coûts** supplémentaires pour les gens et aussi plus d'**eaux usées industrielles et commerciales** qui aggravent la **qualité de l'eau**. Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 19 : Activités industrielles souterraines

Les **activités industrielles souterraines** sont considérées comme particulièrement problématiques, car les **eaux souterraines** pourraient être polluées et elles sont la principale source **d'eau potable**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 20 : Le réseau routier et l'aménagement paysager résidentiel

D'autres causes de l'**épandage** de la pollution de l'eau sont les **apports du réseau routier** et les rejets de l'**aménagement paysager résidentiel**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 21 : L'épandage de la pollution de l'eau dans le secteur agricole

Les autres causes de l'**épandage** de la pollution de l'eau sont les **débordements des fosses à purin** (**élevage**) et les apports supplémentaires provenant des **activités agricoles** (culture de la terre).

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 22 : Mesures pour éviter l'épandage de la pollution de l'eau dans le secteur de l'agriculture

Afin d'éviter l'**épandage** de la pollution de l'eau dans le secteur de l'agriculture, deux mesures ont été proposées: l'établissement des **bandes riveraines** et le changement des **pratiques culturelles agricoles**. Ces deux mesures peuvent être facilitées par l'assistance (**accompagnement terrain**) du **club de l'agriculture**.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 23 : L'impact du filtre naturel sur l'épandage de la pollution des eaux

Le **filtre naturel** limite l'**épandage** de la pollution de l'eau et, entre autre, limite l'impact des **eaux usées municipales**. **Le drainage souterrain** mène à l'**assèchement des milieux humides connexes** et enfin, entraîne la diminution de la filtration naturelle.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 24 : Impacts de l'eau de mauvaise qualité sur le secteur agricole

Une **qualité de l'eau** amoindrie peut entraîner des **maladies aux humains et aux animaux**. Cela conduit à une augmentation de la **mortalité des animaux d'élevage** et aussi une baisse de **rentabilité des petites entreprises agricoles,** ce qui conduit à une diminution des **activités agricoles**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

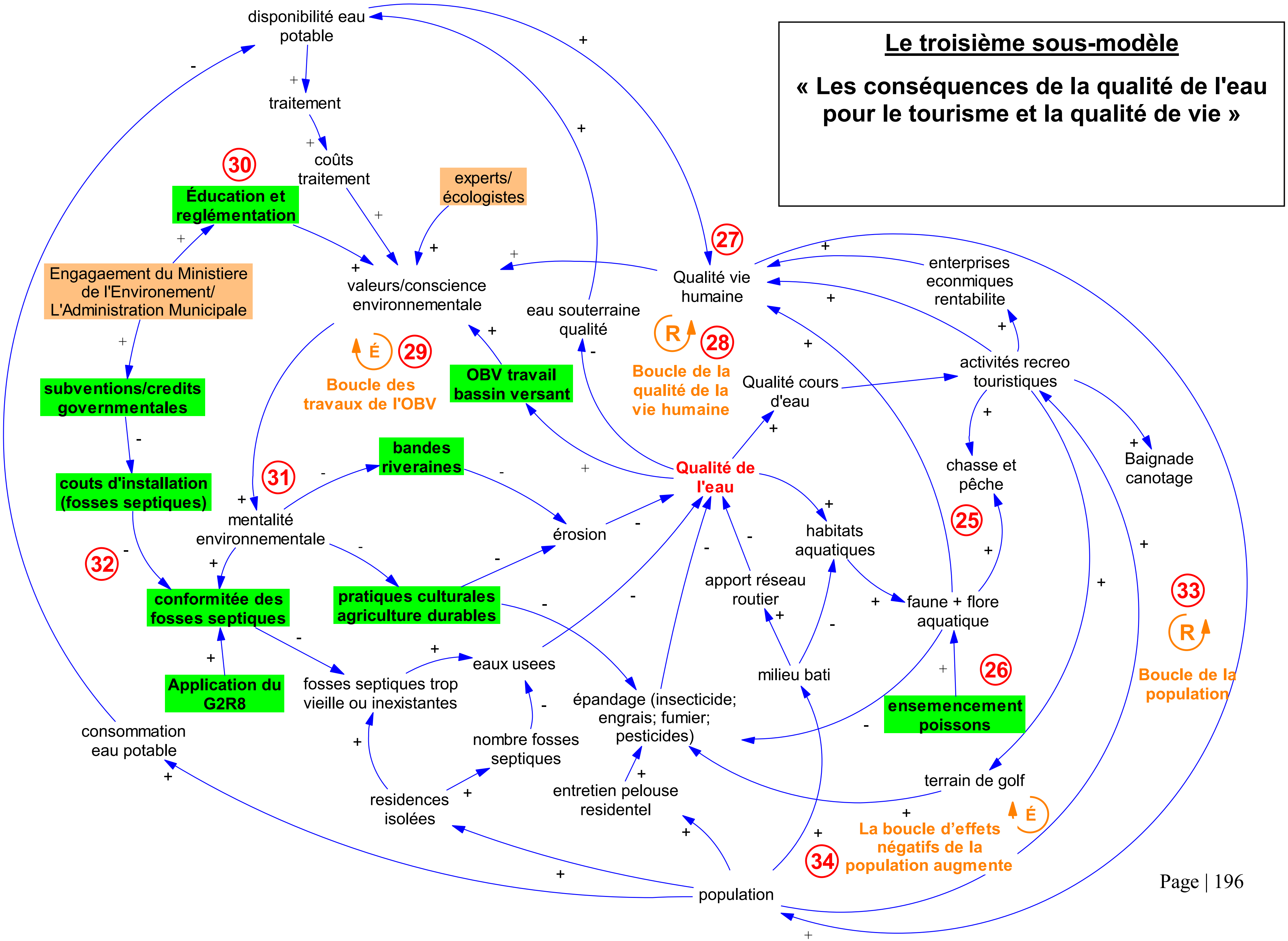
- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

Le troisième sous-modèle

« Les conséquences de la qualité de l'eau pour le tourisme et la qualité de vie »



Le troisième sous-modèle

Les conséquences de la qualité de l'eau pour le tourisme et la qualité de vie

Le troisième sous-modèle traite des conséquences de la qualité de l'eau pour le tourisme et la qualité de vie. Par ailleurs, le modèle contient plusieurs solutions pour régler le problème de qualité de l'eau.

n ° 25 : Impacts de l'eau de mauvaise qualité sur les activités récréo-touristiques

Une eau de mauvaise **qualité** a des conséquences néfastes pour les **activités** récréo-touristiques (c'est-à-dire **baignade**, **canotage**, **chasse**, **pêche**, et **golf**). De plus, une mauvaise **qualité d'eau** détériore l'**habitat aquatique** comprenant la **faune et la flore**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 26 : L'ensemencement des poissons

Une mesure visant à augmenter la qualité de la **flore et la faune aquatique** est l'**ensemencement des poissons**.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 27 : La qualité vie humaine

Si la **qualité de l'eau** est en baisse, la qualité de la vie humaine est en baisse aussi. Premièrement, la **qualité des eaux souterraines** et la **disponibilité de l'eau potable** diminue, ce qui conduit à une moindre **qualité de vie**. Deuxièmement, si la **faune et la flore** et les **activités de récréo-tourisme** dégradent, la **qualité de vie** diminue aussi. Troisièmement, la **rentabilité économique des entreprises de** tourisme pourraient diminuer en raison de moins **activités récréo-touristiques**. Cela entraînera également une détérioration de la **qualité de vie**.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 28 : La boucle de la qualité de la vie humaine (boucle de renforcement)
Si la **qualité de la vie humaine** (c'est-à-dire en termes sociaux, économiques et environnementaux) diminue, aussi la **conscience de l'environnement** et les **valeurs** diminue. Ainsi, la **mentalité de l'environnement** diminue, et les gens sont moins enclins à entreprendre des mesures pour préserver et protéger l'environnement (par exemple, les **bandes riveraines** et **la conformité des fosses septiques**). En fin de compte, la **qualité de l'eau** diminue à cause de cela et la **qualité de la vie humaine** est encore réduite.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 29 : La boucle des travaux de l'OBV (boucle d''équilibrage)

Opposée à «La Boucle de la Qualité Humaine", la " Boucle des Travaux de l'OBV" tempère le problème de la qualité de l'eau. Si la **qualité de l'eau** diminue, l'**OBV** augmente **sa charge de travail** qui mènera à une augmentation des **valeurs et de la conscience environnementale**. Cela finira par conduire à une plus grande **mentalité de l'environnement** et plus d'efforts seront entrepris pour sauver l'environnement par tous les acteurs. En fin de compte, la **qualité de l'eau** va augmenter à cause de cela.

Pensez-vous que cet énoncé est correct?

- Oui ☐
- Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 30 : Les valeurs/ La conscience environnementale

D'autres approches pour augmenter les **valeurs** et la **conscience environnementale** des acteurs comprennent: 1) l'engagement des **experts et des écologistes**, 2) plus d'**éducation et de réglementation** (initiée par le **Ministère de l'Environnement et de l'administration municipale**) et 3) l'augmentation des **coûts** due à un besoin croissant pour le **traitement des eaux** (épuration).

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance

☐ Peu d'importance

☐ Une importance considérable

☐ Une grande importance

☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 31 : L'attitude environnementale

Mentalité de l'environnement conduit à la mise en œuvre accrue de différentes mesures : 1) **bandes riveraines** (à savoir que l'**érosion** diminue ce qui entraîne une meilleure **qualité de l'eau**) ; 2) les **pratiques de cultures agricoles durables** (**érosion** soit décroissante ainsi que **l'épandage**), 3) la **conformité des fosses septiques** (c'est-à-dire moins de **fosses septiques trop vieilles ou inexistantes** ce qui conduit à une meilleure **qualité de l'eau**).

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

n ° 32 : La conformité des fosses septiques

La **conformité des fosses septiques** peut être favorisée par des mesures complémentaires: 1) L'**application du G2R8**; 2) les **subventions/crédits gouvernementaux** pour l'installation de fosses septiques.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 33 : La boucle de la population

Si la **qualité de vie humaine** augmente, la **population** va augmenter en raison de la migration. Cela provoquera plus d'**activités récréo-touristiques** qui conduiront une **rentabilité** élevée des **entreprises économiques**. En fin de compte, la **qualité de vie humaine** augmentera à nouveau.

Pensez-vous que cet énoncé est correct?

Oui ☐

Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

- ☐ Aucune importance
- ☐ Peu d'importance
- ☐ Une importance considérable
- ☐ Une grande importance
- ☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

- ⇧ Augmentera
- ⇨ Restera stable
- ⇩ Diminuera

n ° 34 : La boucle d'effets négatifs de la population augmente (boucle d'équilibrage)
Ill existe également divers effets négatifs d'un nombre croissant de la **population**: 1) le **milieu bâti** augmente qui a des effets négatifs sur la **qualité de l'eau** (par exemple par une augmentation de l' **apport du réseau routier**) et des **habitats aquatiques**; 2) l'**entretien de la pelouse résidentielle** augmente ce qui entraîne plus d'**épandage** des substances (insecticides par exemple); 3) si le nombre de **résidences isolées** augmente trop, la quantité des **eaux usées** peut remonter; 4) la **consommation d'eau potable** augmente ce qui entraîne une baisse de la **disponibilité de l'eau potable**.

Pensez-vous que cet énoncé est correct?

Oui ☐
Non ☐

Pourquoi pas?

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Comment jugez-vous l'importance de ce processus dans la situation actuelle?

☐ Aucune importance
☐ Peu d'importance
☐ Une importance considérable
☐ Une grande importance
☐ Très grande importance

Est-ce que l'importance de ce processus, augmentera, restera au même niveau, ou diminuera dans le futur?

⇧ Augmentera

⇨ Restera stable

⇩ Diminuera

Questions générales

Dans cette section, je veux vous poser trois questions générales sur, entre autres, vos impressions sur l'applicabilité de la méthode. Si l'espace n'est pas suffisant, merci de bien vouloir utiliser les feuilles vierges à la fin du livret.

1) Comment pouvez-vous évaluer la méthode et le modèle résultant? Pensez-vous que cette méthode est applicable et efficace pour la collecte de connaissances et la représentation de perspectives controversées?

----

2) Avez-vous obtenu de nouvelles perspectives sur le problème en construisant votre propre modèle, ou en étudiant le modèle holistique? (Si oui, merci de spécifier les éléments que vous avez retenus du questionnaire)

☐ **Oui**

☐ **Non**

3) Avez-vous des suggestions d'amélioration, concernant la procédure des interviews, présentation des modèles, etc.?

☐ **Oui, à savoir:**

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☐ **Non**

CONNECTING TEXT TO CHAPTER 6

In the following chapter, the Vision Design and Assessment Framework (VDAF) is presented, which was developed in the scope of this research. The VDAF is a conceptual and methodological framework for the design and assessment of sustainability visions. The framework addresses Objective 3 (‘vision design’) and Objective 4 (‘vision assessment’) of this thesis. The VDAF deals with a major research challenge by guiding the development of sustainability visions that consist only of a future system state rather than a combination of potential pathways towards the vision. Thus, the framework makes a clear distinction between target knowledge (Where do we want to go?) and transformation knowledge (How do we get there?). The visions are supposed to provide motivation and guidance in environmental management. By using methods from systems engineering, the visioning process allows for the design of specific visions of sustainable supply systems for water, energy and food. The conceptual focus of the VDAF on target knowledge and visionary supply systems leads to simpler vision models, which support the involvement of stakeholders (i.e., models remain understandable) and reduces resource requirements (i.e., less time is required to develop vision models).

The VDAF presented in the following chapter includes the conceptual methods of functional analysis (see Chapter 3) and systems thinking (see Chapter 4 and 5) and the dynamic modeling method of fuzzy cognitive mapping (FCM) for vision design and assessment. FCM is particularly suited to dealing with data-scarce situations (cf. Objective 1) and involving stakeholders in model development (cf. Objective 2). The VDAF was further developed by adding system dynamics modeling as a potential modeling method for vision assessment (along with FCM). The revised VDAF is presented in Chapter 7 of this thesis. Both methods, FCM and system dynamics modeling, allow for interdisciplinary analysis and can deal with a lack of empirical data with regards to parameters, variables and functional relationships.

Along with the presentation of the conceptual and methodological VDAF, this chapter presents an application of the framework to the topic of sustainable food systems in Southwestern Ontario. Three alternative visions have been developed in the case study using functional organization analysis (see Chapter 3), namely urban organic gardening, a local diversified organic food system and a globalized commodity-based organic food system. Key concepts raised in Chapter 2 have been included in the vision design, such as ecosystem services, system functions and further socio-economic indicators. As multi-scale systems have a high potential to utilize synergies between scales, all system designs have been combined in a multi-scale organic food system design. Vision assessment indeed showed a superior sustainability of the multi-scale design compared to other system designs.

This chapter was published in the Journal of Environmental Management (Halbe and Adamowski 2019). The format of the paper has been modified to ensure consistency with the style of this thesis. A list of references cited in this article is provided at the end of the chapter. The author of the thesis developed, tested and applied the conceptual and methodological framework and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided valuable advice on all aspects of the research and contributed to the review and editing of the manuscript.

Chapter 6: Modeling sustainability visions: A case study of multi-scale food systems in Southwestern Ontario

Johannes Halbe, Jan Adamowski

Abstract

The process of systematically developing a sustainability vision is an important element of effective environmental management. Sustainability visions can, however, include contradictions and counterintuitive effects due to complex system behavior (e.g., feedback loops, multi-causality) and ambiguous system boundaries (e.g., choice of a scale, such as a regional or national scale). This paper proposes an innovative methodological framework for vision design and assessment to analyze the sustainability of future visions on multiple scales with consideration of ecosystem services, and to test their plausibility based upon expert and local knowledge. First, requirements and functions of visionary system designs are identified. Second, a functional organizational analysis defines structures and processes that generate functions. Third, a literature review and participatory modeling process are conducted to analyze the system structures of visionary system designs using causal loop diagrams. Fourth, fuzzy cognitive mapping is applied to assess visions based upon sustainability indicators. A case study on sustainable food systems in Southwestern Ontario, Canada, is provided to demonstrate the application of the methodology. Three designs of a sustainable food system were analyzed and tested: urban organic gardening, a local diversified organic food system and a globalized commodity-based organic food system. The results show the advantages and disadvantages of each system design and underline the sustainability benefits of a multi-scale food system based upon a combination of system designs.

Keywords: Vision modeling; sustainability visions; integrated assessment; organic agriculture; food systems; ecosystem services

6.1 Introduction

Diagnoses and solution strategies for environmental issues such as water pollution or biodiversity loss are often highly complex, and include factors such as multi-causality, trade-offs, feedback processes, and multiple stakeholder interests. Well-intended environmental policies sometimes fail because they do not anticipate these important side-effects or system dynamics (Dörner, 1996). Promotion of biofuels is an example of a policy that aimed to reduce fossil fuel consumption but also contributed to the expansion of monoculture cropping, diminishing groundwater quality and the deterioration of ecosystems (Azhar et al., 2017; Pahl-Wostl 2017). Environmental modeling is widely applied to anticipate such detrimental policy effects and to identify robust strategies and policies through scenario analyses (Mahmoud et al., 2009).

The first step towards defining suitable policies or strategies is the conceptualization of a desirable future system state. While desirable future states are evident for specific environmental issues (e.g., eutrophication of a lake), multiple plausible future visions of a desirable system state often exist for broader social-ecological issues (e.g., food security or climate change), as the definition of the desirable end state can vary with different values or interests (e.g., Shaw et al., 2009; Iwaniec and Wiek, 2014). Personal visions of the future may be developed in an unconscious way, influenced by societal norms and worldviews (e.g., originating from family or culture). Stakeholder groups (e.g., consisting of environmental managers or policy-makers) can also hold shared visions and goals, which can have a substantial impact on the effectiveness of environmental management (van der Helm, 2009). Without the foundation of a clear shared future vision, solution strategies can be delayed or rendered ineffective by a focus on problem symptoms and short-term objectives rather than the underlying causes of the problem and long-term solutions (e.g., Lindenmayer and Hunter, 2010). Thus, an explicit and collaborative discussion of shared visions is an important element of the effective management of environmental problems (e.g., Gunderson, 1999; Schultz et al., 2010).

A modeling approach for the design and assessment of sustainability visions offers various promising opportunities. Vision modeling has been defined "as the process of constructing sustainability models such that the structure and function of the future desirable state is explicitly articulated as a systems model" (Iwaniec, 2013, p. 118). Wiek and Iwaniec (2014) describe visions (desirable future states) as a subgroup of scenarios (possible future states) clearly different from predictions (likely future states). Vision models do not focus on how the future could unfold depending upon different conditions (i.e., exploratory scenarios) or analyze potential pathways towards a desired future, such as suitable policies and measures (i.e., a backcasting approach). Instead, vision models focus on designing and analyzing a desired future state of a system, such as a sustainable supply system for food, energy or water. A vision model focuses on answering the question of whether a future system state is really desirable by analyzing sustainability benefits, potential contradictions, unintended side-effects or surprising system behaviors. In a nutshell, vision models develop goal-oriented knowledge (Where do we want to go?) while exploratory and backcasting scenarios develop process-oriented knowledge (How do we get there? Which path shall we choose?).

Holtz et al. (2015) review several general benefits of a modeling approach for transition research that can also be related to vision modeling. First, models are explicit, clear and systematic with regard to assumptions, definitions and the underlying system structure. Second, modeling allows for the investigation of dynamics in complex systems which might be counterintuitive due to multiple causality, feedback processes and delays. Third, models facilitate systematic experiments by allowing the analysis of measures and context conditions that cannot be tested in the real world (e.g., extreme events such as a fuel crisis). Similar to the benefits discussed by Holtz et al. (2015), Iwaniec (2013) states that modeling allows for a rigorous and systemic investigation of sustainability visions in terms of internal consistency (e.g., existence of trade-offs), plausibility (Are realistic constraints considered?), desirability (Are sustainability benefits reached?) or sensitivity to assumptions.

Despite these various benefits, only a few studies have been published to date that explicitly apply a vision modeling approach. These studies can be separated into two categories: studies that use conceptual vision modeling and dynamic vision modeling (Iwaniec et al., 2014)[9]. Conceptual modeling allows for the analysis of the system structure of a vision including the elements and their relationships. Potential methods for conceptual modeling are systems thinking (Halbe et al., 2015; Iwaniec and Wiek, 2014), influence matrices (Iwaniec et al., 2014) and functional analysis (Halbe et al., 2014). Dynamic vision models build upon conceptual models and allow for quantitative analysis of the dynamics of a future vision, for instance by using a system dynamics modeling approach (Iwaniec, 2013). By specifying variables, parameters, and functional relationships, dynamic models allow for a closer analysis of non-intuitive system behavior due to multi-causality or feedback processes. In particular, semi-quantitative methods, such as fuzzy cognitive mapping (FCM), are suitable

[9] Iwaniec et al. (2014) introduce a third vision modeling approach termed "pathways of vision models", which is not addressed in this article and therefore might distract the reader. Thus, this category is not introduced here.

for dealing with a lack of data and different stakeholder perspectives but have not yet been applied to vision modeling. The current paper identifies two current limitations of vision modeling that constrain its more widespread application. First, methodological frameworks that structure the development of vision models are missing. It is unclear which aspects should be included in the vision model, how to involve stakeholders, and which methods should be applied for vision assessment. Second, dynamic vision modeling methods that can deal with high uncertainties and data limitations need to be further developed. In particular, testing a quantitative vision model is particularly challenging since a comparison of model results to empirical data is usually impossible.

This article proposes a methodological framework for the development and assessment of future visions to address the aforementioned research gaps. The Vision Design and Assessment Framework (VDAF) allows for the design and assessment of visions of sustainable supply systems (e.g., water, energy or food supply), through conceptual and dynamic vision modeling. Functional analysis, causal loop diagrams (CLDs) and FCM are applied to systematically develop and test alternative system designs. Functional analysis comes from system engineering and has been widely applied to design technical systems based upon customer demands and tailored to specific contexts (Blanchard and Fabrycky, 2006; Halbe et al., 2014). Participatory modeling approaches, such as CLDs, allow for the elicitation and analysis of mental models held by stakeholders and can support the involvement of stakeholders in vision development (Vennix, 1996; Halbe et al., 2018a). FCM is a suitable method to assess sustainability visions, as it does not require any empirical data and allows for a semi-quantitative assessment of system dynamics including feedbacks and multi-causalities (Jetter and Kok, 2014).

This article begins with a presentation of the Vision Design and Assessment Framework (VDAF) including the methods of functional analysis, participatory modeling and FCM. A case study is then presented on sustainable food systems in Southwestern Ontario. Finally, the capabilities and limitations of the methodology are discussed.

6.2 The Vision Design and Assessment Framework (VDAF)

The VDAF is based on (1) a functional organizational analysis (FOA) method for the design of visionary supply systems (Halbe et al., 2014); (2) a qualitative participatory modeling method for structural analysis (Halbe et al., 2015, 2018a) and (3) FCM to analyze trade-offs and consequences of sustainability visions (e.g., Reckien, 2014; Jetter and Kok, 2014). Thereby, methods from systems engineering are applied to vision design (i.e., FOA) while methods from systems science are used to further analyze and assess the plausibility, consistency and desirability of system designs. Figure 6.1 shows the steps of the VDAF as well as related methods.

Step 1 of the VDAF involves the specification of needs that are supported by the vision (e.g., drinking water supply), requirements that are linked to the vision (e.g., low carbon footprint and resource requirements) as well as functions (e.g., water storage and distribution). In Step 2, FOA helps to analyze the interconnection of functions and the specific structures and processes that provide these functions. In Step 3, CLDs are applied to a structural analysis of system designs, in particular for analyzing the causalities between functions and requirements. In Step 4, vision assessment is finally accomplished via FCM. This includes the weighting of causal relationships and the definition of context conditions (i.e., scenario variables) in which the performance of system designs is assessed using system requirements from Step 1 as sustainability indicators.

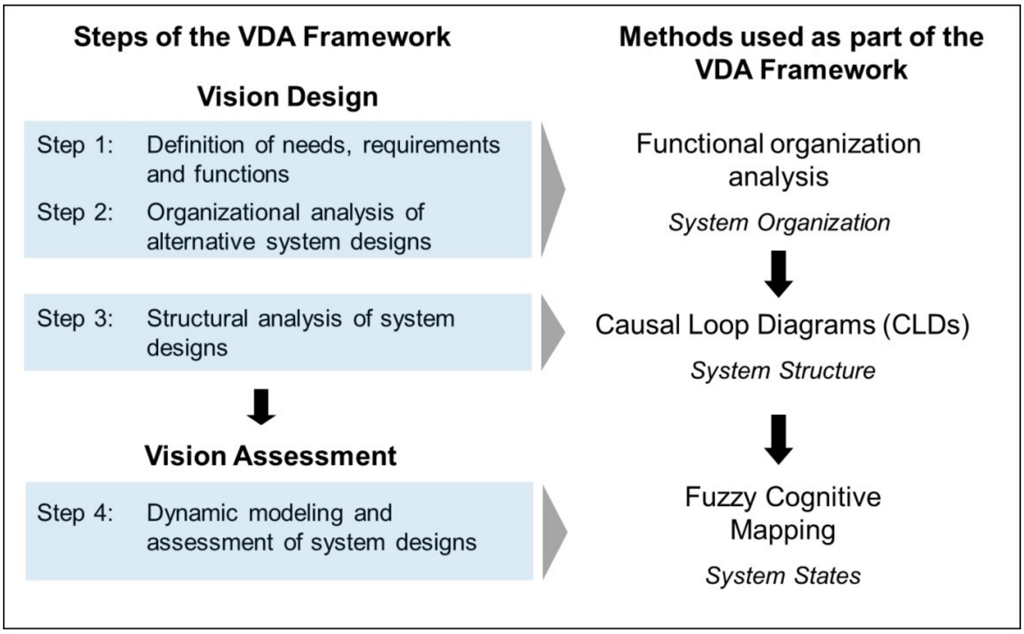

Figure 6.1: The VDAF

Visions of sustainable supply systems involve various environmental, social, technical and economic aspects that need to be considered in their design and assessment. Two features of supply systems are particularly important: the scale of the system and links to ecosystem services. Supply systems can be designed at various scales ranging from individual households to neighborhoods, cities, regions, and countries, to the globe. For instance, household water supplies can be provided by private springs as well as communal or regional water supply schemes. Food systems can also be organized at a household scale (i.e., home gardening), local or regional scale (i.e., local food systems) or globally in commodity-based food systems. Another important aspect addressed by the VDAF is the consideration of the complementary or substitutional utilization of technical and nature-based solutions (Halbe et al., 2014). In addition, the impacts of system designs on ecosystems services (Fiksel 2006; Bennett et al. 2009) are considered.

In the following sections, each methodological step of the VDAF is presented in detail.

6.2.1 Step 1: Definition of requirements and functions

Requirements and functional analysis methods originally stem from the field of systems engineering where they are applied to conceptual and preliminary system design (Blanchard and Fabrycky, 2006). These methods support a purposeful design of systems by specifying the performance requirements of the system as well as primary and secondary system functions. A first step of requirements analysis is the elicitation of requirements from a customer or other stakeholders (Nuseibeh and Easterbrook, 2000). This includes the identification and analysis of relevant stakeholders and their needs with regards to a specific engineering system. In the next steps, stakeholder requirements are translated into system requirements, upon which alternative designs are developed (Hull et al., 2005). There is a large body of work on communication technologies and methods that support the analysis of requirements (see Chakraborty et al., 2010). Stakeholder analysis, interview techniques and literature analyses can be applied towards requirements elicitation (Nuseibeh and Easterbrook, 2000). Originally applied in software development, requirements analysis is used in various application areas, such as infrastructure planning and structural design.

Functional analysis is a key approach to bridge requirements analysis with systems design (see Cole, 1998; Ratchev et al., 2003; Falgarone and Chevassus, 2006). Cole (1998, p. 355) defines functions as "[…] actions a system must perform in response to its environment in order to achieve the mission or goals given to it. The objective of functional analysis is to define the set of functions that need to be included in the system design in order to satisfy the users' needs". System functions can be analyzed from a hierarchical viewpoint by using functional identification diagrams (Cole, 1999). These diagrams show the different abstraction levels of functions ranging from overarching primary functions to lower-tier functions.

6.2.2 Step 2: Functional Organizational Analysis of alternative system designs

The FOA method allows for an analysis of the linkages between primary functions and sub-functions as well as the underlying structures and processes that provide these functions. Halbe et al. (2014) present a FOA approach for the joint design of ecological and technical systems that builds upon conventional functional analysis from systems engineering. The hierarchy of functions is examined in a participatory process by using the conceptual modeling tool Cmaps (Novak and Canas, 2008). After the specification of the system's needs and requirements (e.g., provision of drinking water in a given quantity) and primary and subsidiary functions (e.g., water storage), ecosystem/technical structures and processes underlying the functions are determined (e.g., dams or wetlands). Thus, alternative system designs can be based upon different technical or nature-based solutions at various scales. For instance, food system designs can comprise local, diversified farming approaches (i.e., focusing on the utilization of ecosystem services at a local scale) as well as a global, commodity-based system (i.e., input-based and less focused on the utilization of ecosystem services at a global scale) (Halbe et al., 2014; Therond et al., 2017).

The FOA method can support the envisioning and analysis of alternative system designs by highlighting the diversity of technical and nature-based solutions (Halbe et al., 2014). For instance, the sub-function of pest control can be accomplished using technical solutions (e.g., application of herbicides, pesticides or mechanical pest control) or nature-based solutions (e.g., biological pest control, or crop rotation, cf., Bianchi et al., 2006; Chatterjee et al., 2009). Thus, options for replacement of technical infrastructure with natural infrastructure can be analyzed. The explicit consideration of ecosystem structures and processes can induce a reframing of current system designs and highlight alternatives to technical approaches (Halbe et al., 2014). A combination of alternative system designs allows for the investigation of synergies and trade-offs between designs at different scales.

6.2.3 Step 3: Structural analysis of system designs

Based upon results of the FOA, a more detailed analysis of alternative system designs is needed to test their applicability and assess their economic, ecological and social performance. We propose the use of systems thinking to analyze linkages between functions and system requirements. CLDs are flexible and transparent tools that depict causal relationships between concepts (Sterman, 2000). CLDs for individual system designs can be built by experts and stakeholders in the scope of a participatory modeling process. Reed et al. (2009) highlight the complementary character of expert and stakeholder-based methods to draw upon available knowledge and expertise, while also considering the diverse viewpoints, ideas and interests of stakeholders.

Halbe et al. (2015) present a participatory modeling method to analyze sustainability innovations, which can also be applied to broader sustainability visions. In the first step of the participatory modeling process, the stakeholder interviewee is asked to find a general term for the desired sustainability vision (such as a local food system or a renewable energy system). This term is written on a sticky note and is used as a start variable. In the second step, consequences of this vision are added (e.g., a link to a requirement or an ecosystem service), which can be directly linked to the start variable or to another variable that has already been added to the model (i.e., forming an indirect link). After variables have been written on sticky notes, causal linkages are drawn, which can have a negative or a positive polarity. In the third step, potential influencing factors such as functions or context conditions are added to the model; these factors may either support or impede the sustainability visions. In the fourth step, feedback loops are drawn that connect consequences and influencing factors through causal linkages. In the fifth step, scenario variables that have a profound impact on the performance of the supply system, such as societal or environmental crises, are added to the model. Models resulting from individual interviews can be merged into a comprehensive system structure for each sustainability vision (see Inam et al. 2015 for details on the merging process).

The resulting CLDs of visionary supply systems can be complemented by other methods, such as expert interviews, surveys or a systematic literature review. Expert interviews can follow the same participatory modeling method as described above (see Halbe et al., 2015; 2018b). Surveys can also be used to investigate further system elements or verify a preliminary system structure (e.g., Halbe et al., 2014, 2018a). A systematic literature review can help to identify further requirements, functions and scenario variables not mentioned by stakeholders (e.g., Halbe, 2016). A systematic review is defined as “a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyze data from the studies that are included in the review" (Moher et al., 2009, p. 1). Thus, search terms, quality checks and review protocols should be made explicit to assure transparency and traceability.

The researcher should pay attention to the clarity of the model, as a multitude of variables and linkages can render a model unwieldly and hard to understand. Even for semi-quantitative modeling techniques, such as FCM, it is advised to constrain the number of variables to 20-30 concepts (Özesmi and Özesmi, 2004). This can be achieved through a high level of abstraction (i.e., details are omitted) that provides an overview of the most important aspects of the sustainability visions. Quantitative modeling methods, such as system dynamics modeling, also allow for more detailed analyses of sustainability visions and can be applied afterwards in the "detailed system design" step of systems engineering.

6.2.4 Step 4: Dynamic modeling and assessment of system designs

Qualitative models, such as CLDs, only allow for the analysis of dynamic system behavior to a limited extent. In particular, larger model structures impede a qualitative system analysis, as effects of feedback processes and multi-causality are difficult to trace through the model structure. On the other hand, an integrated assessment of complex issues through quantitative modeling is often constrained by data availability. This can necessitate the reduction of the model boundary to aspects for which data is available. System dynamics modeling offers approaches that can handle relationships and variables that are challenging to quantify (Forrester 1980), but even using this method, substantial resources and data are required to build a reliable simulation model.

FCM is a semi-quantitative method that does not require any empirical data for quantification of causal models and allows for the analysis of feedbacks and multi-causalities. FCMs are a type of recursive neural network (Kosko, 1993) in which impulses pass through the network until a stable state or a stable limit cycle is reached. To build a FCM, causal links are weighted by assigning numerical values in the range of -1 to 1. These weights can be set during stakeholder or expert interviews by using a qualitative scale or graphical symbols (Jetter and Kok, 2014). For example, three weights for positive and negative links can be set by the interviewee (in the case of positive links: '+++' for strong positive links, '++' for moderate positive links and '+' for weak positive links).

The results of a FCM exercise are quantitative in nature, but need to be interpreted qualitatively; thus, variables usually attain values between 0 and 1 depending on the choice of a squashing function, such as a bivalent exponential function (another option is the use of a trivalent function, which involves variable values between -1 and +1). The results of FCM can also be interpreted by comparing the relative difference between variable values (i.e., variable X increases more strongly than variable Y in a certain scenario). Various FCM software tools exist, such as the FCMapper (Wildenberg et al., 2010; Olazabal and Pascual, 2016) or Mental Modeler (Gray et al., 2013; Henly-Shepard et al., 2015).

The performance of system designs is assessed by changing the values of food system and scenario variables, which reflect different design specifications (e.g., extent of local food production in a food system design) or context conditions (e.g., climate change impacts). It must be noted that scenario analysis is applied to analyze the performance of a sustainability vision under different conditions (see Walker et al., 2003) rather than to analyze different pathways through exploratory scenarios (e.g., Kok et al., 2011). After food system and scenario variables are set, impulses are subsequently sent through the network. The reference scenario is established by setting the food system variable (which describes the sustainability vision) to 1. In other scenarios, various context conditions can be added to the system designs, such as environmental impacts (e.g., climate change) or social developments (e.g., a fuel crisis), to assess their effect on the chosen sustainability vision. The resulting scenarios can be analyzed by comparing the values of specific indicator variables (i.e., system requirements). As sustainability issues often include a large number of indicator variables, these variables can be classified into positive-type, negative-type or neutral variables from a sustainability and resilience point of view (Reckien, 2014; Olazabal and Pasual, 2016). Positive-type variables should increase to achieve sustainability (e.g., environmental protection), while negative variables should decrease (e.g., CO_2 emissions).

6.3 Case study: Sustainable food supply systems in Southwestern Ontario

The VDAF was applied in a study on sustainable food systems in Southwestern Ontario, Canada, comprising the Bruce, Grey, Huron, Wellington and Middlesex counties. A focus on vegetable supply was chosen in the case study region, as vegetables are an important part of a healthy diet, play a central role for a resilient food system (e.g., in times of societal crises) and are particularly suitable for multi-scale analyses including gardening activities of households and communities (cf. Eigenbrod and Gruda, 2014).

The design and assessment of visionary food systems was based on information provided by stakeholders and experts. The stakeholder process included a participatory modeling process using CLDs (27 interviews; see Chapter 6.2.3 for a description of the method), consumer and farmer surveys (53 surveys were completed), and a visioning exercise at an organic food conference[10] (using the FOA approach, see Chapter 6.2.2). Knowledge from experts entered the study through a systematic literature review as well as expert interviews to complement the information provided by stakeholders. Each step in the sustainability vision information gathering process is described below in more detail.

A participatory modeling process was run from September 2012 to March 2014 to investigate visions of a sustainable food system in the case study region (see Halbe et al., 2014). CLDs were built during individual interviews with farmers, distributors, activists and other regional stakeholders. In total, 27 CLDs were constructed that showed the perceived requirements, functions and consequences with regards to the interviewee's vision. During this process, four alternative food supply system designs emerged that were further analyzed in subsequent phases of the study. These included (1) urban organic gardening, (2) a local diversified organic food system, (3) a globalized commodity-based organic food system, and (4) multi-scale organic food systems based upon a combination of the aforementioned food system designs. Consumer and farmer surveys (see Halbe et al., 2014) asked respondents to prioritize their visions of the alternative food system designs. In addition, respondents were asked for their thoughts on the consequences of each system design as well as the factors that supported or impeded the development of the respective food system. The visioning exercise included a FOA, i.e., participants were asked to define functions and underlying structures and processes for different food system designs.

The preliminary analyses of system designs based on stakeholder interviews, surveys and the vision exercise were supplemented by a systematic review of the literature. Search terms[11] were defined for each of the four system designs and 113 articles were identified in the Scopus database. A quality check was conducted by reading the abstract, introduction and conclusions to ensure the thematic proximity of articles and those that did not focus on food systems in the Global North were excluded (for instance, articles focusing on an African context or articles in which food systems were only a side topic were excluded). Second, the full text of the remaining articles (71 articles) was read to determine requirements, functions, influencing factors and consequences of food system designs (including effects on ecosystem

[10] URL of the conference homepage: http://www.guelphorganicconf.ca/.
[11] Search terms of the Scopus analysis (November 11, 2017): Organic urban gardening: "Urban gardening" AND sustainab*; Local diversified, organic agriculture: "Local" OR "regional" AND "food system" AND "organic" AND "diversified"; International organic agriculture: "global" OR "international" AND "food system" AND "organic"

services and links to the water and energy sectors). Another quality check was conducted by removing all articles from the review that did not clearly focus on one of the four system designs under study. Snowball sampling was used to add further relevant articles to the review. Finally, the system designs based on information provided by stakeholders (i.e., interviews, surveys and visioning exercise) and the literature review were presented to two food system experts from academia to avoid inconsistencies and ensure that all important aspects were included in the system structures.

6.3.1 Definition of requirements and functions

In the stakeholder interviews and surveys, various requirements of a sustainable food system design were mentioned and subsequently complemented with information from the literature. Urban gardening was mainly associated with the independent and organic production of fresh and nutritious food, which could improve food access and security to the socially disadvantaged (e.g., Brown and Jemeton, 2000; Dubbeling et al., 2010; Mok et al., 2014; Barthel et al., 2015). Another central requirement is recreation (Armstrong 2000; Dubbeling et al. 2010) and the improvement of well-being including mental and physical health (e.g., Wakefield et al., 2007; Ackerman et al., 2014; Schmutz et al. 2017; Mok et al., 2015). Urban gardens serve an educational function (Eigenbrod and Gruda, 2014) by providing a context in which gardening skills and environmental knowledge can be developed (e.g., Dubbeling et al. 2010; Bendt et al., 2013; Mok et al., 2014). Positive effects on the environment might be achieved through the preservation of green spaces (Brown and Jemeton, 2000; Barthel et al., 2015). Community gardens usually aim to have a positive effect on the community through joint activities that might also improve social inclusion and empowerment (e.g., Twiss et al., 2003; Eigenbrod and Gruda, 2014; O'Kane 2016; Schmutz et al. 2017; Mok et al., 2014), provide a sense of place (Pearson et al., 2010; Bendt et al., 2013) and engage with community issues, such as littering and maintenance of properties (Armstrong, 2000; Wakefield et al., 2007). As the functions of food storage and transportation are usually less relevant to urban gardening, a low carbon footprint is another requirement of this food system design (Ackerman et al., 2014; Eigenbrod and Gruda, 2014).

Local organic food systems mainly focus on the production of high-quality food that is distributed to the consumer along short supply chains (e.g., Darolt et. al., 2016; Milestad et al., 2017; Schmutz et al., 2017). This allows for a high transparency and trust, as the consumer has a relationship with the producer (e.g., Lieblein et al., 2001; Torjusen et al., 2008; Nousiainen et al., 2009; Darolt et. al., 2016; Dörnberger et al., 2016), which might be a personal relationship (e.g., in case of direct marketing or community supported agriculture schemes) or a joint regional identity (e.g., consumers have the opportunity to visit the farm) (Selfa and Quazu, 2005; Darolt et. al., 2016; Kneafsey et al., 2013; Milestad et al., 2017). Thus, local food systems also have positive effects on communities as well as an educative function (Macias, 2008; Torjusen et al., 2008; Darolt et. al., 2016). In addition to close producer-consumer relationships, cooperation between local food actors was identified as a critical requirement (Nousiainen et al., 2009; Dörnberger et al., 2016) to develop farming skills, efficient marketing and distribution systems, and to share production factors, such as technical equipment, labor and seeds (Lucas et al., 2016). Food prices of local products have been found to be comparable or even lower than products from global commodity chains (Macias, 2008; Pirog and McCann, 2009; Donaher and Lynes, 2017). However, the calculation of production cost and appropriate product prices can provide a challenge for small, diversified farms, due to the high variability of labor inputs and production processes (Silva et al., 2017). Another requirement identified by stakeholders is a low carbon footprint, achieved through the reduction of transportation and storage requirements of food through short supply chains (Jones, 2002; Hara et al., 2013; Plawecki et al., 2013; Darolt et. al., 2016). Environmental protection was also identified as important by stakeholders. This could be accomplished by expanding organic practices and an increased diversification of production systems (Kremen et al., 2012).

A central requirement of the globalized commodity-based organic food system is the provision of diverse organic food products year-round through international supply chains, which improve food choice, food availability and access to food (Rahmann et al., 2017). Food quality and safety were mentioned as further important requirements (e.g., by prohibiting the use of synthetic pesticides) for the provision of healthy products to the consumer (Reganold and Wachter, 2016; Rahmann et al., 2017), and transparency is sought through organic food labels (e.g., Campbell and Liepins, 2001; Golan et al. 2001). Farmers receive premiums for organic products, which have a positive effect on their income (Forman et al., 2012). Environmental protection is also a central requirement, which can be encouraged by the maintenance of organic farming standards (e.g., Campbell et al., 2010; Forman et al., 2012; Migliorini and Wezel, 2017). While the local food system design favors a more diversified farming approach, commodity-based organic production utilizes some form of specialization and economies of scale (Kremen et al., 2012; Oostindie et al., 2016).

The functional analysis identified the primary functions of production, storage, transport and distribution for the local and global commodity-based food systems (see Halbe et al., 2014). Urban gardening does not include transport and distribution, as the produce is often directly utilized by households or communities in the Global North (Taylor and Lovell, 2014). The production of vegetables is linked to various sub-functions, comprising the provision of plots, water, seeds, seedlings, and technical equipment, as well as pollination, fertilization and pest control. The specific structures and processes underlying these functions and sub-functions were analyzed in Step 2 of the VDAF.

6.3.2 Organizational analysis of alternative system designs

The FOA built upon the identification of requirements and functions completed in Step 1 of the VDAF. A FOA was accomplished for each food system design by linking primary functions and sub-functions that were identified in Step 1 of the VDAF and adding the technical/ecological processes and structures that provided these functions (see Halbe et al., 2014 for detailed results of the FOA). The FOA clearly showed alternative technical and ecological structures and processes for the provision of functions for each food system design (see Appendix 6.1 for a graphical representation of system designs).

The application of FOA to food supply systems revealed several similarities between globalized commodity-based conventional and organic systems. Differences between these food systems are related to the sub-functions of Provision of Seeds/Seedlings, Fertilization, and Pest Control (see Appendix 6.1). A transition to a globalized commodity-based organic food system could follow the "input substitution paradigm", which involves the replacement of synthetic inputs with biological inputs (mainly referring to the fertilization and pest control functions), more specialized production and the use of longer conventional marketing channels (Lamine, 2011). Regarding the local organic food system, the FOA revealed unique challenges, such as the need for the development of new structures and processes for transportation and marketing functions. Transitioning towards local organic food systems thus relates more to the "system redesign paradigm" that employs a more holistic approach by enhancing natural regulation systems and implementing diversified production systems as well as alternative and shorter marketing pathways. Both paradigms show that food system transitions involve changes in on-farm functions (such as pest control) as well as off-farm functions (such as marketing). Thus, the design of coupled innovations in food production, processing, distribution and consumption is a key challenge requiring technological, organizational and institutional innovations across the whole agri-food system (Meynard et al., 2017). In addition, the FOA highlighted opportunities for cooperation between local farmers and urban gardeners, as a local organic food system and urban gardening utilize similar structures and processes for food production.

6.3.3 Structural analysis of system designs

Based upon the results of Steps 1 and 2, a system structure was developed for each food system design. Following a vision modeling approach, these system structures represent the state of a future food system while implementation barriers or policies are not included (cf. distinction between exploratory scenarios and vision modeling as described in the introduction). Each system structure consists of a food system variable (i.e. a start variable that represented the food system design, such as “local diversified organic food system”), requirements, functions and ecosystem services as well as context conditions that might have an impact on the performance of the food system designs. These context conditions can comprise policies, such as land planning policies, as well as disruptive events and processes, such as societal crises or climate change impacts.

The building of the system structure started with the CLDs from stakeholder interviews, which were complemented by further system elements from the surveys and literature review. In the following paragraphs, the system structures of system designs are presented. For each system design, a general description of the system structure is provided in the first paragraph, before functions and ecosystem services are described in more detail in the second paragraph. An overview of weights of central variables in the alternative food system designs is provided in Appendix 6.3.

6.3.3.1 Urban organic gardening

The structure of the urban gardening system (see Appendix 6.2.1) includes all the requirements mentioned in Chapter 6.3.1. Strong positive weights (i.e., 0.9) were set for the main requirements: to consume fresh food (high transparency and quality), community, saving money and food education (Guitart et al., 2012). Food quality can be diminished by contamination as gardens in urban areas might be affected by air pollution or soil contamination (e.g., Taylor and Lovell, 2014; Mok et al., 2014; Eigenbrod and Gruda, 2014; Schwarz et al., 2016). Food education and gardening skills have a strong dampening effect on the risk of contamination, as gardeners can learn about measures to deal with urban risks (e.g., soil testing or construction of raised beds to deal with potential soil contamination) (e.g., Armstrong 2000; Brown and Jemeton, 2000; Taylor and Lovell, 2014; Schwarz et al., 2016). Land planning is another measure to reduce the risk of contamination (Mok et al., 2014). Food education can improve pro-environmental behavior (as consumers become aware of the effects of food production) and nutrition (as gardeners become more aware of food quality and healthy diets) (e.g., Twiss et al., 2003; Bohn and Viljoen, 2011; Bendt et al., 2013; O'Kane 2016). Community development (Celata and Coleti, 2017; Bendt et al., 2013; Istenic, 2016) as well as physical exercise and recreation can improve the well-being and health of urban gardeners (Armstrong 2000; Wakefield et al., 2007; Brown and Jemeton, 2000). Food contamination can negatively impact health, while consumption of nutritious food induces a strong positive effect on health. The production of food is also an important requirement of urban gardening, but it is influenced by the condition and availability of plots (within cities or their periphery), seed species, weather conditions, reliability of the water source and skills of urban gardeners (Brown and Jemeton, 2000; Mok et al., 2014; Barthel et al., 2015). Food security is positively affected as urban gardening can improve availability, access and quality of food (Ackerman et al., 2014; Eigenbrod and Gruda, 2014; Barthel et al., 2015). Conversely, food expenses in this system design can be higher compared to the commodity-based food system in the Global North (Co Dyre et al., 2015), although this depends upon the case-specific situation (i.e., food prices and availability) and the opportunity costs of the individual. However, in times of crisis, urban gardening can play a key role in securing access to food for city dwellers (Barthel et al., 2015).

Several functions necessary for urban gardening, such as provision of water and seedlings, pollination, pest control and fertilization (Taylor and Lovell, 2014) are included in the model. Technical equipment can be provided by gardeners or through community efforts (Bendt et al., 2013). As urban gardens usually contain a high diversity of plants, positive effects on biodiversity are possible (Brown and Jemeton, 2000; Bendt et al., 2013; Taylor and Lovell, 2014), which also supports pollination and pest control (Barthel et al., 2015). In addition, urban gardening can reduce air pollution (Brown and Jemeton, 2000), mitigate urban heat effects and provide retention areas for storm water (Ackerman et al., 2014). The carbon footprint of urban gardening was identified as a complicated issue on which further research is required (Mok et al., 2014). Even though transportation along the value chain is not needed, urban gardeners might use their car to reach a community garden. However, the potential for a low carbon footprint exists (e.g., Ackerman et al., 2014; Specht et al. 2014; Eigenbrod and

Gruda, 2014), as the spatial proximity to community gardens and plots at the household level allow for the use of low-carbon modes of transportation, such as biking or public transport. Societal crises and climate change are context conditions that will affect the development of this food system in the future. Urban gardening has been identified as an essential food supply system in the case of societal crises, such as an economic downturn (e.g., expanding urban agriculture in Detroit; Colasanti et al., 2012) or war (Barthel et al., 2015).

6.3.3.2 Local diversified organic food system

The most important requirements of a local diversified organic food system (see system structure in Appendix 6.2.2) are the local production and marketing of high-quality food in a transparent (Lieblein et al., 2001; Torjusen et al., 2008; Schwarz et al., 2016) and affordable manner (Donaher and Lynes, 2017). Food production can be constrained by seasonality as well as climatic and soil conditions that impede the growth of certain plants (e.g., citrus fruits) and reduce product variety (Francis, 2010: Dörnberger et al., 2016). Local food systems support food education, which can increase the demand for local food and improve nutrition and pro-environmental behavior (Macias, 2008; Torjusen et al., 2008; Hara et al., 2013; Dörnberger et al., 2016). Food safety is also an important requirement (e.g., Rainey et al., 2011), which can be promoted by a strong farmer-consumer relationship and transparent production processes (Kremen et al., 2012; Darolt et. al., 2016). Community building between farmers, consumers and other local food actors was also included in the model structure (e.g., Lieblein et al., 2001; Macias, 2008; Nousiainen et al., 2009; Hara et al., 2013; Kneafsey et al., 2013; Darolt et. al., 2016). These collaborations and interactions have a positive effect on food production, as farmers can react more quickly to the changing food demands of their customers (Zasada et al., 2012) and support each other in providing functions such as fertilization, seed saving and an efficient marketing and distribution system (Marsden et al., 2000). Similar to the urban gardening system, a sense of community can increase well-being and health of customers and other food system actors (Darolt et. al., 2016). Another central requirement is the generation of sufficient farmer income, which has a positive effect on the regional economy (Nousiainen et al., 2009; Kneafsey et al., 2013; Doernberg et al., 2016). However, food production in a local, diversified system can be lower compared to the global commodity-based system, as the tendency towards more diversified and small-scale farming (e.g., Rainey et al., 2011) lowers economies of scale (Schmitt et al., 2016). The carbon emissions of the local food system stem from food production, transportation, food storage and food processing (Hara et al., 2013; Brodt et al., 2013). The size of the local food system's carbon footprint is disputed in the literature and heavily depends upon the specific distribution system (e.g., food hubs vs. consumers driving to farm shops) (Coley et al., 2009) and the particular food product (Brodt et al., 2013).

Environmental protection is an important requirement in the local food system with positive effects on biodiversity (Dörnberger et al., 2016), which implies improved soil fertility, pest control (Bianchi et al., 2006; Xu et al., 2011) and pollination. Biodiversity can be particularly supported through the planting of diversified crops at the field scale (Darolt et. al., 2016) and a landscape approach to manage biodiversity from a broader point of view than the borders of singular farms (Kremen et al., 2012; Therond et al., 2017). Climate change can negatively affect local food systems through extreme events such as droughts and floods. Conversely, a societal crisis, such as a fuel crisis, that puts pressure on the global commodity-based system could serve to strengthen the local food system (e.g., Davidson et al., 2016). However, a fuel crisis would hinder the transportation function in the local system as well.

6.3.3.3 Globalized commodity-based organic food system

The structure of the globalized commodity-based organic food system (see Appendix 6.2.3) includes the requirements of food production, food quality, food safety and a large variety of goods (i.e., food choice). These requirements are linked to nutrition and consumer health (Strassner et al., 2015; Seconda et al. 2017; Rahmann et al., 2017). This food system allows producers to gain premiums for their products (Forman et al., 2012), while still offering these products at relatively low prices (Medland, 2016; Oostindie et al., 2016) due to economies of scale (Francis, 2010; Therond et al., 2017). Food production in the globalized commodity-based organic food system does not necessarily imply place-based connections to communities and nature (as in the local food system), but can also be motivated by the commercial potential of organic food (Buck et al., 1997; Keahey, 2009; Kremen et al., 2012). In this system, transparency is achieved through organic food labels; however, certification is a costly process that has a negative effect on farmer income (e.g., Golan et al. 2001). Farmer communities, grower networks and cooperation along the value chain are also important for commodity-based food systems (e.g., Campbell et al., 2010; Rahmann et al., 2017). The educational function of the food system is relatively low due to the absence of direct contact between farmers and consumers (O'Kane 2016; Oostindie et al., 2016). This food system strongly depends upon the functions of food storage and transportation, which increase the carbon footprint (Stoessel et al., 2012). The fertilization function is affected by soil conditions (which were assessed to be more favorable for this food system compared to the local food system) (cf. Mäder et al., 2002) and has an impact on the carbon footprint. In general, organic farming has a positive impact on soil fertility and water retention capabilities (Pimentel et al., 2005 Reganold and Wachter, 2016).

In the globalized commodity-based system, ecosystem services such as biodiversity (Reganold and Wachter, 2016; Topping, 2011; Rahmann, 2011), pollination (Gabriel and Tscharntke, 2007) and pest control (Croweder et al., 2010) are positively affected, but to a lower extent than in local food systems. The effects of climate change on agricultural productivity depend upon the particular region (Stavi and Lal, 2013). Thus, extreme events such as floods and droughts are expected to have a negative effect on the food system in general, although higher temperatures can have a positive effect in temperate regions (Stavi and Lal, 2013). However, organically managed soils are better equipped to deal with climate extremes (i.e., excessive rainfall and drought conditions) compared to soil on conventional farms, due to the higher water-holding capacity of organically managed soil (Pimentel et al., 2005; Lotter et al., 2003).

6.3.3.4 Multi-scale organic food system

Various authors mention the importance of mixed scale farming and food systems (e.g., Barthel et al., 2013; Rahmann et al, 2017). To investigate tradeoffs and synergies between food systems, all system designs were combined into a comprehensive system structure called a "multi-scale organic food system". When merging the models, we made sure to retain the original meanings of variables. For example, the "provision of plots" function differed between urban gardening and other food systems, as spaces for urban gardening often do not compete with the spaces required for the other system designs. Other variables, such as scenario variables are the same for all system designs, and the weightings of linkages correspond to the original system designs.

Based on stakeholder interviews, survey results and the literature review, synergies and tradeoffs between system designs were added to the multi-scale food system design. As a synergistic relationship, it is apparent that small-scale farmers could support various inputs to urban gardeners, such as seeds, seedlings and organic fertilizers. Another potential area of cooperation is the provision of expertise by small-scale farmers to urban gardeners. Accordingly, linkages between the local food system and urban gardening skills as well as the functions of seeds/seedlings and fertilization provision were added (at a weight of 0.6) to the multi-scale food system design. Such close cooperation between local farmers and urban gardeners would support resilient local food systems and could also be an interesting strategy for rural development. As another synergy between food system designs, local food systems could use the processing and wholesale systems of global commodity-based food systems (Dörnberger et al., 2016). Due to a rising consumer demand for local food products, which even exceeds demand for organic produce (Bloom et al., 2011), this strategy could become even more relevant in the future, although there are substantial barriers to overcome (Mount, 2012; Milestad et al., 2017). Another synergy is related to the educative function of urban gardening. Through improved gardening skills and knowledge of food production, urban gardeners could become more aware of healthy diets and the sustainability aspects of food production (Twiss et al., 2003; Bohn and Viljoen, 2011), which could have a positive effect on the demand for products from local and global commodity-based organic agriculture.

Competition for scarce land resources is a trade-off between system designs that was included in the combined model. In particular, local food and global commodity-based food systems compete for arable land, while urban gardening can utilize areas that do not typically allow for regular agricultural production (for instance, by constructing raised beds in areas with contaminated soil, e.g., Schwartz et al., 2016).

6.3.4 Dynamic modeling and assessment of system designs

The plausibility of each system structure was initially tested by defining obvious system behaviors that should be reproduced by the FCM. For example, a test was performed to determine whether the increase of functions resulted in an increase of the food system variable and whether the requirements of ‘food production’ and ‘carbon footprint’ increased if the food system variables were set to 1. After testing the system structures, indices calculations and scenario analyses were conducted.

6.3.4.1 Graph indices

The calculated graph indices show a similar density across all individual food system designs (see Table 6.1). Thus, the structural complexity is similar between system designs, while the number of variables and links differ. The local food system shows a higher number of variables and links compared to the urban gardening and global food systems, possibly due to a higher share of interviews with local food system actors compared to other system designs. The multi-scale food system has the highest number of variables and linkages as it was built on the combination of individual system designs. The relatively lower density of its structure indicates that the individual system designs do not share many interlinkages, but still can be seen as separate sub-models in the multi-level food system.

Food system variables and food production variables have the largest degree centralities across all system designs (see Table 6.1). The centrality of other variables differs across system designs reflecting their diverging importance (e.g., ‘community’ has the fifth highest centrality in the urban gardening system compared to rank 38 in the global food system design). In the multi-scale food system, local food variables have the highest degree centrality, followed by global food production and urban gardening variables.

Table 6.1: Graph Indices

	Urban Gardening	Local Food	Global Food System	Multi-Level Food System
Density	0.037	0.031	0.036	0.025
Number of Variables	44	51	41	84
Number of Links	68	81	60	170
Degree Centrality (top 5 variables)	Urban gardening (9.9) Food production (5.7) Nutrition (4.2) Food Education (3.9) Community (3.6) Health (3.3)	Local food (9.1) Local food Production (9.0) Nutrition (4.2) Collaboration of local food actors (3.3) Access to food; Efficient marketing and distribution local food (3.3)	Global food production (8.7) Globalized commodity-based organic food (7.8) Access to food (3.9) Nutrition (3.6) Efficient marketing and distribution global food (3.6)	Local food production (10.5) Local food (10.5) Global food production (9.6) Urban gardening (9.1) Globalized commodity-based organic food (7.2)

6.3.4.2 Scenario analyses

Three scenarios were used to assess the sustainability of each system design. In the Basis Scenario A, the food system variable was set to 1 to investigate the implications of the system design on requirements and ecosystem services. In Scenario B, the impact of land planning policies was analyzed by setting the food system and land planning variables to 1. In Scenario C, the climate change and societal crisis variables were set to 1 to simulate their effects on the food system. The results of these scenarios were qualitatively compared between the four food system designs by using a sustainability score ranging from 4 (high sustainability) to 1 (low sustainability) (see Table 6.2).

In Scenario A, the numerical values of requirements and ecosystem services variables were compared between system designs, i.e., in the case of positive variable types, the system design with the highest value received a sustainability score of 4 and the design with the lowest value a score of 1 (for negative variables, the lowest value had a score of 4). For Scenarios B and C, only the relative change of variable values, as calculated by the FCMapper Software, is shown in Table 6.2 ranging from -4 (denoting a strong negative change) to +4 (a strong positive change). A 0 is assigned for each variable that does not change in the respective scenario. Finally, the sustainability scores were added to determine the most sustainable system design in terms of requirements and ecosystem services (Scenario A), including the effects of landscape planning policies (Scenario B) and resilience to change in the case of climate change and a societal crisis (Scenario C).

In Scenario A, the urban gardening system performed best in terms of food education and showed promising results (a score of 3) for the requirements of nutrition, transparency and carbon footprint. In addition, urban gardening provided the services of storm water retention, air purification and air cooling (which were not included in the local and global food system designs). The local food system showed the lowest carbon footprint and the highest value for environmental protection among all system designs. Promising results were also related to food quality, health, community, biodiversity and pollination. The global food system had the highest food production and food choice across all designs, and relatively low food expenses (a score of 3). Relatively high sustainability scores were associated with food security and farmer income. The multi-scale food system had the highest sustainability score for food quality, food expenses, food security, nutrition, health, transparency, community, farmer income, biodiversity and pollination (a score of 4), and a high score for food choice, food education, environmental protection, storm water retention, air purification and air cooling (all with a score of 3). However, the multi-scale system had the highest carbon footprint due to the combined impact of functions from the local and global food systems (e.g., fertilization, transport and food storage). Summing up all sustainability scores, the multi-scale food system clearly outperformed the other system designs, followed by the local food system. This was due to the combination of strengths from each food system as well as the utilization of synergies between system designs.

Various multi-scale food systems are imaginable, as underlying system designs could play different roles in the overall system. Thus, a multi-scale food system could rely more on global food supply chains and less on local food and urban gardening. Another option would be a focus on local food, with only a limited amount of food supplied by a global food system. We investigated the effects of different shares of food system designs in an overall multi-sale system using sustainability scores (Table 6.3). The model results showed that the superior multi-scale design was made up of 50 % local food, 30% global food and 20% urban gardening. This system design was also used in the comparative analysis, as reported in the previous paragraph (Table 6.2).

The effect of land planning policies on system designs (Scenario B) is shown in Table 6.2. The urban gardening system improved most across all system designs, as food quality and health increased strongly (a score of 4) as the risk of contamination was reduced. Food production, food security and nutrition improved for urban gardening as well. In the local food system, food production increased strongly, while food security, nutrition, health and farmer income increased to a lesser extent. These positive results were diminished by a strong increase in the carbon footprint (a score of 4) due to an extension of production. The global food system showed a slight increase in production, food security, nutrition, health, farmer income and carbon emissions. In the multi-scale system, a strong increase in the health and food quality variables was evident (mainly due to positive effects in the urban gardening system). In addition, food production, nutrition, food security, and farmer income improved while carbon emissions rose only minimally. Overall results showed that the urban gardening and multi-scale designs benefited most from land planning policies and regulations.

The effects of climate change and societal crises were calculated in Scenario C. In the urban gardening system, food production decreased compared to the reference scenario, along with food security, nutrition, health and the carbon footprint. A strong positive effect was calculated for the ecosystem services of storm water retention and air cooling. The same tendencies occurred in the local food system, except that food security and the carbon footprint showed a more pronounced reduction, and farmer income decreased slightly. The global food system experienced the strongest decrease in food production, as transport and storage functions were diminished. This implied a strong decrease in carbon emissions and a slight reduction in food security, nutrition, health and farmer income. The multi-scale food system showed a decrease in food production and carbon emissions, and a lesser reduction in food security, nutrition, health and farmer income. Similar to the urban system, the ecosystem services of storm water retention and air cooling increased significantly. In total, the sustainability scores are negative for all food systems; by taking ecosystem services into account, the multi-scale system turned out to be the most resilient followed by the urban gardening system. Nevertheless, food production in the multi-scale system showed a strong decrease, which is even more profound for the urban and local food systems (-3 for both) compared to individual designs (-2 for both). This is due to a stronger competition for scarce resources in the multi-scale system design, in particular for water and area of cultivable land.

Table 6.2: Scenario results

		Basis Scenario A								**Scenario B**				**Scenario C**			
	Type (pos/neg)	**Urban gardening**	Sust. Score	**Local**	Sust. Score	**Global**	Sust. Score	**Multi-scale**	Sust. Score	Urban gardening	Local	Global	Multi-scale	Urban gardening	Local	Global	Multi-scale
Requirements																	
Food production	Pos	0.97	1.5	0.98	3	0.99	4	0.96 (Urban) 0.97 (Local) 0.98 (Global) **ϕ: 0.97**	1.5	2	3	1	2 (Urban) 2 (Local) 2 (Global) **ϕ: 2**	-2	-2	-3	-3 (Urban) -3 (Local) -3 (Global) **ϕ: -3**
Food quality		0.81	2	0.87	3	0.80	1	0.88	4	4	0	0	3	0	0	0	0
Food choice	Pos	0.8026	1.5	0.8026	1.5	0.85	4	0.81	3	0	0	0	0	0	0	0	0
Food expenses	Neg	0.80	1	0.59	2	0.51	3	0.40	4	0	0	0	0	0	0	0	0
Food security		0.922	1	0.927	2	0.929	3	0.94	4	1	2	1	1	-1	-2	-2	-2
Nutrition	Pos	0.96	3	0.95	2	0.93	1	0.98	4	2	1	1	2	-1	-1	-1	-1
Health		0.93	2	0.95	3	0.91	1	0.96	4	4	1	1	3	-1	-1	-1	-1
Transparency	Pos	0.85	3	0.78	2	0.74	1	0.86	4	0	0	0	0	0	0	0	0
Community	Pos	0.83	2	0.89	3	0.74	1	0.94	4	0	0	0	0	0	0	0	0
Farmer income	Pos	-	-	0.921	2	0.922	3	0.95 (Local) 0.92 (global) **ϕ: 0.935**	4	-	1	1	1 (Local) 1 (Global) **ϕ: 1**	-	-1	-1	-1 (Local) -1 (Global) **ϕ: -1**
Carbon footprint	Neg	0.88	3	0.87	4	0.92	2	0.97	1	-1	-4	-1	-1	1	3	4	4
Food education	Pos	0.94	4	0.74	2	-	1	0.87	3	0	0	0	0	0	0	0	0
Environmental protection	Pos	0.73	1	0.84	4	0.80	2	0.83	3	0	0	0	0	0	0	0	0
Sub-Total:			**25**		**33.5**		**27**		**43.5**	**12**	**4**	**4**	**11**	**-4**	**-4**	**-4**	**-4**

Ecosystem Services																	
Biodiversity	Pos	0.821	1	0.891	3	0.886	2	0.910	4	0	0	0	0	0	0	0	0
Pollination	Pos	0.725	1	0.731	3	0.728	2	0.732	4	0	0	0	0	0	0	0	0
Storm water retention	Pos	0.78	4	-	-	-	-	0.73	3	0	-	-	0	3	-	-	4
Air purification	Pos	0.74	4	-	-	-	-	0.68	3	0	-	-	0	0	-	-	0
Air cooling	Pos	0.78	4	-	-	-	-	0.73	3	0	-	-	0	3	-	-	4
Sub-Total:			**15**		**6**		**4**		**17**	**0**	**0**	**0**	**0**	**6**	**0**	**0**	**8**
Sustainability Score Total			**40**		**39.5**		**31**		**60.5**	**8**	**4**	**3**	**11**	**2**	**-4**	**-4**	**4**

Table 6.3: Comparison of different multi-scale food system designs.

	0.1 (Urban) 0.2 (Local) 0.7 (Global)	Sust. Score	0.2 (Urban) 0.5 (Local) 0.3 (Global)	Sust. Score	0.2 (Urban) 0.3 (Local) 0.5 (Global)	Sust. Score	0.3 (Urban) 0.6 (Local) 0.1 (Global)	Sust. Score
Requirements								
Food production	0.9553 (Urban) 0.9672 (Local) 0.9900 (Global)	1 1 4 **ϕ: 2.0**	0.9580 (Urban) 0.9732 (Local) 0.9844 (Global)	3 3 2 **ϕ: 2.67**	0.9573 (Urban) 0.9694 (Local) 0.9875 (Global)	2 2 3 **ϕ: 2.33**	0.9598 (Urban) 0.9750 (Local) 0.9805 (Global)	4 4 1 **ϕ: 3.0**
Food quality	0.8877	4	0.8813	2	0.8817	3	0.8749	1
Food choice	0.8340	4	0.8082	2	0.8189	3	0.7910	1
Food expenses	0.3772	4	0.3987	2	0.3929	3	0.4165	1
Food security	0.9375	1	0.9391	2	0.9392	3	0.9408	4
Nutrition	0.97551	2	0.97554	4	0.97553	3	0.97541	1
Health	0.9550	1	0.9554	3	0.9553	2	0.9557	4
Transparency	0.8556	1	0.8572	2	0.8617	3	0.8630	4
Community	0.9299	1	0.9359	3	0.9330	2	0.9385	4
Farmers income	0.9499 (Local) 0.92223 (Global)	4 3.5 **ϕ: 3.75**	0.9482 (Local) 0.92222 (Global)	2 2 **ϕ: 2.0**	0.9491 (Local) 0.92223 (Global)	3 3.5 **ϕ: 3.25**	0.9473 (Local) 0.92221 (Global)	1 1 **ϕ: 1.0**
Carbon Footprint	0.9731	1	0.9705	3	0.9719	2	0.9689	4
Food Education	0.8363	1	0.8700	3	0.8589	2	0.8874	4
Environmental protection	0.8354	4	0.8258	3	0.8257	2	0.8156	1
Sustainability Score Total		**29.75**		**33.67**		**33.58**		**33.0**

6.4 Discussion

The VDAF allowed for a systematic analysis of alternative food systems designs including environmental, economic and social aspects, based upon information from stakeholders, experts and the literature. The framework provided guidance in the development and assessment of system designs from the definition of requirements and functions to developing intricate system structures and modeling system dynamics. While methodological frameworks for exploratory scenarios (e.g., Mahmoud et al., 2009) and backcasting (e.g., Robinson et al., 2011) exist, the VDAF fills a methodological gap with respect to dynamic vision modeling by combining engineering design methods (i.e., requirements and functional analyses) and complex system modeling methods (i.e., CLDs, FCM). Methods borrowed from systems engineering simplified the vision models down to the most important elements from a system design point of view (i.e., requirements, functions). FCM was found to be a powerful approach to dynamically analyze the implications of designs using economic, ecological and social indicators.

The vision assessment method was able to deal with the lack of empirical data by weighting causal relationships based upon expert assessment and a literature review. In addition, the FCM method showed its ability to deal with concepts that are difficult to quantify, such as 'community' or 'transparency'. This turned out to be an asset in the stakeholder engagement process as stakeholders were not required to consider the quantification feasibility of their chosen variables, and were able to freely 'speak their minds'. Nevertheless, methods applied in the VDAF demand analytical thinking and the interpretation of results requires mathematical knowledge. This points to the potential benefits of a complementary application of more visual approaches, such as 3D visualization (Robinson et al. 2011), narratives (Iwaniec and Wiek, 2014) or artwork (e.g., Schneidewind, 2018), which will be explored in future research.

The modeling results showed the various consequences of organic food system designs and allowed for their comparative assessment. The model results demonstrated the overall benefits of a multi-scale food system that did not merely represent a combination of singular food systems, but covered tradeoffs (e.g., space restrictions or water scarcity) and synergies (e.g., knowledge exchange between local farmers and urban gardeners) between system designs. As an example, the effects of such synergies could be seen in the higher income of local farmers in the multi-scale design (0.95) compared to the local food system (0.92). The overall results indicated that the multi-scale design was the most promising with respect to sustainability indicators and scenario analyses. In addition to the high sustainability score of the multi-scale design in Basis Scenario A, land planning policies had a strong positive effect (Scenario B) and impacts of climate change and societal crises were absorbed relatively well (Scenario C) in the multi-scale system. The assessment is, however, allayed by the comparatively high carbon footprint of the multi-scale system (0.97). This aspect highlights that vision modeling must be embedded in a social learning process, in which such thought-provoking modeling results inspire new research questions and follow-up analyses (Robinson et al. 2011). In this case, the modeling results suggest the need for a more detailed analysis of the carbon footprint of system designs, which could be carried out using other modeling approaches, such as system dynamics or resource allocation scenarios.

The VDAF allowed for an analysis of food systems from a whole system perspective comprising production, distribution and consumption on multiple scales. Thereby, the VDAF addresses an important research gap, as studies are lacking that address the complete organic food system (e.g., Strassner et al., 2015). Studies are mainly focusing on the benefits and challenges of a singular system design rather than taking a multi-scale perspective (there are some notable exemptions, such as Barthel et al., 2013 or Rahmann et al, 2017). Research and policy-making have also followed a more polarized discussion on the superiority of local or global food systems. Such a polarized discussion was also reflected in the stakeholder interviews, as food system designs from stakeholders were usually either based upon local food, urban gardening or global supply chains (some stakeholders combined a local food system with urban gardening though).

The quality criteria for visioning methodologies (printed in cursive in the following sentences), as elaborated by Wiek and Iwaniec (2014), summarize the capabilities of the VDAF as well as the potential for further development. The framework provided a *meaningful sequence of methods* including *visualization techniques* (e.g., CLDs), which can be applied in a *participatory setting* (i.e., using participatory modeling). The methodology furthermore supported *vision review* (i.e., the sustainable food system designs were qualified by stakeholders as desirable states in the future) as well as *system analysis*, *sustainability assessment*, *consistency analysis* and *plausibility appraisal* using FCM. Future research on the VDAF should focus on its *iterative application* in the scope of social learning processes, further utilization of *creativity and visualization techniques* (e.g., artwork), and its application in *group settings* (in addition to individual interviews). *Actor-oriented analyses* could support the implementation of visions by specifying explicit actions and roles of actors in transition governance processes (e.g., Halbe, 2016). Further interesting extensions of the methodology relate to *target specification* (for instance, explicitly including planetary boundaries in vision models, cf. Rockström et al., 2009) and *priorities assessment* (for instance, by prioritizing certain sustainability indicators). While the FCM approach is suitable to analyze multi-causality and feedback processes and can deal with a limited availability of data, other modeling methods for *system analysis*, such as system dynamics modeling, can also be worthwhile to further analyze important system properties such as accumulation or temporal dynamics.

6.5 Conclusions

The VDAF provides a structured approach to design and assess sustainability visions. Methods from systems engineering help to focus on the most important aspects of sustainability visions from a systems science perspective, namely the system requirements, functions, scales, and technical and nature-based solutions, thereby reducing the complexity of vision models. CLDs are applied to investigate system structures of sustainability visions in the scope of a participatory modeling process. Finally, FCM allows for an assessment of alternative system designs in a semi-quantitative way. Thus, the quantitative modeling results need to be interpreted qualitatively by comparing the numerical values of sustainability indicators between system designs and analyzing their relative change.

The case study on sustainable food systems in Southwestern Ontario underlined the potential of the VDAF. Visionary system designs were developed based on stakeholder and expert knowledge (using participatory modeling and surveys) along with a literature review. Four alternative food system designs were assessed: urban organic gardening, a local diversified organic food system, a global commodity-based organic food system and a multi-scale organic food system in which the singular system designs were combined and synergies and tradeoffs were added. The FCM analysis revealed the relative advantages and disadvantages of each system design from a sustainability perspective; the multi-scale food system received the highest sustainability score.

Given that previous research on multi-scale food systems has been limited by the complexity of the topic and a lack of data, the VDAF demonstrated its capability to systematically assess complex sustainability visions. The results point to various interesting research questions, such as the impact of multi-scale food systems on carbon emissions, competition for water and area of cultivatable land between food systems, and opportunities for joint distribution networks between local and global food systems. Future research should also examine the transferability of results, an endeavor which requires the application of the VDAF in other regions and socio-cultural contexts along with a comparative analysis of the resulting food system visions. While a FCM approach can only provide insights on relative changes and trends, quantitative modeling methods could be applied in future research to investigate more detailed questions. In addition, the 'target knowledge' generated through vision modeling could be further utilized in exploratory scenario analyses that generate 'process knowledge' by investigating potential pathways towards a multi-scale organic food system.

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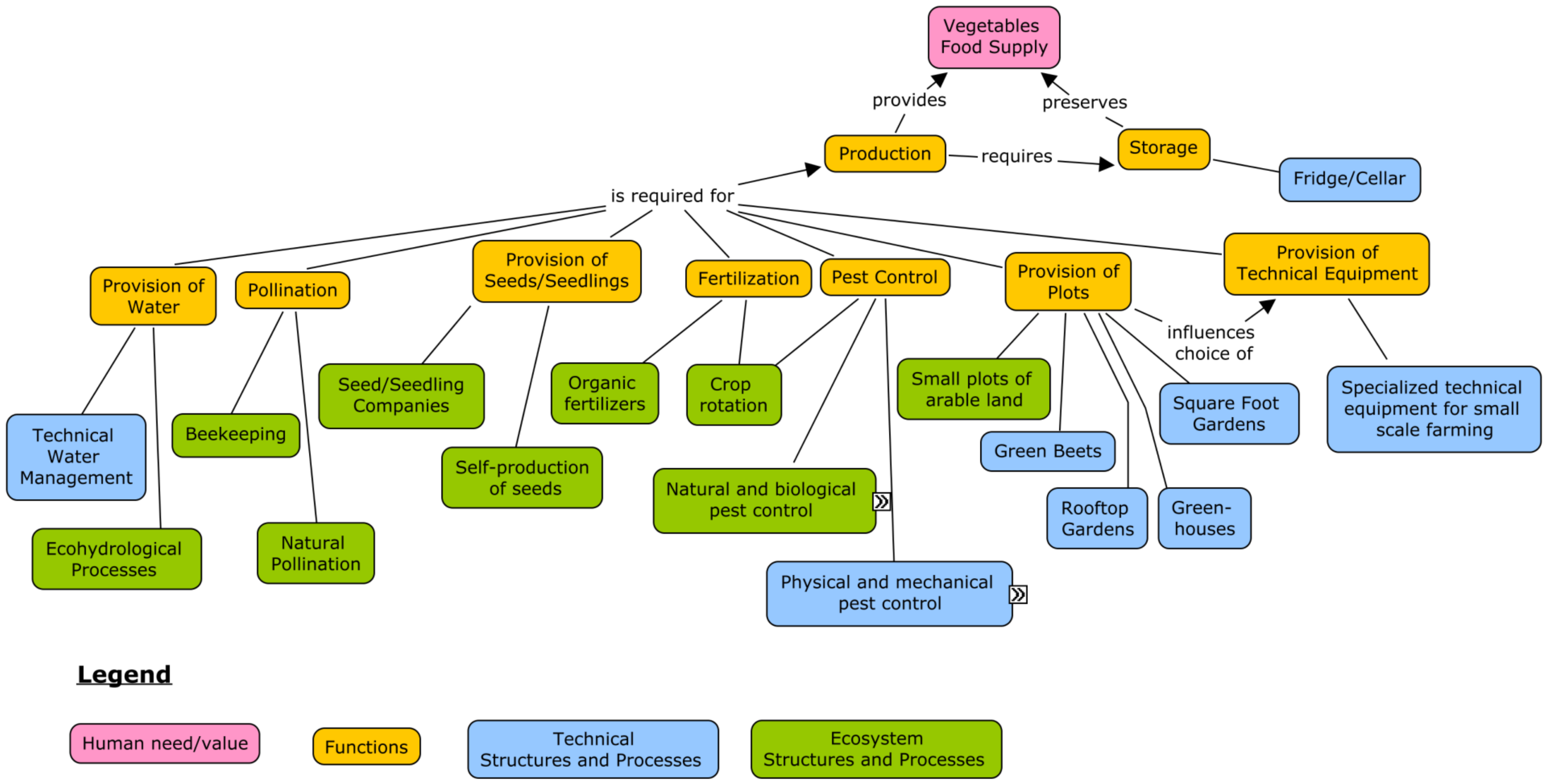
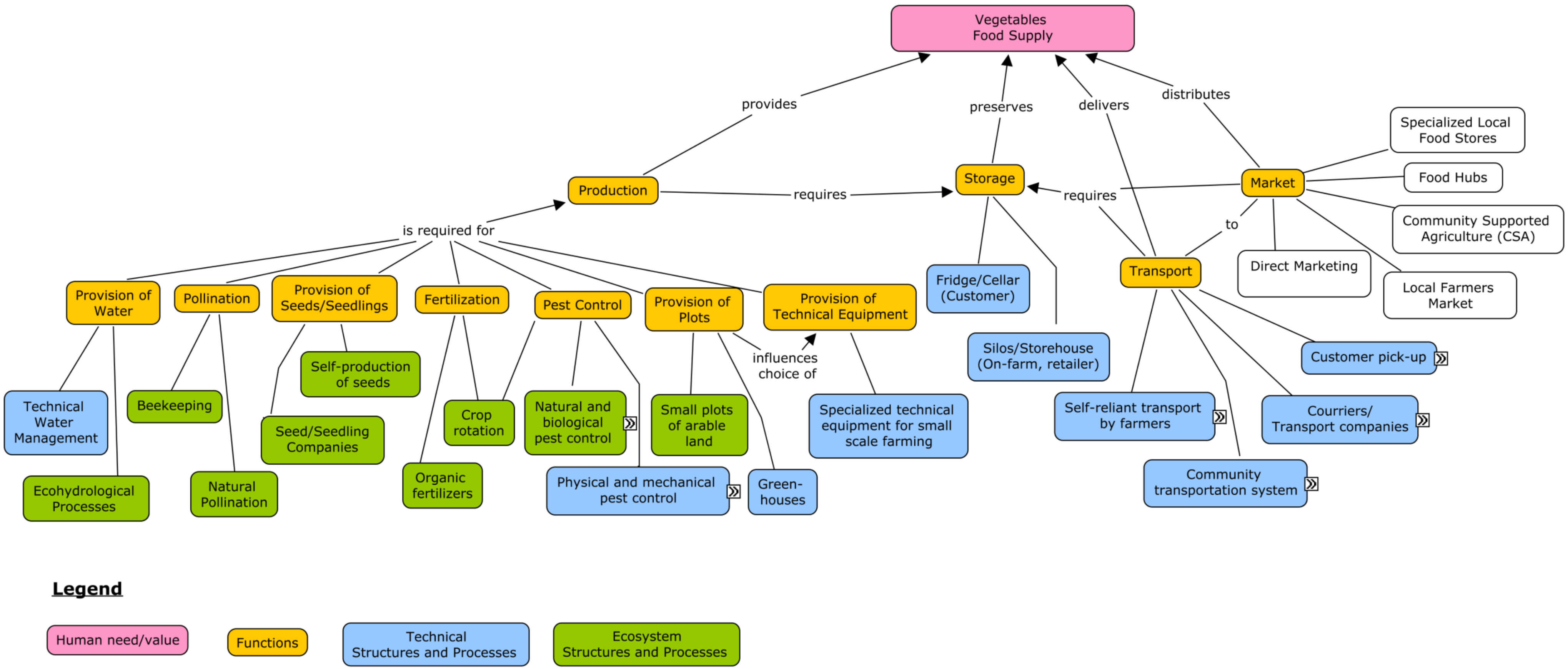
Appendix 6.1: Functional organizational analysis of food system designs (from Halbe et al., 2014)

Comment referring to graphics in Appendices 6.1.1 – 6.1.3: The labeling as technical or ecosystem-based structures/processes show merely a tendency, as structures and processes usually consist of both components (see Halbe et al., 2014 for more details).

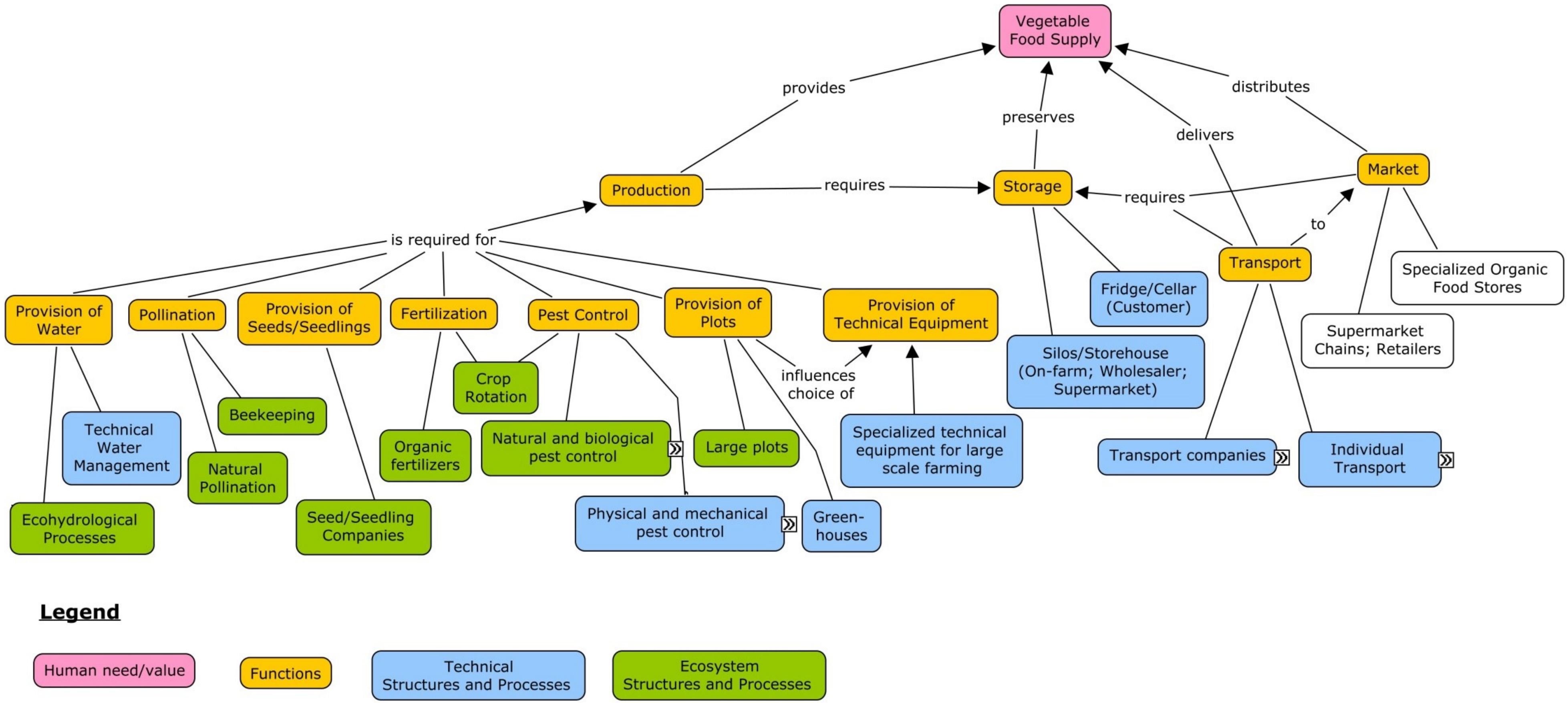
Appendix 6.1.1: Urban organic food system



Appendix 6.1.2: Local diversified organic food system

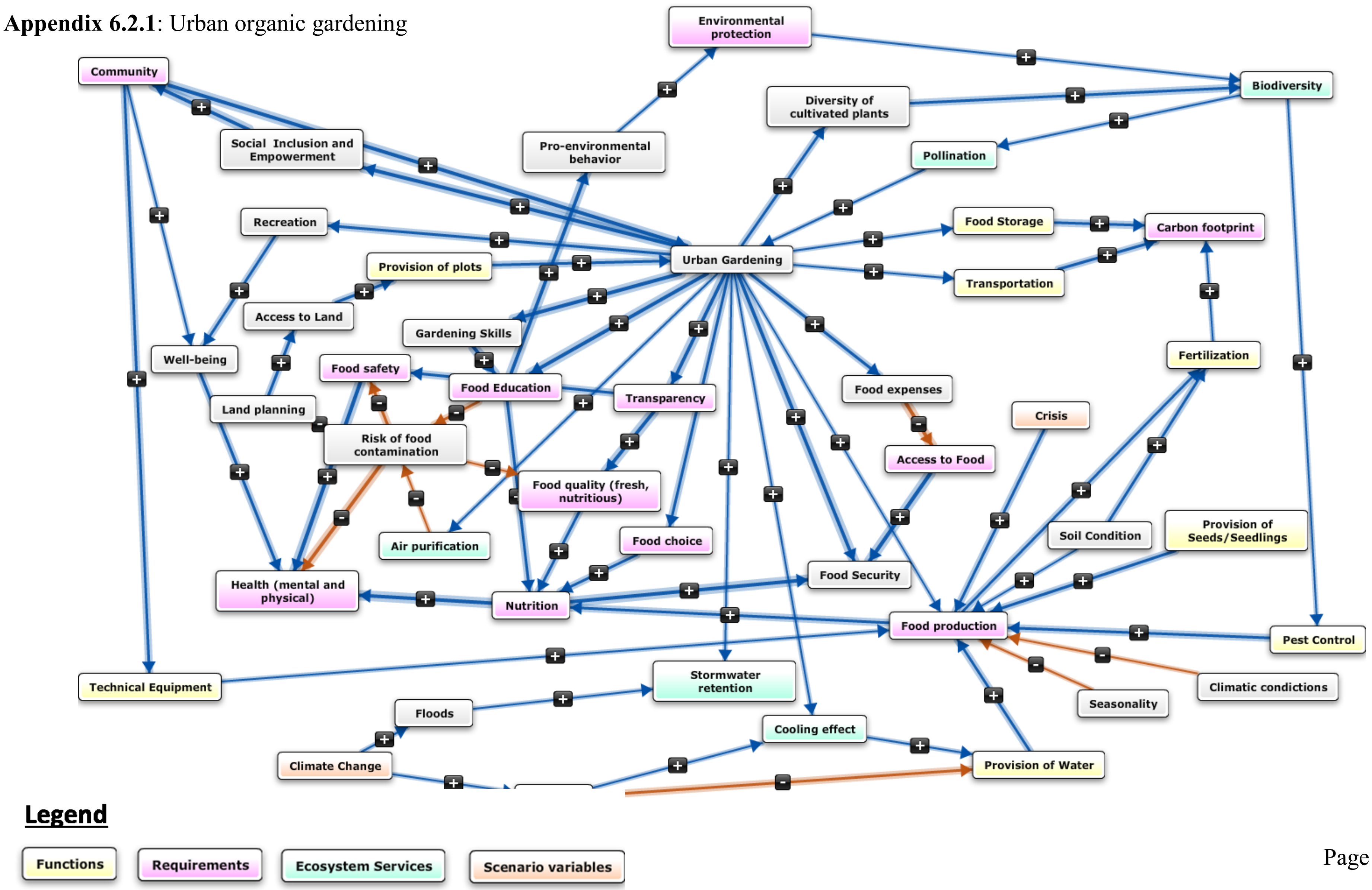


Appendix 6.1.3: Global commodity-based organic food system

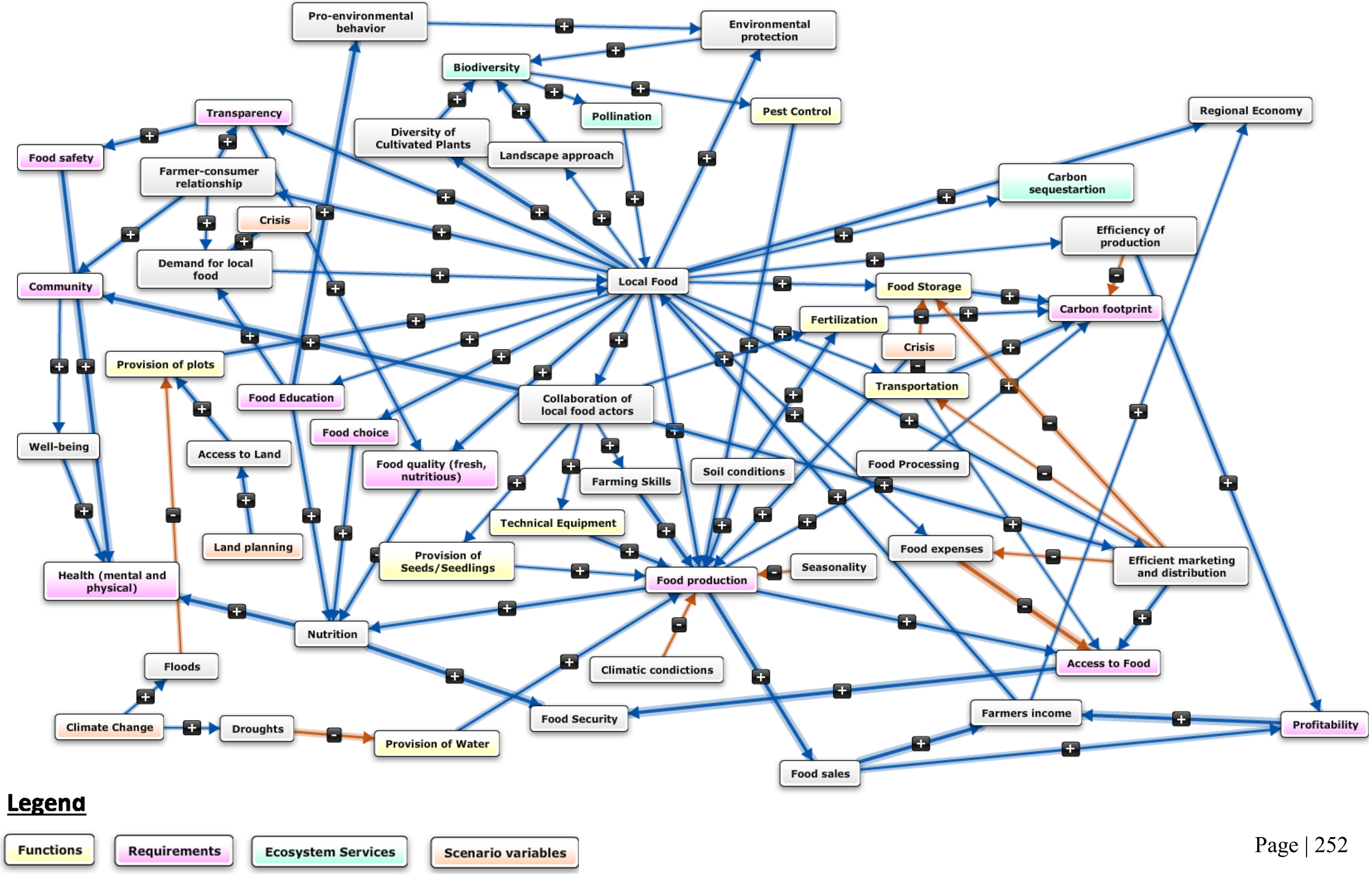


Appendix 6.2: Weighted causal structures of food system designs

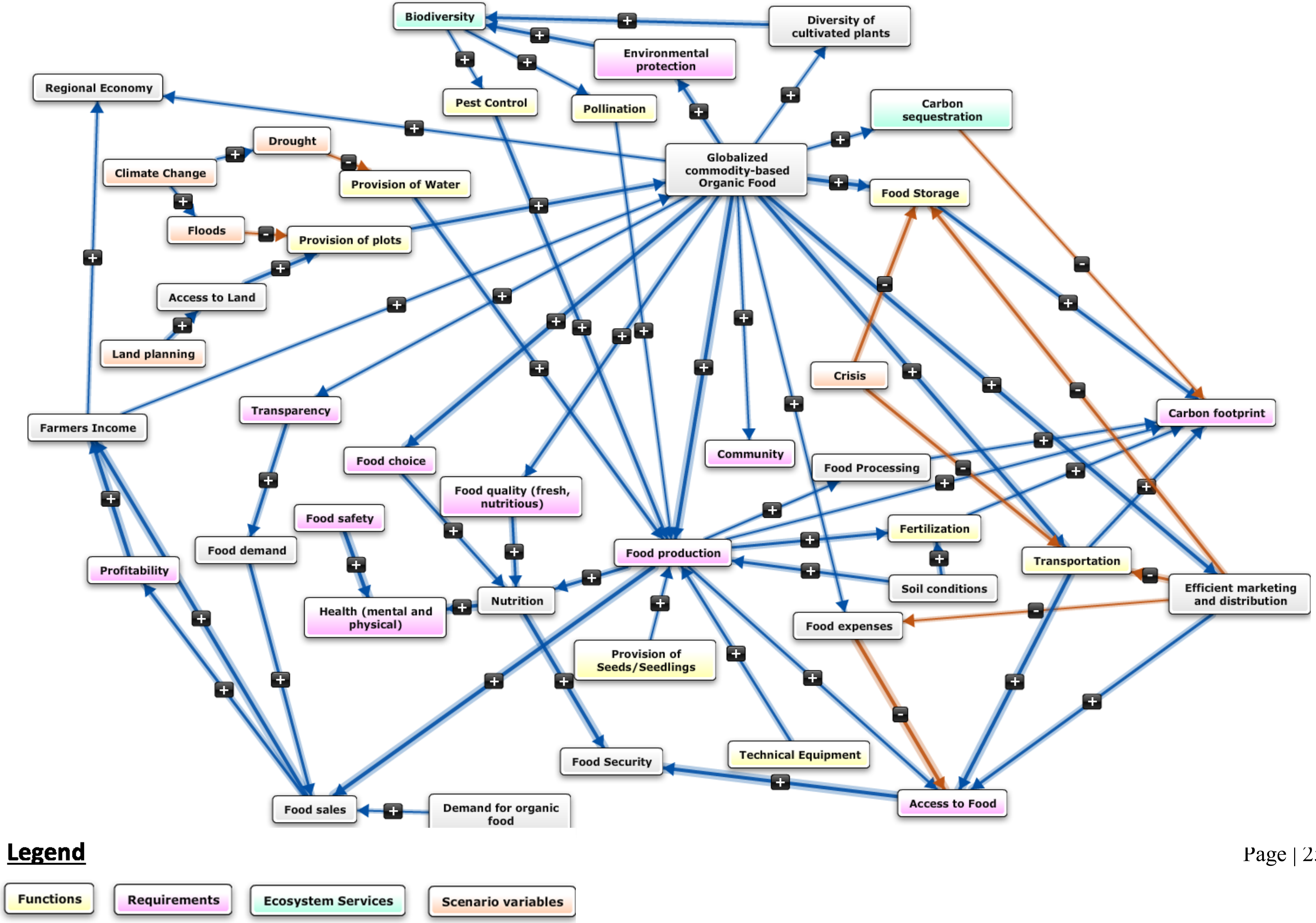
Appendix 6.2.1: Urban organic gardening



Appendix 6.2.2: Local diversified organic food systems



Appendix 6.2.3: Global commodity-based organic food system



Appendix 6.3: Comparison of weighted causal links between system designs

The weights are related to the causal link between the ‘food system variable’ and the respective variable in Table A1.

Table A1: Comparison of weights of links between food system variables and other central variables in the food system designs

	Urban Gardening	**Local Food System**	**Global food system**
Food production	Low (0.3)	Medium (0.6)	High (0.9)
Transparency	High transparency (0.9)	Medium transparency due to close consumer-farmer connection (0.6)	Relatively low transparency through food labels (0.3)
Food education	High through personal experience (0.9)	High, due to close consumer-farmer connection (0.9)	Food education not included in model
Community	High, e.g., through community gardens (0.9)	High, due to close consumer-farmer connection and collaboration between local food actors (0.9)	Low (0.3)
Food storage and transportation	Low (0.3)	Low (0.3)	High (0.9)
Food choice	Reduced food choices, as constrained by soil and weather conditions (0.3)	Medium food choices, as constrained by soil and weather conditions (0.6)	High food choices (0.9)
Food expenses	Medium (0.6)	Low (0.3)	Low (0.3)
Diversity of cultivated plants	High (0.9)	High (0.9)	Medium, due to specialization ad economies of scale (0.6)

Food production is highest for the global commodity-based food system design followed by the local food system. Food education is only included in the urban gardening and local food system designs. Community is strongest in these two designs, while being relatively low in the global food system. The functions of food storage and transportation are high for the global system and low for the other system designs. Food choice is high for the global food system, medium for the local food system and low for urban gardening. The global and local food systems have the lowest value for food expenses, while the urban gardening system design has a medium value due to high opportunity costs. Finally, the diversity of cultivated plants is high for urban gardening and local food systems and medium for the global food system due to specialization and economies of scale. A more detailed description of the model structures is provided in Chapter 6.3.3.

CONNECTING TEXT TO CHAPTER 7

Chapter 7 presents an extension of the Vision Design and Assessment Framework (VDAF) that was presented in Chapter 6. The revised VDAF includes system dynamics modeling in the vision assessment step. In addition, a methodology is introduced and tested for a systematic handling of uncertainties in modeling sustainability visions (Objective 4). System dynamics modeling is a powerful method to deal with complex issues for which empirical data on variables, parameters and functional relationships are lacking. The proposed approach for quality assurance of vision models is based on a systematic conceptualization of uncertainties in model-based decision-support (Objective 4) drawing on the work of Walker et al. (2003). A systematic approach is suggested to deal with different locations and levels of uncertainties. An application of the revised VDAF to a case study on the vision of a renewable energy system in Germany is provided in Chapter 8.

This chapter was submitted to the Energy Journal (Halbe et al, 2021a). The format of the article has been modified to ensure consistency with the style of this thesis. A list of references cited in this article is provided at the end of the chapter. The author of the thesis developed, tested and applied the conceptual and methodological framework and wrote the manuscript presented here. Dr. Peter Viebahn, Head of the Research Unit ‘Sectors and Technologies’, Wuppertal Institute for Climate, Environment and Energy, Germany, contributed to the review and editing of the manuscript and provided valuable advice on all parts of the article. Prof. Adamowski, the supervisor of this thesis, gave advice on all aspects of the research and contributed to the review and editing of the manuscript.

Chapter 7: Vision modeling and assessment using system dynamics – Part 1: Methodological framework

Johannes Halbe, Peter Viebahn and Jan Adamowski

Abstract

Scenario analysis is a widely used approach to support decision-making under complexity. Exploratory scenarios start from the present and analyze various possible future developments, while backcasting scenarios start from a future system state to explore potential pathways towards that vision. As an additional scenario category, the current article proposes vision assessment scenarios that focus on the generation of target knowledge by investigating the dynamic coherence and desirability of energy system designs. Vision modeling and assessment reduces complexity by focusing on the analysis of alternative system states of a future supply system, and is proposed in this article as a preceding step of more detailed exploratory or backcasting scenarios. This article introduces a vision modeling and assessment approach along with its promises and challenges, and proposes a methodological framework. The Vision Design and Assessment (VDA) framework involves (1) quantitative vision modeling using system dynamics and (2) a systematic model testing approach. A companion article presents an application of the framework on a visionary renewable energy system for the supply of power, space heating and mobility in Germany based upon Power–to-Gas (PtG) and Power–to-Liquid (PtL) technologies.

Keywords: sustainability visions; scenario analysis; system dynamics; participatory modeling; sustainability transitions research

7.1 Introduction

Scenario analysis is an important approach for examining suitable strategies and policies for decision-making processes. Exploratory scenarios are widely applied to explore future developments of energy systems and their environmental, economic and social consequences (e.g., Phdungsilp, 2010). In contrast, backcasting scenarios start with the definition of a desired future system state, mostly through a collection of target values or critical values, before potential development pathways are explored towards the future system state (Dieckhoff et al., 2014). However, exploratory and backcasting scenario analyses present a number of challenges. The development of comprehensive models can become very resource intensive (i.e., substantial time and financial requirements) due to the complexity of systems under study. For example, integrated models for energy policy analysis consider various system components, such as technical infrastructure (e.g., energy transmission infrastructure), resource requirements (e.g., fossil or renewable fuels), multiple environmental effects (e.g., CO_2 emissions, water consumption), multiple technical options (e.g., internal combustion engine vehicles or electric cars) and customer behavior (e.g., purchasing behavior or driving habits) (e.g., Köhler et al., 2009). Further challenges exist in the handling of uncertainties, qualitative aspects and data requirements that can hamper the development of exploratory and backcasting scenarios in practice (Mahmoud et al., 2009).

In the current article, the authors suggest vision assessment scenarios as a preceding step of detailed exploratory and backcasting scenario studies. Vision assessment scenarios focus on the generation of target knowledge by investigating the dynamic coherence and desirability of supply system designs using systems modeling methods. Vision modeling is defined as "the process of constructing sustainability models such that the structure and function of the future desirable state is explicitly articulated as a systems model" (Iwaniec, 2013, p. 118). Thus, vision models specify a future vision and allow their subsequent assessment through scenario analysis. Vision assessment scenarios do not aim to analyze how the future could unfold depending upon different conditions (as with the explorative scenario method), or to examine potential pathways towards a desired future with appropriate policies and measures (as with the backcasting approach). Instead, a vision model represents a design of a future system state (e.g., a fully renewable energy system) and allows the assessment of its sustainability performance (e.g., resource requirements, economic and environmental indicators) through scenario analysis. Through analyses of potential trade-offs, unintended side-effects or surprising system behaviors, vision assessment scenarios answer the question of whether a specific future system state truly offers sustainability benefits. In a nutshell, vision assessment scenarios generate target knowledge (Where do we want to go?) while exploratory and backcasting scenarios generate process-oriented knowledge (What are potential paths to get there?).

This article addresses two major research gaps in the modeling and assessment of sustainability vision in general as well as energy system modeling in particular. First, methodological frameworks are currently lacking for the development of vision models that take an integrated approach (i.e. include technical, economic, ecological and social system aspects) and promote the involvement of stakeholders (see Grunwald, 2019, for highlighting the research challenge for energy system models). In this respect, system dynamics modeling is a particularly promising method for analyzing multi-causality, feedback structures, and stock-and-flow dynamics from an integrated viewpoint (Sterman, 2000). Furthermore, system dynamics supports the involvement of stakeholders in model development (e.g., Vennix, 1996) and addresses the issue of insufficient data on parameters and functional relationships (e.g., Forrester, 1980). Second, the testing[12] of quantitative vision models is a huge challenge, as conventional model testing approaches usually depend upon the availability of empirical data, which is often lacking for future system designs. In general, quantitative vision modeling studies (e.g., Iwaniec et al., 2014) have not addressed the issue of model validation and testing at all.

The research presented in this article addresses these research gaps by developing a Vision Design and Assessment (VDA) Framework that involves (1) quantitative vision modeling and assessment using system dynamics and (2) a systematic model testing approach that can deal with the particular challenges of vision modeling. A companion article presents an application of the framework on a visionary renewable energy system for the supply of power, space heating and mobility in Germany based upon Power–to-Gas (PtG) and Power–to-Liquid (PtL) technologies (see Halbe et al., in review).

The structure of this article is as follows: First, the conceptual and methodological backgrounds of this research are provided including the concept of target knowledge and methods for vision modeling and assessment. Second, a methodological framework for the development and testing of vision models using system dynamics is presented. Finally, a

[12] Instead of “model validation” or “model verification”, we use the term “model testing”, which is defined as the process to “build confidence that a model is appropriate for the purpose” (Sterman, 2000, p. 846). See a discussion of this topic in Sterman (2000), Chapter 21, pp. 845 ff.

discussion and conclusions on the benefits of vision modeling for energy system modeling are provided.

7.2 Conceptual and methodological background

This section presents the ‘target knowledge’ concept (Section 7.2.1) that provides the epistemological background of vision modeling and assessment. Subsequently, the state-of-the-art of vision modeling is presented (Section 7.2.2).

7.2.1 Target knowledge

Bierwirth et al. (2014) distinguish between three types of knowledge, which are essential for facilitating sustainability transitions. The process is portrayed as a transition cycle starting with a problem analysis to generate systems knowledge. The second phase of the transition cycle consists of the development of future visions to gain target knowledge. This phase is followed by the implementation of innovations in real-world laboratories (see Schneidewind and Scheck, 2013; Wagner and Grunwald, 2015) to develop transformation knowledge, which supports the diffusion and upscaling of innovations and closes the cycle in order to refine the systems knowledge. While systems knowledge and transformation knowledge can be analyzed based upon a positivist philosophy of science (cf. Geels et al., 2016, on philosophies of science relevant for socio-technical transition research), target knowledge is inherently normative, i.e., influenced by the goals, values and worldviews of the individual or group holding a future vision, which is more in a line with constructivist and relativist philosophies of science (cf. Geels et al., 2016). Nevertheless, the term ‘target knowledge’ implies a need for quality assurance, in the sense that the design process of future visions should be followed by a rigorous assessment procedure.

Futures studies is an established field that aims at the generation of system, target and transformation knowledge through the systematic and rigorous specification, analysis and assessment of predicted, possible and preferable futures (e.g., Bell, 1996; Marien, 2002). Grunwald (2014) distinguishes between three modes of orientation that futures studies can provide. In mode 1, future studies can provide orientation to decision-making by analyzing future developments for which sufficient causal and statistical knowledge is available, i.e., future projections converge and allow for a ‘forecasting’ approach. The quality of these forecasts can be assessed through conventional model validation techniques using empirical data. In mode 2 orientation, futures studies are not able to forecast a future system development, as uncertainties and epistemological challenges are too high. Instead, only alternative plausible ‘foresights’ (i.e., alternative future developments) can be identified. Thus, scenarios are located in a plausible corridor (e.g., between a best case and a worst-case scenario), which allows for the design of ‘robust strategies’ (Grunwald, 2014). In mode 3 orientation, futures studies are not able to identify separate foresights, as the diversity of potential futures is too high. In this case, Grunwald (2014) proposes semantic and hermeneutic approaches to provide orientation for a reflected debate and decision-making.

Vision modeling and assessment is linked to the mode 2 orientation of futures studies. However, instead of examining multiple plausible scenarios, vision modeling focuses on a set of positive visions, i.e., desirable futures that are inspiring and sustainable (e.g., Rosa et al., 2017; Pereira et al. 2018; Falardeau et al., 2019). The following section provides an overview of the state of the art in vision modeling and assessment.

7.2.2 Vision modeling and assessment

Wiek and Iwaniec (2014) describe visions (desirable future states) as a subgroup of scenarios (possible future states and developments), which are clearly different from predictions (likely future states). More specifically, vision assessment scenarios and backcasting scenarios can be considered as sub-groups of anticipatory scenarios. Vision modeling specifically aims at specifying a future system state as a systems model (Iwaniec, 2013), while backcasting usually describes the future system merely as a set of targets or critical values in order to develop alternative pathways towards reaching this target (Dieckhoff et al., 2014).

Iwaniec (2013) distinguishes different approaches for vision modeling. *Conceptual modeling* allows for the analysis of the system structure of a vision including its elements and their relationships. Potential methods for conceptual modeling are systems thinking (Iwaniec and Wiek, 2014; Halbe et al., 2015), influence matrices (Iwaniec et al., 2014) and functional analysis (Halbe et al., 2014). *Dynamic vision models* build upon conceptual models and allow for quantitative scenario analysis of the dynamics of a future vision. By specifying relationships and parameters, dynamic models allow for a closer analysis of non-intuitive system behavior due to multi-causality or feedback processes. Potential methods for dynamic vision modeling range from semi-quantitative methods, such as fuzzy cognitive mapping

(Halbe and Adamowski, 2019) and cross impact balance analysis (Weimer-Jehle, 2006), to quantitative modeling methods, such as system dynamics modeling (e.g., Iwaniec et al., 2014).[13]

Only a few studies have been published to date that explicitly apply a dynamic vision modeling approach (see Halbe, 2020; Halbe et al., 2020). Iwaniec et al. (2014) underline the suitability of system dynamics modeling to analyze complex visions in an integrated way. They present a simple vision model[14] using system dynamics that was created in a participatory process designed to develop an urban vision for the City of Phoenix, USA. Schmitt-Olabisi et al. (2010) used system dynamics modeling to model different sustainability visions for the region of Minnesota in the year 2050. Even though the authors do not explicitly use the term 'target knowledge', they aim at the modeling of a "a 'snapshot' of each scenario, meaning that the modeled relationships represented only the year 2050" (p. 2692), which is in line with a vision modeling approach. However, the authors do not provide details on the system dynamics model, such as the time steps and temporal boundaries, so it remains unclear how exactly the system was modeled. Although, Schmitt-Olabisi et al. (2010) do provide details on how the results of the system dynamics model revealed several side-effects and trade-offs that were not considered in the preceding process of developing qualitative future visions; for instance, participants underestimated the land requirements of bioenergy production for the mobility sector.

Energy system models can also be applied to assess future energy system visions. Bottom-up models are particularly suitable to analyze future system states, due to their ability to represent energy systems in detail (e.g., determining the use of certain technologies) (cf. Mai et al., 2013). However, energy system modeling studies usually do not clearly differentiate between target and transformation knowledge, but include both elements of a future system state (e.g., renewable energy technologies) as well as the transition pathways (e.g., the intermediate status of key parameters such as the changing number of coal-fired power plants and their emissions per decade, which are influenced by supposed policy instruments such as a CO_2 tax). Furthermore, energy system models are often constrained to technical and economic aspects, while leaving out links to social and environmental aspects (Grunwald, 2019). Vision modeling and assessment thus requires a more integrated and participatory modeling approach, due to the complexity and normativity of sustainability visions.

[13] Iwaniec et al. (2014) introduce a third vision modeling approach termed "pathways of vision models", which is not addressed in the current article as it might distract the reader.
[14] Iwaniec et al. (2014) highlight that the simple system dynamics model is only one sub-model, but do not provide details on the other sub-models.

Trutnevyte et al. (2011, 2012) serve as one of the few examples in which participatory energy scenarios were developed that focus on target knowledge generation. In this study, qualitative vision statements of future energy systems for heat and electricity in small communities were developed with stakeholders before quantitative modeling took place in order to assess their technical feasibility. Resource allocation scenarios were subsequently applied that represent consistent options to implement future visions. Finally, multi-criteria assessment was used to assess the consequences of visions and scenarios on multiple criteria that were defined by stakeholders (Trutnevyte et al., 2011). Zelt et al. (2019) provide another application of multi-criteria analysis to assess future visions, namely visions of future power systems in Jordan, Morocco, and Tunisia. In this study, possible target power systems (a mix of different power generation technologies and different energy sources such as renewable energies, coal, natural gas and uranium) for the year 2050 were first developed for each country. An hourly resolved electricity system model subsequently validated that the discussed technology mixes would be able to cover the expected electricity demand and supply in 2050. Finally, in stakeholder workshops, multi-criteria analysis was used to select those target systems that met the preferences of the participants (Zelt et al., 2019).

While singular vision modeling studies exist, as illustrated above, a comprehensive conceptual and methodological framework for quantitative vision modeling and assessment is currently missing. In particular, methodologies for integrated and participatory assessment of sustainable energy systems are required that, on the one hand, address complex interdependencies of central system variables and, on the other hand, can deal with technical, economic, environmental and social aspects. System dynamics modeling is a suitable method for integrated modeling and assessment (Ness et al., 2009), but its application for vision modeling in general and energy systems modeling in particular has been limited. The following section presents such a framework for integrated and participatory vision modeling and assessment using system dynamics.

7.3 Methodology: Vision Design and Assessment (VDA) Framework

Halbe and Adamowski (2019) developed a preliminary version of a stepwise methodological framework for the design and assessment of visions for sustainable supply systems (e.g., energy, water or food supply). The Vision Design and Assessment (VDA) framework is based on a concerted set of methods from systems engineering and integrated modeling, including the functional analysis method for the design of visionary supply systems (Halbe et al., 2014), causal loop diagrams (CLDs) as a qualitative participatory modeling method for structural analysis (Halbe et al., 2015b, 2018), and fuzzy cognitive mapping (FCM) to analyze the trade-offs and consequences of sustainability visions (e.g., Reckien, 2014; Jetter and Kok, 2014; Halbe and Adamowski, 2019) (Steps 1.1 – 1.3 and left side of Step 2.1 in Figure 7.1). In the current article, the VDA framework is further developed by adding quantitative system dynamics modeling for vision assessment, which allows for a more in-depth analysis of vision dynamics. In addition, a model testing approach is provided that supports the systematic investigation of uncertainties (see right side of Step 2.1 and Step 2.2 in Figure 7.1). In the following sections, each step of the VDA framework is presented in more detail, with a focus on the development and testing of system dynamics models in Steps 2.1 (see section 7.3.4) and 2.2 (see section 7.3.5).

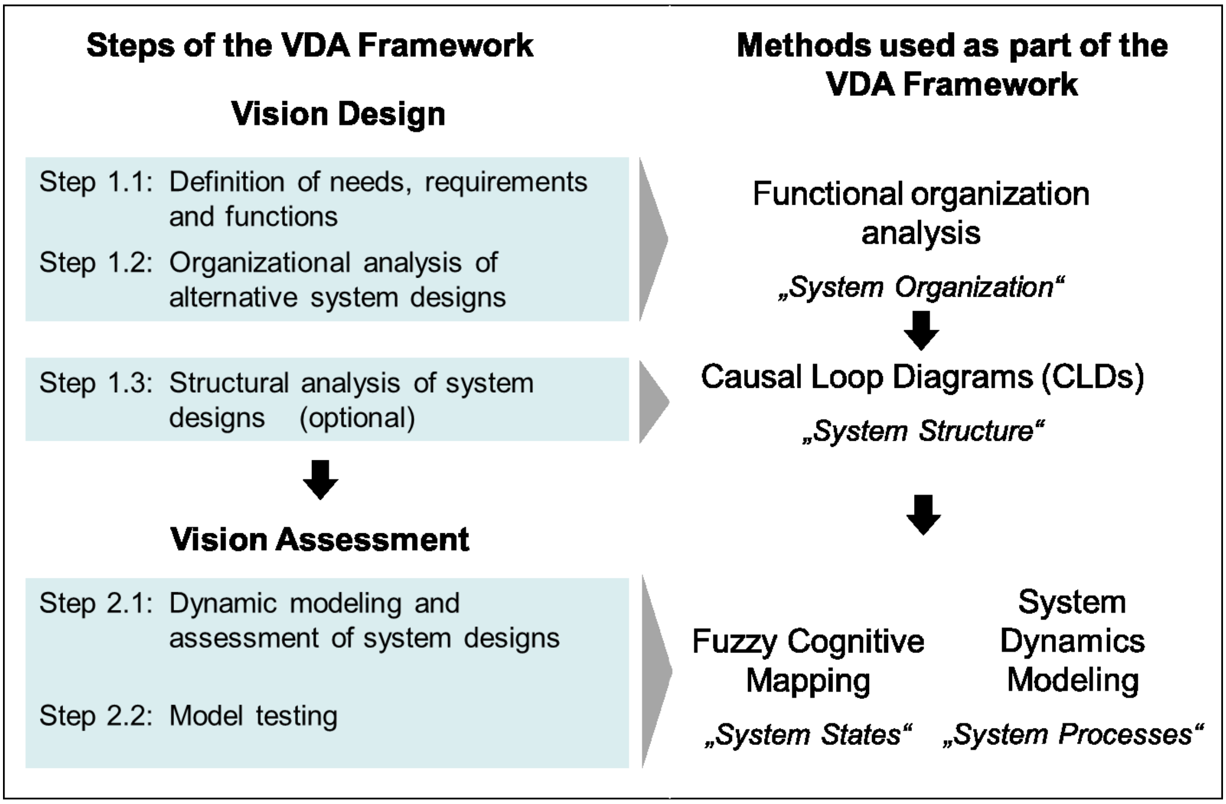


Figure 7.1: The extended Vision Design and Assessment (VDA) framework, based on Halbe and Adamowski (2019). System dynamics modeling (Step 2.1) and a systematic model testing approach have been added to the framework.

7.3.1 Definition of needs and requirements

Step 1.1 of the VDA framework involves the specification of (1) needs that are supported by the vision (e.g., water supply), (2) requirements that are linked to the vision (e.g., low carbon footprint and resource requirements), and (3) functions that are structures and processes (e.g., technical infrastructure and ecosystem processes) required to satisfy a need. Requirements and functional analysis methods originally stem from the field of systems engineering where they are applied for conceptual and preliminary system design (Blanchard and Fabrycky, 2006). The methods support a purposeful design of systems by specifying the performance requirements of the system as well as primary and secondary system functions.

The first step of requirements analysis is the elicitation of requirements from a customer or other stakeholders (Nuseibeh and Easterbrook, 2000). This includes the identification and analysis of relevant stakeholders and their needs with regard to a specific engineering system. In the next steps, stakeholder requirements are translated into system requirements, upon which alternative designs are developed (Hull et al., 2005). There is a large body of work on communication technologies and methods that support the analysis of requirements (see Chakraborty et al., 2010). Stakeholder analysis, interview techniques and literature analyses can be applied for requirement elicitation (Nuseibeh and Easterbrook, 2000). Originally applied in software development, requirements analysis is used in various application areas, such as infrastructure planning (e.g., Masood et al., 2016) and structural design (e.g., Jansson et al., 2013).

7.3.2 Functional Organization Analysis (FOA)

In Step 1.2, functional organization analysis (FOA) is applied to analyze the interconnection of functions and the specific structures and processes that provide them. Halbe et al. (2014) present a FOA approach for the joint design of ecological and technical systems that builds upon conventional functional analysis from systems engineering. The hierarchy of functions is examined in a participatory process using the conceptual modeling tool CMaps (Novak and Canas, 2008). After the needs and requirements (e.g., secure power supply) and the system's primary and subsidiary functions (e.g., electric power transmission) are specified, structures and the processes underlying the functions are determined (e.g., overhead lines). Alternative system designs can be based upon different technical and ecological structures at various scales. For instance, food system designs can comprise local, diversified farming approaches (i.e., focus on the utilization of ecosystem services at a local scale) as well as global, commodity-based systems (i.e., input-based with less focus on the utilization of ecosystem services at a global scale) (Halbe et al., 2014; Therond et al., 2017).

7.3.3 Structural analysis

Based upon results of the FOA, a more detailed analysis of alternative system designs is needed to test design applicability and assess their economic, ecological and social performance. This can be achieved by directly developing a system dynamics model (see Step 2.1) or building a CLD in a preceding step (see Warren, 2012, on agile system dynamics modeling processes in which quantitative modeling is applied from the beginning). In the optional Step 1.3, CLDs are applied to analyze linkages between needs, functions and system requirements. CLDs are flexible and transparent tools that depict causal relationships between concepts (Sterman, 2000).

CLDs for individual system designs can be built by experts and stakeholders in the scope of a participatory modeling process. Halbe et al. (2015b) present a participatory modeling method using CLDs to analyze sustainability innovations that can also be applied for analyzing broader visionary system designs. Sustainability innovations are specific "innovative approaches for the provision of societal functions (e.g., for water, energy and food supply), which reside at a niche level today, but might be important elements of a sustainable supply system in the future" (Halbe et al., 2015b, p. 2). In contrast to niche-level innovations, sustainability visions are broader, regime-level phenomena (see multi-level perspectives of sustainability transitions, Geels, 2005). In summary, the application of the participatory modeling method described in Halbe et al. (2015b) begins with a particular sustainability innovation, while in the VDA framework a general sustainability vision is chosen as a starting point in order to define a more specific visionary system design structure.

In the first step of the participatory modeling process, the stakeholder interviewee is asked to find a general term for the desired sustainability vision (such as a renewable energy system or a local food system). This term is written on a sticky note and is used as a starting variable. In the second step, the consequences of this vision are added (e.g., a link to a requirement or an ecosystem service), which can be directly linked to the starting variable or to another variable that has already been added to the model (i.e., forming an indirect link). After several relevant variables have been written on sticky notes, causal linkages are drawn between them; these can have a negative or a positive polarity. A positive link is set if variables behave in the same direction, i.e., if an increase in the causing variable promotes an increase in the affected variable, while a decrease in the causing variable implies a decrease in the affected variable. A negative link represents an inverse relation between variables. In the third step, potential influencing factors are added to the model. These can be factors that either support or impede the sustainability visions. In the fourth step, feedback loops are drawn that connect consequences and influencing factors through causal linkages. In the fifth step, scenario variables, such as societal or environmental crises that may have a profound impact on the performance of the supply system, are added to the model. Models resulting from individual interviews can be merged into a comprehensive system structure for each sustainability vision (see Inam et al. 2015 for details on the merging process).

7.3.4 Dynamic modeling and assessment

In Step 2.1, vision assessment is finally accomplished by using FCM (Jetter and Kok, 2014) or system dynamics modeling (Sterman, 2000). Both modeling approaches require the definition of context conditions (i.e., scenario variables) in which the performance of system designs is assessed using the system requirements from Step 1.1 as sustainability indicators.

FCM is a semi-quantitative modeling method that allows for the analysis of complex systems including feedbacks and multi-causalities. FCMs are a kind of recursive neural network (Kosko, 1993) in which causal links are weighted by assigning numerical values in the range of -1 to 1. These weights can be set based upon empirical data or stakeholder interviews (Jetter and Kok, 2014). During simulation of FCMs, impulses pass through the network structure until a stable state or a limit cycle is reached. Variables usually attain values between 0 and 1 depending on the choice of the "squashing function", such as a bivalent exponential function. Another option is the use of a trivalent function, which computes variable values between -1 and +1. Even though being quantitative in nature, the results of a FCM exercise need to be qualitatively interpreted by comparing the relative difference between variable values (i.e., variable X increases more significantly than variable Y in a given scenario).

In contrast to the FCM approach, which allows for the analysis of system states, system dynamics modeling is a continuous modeling approach that allows for a more detailed and time-sensitive systems analysis. System dynamics models support the analysis of stock-and-flow dynamics (i.e., accumulation), feedback processes and multi-causality (Sterman, 2000). The relationships between variables can be defined using mathematical functions as well as table functions (Sterman, 2000). Compared to FCM, system dynamics models allow for the development of more realistic models (e.g., by using physical units) and much more sophisticated analysis of system dynamics (e.g., accumulation and oscillations). However, compared to a FCM approach, system dynamics models generally require more expertise to define functional relationships, set parameters and systematically test the model. System dynamics aims to capture the full complexity of a topic, rather than reducing the model boundary and structure to aspects that are well understood and for which the parameters are at hand (Forrester, 1980). Several approaches have been developed to quantify uncertain relationships (e.g., Forrester, 1980) and examine the influence of parameter uncertainty on model output (e.g., Ford and Flynn, 2005).

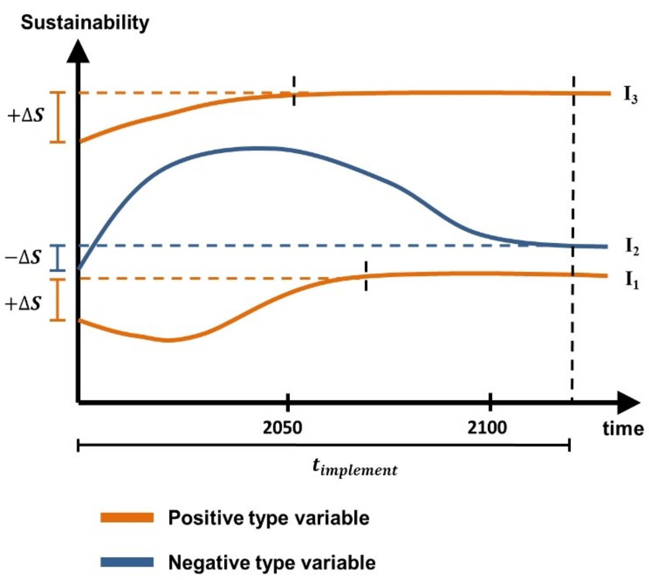


Figure 7.2: Development of variables within a system dynamic model over time.

As dynamic vision modeling and assessment aim at analyzing visionary system designs, a vision model based on system dynamics does not examine potential pathways of the implementation process of a vision, but the coherency of the envisioned future state. In the end, a system dynamics-based vision model allows for analysis of a seemingly fixed vision state, which in fact either resides in a dynamic equilibrium (i.e., state variables do not change, due to corresponding in- and outflows) or limit cycle (i.e., state variables are oscillating). A gradual implementation of the vision is assumed without including implementation barriers and supporting policies in the model structure. Instead, the implementation of technological, social or nature-based innovations is simplified by using a logistic growth function (cf. Davidsson et al., 2014; Hansen et al., 2017). The use of learning curves is another simplification to calculate cost reductions resulting from an increase of cumulated production (cf. Ferioli et al., 2009). The model runs from the present into the distant future in which the vision is fully implemented, i.e., until sustainability indicators remain stable and the system has reached a dynamic equilibrium (see $t_{implement}$ in Figure 7.2). Sustainability indicators can be positive-type indicators (i.e., they are meant to increase; I_1 and I_3 in Figure 7.2), such as water quality, and negative-type indicators (i.e., they are meant to decrease; I_2 in Figure 7.2), such as CO_2

emissions. Vision assessment focuses on analyzing the states of sustainability indicators after a dynamic equilibrium is reached. Thus, the achievement of sustainability indicators and potential trade-offs (i.e., some sustainability indicators improve, such as I_1 and I_3 in Figure 7.2 while others worsen, such as I_2) are assessed. In addition, temporal dynamics can be analyzed, such as worse-before-better dynamics (cf. dynamic of I_1 in Figure 7.2).

7.3.5 Model testing

As mentioned in the introduction, the testing of vision models presents particular challenges, due primarily to the lack of empirical data. Walker et al. (2003) distinguish between three different dimensions of uncertainty, namely the uncertainty *level* (ranging from deterministic knowledge to total ignorance), *location* in a system model (e.g., model structure uncertainty or parameter uncertainty) and *nature* (imperfect knowledge or natural variability). The nature of uncertainty specifies whether uncertainty is of epistemic nature (i.e., more research would be helpful to reduce uncertainties) or ontological nature (i.e., uncertainties cannot be reduced by further research due to inherent variability). The other two dimensions of uncertainty (level and location) are discussed in more detail, as they are highly relevant for developing a practical approach to address uncertainties in vision models.

The level of uncertainty has been conceptualized by Walker et al. (2003) as a continuum including statistical uncertainty, scenario uncertainty, recognized ignorance and total ignorance. *Statistical uncertainty* comes nearest to the ideal of determinism. This uncertainty level can be dealt with by deterministic modeling and probabilistic modeling techniques (e.g., Liu and Gupta 2007). If a topic only involves statistical uncertainty, future projections can converge and allow a 'forecasting' approach (cf. mode 1 orientation of futures research, Grunwald, 2014). The next level of uncertainty is called *scenario uncertainty*, which is linked to phenomena for which probabilities cannot be set and only alternative plausible 'foresights' (i.e., alternative future developments) can be identified (cf. mode 2 orientation of futures research, Grunwald, 2014). For this level of uncertainty, the scenario method is a helpful approach to explore alternative system trajectories (cf., Mahmoud et al. 2009). Thus, scenarios are located in a plausible corridor (e.g., between a best case and a worst-case scenario), which allows for the design of 'robust strategies'. However, there are also processes where the model structure, parameters, functional relationships and potential outcomes are ambiguous or totally unknown so that even a plausible corridor of scenarios cannot be established. This level of uncertainty is called *recognized ignorance*. Participatory model building can help to deal with such a high level of uncertainty as assumptions are set and discussed transparently with stakeholders (e.g., Vennix 1996). In addition, Grunwald (2014) proposes semantic and hermeneutic approaches to provide orientation for a reflected debate and decision-making (cf. mode 1 orientation of futures research). Research at this uncertainty level does not provide insights into the future itself (due to the irreducible divergence of future visions), but about the present state of society, including diverging values, fears and perceptions that influence discussion processes about the future. By making the implicit process of visioning explicit, a more informed and transparent democratic debate is possible. Finally, *total ignorance*_acknowledges that there will always be surprises, i.e., factors that were not anticipated during the model building process will influence model behavior. Therefore, models need to be continuously adapted to include new knowledge or policy options. The institutionalization of participatory modeling processes offers a means to implement long-term social learning processes (Halbe et al., 2018).

Uncertainties can furthermore arise from several different model locations (Walker et al., 2003). For example, contextual uncertainties address ambiguity in the selection of the system boundary. Uncertainties can be linked to the model structure as well as to the choice of model technique. Model input uncertainties address external forces that have an impact on system dynamics. Parameter uncertainty is related to uncertainties in setting model parameters. Together, these uncertainties influence model outcome uncertainty, which is related to indicators that are relevant for decision-making.

In general, modeling of sustainability visions usually involves each of the sources of uncertainty mentioned above. Here, we propose a multi-method approach to systematically address all uncertainty levels and locations, as well as the specific challenges of sustainability vision modeling (i.e., lack of data for model calibration and validation). Table 7.1 provides an overview of each of the proposed approaches for uncertainty analysis and management that are part of the VDA framework, and list their benefits in terms of handling different dimensions of uncertainty. In the following section, each approach is explained in more detail.

Table 7.1: Approaches applied as part of the VDA framework to manage different dimensions of uncertainty.

		Approaches for managing uncertainties in the VDA framework				
Uncertainty dimension		Integrated Assessment framework / system dynamics	Scenario analysis	Sensitivity analysis (global / local)	Model-to-model analysis	Expert assessment
Level	Statistical uncertainty	+		++		++
	Scenario uncertainty	+	++			++
	Recognized ignorance	+			+	++
Location	Model boundary	++			+	++
	Model structure	+	++		+	+
	Model technique / paradigm				++	+
	Input variables	++	+			+
	Parameters	+	+	++		+
	Model outcomes	+	+	++	++	+

+: approach considers this uncertainty dimension; ++: approach focuses on addressing this uncertainty dimension

7.3.5.1 Integrated assessment framework using system dynamics modeling

Integrated assessment (IA) aims at solving sustainability issues from an integrated viewpoint and therefore provides guidance in selecting appropriate model boundaries as part of the VDA framework. Various definitions of IA exist (Parker et al., 2002). A widely used definition considers IA as "[…] an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena" (Rotmans and van Asselt, 1996). Such an improved understanding of sustainability issues is aimed at informing policy and decision making. System dynamics is a specific IA method (Ness et al., 2007) supporting stakeholder participation (e.g., van den Belt, 2004) and integration of disciplinary knowledge (e.g., Sterman, 2001), each of which have an impact on most dimensions of uncertainty (see Table 7.1).

Therefore, the VDA frameworks includes system dynamics modeling, which allows a systematic handling of statistical and scenario uncertainty (e.g., Homer and Hirsch, 2006) as well as recognized ignorance through using system dynamics in a participatory modeling process (e.g., van den Belt, 2004). IA further expands the model boundary towards inclusion of relevant social, economic and environmental aspects of an issue. In addition, the IA framework encourages the inclusion of stakeholders in the definition of a suitable model boundary as well as other uncertainty dimensions, such as model structure uncertainty. In this respect, system dynamics aims to secure an endogenous explanation of system behavior so that the influence of input variables on model output is minimized (Sterman, 2000).

7.3.5.2 Scenario analysis

Scenario-building can be a useful approach for dealing with highly uncertain model parameters and variables for which uncertainty cannot be expressed through probability distributions (Walker et al., 2003). Scenarios for the analysis and assessment of sustainability visions represent sub-designs of the vision, potentially including alternative model structures, input variables and parameters. For example, visionary sub-designs could comprise supply systems at a household, regional and international scale (cf. Halbe et al., 2014). These sub-designs include different types of technologies, infrastructures and resource requirements and represent distinct system structures. Alternative designs of renewable energy systems that provide 100% or 80% of electricity by renewables or different context conditions (e.g., climate change impacts or resource limitations) are examples of sub-designs based on different parameter values that can be assessed through different scenarios. Scenario analysis is therefore included in the VDA framework to deal with scenario uncertainty and model structure uncertainty. By comparing sustainability indicators across all scenarios, superior scenarios, those with higher sustainability benefits, can be identified. In addition, scenario analysis can reveal trade-offs between sustainability indicators.

7.3.5.3 Global and local sensitivity analyses

Sensitivity analysis helps to assess the influence of statistical uncertainties on model outputs by varying parameter values in a predefined range. Global sensitivity analysis methods, such as Monte Carlo sampling, vary various parameters simultaneously. Local sensitivity analysis methods, such as the statistical screening approach by Ford and Flynn (2005), vary parameter values individually while all other parameters are set to their nominal value (Schouten et al., 2014). Agusdinata (2008) reviews several sampling methods that create parameter combinations in the uncertainty space to perform a global sensitivity analysis. Random Monte Carlo sampling is a widely applied and convenient technique but has some limitations in the coverage of the uncertainty space in comparison to Latin Hypercube samplings. Latin Hypercube sampling has been shown to be the most efficient sampling approach for models with a large number of parameters (McKay et al., 1979); for this reason, Latin Hypercube sampling is the method proposed for the global sensitivity analysis of the sustainable vision model in the current VDA framework.

Local sensitivity analysis methods aim to identify the influence of particular parameters on model output. Ford and Flynn (2005) present a statistical screening approach to define key influencing parameters on model outputs at different time steps in system dynamics models. Their step-by-step approach (based on Ford, 1990) is applied as part of the current VDA framework. The steps are as follows: (1) uncertainty ranges are set for each parameter, (2) Latin Hypercube sampling is used, (3) simulations are performed (50 runs are recommended by Ford and Flynn (2005)) and (4) correlations between parameter values and selected model outcome variables at different time steps are calculated. The correlation coefficients of all parameters can be plotted over time, which allows for assessment of changes in parameter influence through time. After identifying the most influential parameters, the model can be refined, for instance by endogenizing parameters (i.e., adding a model structure that represents processes behind these parameters in more detail).

7.3.5.4 Model-to-model analysis

Model-to-model analysis, also called meta-analysis, involves the comparison of different models that have been built on similar topics. There are various application areas for model-to-model analysis, as categorized by Rouchier et al. (2008). During the analysis, model designs can be compared and models replicated to verify and critique model findings. Another application area is the comparison of models with a different degree of complexity that operate at different spatial, organizational or temporal scales. Model findings can be compared across different modeling methods (e.g., an agent-based model and a system dynamics model) and paradigms (e.g., vision models and exploratory scenarios). Model-to-model analysis can also support the classification of models and identify appropriate reuse applications.

Due to the normativity and complexity of sustainability visions, model-to-model analysis is an important component of the VDA framework. Model-to-model analysis helps to consolidate knowledge and evaluate model paradigms, boundaries, structures and outcomes (see also Halbe et al., 2015a). Often various models exist to address a particular sustainability issue, with variations based on different modeling methods (e.g., agent-based modeling, system dynamics modeling or multi-criteria analysis) or area of focus (e.g., resource management, technical infrastructure or ecosystem health). For instance, several models exist to analyze the potential of renewable energy systems (e.g., Kronenberg et al., 2012; Melikoglu, 2013; Child and Breyer, 2016). Model comparison can reveal congruent and divergent findings among modeling studies. Thus, results of sustainability vision models built using the VDA framework should be compared to other thematically related modeling studies using model-to-model analysis. Comparative model analyses can however be challenged by limited information about the model (Dieckhoff et al., 2014), such as information on model boundaries, equations and parameter values.

7.3.5.5 Expert assessment

Expert assessment is an established methodology able to manage all uncertainty dimensions (for an overview on the role of expert opinion in modeling, see Krueger et al., 2012). The *expert* term includes not only technical or scientific experts in a particular field, but is used to broadly include stakeholders (cf. Krueger et al., 2012) who are “experts in aspects of the system being discussed” (Anderson and Richardon, 1997, p. 109). Expert assessment can be applied to quantify statistical uncertainty (e.g., O’Hagan, 2012), and the participation of experts in scenario design can be used to address scenario uncertainty (e.g., Lienert et al., 2006). Experts can help manage recognized ignorance by providing advice on vision model boundaries (e.g., through the use of conceptual models, cf. Engelen, 2004). Experts can also be consulted to guide the selection of a system structure, input variables, parameters and outcome variables (cf. van den Belt, 2004).

As part of the VDA framework, expert advice should be obtained, ideally, with regard to all dimensions of uncertainty, as specified in Table 7.1, in the scope of individual interviews or workshops. In particular, we recommend involving experts to address the uncertainty level of ‘recognized ignorance’, as this is the only uncertainty dimension which is not mitigated by the other approaches (i.e., the row does not show '++' related to other approaches). This can be achieved through discussions of aspects of sustainability visions that are not included in the model, as well as general societal trends (e.g., demographic changes) that might be linked to particular system designs.

7.4 Discussion

The VDA framework addresses a significant research gap in the model-based design and assessment of future visions. The analysis of potential pathways into a sustainable future has been the subject of numerous modeling studies that apply an explorative or backcasting scenario approach. However, the modeling of a desirable future system state has been only addressed by a limited number of studies (see Section 7.2.2) without using a systematic conceptual and methodological framework. In particular, the conceptualization of vision assessment scenarios as a specific sub-category of anticipatory scenarios is an innovative contribution of this article. The specification of this scenario category helps to sharpen the purpose of scenario studies, as target and transformation knowledge have been often jointly generated in previous studies. Based upon the conceptualization of vision assessment scenarios, future energy system modeling studies could specifically focus on the generation of target knowledge and benefit from this conceptual clarity.

One of the benefits of focusing on the development of target knowledge is that it leads to simpler models, as aspects pertaining to the implementation of visions (e.g., policies or resource price dynamics) are not included. Thereby, the development of vision assessment scenarios tends to require less time and can be conducted as a preparatory study to define consistent future system states that can later be used in explorative or backcasting scenarios. Simpler models can also support stakeholder engagement, as models remain more understandable for non-modelers. Finally, the simpler formation of vision models leaves room for a more integrated modeling approach that also considers environmental and social aspects of energy systems in more detail.

By using methods from systems science and systems engineering, the VDA framework provides a structured methodology for an integrated modeling of sustainability visions, including technical, economic, environmental and social aspects. The functional analysis method required some further development in order to extend its traditionally technical focus to also include nature-based and social solutions (Halbe et al., 2014, 2020). Causal loop diagrams and system dynamics models have a long tradition of addressing complex issues and involving stakeholders in model development (e.g., van den Belt, 2004). Nevertheless, using system dynamics for vision design and assessment required some methodological considerations, as system dynamics is a continuous modeling approach (i.e., system dynamics analyzes the dynamics of systems through time).

The systematic approach to quality assurance in vision modeling and uncertainty handling addresses various uncertainty dimensions of model-based decision support. Several approaches to handle uncertainties in exploratory scenarios have been developed (e.g., Kwakkel, 2017). However, vision modeling and exploratory scenarios show profound conceptual differences, which necessitated research on quality assurance specifically for vision models. While this article presents the model testing approach and its conceptual and methodological background, a companion article shows an application to a case study on a fully renewable energy system in Germany (see Halbe et al., in review).

7.5 Conclusions

The VDA framework provides a structured approach to design and assess sustainability visions. This article presented the VDA framework and its conceptual and methodological background. The specification of vision assessment scenarios as a sub-category of anticipatory scenarios is an innovative contribution of this article that helps to specify the benefits of this modeling approach. Vision models aim at an integrated analysis and assessment of sustainability visions, including environmental, economic and social aspects. Furthermore, vision models tend to be simpler models, which can save time and financial resources and support the engagement of stakeholders in model development. The VDA framework specifies methodological steps for an integrated modeling and assessment of sustainability visions, such as energy system visions, using system dynamics modeling. A model testing approach is proposed to deal with the challenges of vision modeling, such as the lack of empirical data and the complexity of sustainability visions. Based upon the conceptual and methodological research presented in this article, a companion article provides an application of the VDA framework to the design and assessment of a fully renewable energy system in Germany.

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CONNECTING TEXT TO CHAPTER 8

Chapter 8 provides an application of the revised VDA framework (see Chapter 7) to a case study on the vision of a renewable energy system in Germany (Objectives 3 and 4). A system dynamics model was developed to design and assess different configurations of a renewable energy system. In the sustainability vision, electricity is mainly produced by fluctuating renewable energy sources (i.e., wind and solar energy). Energy storage is accomplished through Power-to-Gas and Power-to-Liquid technologies, which also support the coupling of energy sectors, i.e., the power, heating and mobility sectors. The simulation results show various trade-offs within the sustainability vision. For example, CO_2 emissions can be significantly reduced, but space requirements and energy costs increase at the same time. System dynamics modeling allowed for an assessment of these trade-offs in quantitative terms. In addition, context-specific limitations were revealed, such as the limited renewable energy potential in Germany to fuel the mobility sector. The model testing approach allowed for a systematic account of different types of uncertainties involved in vision modeling. Critical parameters could be identified that require more research to reduce uncertainties and set realistic values.

This chapter was submitted to the Energy Journal (Halbe et al. 2021b). The format of the article has been modified to ensure consistency with the style of this thesis. A list of references cited in this article is provided at the end of the chapter. The author of the thesis developed, tested and applied the conceptual and methodological framework and wrote the manuscript presented here. The system dynamics model presented in Chapter 8.2.3 was developed in cooperation with Stefan Gausling, former Master's Student at the Institute of Environmental Systems Research, Germany. Stefan Gausling developed a model prototype with Johannes Halbe that included the generation of renewable energy, its conversion into synthetic natural gas (i.e., the Power-to-Gas component), and the calculation of several sustainability indicators. In addition, Stefan Gausling was involved in the organization of a stakeholder workshop aimed at the discussion of model results. The model was revised by Johannes Halbe and extended to also include Power-to-Liquid technologies and a detailed account of energy demand dynamics. Model testing was conducted by Johannes Halbe, including global and local sensitivity analysis. Dr. Peter Viebahn, Wuppertal Institute for Climate, Environment and Energy, Germany, contributed to the review and editing of the manuscript and provided valuable advice on all parts of the article. Prof. Adamowski, the supervisor of this thesis, gave advice on all aspects of the research and contributed to the review and editing of the manuscript.

Chapter 8: Vision modeling and assessment using system dynamics – Part 2: Application to a sustainable energy system in Germany based upon Power-to-Gas and Power-to-Liquid technologies

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Abstract

The Vision Design and Assessment (VDA) framework guides the design and assessment of sustainability visions by specifying a concerted set of modeling methods from systems science and systems engineering, including functional analysis, causal loop diagrams and system dynamics modeling. As part of the framework, a model testing approach is proposed to assure the coherence, plausibility and desirability of sustainability visions. A companion article presented the VDA framework and its conceptual and methodological background. This article shows an application of the framework on a visionary renewable energy system for the supply of power, space heating and mobility in Germany based upon Power–to-Gas (PtG) and Power–to-Liquid (PtL) technologies. The results support the comparison of system designs by using various sustainability indicators such as CO2 emissions, space requirements and energy costs. In the end, a fully renewable energy system for the supply of electricity and gas using PtG technologies is revealed to be a feasible vision with promising sustainability benefits. However, given the German capacity for renewable energies, this energy system design only partially meets liquid fuel demand. These results highlight the importance of renewable energy imports, e.g., from other European countries or the Middle East and North Africa (MENA) region.

Keywords: sustainability visions; vision assessment; system dynamics modeling; uncertainty analysis; power-to-gas; power-to-liquid

8.1 Introduction

The governance of transitions towards renewable energy systems is a pressing sustainability challenge, which is reflected in various research and policy initiatives. For example, the Future Earth Knowledge-Action Network on the Water-Energy-Food Nexus highlights the interconnectedness of energy systems to other basic needs for water and food. From a policy perspective, the Sustainable Development Goals (SDGs) underline the ambition of states around the world to increase the use of renewable energy globally (UN, 2015, 2018). National strategies further specify goals and measures for achieving the SDGs. For example, Germany has the goal to increase the share of renewable energy production in relation to the gross final energy consumption from 14.9 % in 2015 to 30 % in 2030 and 60 % in 2050 (Bundesregierung 2018). The share of renewable energy production in relation to the gross electricity consumption is even planned to increase from 31.9 % in 2015 to 80 % in 2050 (Bundesregierung 2018). How exactly this transformation can be achieved is, however, still debated. Thus, the generation of target knowledge (Where do we want to go?) and transformation knowledge (What are potential paths to get there?) of future energy systems is still required.

A companion article presented the Vision Design and Assessment (VDA) framework, a methodological framework to generate target knowledge through model-based assessment of sustainability visions (Halbe et al., in review). Vision design is accomplished through the definition of needs requirements and functions (Step 1.1) and organizational analysis of alterative system design (Step 1.2). Vision assessment comprises the dynamic modeling and assessment of system designs (Step 2.1) and model testing (Step 2.2). This article applies the VDA framework to a vision for a sustainable energy system in Germany using system dynamics modeling.

System dynamics modeling allows the analysis of sustainability issues in an integrated way (i.e., considering technical, economic, environmental and social factors). There is a long tradition in the system dynamics modeling community to analyze sustainable energy systems as an alternative to fossil fuels (e.g., Naill, 1977; Sterman, 1982). However, system dynamics models usually focus on specific renewable energy technologies (e.g., biomethane, see Barisa et al., 2020), sustainability issues (e.g., policy resistance, see Kelly et al., 2019) or sectors (e.g., electricity production, see Aslani and Wong, 2014). In a review of system dynamics applications in the modeling of renewable energy systems, Saveedra et al. (2018) underline that integrated frameworks for system dynamics modeling that address the full supply chain of energy systems are lacking. Some notable exceptions exist, such as the UniSyD model that focuses on the analysis of sustainable transportation pathways and also includes resource use and electricity generation (Leaver et al., 2009). The model has been applied to energy systems in New Zealand (e.g., Shafiei et al., 2017) and Iceland (e.g, Spitter et al., 2020). However, a system dynamics model focusing on the generation of target knowledge, i.e., the integrated assessment of a vision of a sustainable energy system, is missing according to our knowledge. Instead, system dynamics modeling of energy systems generally focuses on the examination of policies (e.g., Aslani et al., 2014; Robalino-Lopez et al., 2014; Barisa et al 2020), which is related only to transformation knowledge. Another research gap is related to systematic testing approaches for vision modeling using system dynamics, which pose special challenges due to high uncertainties involved with the modeling of future system designs. Previous quantitative vision modeling studies did not explicitly address this challenge.

This article addresses the aforementioned research challenges by applying the VDA framework (Halbe et al., in review) to the design of a visionary, fully renewable energy system based upon Power-to-Gas (PtG) and Power-to-Liquid (PtL) technologies in Germany. First, a system dynamics model for assessing this vision is presented, specifically focusing on the generation of target knowledge. Second, the systematic model testing approach is applied to deal with the uncertainties involved in modeling future visions using system dynamics.

The structure of the article is as follows: Section 8.2 provides the design of the visionary energy system, along with its implementation in a system dynamics model. Section 8.3 presents the modeling results, followed by the testing results in Section 8.4. Finally, discussion and conclusions sections complete the article.

8.2 Design of a sustainable energy system based upon Power-to-Gas (PtG) and Power-to-Liquid (PtL)

This section presents the design of a future vision of a fully renewable energy system for power, space heating and mobility in Germany, which will be assessed through a system dynamics modeling approach. PtG and PtL technologies have been chosen as core technologies in this energy system vision. The original idea behind the Power-to-X (PtX) concept is to convert excess electricity from the fluctuating power generation of renewable energies into hydrogen (H_2) through electrolysis (e.g., Gahleitner, 2013). In the next process step, H_2, together with CO_2 or CO, is converted into methane (Synthetic Natural Gas (SNG)) using methanation technologies, into methanol or dimethyl ether (DME) using methanol synthesis or DME synthesis (see Bailera et al., 2017 for an overview on chemical reactions and technological options) or into higher hydrocarbons via Fischer-Tropsch synthesis and subsequently into gasoline, diesel and kerosene. All fuels produced in this way can be stored and transported using existing gas and liquid fuel infrastructure. The production of H_2 or SNG provides the opportunity to store surplus electricity in the gas grid and to re-use it as needed (i.e., re-conversion) or, alternatively, to make the stored gas available to other consumption sectors such as mobility and heat supply industries (Dena, 2015). Methanol and DME can be used in the heating and mobility sector as well (e.g., Varone and Ferrari, 2015). Such a visionary energy system offers energy storage options and long-distance energy transmission using, primarily, existing infrastructure, while promoting the integration of the mobility, heat and power supply sectors ("sector coupling"). However, considerable energy losses occur in the conversion process from electricity into gaseous and liquid fuels, presenting a major challenge. Further research and development are needed to reduce costs and improve conversion efficiencies. In addition, for the long-term success of such an energy system, the integration of basic industries will be increasingly important. This can be achieved through, for example, using hydrogen-based steel making processes (UBA, 2014; Lechtenböhmer et al. 2016).

In the subsequent sections, the VDA framework is applied to the design of a fully renewable energy system. First, requirements of renewable energy systems are presented (Section 8.2.1), followed by an exploration of the design of an energy system based upon PtX using functional analysis (Section 8.2.2) and subsequently, the development of a system dynamics model of the energy vision (Section 8.2.3). The optional step of the VDA framework, the construction of causal loop diagrams (CLD) of the system designs, is skipped here due to length constraints.

8.2.1 Definition of needs and requirements

Various requirements are associated with a fully renewable energy system. These can be sorted into the categories of ecological, economic and social requirements. An ecological requirement is the minimization of space for wind turbines and solar parks, as well as for air capture facilities to mitigate negative effects on biodiversity and other ecosystem services (Gasparatos et al., 2017). Low greenhouse gas (GHG) emissions are another requirement related to the reduction of climate change impact. In terms of economic requirements, the total system costs as well as the energy costs should be considered. Levelized Cost of

Electricity (LCOE) and levelized costs of SNG (LCOS) can be used as proxies for the latter, which is calculated based on plant construction and operation costs (e.g., Kost et al., 2018). In regard to social requirements, the security of supply has to be assured as well as the opportunity for participation; these can be supported by the decentralization of renewable energy supply due to a diversification in the ownership structure (Mautz, 2013).

8.2.2 Organizational analysis of alternative system designs

Figure 8.1 shows the results of a functional organizational analysis (FOA) of a visionary renewable energy system based on PtX. The function of power production is provided by wind (onshore and offshore), photovoltaics (PV), and hydropower. Electricity can be directly fed into the grid-type network and used for space heating, industrial purposes or e-mobility. Another option is to convert electrical energy into H_2, SNG, methanol or DME using PtG and PtL technologies. In the electrolysis process, electricity is used to decompose water (H_2O) into hydrogen (H_2) and oxygen (O_2). The hydrogen produced in this way can be fed into the natural gas grid up to a certain concentration (~10%, Sterner et al., 2012). Hydrogen can be converted into synthetic methane gas (CH_4)[15], liquid methanol (CH_3OH)[16] or DME (C_2H_6O)[17] by adding CO_2 (DLR, 2014). The feeding of the methane into the natural gas grid is possible at any time and limited only by the maximum storage capacity of the grid and the natural gas storage facilities (Dena, 2015). Biomass is also used to generate gas to be fed into the natural gas grid. Furthermore, solar heat serves as a second option for heat production.

[15] For details on the chemical reactions and potential technologies for methanation, see Rönsch et al., 2016.
[16] For details on the chemical reactions and potential technologies for the production of methanol using renewable energies, see Pontzen et al., 2011; Ganesh, 2014.
[17] For details on the chemical reactions and potential technologies for the production of dimethyl ether using renewable energies, see Semelsberger et al., 2006.

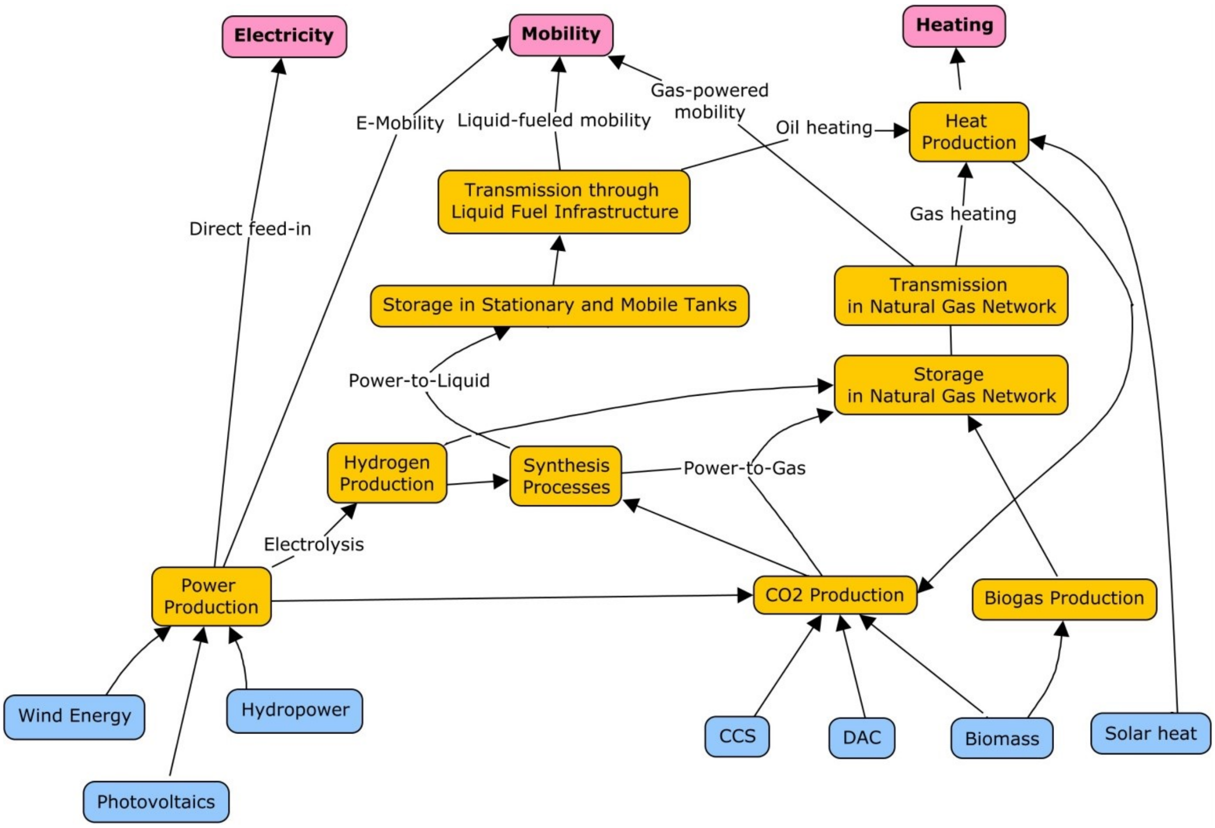

Figure 8.1: Simplified version of a functional organizational analysis (FOA).

A renewable energy system based upon PtX would render CO_2 an asset rather than a liability (Rubbia, 2012). Various CO_2 sources are available for fuel synthesis. It is possible to separate CO_2 from conventional power plants or biomass plants, to capture CO_2 emissions from industry or to extract it from the atmosphere (DAC, direct air capture) (Görner and Lindenberger 2014). In a carbon neutral economy, as it is intended here, only CO_2 from biomass or from the air would be viable, since the produced SNG, methanol and DME will be used for space heating, mobility, industrial applications or re-conversion into electricity, thereby releasing the CO_2 again. Since biomass is only available on a limited basis, DAC might be a more suitable method for a carbon neutral future. However, DAC requires considerable land and energy if applied at the scale needed for a fully renewable energy system (Viebahn et al., 2019). In our model, CO_2 is first taken from fossil fired power plants and gradually replaced by DAC to consider the need for building up a CO_2 infrastructure.

8.2.3 Model design

The simulation period starts in 2019 and ends in 2200 using yearly time steps. The extensive time horizon allows for a long-term analysis of the system's dynamics, which allows variable values to reach a dynamically stable state. The study area is Germany. Vensim DSS is used to apply a lumped modeling approach, with no spatial representation of the energy supply system. The model includes all major renewable energy technologies on the power generation side as well as conventional power plants until 2050 (i.e., a gradual phasing out is assumed). The potentials for onshore wind (350 GW, UBA, 2014), offshore wind (45 GW, UBA, 2010), PV (275 GW, UBA, 2010) and hydropower (5.4 GW, DLR et al., 2004) are set based upon previous studies. Additional capacity installation of renewable energies was modeled using a logistic growth term. The installed capacity for bioenergy is assumed to remain stable. Two scenarios are considered for final energy consumption in 2050, which both assume efficiency improvements (improved energetic refurbishment in the building sector) and a higher relevance of electricity and SNG in the mobility sector. In the reference scenario, electric energy and SNG are assumed to play a more dominant role in the power, heating and mobility sectors. In addition, moderate efficiency gains are assumed, which result in the following final energy consumption in 2050: electricity: 447.6 TWh, gas: 644.0 TWh; and liquid fuels: 558.0 TWh. More profound efficiency gains are assumed in electricity and gas consumption in an alternative demand scenario: electricity: 425.3 TWh; gas: 266.52 TWh; and liquid fuels: 558.8 TWh. Appendix 8.1 provides a detailed overview of the calculations that result in the aforementioned assumptions for final energy consumption.

The PtX technologies together with gas-fired power plants for electricity re-conversion are the connecting elements of the electricity, gas and liquid fuel sectors. Figure 8.2 shows the stock-and-flow structure of the major energy flows. The electricity grid is included as a stock but cannot take over storage functions in the annual energy balance, as the power grid itself can only store power for a relatively short period of time. If the energy demand cannot be settled by national gas and fuel sources, imports of natural gas and liquid fuels are assumed; possible surpluses can be exported. The installed capacity of the current power plant portfolio in Germany is based on the power plant list, which is published at regular intervals by the Federal Network Agency. It is furthermore assumed that excess power supply from renewable sources is first used to produce SNG (i.e., PtG) to minimize conversion losses. If the gas demand is fully settled by SNG, methanol and DME (i.e., PtL) are produced.

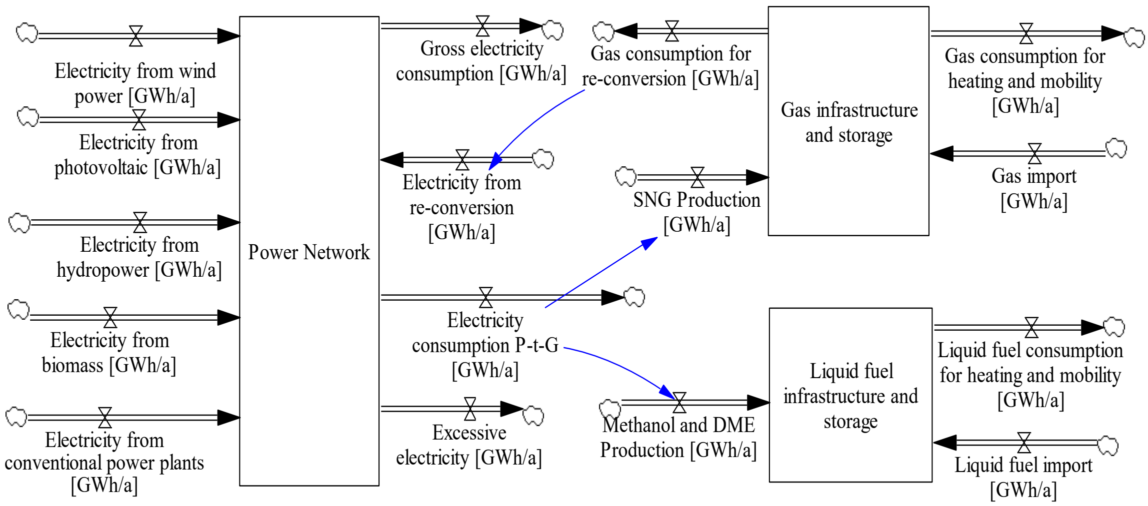

Figure 8.2: Simplified stock-and-flow structure of the system dynamics model.

8.3 Model results

The sustainability of the energy system is assessed using five scenarios, each representing another energy system design. In the scenario "PtX 3000", PtG technologies are implemented assuming an average of 3,000 full-load hours for electrolysis and methanization processes and a reference demand and renewable energy capacities as explained above. Further scenarios consider 2000 full load hours (PtX 2000) and 4000 full load hours (PtX 4000). The scenario "PtX 3000 Demand" includes 3,000 full-load hours and profound demand reductions for electricity, gas and liquid fuels (as described in section 8.2.3). Finally, the "PtX 3000 RE+" scenario considers higher capacities for onshore wind energy (410 GW) and solar energy (350 GW).

The following eight sustainability indicators that were identified from the requirement analysis (see Section 8.2.1) have been calculated for each scenario (see Figure 8.3): (a) share of renewable energy in power supply, (b) share of SNG in overall gas consumption, (c) levelized costs of electricity (LCOE), (d) levelized costs of SNG, (e) share of synthetic liquid fuels, (f) power supply GHG emissions, (g) net GHG emissions of the energy system (all energy-related emissions minus CO_2 absorption from air), and (h) space requirements for renewable energy infrastructure.

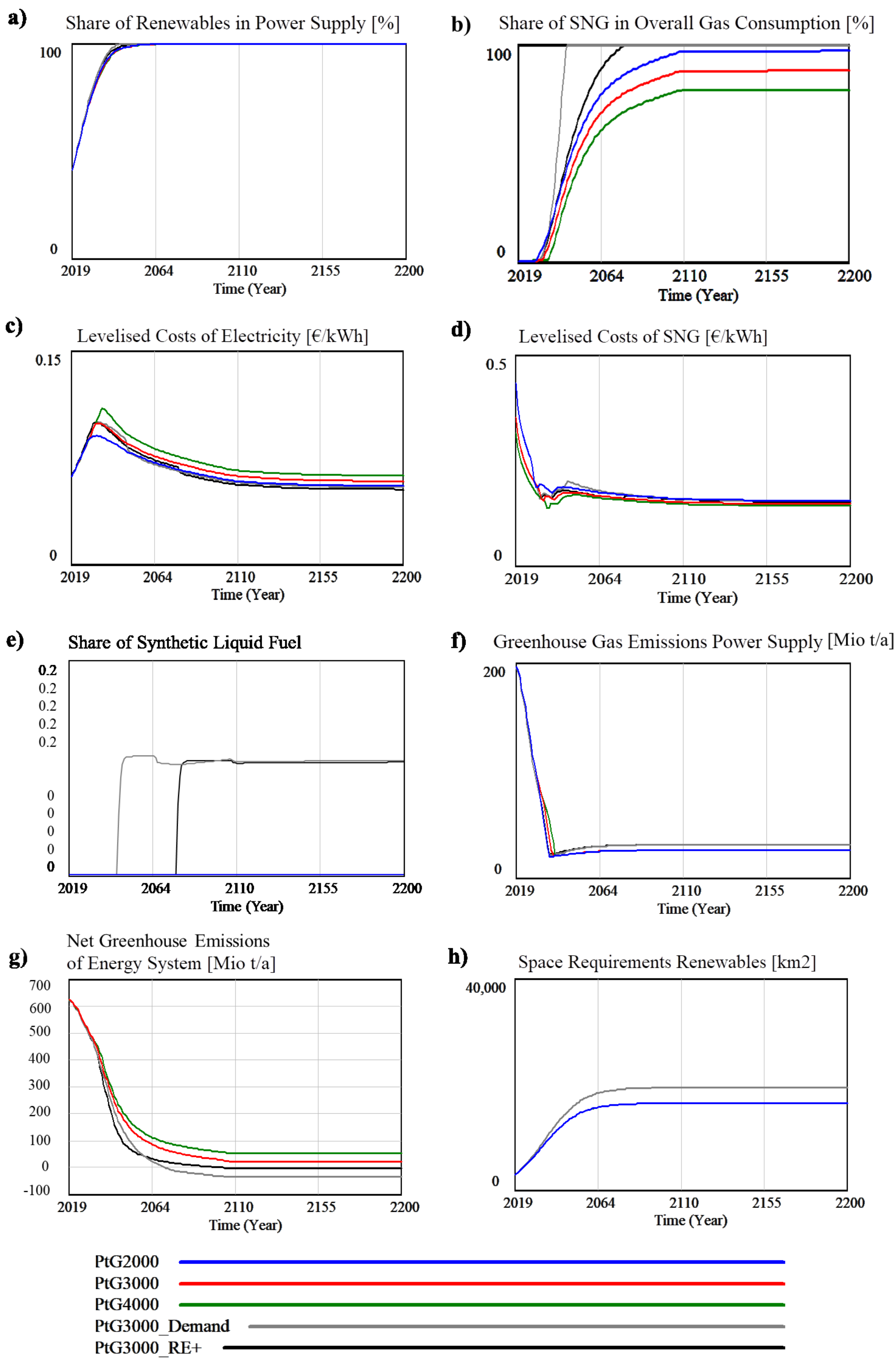

Figure 8.3: Results of scenario runs.

In all scenarios, the share of renewables in the power supply exceeds 98% by 2050 and finally reaches 100% (see Figure 8.3a). The PtG3000_Demand scenario achieves a fully renewable power supply in the year 2044, due to a lower electricity demand. The PtG3000_RE+ scenario reaches a share of nearly 100% in the year 2052 (due a quicker and more profound extension of renewable energy capacities), while the other scenarios reach this milestone in the year 2063.

SNG can satisfy the gas demand only in the PtG3000_Demand scenario (by the year 2046) and the PtG3000_RE+ scenario (by the year 2077), due to higher overcapacities of power supply in both scenarios (i.e., a lower electricity demand and more electricity production) and a lower gas demand in the PtG3000_Demand scenario (see Figure 8.3b). The PtG2000 scenario results in a share of ~97% of SNG in gas consumption (in case of a deficient gas supply, it is assumed that conventional natural gas is imported), followed by the PtG3000 scenario (88%) and the PtG4000 scenario (79%). This is explained by the fact that lower full load hours of PtG facilities allow for the utilization of a higher share of excess renewable energies for the conversion process into SNG.

In the long term, the lowest LCOE is achieved in the PtG3000_RE+ and PtG3000_Demand scenarios, amounting to about 0.055 €/KWh in 2120 (see Figure 8.3c). However, the LCOE initially increases to 0.100 €/KWh in 2033 in both scenarios before it steadily decreases towards 0.053 €/KWh in 2200. These results suggest that the LCOE will initially increase with a higher installed capacity of renewable energies due to investment costs (PtG3000_RE+) or a lower electricity demand (PtG3000_Demand). The highest costs stem from the PtG4000 scenario with a peak of 0.109 €/KWh in 2036 and a long term LCOE of 0.065 €/KWh in 2120 due to high re-electrification, which costs much more than direct electricity production. A promising result is achieved by the PtG2000 scenario with the lowest LCOE peak of all the scenarios (0.090 €/KWh in 2032) and a relatively low long-term LCOE of 0.057 €/KWh in the year 2120. The results of the PtG3000 scenario lie between those of the PtG_2000 and PtG_4000 scenarios (peak: 0.099 €/KWh in 2034; 0.061 €/KWh in 2120).

The LCOS show that scenarios converge in the long term: the PtG3000_Demand and PtG_2000 scenarios show the highest costs, with 0.156 €/KWh in the year 2120 (when the graph in Figure 8.3d has nearly leveled off), followed by the PtG3000_RE+ scenario (0.155 €/KWh in 2120), the PtG3000 scenario (0.149 €/KWh in 2120) and the PtG4000 scenario (0.144 €/KWh in 2120). This suggests that the LCOS decrease with the degree of capacity utilization of PtG plants, which is highest in the PtG4000 scenario.

The PtG3000_Demand and the PtG3000_RE+ scenarios are the only scenarios that allow for production of liquid fuels (assuming a sequential provision of electricity, SNG and liquid fuels) (see Figure 8.3e). In the PtG3000_Demand scenario, about 10.6% of the liquid fuel demand can be met by green fuels by 2050 (analogous to the gas supply, in case of a deficient synthetic fuel supply, it is assumed that conventional fossil fuels are imported); in the PtG3000_RE+ scenario a share of 10.6% is achieved by 2082.

A sharp reduction in GHG emissions by the power supply system to about 20-30 Mio t/a is achieved in all scenarios by 2050 (see Figure 8.3f). The fastest reduction is accomplished in the PtG2000, PtG3000_Demand and PtG3000_RE+ scenarios by 2037, followed by the PtG3000 scenario (by 2039) and the PtG4000 scenario (by 2041). These results resemble the model output of the share of renewable energy in the power supply, i.e., scenarios that show a quicker development of renewable energy capacities also show a faster reduction of GHG emissions. Even though GHG reductions are rather quickly achieved in the PtG3000_RE+ and PtG3000_Demand scenarios, they exceed the emissions of other scenarios in the long term (i.e., 31.25 Mio t/a in the year 2100 compared to 25.8 Mio t/a in the other scenarios). The PtG2000 scenario turns out to be the best scenario with regard to avoidance of GHG emissions in the power supply system, as a reduction is achieved relatively quickly and long-term emissions are lowest among the scenarios. As Figure 3f shows, GHG emissions are not totally avoided in the energy system, as emission factors also consider emissions during the production of solar panels, windmills and other energy sources. If these items are produced in the future in a country with a decarbonized industry, these emissions can be avoided.

As fossil power plants are phased out in the simulation model, carbon capture from power plants is limited to gas-fired power plants for electricity re-conversion, which amount to 2.6 Mio t/a. Thus, DAC technologies are required to extract CO_2 from the air (see Section 8.2.2). The PtG3000_RE+ scenario exhibits the highest CO_2 requirements amounting to 215 Mio t/a., followed by the PtG2000 (186 Mio t/a), the PtG3000_Demand (176 Mio t/a), the PtG3000 (167 Mio t/a) and the PtG4000 (149 Mio t/a) scenarios. Given that CO_2 emissions from liquid and gaseous fuels amount to between 170 and 200 Mio t/a across all scenarios, negative values were found for total GHG emissions in some scenarios (see Figure 8.3g). A negative net of total GHG emissions (including emissions from burning liquid and gaseous fuels) is reached in the PtG3000_RE+ (-35 Mio t/a), PtG2000 (-8.5 Mio t/a) and PtG3000_Demand (-4.8 Mio t/a) scenarios. Low, but positive net emissions are achieved in the PtG3000 (21.4 Mio t/a) and PtG4000 (50.9 Mio t/a) scenarios.

Space requirements are highest for the PtG3000_RE+ scenario with 19,358 km^2 by 2100 (5.2% of the land surface of Germany) (see Figure 8.3h). All other scenarios show a space requirement of approximately 16,408 km^2 by 2100 (4.4 % of the land surface of Germany).

8.4 Model testing

This section presents the results of the global and local sensitivity analyses linked to the scenario "PtX 3000". A presentation of the model testing results for all scenarios would be beyond the scope of this article. For sensitivity analyses in the current VDA framework, a Latin hypercube approach was chosen (see companion article, Halbe et al., in review, for more details; see parameter list and ranges in Appendix 8.2).

8.4.1 Global sensitivity analysis

The results of the global sensitivity analysis are shown in Figure 8.4. Both shares of renewable energies and GHG emissions of the power supply system were identified as robust model indicators. The difference between the largest and smallest share of renewable energies in the year 2100 across all scenarios is approximately 7%, while the difference between the highest and lowest GHG emissions across all scenarios in the year 2100 is 13.6 Mio t/a.

The global sensitivity analysis resulted in a medium variation for the following indicators: LCOE, LCOS and net GHG emissions of the energy system. In the year 2100, values of the LCOE range between 9.4 Cents/kWh and 5.1 Cents/kWh (i.e., a difference of 4.3 Cents/kWh). The LCOS reach values between 11.3 Cents/kWh and 18.6 Cents/kWh (i.e., a difference of 7.3 Cents/kWh). The net GHG emissions of the energy system (emissions from power supply, liquid and gaseous fuel combustion minus CO_2 absorption from air) range between -103 Mio t/a and 168 Mio t/a, which amounts to a difference of 271 Mio t/a. This result indicates that some parameter combinations allow for negative net emissions, in the sense that more CO_2 is removed from the atmosphere than is emitted from the energy supply, mobility and heating sectors. The highest parameter uncertainties are calculated for the share of SNG in the overall gas supply, the share of synthetic liquid fuel and the space requirements. In 2100, the difference between the largest and smallest share of SNG in the overall gas supply amounts to 82.0% (maximum: 100%; minimum: 18.0%). The share of synthetic liquid fuels in the overall fuel supply varies between 0% and 60%, and space requirements range from 12,089 km^2 to 21,812 km^2 (a difference of 9,723 km^2).

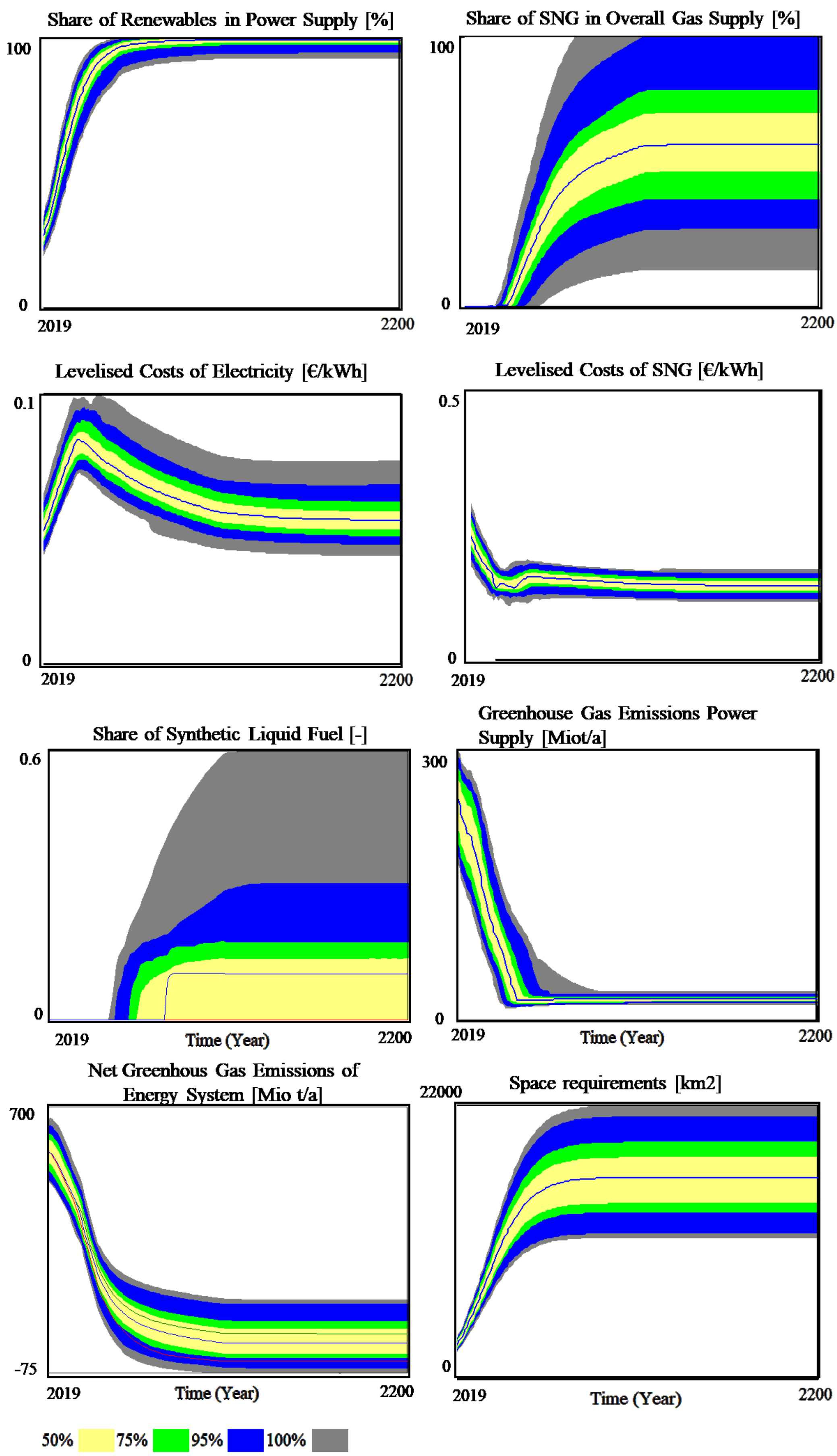

Figure 8.4: Results of the global sensitivity analysis.

The global sensitivity analysis points to a number of model outputs (i.e., share of renewables in power supply and GHG emissions) that are robust given the parameter uncertainties involved in vision modeling. However, other model outputs exhibit significant parameter uncertainty (i.e., share of SNG in overall gas supply, LCOE, LCOS, share of synthetic liquid fuels, net GHG emissions and space requirements) that limit the validity of model results. To improve the robustness of model results, a local sensitivity analysis was conducted to identify parameters with a high impact on the model results through time.

8.4.2 Local sensitivity analysis

Figure 8.5 indicates the results of the local sensitivity analysis for model outputs that showed the highest parameter uncertainties. The share of SNG in overall gas consumption is positively affected (i.e., showing a high positive correlation coefficient) by the potential and full load hours of onshore wind power, as higher capacity and higher full load hours lead to an increasing electricity generation that, in turn, allows for enhanced production of SNG. The PV potential is another parameter with a high positive correlation coefficient; higher PV electricity production also supports the production of SNG. The share of SNG is negatively affected (i.e., a high negative correlation coefficient) by gross electricity consumption up to 2050, and later, by the gas demand. A rising electricity consumption decreases the amount of surplus energy available to produce SNG. Assuming a constant production of SNG, a higher gas demand requires increased import of natural gas, leading to a decrease in the share of SNG in overall gas production.

The investment costs and the full load hours of PtG facilities show a high positive correlation with the LCOE. Due to the high share of onshore wind energy in the overall renewable energy supply, the investment costs of onshore wind have a high impact on the LCOE. Another strong positive correlation is related to the full load hours of PtG facilities, as high full load hours reduce the share of electricity from fluctuating sources that can be converted into SNG (due to the low capacity of PtG facilities), which might require import of natural gas for re-electrification. Gross electricity consumption is initially negatively correlated with the LCOE, but switches towards a positive correlation in the year 2040. The reason for this is the energy transition that occurs from 2035 to 2040. Until 2035, conventional power plants provide the base load and PtG facilities are not required. The requirements for production and re-conversion of SNG after 2035 ultimately lead to an increase of the LCOE. High full load hours of wind energy are negatively correlated with the

LCOE. Thus, an increase of full load hours enables a higher utilization of wind power, which has a lowering effect on the LCOE.

The LCOS are strongly correlated to the costs of CO_2 extraction from the air. The positive correlation coefficient increases as CO_2 emissions from gas fired power plants, the other CO_2-source considered in the model, become less relevant over time due to a phasing out of coal power plants.

The share of synthetic liquid fuel is positively correlated with the potential of onshore wind energy, as an increase in onshore wind energy sources increases the capacity to produce SNG and synthetic liquid fuels. A negative correlation is shown for gas demand, as a high gas demand contributes to a lower capacity for synthetic liquid fuel production. This effect is caused by the sequential utilization of electricity: first, the electricity demand is fulfilled, followed by the gas demand, and finally the liquid fuel demand.

Net GHG emissions are positively correlated with gross electricity consumption, liquid fuel demand, and, to a lesser extent, gas demand. In addition, the full load hours of PtG plants are positively correlated with net GHG emissions, as high full load hours increase the amount of electricity that needs to be curtailed, and thereby cannot be utilized for the production of SNG or synthetic liquid fuels. As a consequence, more fossil fuels must be used. Net GHG emissions are, however, negatively correlated to the potential and full load hours of onshore wind power, as increased wind power potential and full load hours supports a higher production of renewable energies.

The potential of onshore wind power and the specific space requirement of onshore wind energy show a high positive correlation coefficient with regard to the overall space requirement of renewable energy. The high correlation coefficient of these variables for onshore wind is due to the high share of onshore wind power in the overall energy production in comparison to PV energy.

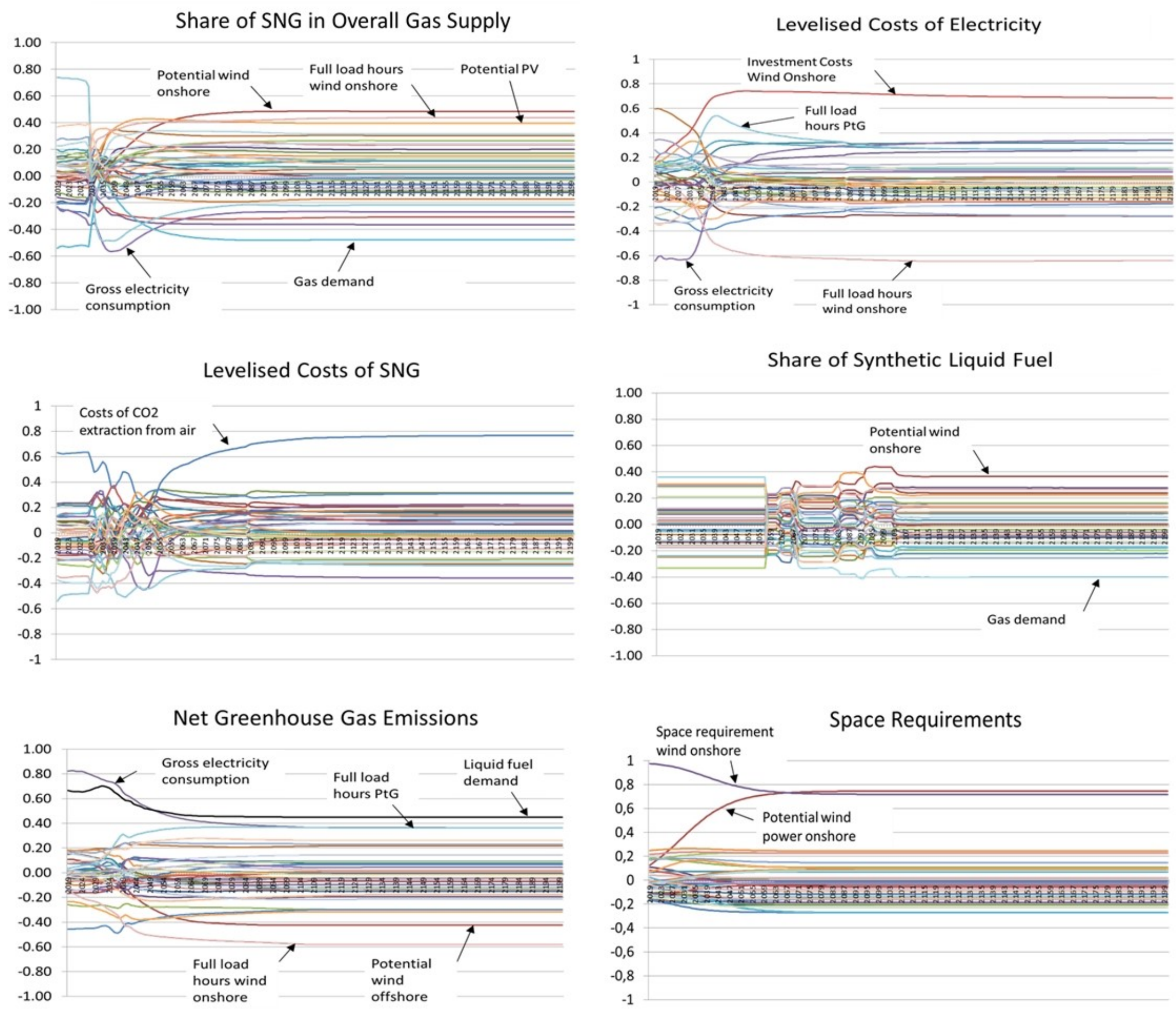

Figure 8.5: Results of local sensitivity analysis for selected model outputs (correlation coefficients between parameters and selected sustainability indicators).

8.4.3 Model-to-model analysis

For the model-to-model analysis, we draw upon studies from the Fraunhofer Institute for Solar Energy Systems (Henning and Palzer, 2012; 2013; 2015) that analyze the potential of implementing a fully renewable energy system for electricity, heat, mobility and industrial processes in Germany. An optimization model is used to analyze various configurations of a renewable energy system in 2050, such as the required installed capacity for wind energy, PV, solar heat, PtG facilities, and gas and steam power stations among other elements, in order to minimize cumulative energy system costs. The following are included in the cumulative energy system costs: investment cost for the construction, conversion or replacements of system components (only costs that exceed costs that would have been incurred to maintain the reference energy system are considered), financial, operating and maintenance costs, and costs for fossil or bionic energetic raw materials.

In the studies by Henning and Palzer, the demand for electricity amounts to about 500 TWh in the initial year and decreases by 25 % by 2050. These values are comparable to the UBA study (2014) and the system dynamics model results presented in the current article. The following maximum capacities are assumed for renewable energies (Henning and Palzer, 2015): 189 GW for onshore wind, 45 GW for offshore wind, 300 GW for PV, 5 GW for hydropower plants and 335 TWh/a for biomass. The capacity for onshore wind is lower than that of the 2014 UBA study (~410 GW), while the current system dynamics model resulted in 350 GW. PV is slightly higher in the Henning and Palzer studies compared to the other studies (both 275 GW) while the other values are similar. However, the demand for heating energy in the current study is tremendously reduced due to heat pumps, solar heat, district heating and other technologies that reduce requirements for gas and liquid fuels.

Various scenarios are tested by Henning and Palzer (2015) including different drive systems in the mobility sector, different degrees of energetic refurbishment in the housing sector, the phase out of coal power plants, CO_2 reduction goals and various levels of energy imports. Conversely, the system dynamics model presented in the current article assumes a “classic mobility scenario” (combustion engines, higher relevance of electric mobility) with an increased relevance of gas combustion engines. In terms of energetic refurbishment, a “moderate energetic refurbishment scenario” (refurbishment rate of about 1% in all scenarios except PtG3000_Demand) and “ambitious energetic refurbishment scenario” (2.7 % refurbishment rate in PtG3000_Demand) are both assumed in the system dynamics model. The phasing out of coal power plants is assumed to take place by 2050 in the system dynamics model, a progression that resembles the “non-accelerated phase out scenario” in Henning and Palzer (2015). In the system dynamics model, a CO_2 reduction of 85% is achieved (Henning and Palzer, 2015, consider 80%, 85% and 90% reduction goals) and energy imports are only a backup option. Similar scenarios (i.e., those with 80-85% CO_2 reduction, non-accelerated phase-out, and a mix of mobility options) show lower installed capacities for wind and PV compared to the system dynamics study: wind offshore (~31.5 GW in Henning and Palzer (2015) vs. 45 GW in the system dynamics model), wind onshore (168.5 GW vs. 350 GW), and PV (180 GW vs. 275 GW). However, the installed capacity of biogas is higher in the study by Henning and Palzer (2015) amounting to approximately 8 GW for electricity production, 16 GW for gas generation and 12 GW for higher temperature applications in industrial processes. The system dynamics model considers only the installation of 6.5 GW for the production of electricity.

The system dynamics model does not examine opportunities for reduced capacity utilization of renewable energies. In the current study, it is assumed that the full capacity is utilized in order to satisfy the demand for gaseous and liquid fuels (the latter is not fully satisfied in any scenario; in the PtG3000_Demand and the PtG3000_RE+ about 10.6 % of the liquid fuel demand is satisfied). As import of electricity (maximum 5 GW), natural gas and liquid fuels are optimized in Henning and Palzer (2015) to allow for minimal cumulative system costs, the results are not comparable to the current study with regard to the installed capacity and system costs. Henning and Palzer (2015) calculate total energy system costs at 200 Billion € per year in 2050 and 190 Billion € per year in a steady state, i.e., when the energy system is fully implemented. In such an energy system, about 33% of primary energy would still be provided by gaseous or liquid fuels. In a former study that considered only the assessment of a renewable energy system for electricity and heating supply (Henning and Palzer, 2012) the total energy system costs amounted to approximately 120 Billion € per year. The system dynamics model presented here shows total systems costs of 103 Billion € per year in the year 2050, which slightly increases in the following years to about 114 Billion € per year (in a “steady state”).

8.4.4 Expert assessment

As part of the expert validation process, a preliminary version of the model was presented in a workshop to nine experts comprised of scientists engaged in PtX research activities and generally working in the field of energy systems modeling. The expert validation was divided into an introductory presentation and a subsequent discussion, along with concrete questions. First, the basic model structure was demonstrated in the presentation, including the developed scenarios and indicator variables. This was followed by a discussion and the processing of a prepared questionnaire. The presented model results and assumptions of the system dynamics model were considered plausible. Based on the expert validation, an alternative interpretation of the LCOE has been developed. The inclusion of the CO_2 requirements of the PtX plants was also stimulated by the expert discussion.

8.5 Discussion

The VDA framework applied here supported a systematic analysis of alternative, fully renewable energy system designs. The framework provided guidance in the development and assessment of the system design from the definition of requirements and functions to the development of intricate system structures and system dynamics models. Methods taken from systems engineering simplified the vision models to their most important elements from a system design point of view (i.e., requirements, functions). System dynamics modeling was a suitable approach to analyze the implications of designs using economic, ecological and social indicators. To the best of the authors' knowledge, this model of a fully renewable energy system in Germany is the first in-depth vision model developed using system dynamics. This research developed important methodological knowledge with respect to the application of continuous modeling approaches (such as system dynamics) in vision modeling. Using this process, visions are modeled over time without explicitly modeling implementation barriers and supporting policies until a dynamic equilibrium is reached.

The model testing strategy is another innovative element of the current research, which builds upon a concerted set of methods. The model testing strategy was found to be suitable to address the challenges of vision modeling (i.e., data limitations and complexity). The global sensitivity analysis method allowed for an assessment of uncertainties in the model output and identified a number of robust outputs (i.e., shares of renewable energies in power supply; GHG emissions) as well as model outputs that were more sensitive to parameter uncertainty (e.g., share of SNG in overall gas supply; LCOE). The local sensitivity analysis supported a more in-depth analysis of uncertainties by quantifying the impact of parameters on model outputs. Thus, it was possible to determine the most important parameters (e.g., potential and full load hours of onshore wind), which require special attention to reduce model output uncertainties. Several parameters with high influence on the model output were considered in the design of scenarios, including various PtG plant full load hours (PtG2000, PtG3000, PtG4000), potentials for onshore wind and PV (PtG3000_RE+) and demands for electricity and gas (PtG3000_Demand). Other parameters have been assessed based upon available data, such as investment costs, space requirements and full load hours of onshore wind energy. As large volumes of investment cost and space requirement data are available for onshore wind energy, these parameter values could be substantiated based on the literature. The costs of CO_2 extraction from the air as well as the energy and space requirements of this process call for further research and experimentation. In addition, the models could be extended to include technologies for atmospheric CO_2 extraction in more detail.

Model-to-model analysis showed that the model assumptions and results of the current research are in line with other modeling studies on the topic. However, a detailed understanding of modeling studies is required to allow for a nuanced comparison. For instance, the optimization model by Henning and Palzer (2015) represents a distinct modeling paradigm from the deterministic, continuous system dynamics modeling approach. Such differences have to be considered in the comparison of results in order to draw valid conclusions. The involvement of experts in various stages of the modeling process is another important approach to develop confidence in the model design and results.

The scenario analysis has shown that a fully renewable energy system for the supply of electricity and gas is possible through the use of PtG technologies. Such a system design would initially lead to a sharp reduction in GHG emissions (the primary objective of the energy transition), reaching 85% reduction in the long-term. The model results show an increase of LCOE until 2040, before the LCOE levels off to values similar to the beginning of the simulation period in 2019. The LCOS range between 14 and 16 €-Cents/KWh. This is two to three-times the consumer price of natural gas in 2019; economic incentives to utilize green gas for heating and mobility are therefore quite low. Given that the price of conventional natural gas is hard to predict, gas price development can be better forecasted in an energy system based on PtG due to a lower dependence on imports. Such a decentralized energy system would also allow for a regionalization of the ownership structure, leading to increased value added at a regional scale. In the current study, only the scenario that assumed higher capacities of wind and solar energy (PtG3000_RE+) allowed for the production of methanol for use in the mobility sectors in addition to a full provision of electricity and gas. In this scenario, about 14 % of liquid fuel demand can be met.

Table 8.1 shows an overview of scenario results. For each indictor, a sustainability score is assigned to the scenario, ranging from a '++' for the scenario with the best result in terms of sustainability to a '--' for the least sustainable scenario with regards to the given indicator (see Halbe et al., in review, for a discussion of positive and negative-type sustainability indicators). The results show that a single, superior system design was not identified, as medium or low scores are linked to all scenarios. For instance, the PtG3000_RE+ shows promising results in terms of share of renewable energy, SNG and LCOE. However, the same scenario scores low for the indicators of LCOS, GHG emissions and space requirements. The only scenarios with consistent positive or medium sustainability scores are the PtG3000_Demand and PtG2000 scenarios.

Table 8.1: Overall sustainability assessment of scenarios

	Share of renewable energy	Share of SNG	LCOE	Levelized costs SNG	GG emissions	Space requirements
PtG2000	o	o	+	o	+	+
PtG3000	o	-	-	+	+	+
PtG4000	o	--	--	++	+	+
PtG3000_Demand	++	++	+	o	+	+
PtG3000_RE+	+	+	++	-	--	--

++: very high sustainability score; +: high score; o: medium score; -: low score: --: very low score. In case of only marginal differences between scenarios, the same score has been applied to several scenarios

The current study demonstrates the ability of the VDA framework to support systematic analysis of sustainability visions; however, further research on specific components of the sustainability visions would help to substantiate these results. For example, it would be interesting to analyze the effects of a considerable increase in electricity production by PVs at the expense of onshore wind. We hypothesize that this approach would lead to fewer acceptance problems. It is suggested that a spatial study be carried out to investigate the management of regional surpluses from fluctuating renewable energies, which will be of great importance in the future in regions with low power consumption and a large share of renewable energy. Furthermore, other storage options could be considered, such as pumped hydroelectricity storage in the Alps or in Scandinavia. Another option would be the consideration of an increased utilization of offshore wind potentials or the import of green gas or liquid fuels from the MENA region. Importing a large share of SNG or fuels from South Europe or the MENA region might also enable the use of CSP (concentrated solar power) plants. Hybrid power plants, a combination of CSP and PV, are being envisaged for the production of base-load solar electricity in the future (Parrado et al., 2016). This would enable the operation of methanation or other synthesis facilities with much higher full load hours, resulting in a lower production cost.

8.6 Conclusions

The case study on a fully renewable energy system in Germany, described herein, highlights the potential of the VDA framework. The system dynamics model revealed the relative advantages and disadvantages of system design alternatives using sustainability indicators, demonstrating the VDA framework's capability in systematically assessing complex sustainability visions. The model testing approach supported analysis of uncertainties and the influence of parameters on the model outputs. Expert validation and model-to-model analysis were found to be helpful approaches for gaining confidence in the model results.

In the end, a fully renewable energy system for the supply of electricity and gas using PtG technologies turns out to be a coherent vision with promising sustainability benefits. Liquid fuel demand, however, can only be met to a limited extent, given the German renewable energy capacity. These results highlight the importance of renewable energy imports, e.g., from other European countries or the MENA region. Further research is suggested to investigate specific options for energy imports and efficiency measures in the electricity, mobility and heating sectors.

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Appendix 8.1: Calculation of final energy consumption in the scenarios

Appendix 8.1A: Households

All values in TWh

Own assumptions are marked green

	Consumption in 2017		Consumption in 2050 (PtG_2000, PtG_3000, PtG_4000 and PtG_3000_RE+ scenarios)			Consumption in 2050 in PtG3000_Demand scenario	
Households		Comments	2050	Reductions to 2019 in %	Comments		Comments
Electricity	129	based upon UBA (2018)	86.5	33%	based upon UBA (2014), Option "V2"	104.7	based upon UBA (2014), Option "V3"
Gaseous fuel	266	based upon UBA (2018)	206	33%	based upon UBA (2014),Combination of Option "V2" and "V1"; values from V2, but assumption that gas consumption decreases at the same rate as electricity consumption due to renewable heat (e.g., heat pumps, solar heat)	44.5	
Gasoline	-		-			-	
Heating oil	129	based upon UBA (2018)	10	-	Assumption: Heating oil cannot completely substituted	10	Assumption: Heating oil cannot completely substituted
Miscellaneous (renewable heat; long distance heat)	134	based upon UBA (2018)	-	-	indirectly considered through reduce electricity and gas consumption	-	indirectly considered through reduce electricity and gas consumption

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Appendix 8.1B: Mobility sector

All values in TWh

Own assumptions are marked green

Mobility	Consumption in 2017		Comments	Consumption in 2050 (PtG_2000, PtG_3000, PtG_4000 and PtG_3000_RE+ scenarios) 2050		Comments	Consumption in 2050 in PtG3000_Demand scenario	Reductions to other demand scenarios in %	Comments
Electricity	11			91.1		based upon UBA (2014)	91.1		based upon UBA (2014)
Gaseous fuel	2		based upon UBA (2018); shares gasoline/diesel based upon UBA (2019)	176.5	25%	Assumption that current consumption of 706 TWh for synthetic fuels remains (UBA, 2018); assumption that gasous fuel accounts to 31% of fuel consumption	0		360.8 TWh for synthetic fuels based upon (UBA, 2014); percentages are own assumptions
Gasoline	232.98	33%		176.5	25%		175.89	33%	
Diesel	473.02	67%		353	50%		357.11	67%	
Miscellaneous	30			0			0		

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Appendix 8.1C: Industry

All values in TWh

Own assumptions are marked green

Industry	**Consumption in 2017**	Comments	**Consumption in 2050 (PtG_2000, PtG_3000, PtG_4000 and PtG_3000_RE+ scenarios)** 2050	Comments	**Consumption in 2050 in PtG3000_Demand scenario**	Reductions to 2019 in %	Comments
Electricity	226	based upon UBA (2018)	179.7	based upon UBA, (2014)	152.7	15%	Due to sufficiency, power demand is reduced by 15 % compared to other scenarios in 2050
Gaseous fuel	251		198.8		169.0	15%	
Gasoline	17		0		0.0	15%	
Diesel			0		0.0	15%	
Miscellaneous (not considered in the model)	223		15.1		12.8	15%	

References

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Appendix 8.1D: Trade and Services

All values in TWh

Own assumptions are marked green

Trade and Services	Consumption in 2017		Comments	Consumption in 2050 (PtG_2000, PtG_3000, PtG_4000 and PtG_3000_RE+ scenarios) 2050	Reductions to 2019 in %	Comments	Consumption in 2050 in PtG3000_Demand scenario	Reductions to 2019 in %	Comments
Electricity	149		based upon UBA (2018)	90.3		based upon UBA, (2014); percentages are own assumptions	76.8	15%	Due to sufficiency, power demand is reduced by 15 % compared to other scenarios in 2050
Gaseous fuel	125			62.4			53.0	15%	
Gasoline	0			0			0.0	15%	
Diesel	83			18.6			15.8	15%	
Miscellaneous (not considered in the model)	54			0			0		

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Appendix 8.1E: Overview of assumptions

Total	Consumption in 2017	Consumption in 2050 (PtG_2000, PtG_3000, PtG_4000 and PtG_3000_RE+ scenarios)	Consumption in 2050 in PtG3000_Demand scenario
Electricity	515	447.6	425.30
Gaseous fuel	644.00	643.95	266.52
Gasoline/Methanol	249.98	176.5	175.89
Diesel/DME	685.02	382	382.92
Miscellaneous	441	15	12.84

Appendix 8.2: Parameters for sensitivity analysis

Parameter	Assumed value	References	Variation in sensitivity analysis
Fixed operating costs PtG	3.0 %	Samweber et al. (2015)	+/- 20 %
Fixed operating costs PV	2.5 %	Kost et al. (2018)	+/- 20 %
Fixed operating costs onshore wind	2.0 %	Based on Kost et al. (2018)	+/- 20 %
Fixed operating costs offshore wind	2.9 %	Based on Kost et al. (2018)	+/- 20 %
Fixed operating costs gas turbines	2.3 %	Based on Kost et al. (2018)	+/- 20 %
Gas price import	0.025 €/kWh in 2020; 0.034 €/kWh ab 2035	Based on Kost et al. (2018)	+/- 20 %
Potential of CO_2 from industrial sources	52 Mio t CO_2/a in 2020; 2 Mio t CO_2/a in 2050	Öko-Institut (2014)	+/- 20 %
Potential onshore wind	Scenario RE+: 410 GW Other scenarios: 350 GW (authors' assessment)	410 GW based on UBA (2014)	+/- 20 %
Potential offshore wind	45 GW	UBA (2014)	+/- 20 %
Potential PV	275 GW	UBA (2014)	+/- 20 %
Potential hydropower	5.4 GW	UBA (2014)	+/- 20 %
Costs of Carbon Capture in power plants	50 €/t	McKinsey (2009)	+/- 30 %
Costs of CO_2 extraction from air	200 €/t in 2020, 80 €/t in 2050	Viebahn et al. (2019)	+/- 30 %
Variable operating costs biomass	0 €/kWh	Kost et al. (2018)	+/- 20 %
Variable operating costs gas turbines	0.003 €/kWh	Kost et al. (2018)	+/- 20 %
Variable operating costs onshore wind	0.005 €/kWh	Kost et al. (2018)	+/- 20 %

Variable operating costs offshore wind	0.005 €/kWh	Kost et al. (2018)	+/- 20 %
Variable operating costs PV	0 €/kWh	Kost et al. (2018)	+/- 20 %
Investment costs biomass	3000 €/kW	Kost et al. (2018)	+/- 20 %
Investment costs PtG	420 €/kW	Samweber et al. (2015)	+/- 30 %
Investment costs onshore wind	1500 €/kW	Based on Kost et al. (2018)	+/- 20 %
Investment costs PV	1200 (2019) – 800 (2050) €/kW	Based on Görner und Lindenberger (2015) and Kost et al. (2018)	+/- 20 %
Investment costs offshore wind	3500 €/kW	Based on Kost et al. (2018)	+/- 20 %
Gross electricity consumption	Logistic growth term (depends on scenario): 520 TWh in 2019; 356.3 TWh in 2050 (PtG3000_Demand); 450 TWh in 2050 (other scenarios)	Current values based on UBA (2018); Household consumption based on SRU (2010) in terms of saving potentials and UBA (2014); All other values based on UBA (2014) and author assumptions	+/- 20 %
Gas demand	Logistic growth term (depends on scenario): 657 TWh in 2019; 402.4 TWh in 2050 (PtG3000_Demand), 680 TWh in 2050 (other scenarios)	Current values based on UBA (2018); All other values based on UBA (2014) and author assumptions	+/- 20 %
Liquid fuel demand	Logistic growth term (depends on scenario): Benzin/Methanol: 439 TWh in 2019; 201 TWh in 2050 (PtG3000_Demand), 236 TWh in 2050 (other scenarios); Diesel/DME: 575 TWh in 2019; 175 TWh in 2050 (PtG3000_Demand), 201 TWh in 2050 (other	Current values based on UBA (2018); All other values based on UBA (2014) and author assumptions	+/- 20 %

	scenarios);		
Full load hours biomass	Linear growth term (efficiency gains): 5200 h/a - 6200 h/a	AEE (2013)	+/- 20 %
Full load hours PtG	2000 h/a, 3000 h/a, 4000 h/a (depending on scenario)		+/- 20 %
Full load hours PV	Linear growth term (efficiency gains): 870 h/a - 1000 h/a	Based on AEE (2013)	+/- 20 %
Full load hours onshore wind	Linear growth term (efficiency gains): 1800 h/a - 2500 h/a	Based on AEE (2013)	+/- 20 %
Full load hours offshore wind	Linear growth term (efficiency gains): 3000 h/a - 4000 h/a	Based on AEE (2013)	+/- 20 %
Tolerance of hydrogen in gas infrastructure	10 %	Müller-Syring and Henel (2014)	+/- 20 %
Gas turbines efficiency	Logistic growth term (efficiency gains): 0.4 – 0.6	Based on Görner und Lindenberger (2015)	+/- 20 %
Electrolysis efficiency	Logistic growth term (efficiency gains): 0.45 – 0.7	Görner und Lindenberger (2015)	+/- 5 %
Methanization efficiency	Logistic growth term (efficiency gains): 0.7 – 0.85	Görner und Lindenberger (2015)	+/- 20 %
Space requirements PV	Logistic growth term (due to efficiency improvements): 10 km^2/GW in 2019; 5 km^2/GW in 2100	Based on Fraunhofer IWES (2012)	+/- 20 %
Space requirements onshore wind	41.5 km^2/GW	Based on UBA (2013)	+/- 20 %
Space requirements Direct Air Capture (DAC	0.1 $km^2/MtCO_2$	Viebahn et al. (2019)	+/- 20 %

“We cannot know what the future holds,
but we can know that everything we do (or say) contributes significantly to it.”

Lloyd Fell and David Russell, 1994, p. 15

Chapter 9: Summary and Conclusions

This research provided a conceptual and methodological framework for the design and assessment of sustainability visions and thereby addresses significant challenges in the field of vision modeling. The framework allows for a systematic development and assessment of sustainability visions by utilizing a concerted set of modeling methods. In comparison to the use of qualitative methods for visioning, such as narratives or collages, a modeling approach has a number of advantages (cf. Holtz et al., 2015): first, modeling can provide an explicit and systematic approach for clarifying assumptions, definitions and system structures with regard to a future vision. Second, modeling supports the study of dynamics in future system states, which might be counterintuitive due to feedback processes, multi-causality and delays. Third, modeling enables systematic testing of sustainability visions by allowing for the analysis of alternative system designs and context conditions (e.g., extreme events such as a fuel crisis). Similar to Holtz et al. (2015), Iwaniec (2013) highlights the ability of vision modeling to analyze the internal consistency, plausibility and desirability of sustainability visions as well as its sensitivity to assumptions. Thus, the application of models can be a central approach to designing and assessing sustainability visions.

Potential disadvantages of a modeling approach in comparison to narratives and other non-modeling approaches (e.g., collages) could include a lack of comprehensibility for stakeholders without a background in modeling and mathematics. In particular, complicated expert models can constitute blackboxes for stakeholders, which can diminish their motivation to participate and lower learning opportunities (see Salter et al., 2010). To address this challenge, the Vision Design and Assessment Framework (VDAF) starts with conceptual modeling methods, which are particularly suited for stakeholder engagement (e.g., Gupta et al., 2012). At a later step, the semi-quantitative modeling method of fuzzy cognitive mapping (FCM) is applied, which is tangible for non-modelers (Jetter and Kok, 2014). System dynamics modeling is also added to the Vision Design and Assessment Framework (VDAF), which is a widely applied method for participatory modeling, but requires more time and effort to remain understandable to stakeholders (e.g., Stave, 2010).

The research was divided into four main parts, namely (1) the further development of systems modeling methods, (2) the development, testing and application of a participatory modeling framework, and (3) the development, testing and application of a conceptual and methodological framework for the design and (4) assessment of sustainability visions. In the following sections, each part is summarized and the main conclusions are provided.

9.1 Further development of systems modeling methods, including functional analysis, fuzzy cognitive mapping and system dynamics modeling, to be applicable for vision design and assessment

This research identified a number of systems modeling methods that are potentially applicable for vision design and assessment. The further development of these modeling methods required conceptual research to deal with the complexity and data limitations linked to vision modeling. In particular, the methods of functional analysis, FCM and system dynamics modeling were addressed in this research:

1) The functional analysis method was extended from its focus on technical solutions to include nature-based (Halbe et al., 2014) and social solutions (Halbe and Adamowski, 2021). Therefore, the concepts of ecosystem services, ecosystem functions and natural infrastructure were systematized through a conceptual framework (see Halbe et al., 2014). This conceptual framework can be analogously applied to technical systems, which allows for a combined analysis of nature-based and technical solutions in the design of future visions (Halbe et al., 2014).

2) The aforementioned conceptualization allowed for the further development of the functional organization analysis (FOA) method towards the integrated design of sustainability visions, including technical, nature-based and social solutions (Halbe et al., 2014). While FOA only provides a simplified representation of the system organization, functional flow analysis (FFA) using system dynamics modeling allows for more in-depth analysis of trade-offs and synergies (Halbe and Adamowski, 2021). The further development of FOA and FFA methods broaden the methodological toolbox of engineers from a technical focus towards the consideration of nature-based and social solutions.
3) FCM was found to be a particularly powerful method to analyze sustainability visions (Halbe and Adamowski 2019). This method is able to model future system states, but does not allow for the analysis of temporal dynamics (i.e., the dynamics of systems through time). Its ability to model system states is in line with a vision modeling approach (see Iwaniec, 2013), which also focuses on the analysis of states (i.e., target knowledge) rather than processes (i.e., transformation knowledge). Due to this coherence between the purpose of vision modeling and capabilities of FCM, only minimal methodological developments were required by (1) linking the method to FOA and (2) designing a scoring approach for the comparison of alternative visions. The FOA approach guided the design of alternative sustainability visions (Halbe et al., 2014). For each vision, a separate fuzzy cognitive map was developed, in which specific types of variables were highlighted, namely system functions, requirements, ecosystem services and scenario variables (Halbe and Adamowski 2019). The comparison of the four alternative system designs was conducted by assigning sustainability scores for each indicator, i.e., a '4' was given to the most sustainable system design and a '1' to the least sustainable design.
4) The system dynamics method required more profound development to be applicable for vision modeling (Halbe et al., 2021a). System dynamics modeling is a continuous modeling approach that allows for a more detailed systems analysis through time. Applying system dynamics to vision modeling therefore means that the implementation process of the vision is also incorporated in the

analysis, which entails the risk that the distinction between target knoweldge and transformation knowledge becomes blurred. In order to clearly address the goal of vision modeling to produce target knowledge, the implementation of the vision is only included in a very simplified way, e.g., by using a logistic growth function. On the contrary, implementation barriers and supporting policies should not be included in the model structure. Vision assessment scenarios were suggested as a new scenario category in this research in order to clarify the distinction to exploratory and backcasting scenarios. The two applications of system dynamics modeling demonstrated the suitability of the method for vision modeling. The system dynamics model for FFA consists of a relatively abstract and simple system structure (Halbe and Adamowski, 2021). Nevertheless, this simple model was able to identify trade-offs and synergies within alternative water supply system designs. The system dynamics model of a fully renewable energy system in Germany is much more detailed and comprehensive, which posed challenges for parameterization and uncertainty analysis (Halbe et al., 2021b). However, this system dynamics model provided specific quantitative results of the advantages and disadvantages of alternative system designs.

5) The systems modeling methods were found to be suitable for dealing with a lack of empirical data, a central challenge in modeling sustainability visions. The FCM method only requires the weighting of causal relationships based on stakeholder and expert assessment or a literature review (Halbe and Adamowski, 2019). System dynamics also has established methods to deal with uncertain parameter values and functional relationships, such as the use of table functions (Halbe et al., 2021b). In this research, the FCM method showed its ability to deal with concepts that are difficult to quantify, such as 'community' or 'transparency' (Halbe and Adamowski, 2019). This turned out to be an asset in the stakeholder engagement process as stakeholders were not required to consider the quantification feasibility of their chosen variables, and were able to freely 'speak their minds'. System dynamics modeling can deal with 'soft variables' as well, but requires more time investment and expertise from the modeler.

9.2 Development, testing and application of a methodological framework that supports the design, implementation, evaluation and analysis of participatory modeling processes

While several participatory modeling frameworks exist to help guide the modeling process using a single modeling method (see Chapter 2.3.2), the Participatory Model Building Framework (PMBF) has a more comprehensive scope, addressing issues, such as process design, a sequential application of qualitative and quantitative modeling methods and institutionalized participatory modeling. The main conclusions of this research addressing participatory modeling are as follows:

1) The PMBF framework is complementary to the VDAF by allowing for the design and analysis of the modeling process. This is an important aspect of quality assurance in post-normal research, such as vision modeling studies, in which not only the product (i.e., the conceptual or dynamic vision model) needs to be evaluated, but also the process, participating persons and the overall purpose of research (cf. Funtowicz and Ravetz, 1993). Institutional and process analysis methods are applied as part of the PMBF, which allows for the detailed analysis of each process step, including its context, outcomes and participating stakeholders (Halbe et al., 2018).
2) Another important aspect of the PMBF is its focus on supporting social learning during the participatory modeling processes. A stepwise approach is proposed that starts with individual interviews and proceeds towards group modeling workshops, in which stakeholders personally meet and discuss environmental issues as well as approaches for their solution (Halbe et al., 2018). The PMBF therefore proposes specific steps towards long-term participatory modeling processes, in which stakeholders collaboratively develop conceptual and dynamic models and test promising measures in practice. This systematic, stepwise and iterative approach to participatory modeling can help vision modeling practice to deal with unreducible uncertainties by iteratively revising models of future visions based on practical experiences (e.g., new side-effects are identified that were not

originally considered in the model) or new ideas (e.g., as new stakeholders join the group).

3) The combination of qualitative and quantitative modeling methods in the PMBF was an important milestone for the subsequent development of the VDAF. Causal loop diagrams (CLDs) are applied to investigate system structures of sustainability problems, goals or visions in the scope of individual interviews (Halbe et al., 2018). FCM can build on CLDs and allows for scenario analysis in a semi-quantitative manner. System dynamics can finally be applied to analyze accumulation and other temporal dynamics in a quantitative manner. However, system dynamics modeling requires substantial modeling skills and time resources to transfer CLDs in a stock-and-flow diagram, which is gradually developed towards a simulation model in the next step (i.e., auxiliary variables, parameters and equations are included, which usually also requires the revision of the model structure). A similar combination of methods was also included in the VDAF (i.e., functional analysis was added to the VDAF, which was not included in the PMBF). This allowed for a gradual development of visions starting with conceptual vision modeling towards dynamic vision modeling.
4) Finally, the PMBF also allows for the envisioning of institutional structures that support stakeholder engagement and participatory modeling in the long-term. This might require changes in legal frameworks and funding structures as well as the development of modeling and mediation skills (Halbe et al., 2018). Thus, the PMBF also helps to analyze requirements for long-term contextual and structural changes. This enables organizers of visioning processes to also consider long-term processes of change that go beyond a single vision modeling process.

9.3 Development, testing and application of a conceptual and methodological vision design framework that allows for the development of sustainability visions using participatory modeling methods

In the first step, a review of concepts from social-ecological and social-technical systems research resulted in a conceptual vision modeling framework that defines key requirements of vision modeling (see Halbe et al., 2014). Based on this conceptual framework, the methodological VDAF was iteratively developed and tested in multiple case studies (Halbe et al., 2018; Halbe and Adamowski, 2019; Halbe et al., 2021a,b). The methodological VDAF consists of different individual methods, which are combined into a coherent framework that starts with qualitative modeling approaches and proceeds to quantitative modeling and model testing. The main conclusions are:

1) The conceptual VDAF was developed based on a review of key elements of sustainability visions. First, in the VDAF a clear distinction is made between target knowledge (i.e., a future system state) and transformation knowledge (i.e., pathways towards a sustainability vision). Second, the analysis of systems theories resulted in the insight that vision design should differentiate between the *organization, structure and processes* related to a sustainability vision (Halbe et al., 2014) and consider *multiple scales, including micro, meso and macro scales (*e.g.*, local, regional, global scales)*, and their interactions (Halbe et al., 2014; Halbe and Adamowski, 2019). Third, the inclusion of nature-based solutions in vision design is a requirement that was realized through linking the VDAF to the concepts of *ecosystem services, ecosystem functions and natural infrastructure* (Halbe et al., 2014). Fourth, the conceptual framework was extended to include *social solutions* in vision design in addition to nature-based and technical solutions (Halbe and Adamowski, 2021). Fifth, the complexity and long-term orientation of sustainability visions requires an iterative and participatory approach. Visions have to therefore be iteratively reflected and revised in a collaborative process. This requirement was addressed through conceptualizing participatory modeling as a *long-term and institutionalized social learning process* (Halbe et al., 2018). Further conceptual frameworks that describe sustainability principles were applied to reflect on the suitability of the VDAF. The eight-point framework of Fenner et al. (2006) defines principles of sustainable engineering, which were included in the design of the VDAF (see Chapter 2.2.2). In addition, quality criteria for visioning processes by Wiek and Iwaniek (2014) were used for developing and assessing the framework (see Chapter 2.3.1 and Halbe and Adamowski, 2019).

2) By clearly focusing on the development of target knowledge, the methodological VDAF simplifies the vision modeling process. Thus, all aspects related to the implementation of the vision (e.g., supportive policies or financial limitations) are excluded from the analysis. The resulting vision models are therefore much simpler than exploratory models that analyze alternative future pathways. The systematic development of simple vision models supports stakeholder engagement (as models remain more understandable) as well as reduces resource requirements (i.e., time and financial resources) for conducting a vision modeling study. In the end, a vision modeling approach using the VDAF can be seen as preceding an explorative modeling approach that examines future pathways. In other words, the 'target knowledge' generated through vision modeling could be used in exploratory scenario analyses that generate 'transformation knowledge' by investigating potential pathways towards a desirable future system state (see Halbe and Adamowski, 2019; Halbe et al., 2021a,b).
3) The utilization of methods from systems engineering and systems science furthermore allows for the development of specific visions at a level of detail that is suitable for environmental management. Global scenarios (as described Chapter 1) provide a rather abstract picture of the future, which can be downscaled to national (e.g., Kubiszewski et al., 2017) and regional scales (e.g., Shaw et al., 2009). The VDAF goes one step further by focusing on visions of case-specific, multi-scale systems, such as energy, water or food supply systems. This is accomplished by including case-specific innovations in vision designs that operate at multiple scales (e.g., local food initatives and innovations in certified organic food systems that sell to international markets). This flexible approach enables linking micro and macro processes, which allows for the development of visions with a degree of specificity that is needed in environmental management and other resource management fields. The structured step-by-step nature of the VDAF can thereby provide a bridge from futures studies to the fields of environmental management and environmental engineering.
4) The consideration of various scales turned out to be an important aspect of vision design. The participatory process as well as a literature review showed that

sustainability visions often focus on one scale, such as a local, regional, national or global scale, and neglect links between multiple scales (Halbe and Adamowski, 2019). These intra-scale system boundaries of sustainability visions are also reflected in the two 'Great Transition' scenarios of the Global Scenario Group (Gallopin et al., 1997). The 'Eco-communalism' sub-scenario focuses on the provision of goods and services at a regional scale with only a small technological input and extensive face-to-face communication. The 'New Sustainability Paradigm', however, has a more global orientation including a high mobility of persons and commercial goods and the utilization of modern technologies. From a socio-economic viewpoint, the 'New Sustainability Paradigm' shows a market-based society, while the 'Eco-communalism' vision has a strong focus on regional self-reliance and autonomy. The consideration of multi-scale designs, as suggested by the conceptual VDAF, provides an incentive to examine trade-offs and synergies between scales. As the case study research and literature review showed a more polarized discussion about the superiority of a particular scale, the analysis of multi-scale designs allowed for the development of innovative sustainability visions. The results of the case study on sustainable food systems in Southwestern Ontario demonstrated the sustainability benefits of a multi-scale organic food system design (see Halbe and Adamowski, 2019). This sustainability vision can help reframe the discussion on sustainable food systems and provide bridges between proponents of singular system designs.

5) The concepts and methods developed in this research have been applied to a number of case studies in Ontario, Québec, Cyprus and Germany. This allowed for a thorough testing of the VDAF in various socio-economic contexts and problem situations. The diversity of case studies further enabled an assessment of the applicability of the VDAF in practice, as the different contexts and problem situations required a flexible methodological framework that can deal with a variety of practical problems, such as lack of data and time constraints. While in some case studies only parts of the frameworks were addressed (e.g., functional analysis in Cyprus; process design and evaluation in Québec), the case studies in Ontario and Germany showed a thorough application of the VDAF. Both types of

case studies were found to be helpful to, on the one hand, test the application of the whole VDAF and, on the other hand, experiment with a partial application in different contexts.

9.4 Development, testing and application of a conceptual and methodological vision assessment framework that allows for the systematic handling of uncertainties in modeling sustainability visions

Uncertainties in the modeling of future visions were explicitly considered in the development of the VDAF. Model validation is often a challenge for system dynamics models, due to the wide model boundaries that include environmental, economic, technical and social aspects. In fact, the term ‘model validation’ is often not used in system dynamics modeling as conventional model validation (i.e., drawing on empirical data to fit parameters and test the model performance) is often not applicable. Instead, Sterman (2000) suggests the term ‘model testing’ to “build confidence that a model is appropriate for the purpose” (Sterman, 2000, p. 846). Various testing approaches are available to build confidence in a system dynamics model, such as model boundary or extreme conditions tests (see Inam et al., 2017).

Standard approaches for model testing are usually not applicable to vision modeling, due to structural incontinuity (i.e., a future system can have another system structure compared to today’s system), lack of data (i.e., empirical data about the various aspects of a future vision are often lacking) and irreducible epistemological uncertainties (i.e., sustainability visions usually involve ethical issues and value judgments). Based on a review of existing approaches for a systematic handling of uncertainties in the modeling of complex systems, a model validation approach for the VDAF was developed (Halbe et al., 2021a,b). The main conclusions are:

1) The framework of Walker et al. (2003) was used to systematically conceptualize the different uncertainty dimensions involved in vision modeling. Walker et al. (2003) distinguish between three dimensions of uncertainty, including the uncertainty level (ranging from deterministic knowledge to total ignorance),

location of uncertainty (e.g., model structure uncertainty or parameter uncertainty) and nature of uncertainty (i.e., imperfect knowledge or natural variability). Based on these dimensions, a systematic methodology for quality assurance was developed by combining different approaches (Halbe et al., 2021a,b): (1) an integrated assessment approach that allows for an integration of interdisciplinary knowledge, which helps to deal with model boundary uncertainty (i.e., models can be tailored to the topic at hand and are not constrained to disciplinary boundaries); (2) scenario analysis is applied to address model structure uncertainty, i.e., the performance of different system designs is assessed, which represent alternative model structures; (3) global and local sensitivity analyses are applied to handle parameter uncertainty and model outcome uncertainty; (4) model-to-model analysis allows for the comparison of different models that have been built on a similar topic and thereby can address uncertainties linked to the choice of a model technique or paradigm; (5) expert assessment can help to deal with all dimensions of uncertainty, for example regarding setting the system boundaries, designing scenarios and assessing parameter ranges.

2) This research demonstrated the synergetic usage of global and local sensitivity analysis in system dynamics modeling to assess the influence of uncertain parameters on model outputs. Global sensitivity analysis revealed those model outputs that showed the highest sensitivity with regards to parameter uncertainty (Halbe et al. 2021b). This prompted a more detailed analysis of the local sensitivity, which involves the identification of parameters that have a strong influence on the respective model output through time. The local sensitivity analysis method of Ford and Flynn (2005) turned out be a very practical approach for system dynamics models and was applied to the study on a fully renewable energy system in Germany. The combination of both global and local sensitivity analysis revealed key parameters (Halbe et al. 2021b). Based on these insights, future research can focus on the parameters identified to decrease parameter and model outcome uncertainty.

3) In general, the methodology for quality assurance and model testing turned out to be a suitable approach to gain confidence in model results. The comparison of

results to other related studies as part of the model-to-model analysis showed a surprising convergence of model results. In addition, the involvement of experts in the development, revision and testing of the model turned out to be critical to making assumptions, improving the model and interpreting results.

9.5 References

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Chapter 10: Contributions to knowledge and recommendations for further research

This research has made various contributions to conceptual and methodological knowledge, as well as to knowledge related to the design of sustainable food, water and energy systems. This chapter summarizes the contributions to knowledge of this research (Chapter 10.1), as well as overall study limitations (Chapter 10.2) and recommendations for further research (Chapter 10.3).

10.1 Contributions to knowledge

The Vision Design and Assessment Framework (VDAF) addresses significant research gaps in the model-based design and assessment of future visions. The analysis of potential pathways into a sustainable future has been the subject of numerous modeling studies that apply an explorative scenario approach. However, the modeling of a desirable future system state has only been addressed by a limited number of studies (see Chapter 2.3.1). A conceptual and methodological framework focused on vision modeling (i.e., the explicit modeling of a future system state) has not been developed until now. Only Iwaniec (2013) provides a methodological framework that embeds vision modeling as part of an overall visioning process (see Chapter 2.3.3). However, due to the breadth of the framework, which covers all steps of the visioning process, the part on vision modeling is quite generic. In this respect, the VDAF is more specific about the sequence and application of methods, including uncertainty analysis and assessment.

By using methods from systems engineering and systems science, the VDAF also supports the design and assessment of sustainability visions at a specificity suitable for environmental management. In particular, the conceptual framework focusing on the development of target knowledge helps to include only the most important aspects of visions from a systems engineering and science perspective. These involve the direction of the vision towards a specific human need (e.g., water, energy or food supply) and specification of underlying functions, processes and structures. Specific design principles are provided (i.e., question of scale, impacts and ecosystem services and use of nature-based, technical and social solutions) that support the design of innovative system designs.

Besides the development and testing of an innovative conceptual and methodological framework, the individual methods applied as part of the frameworks also provide significant contributions to knowledge. The Functional Organization Analysis (FOA) method is a further development of conventional functional analysis in systems engineering. The inclusion of nature-based solutions in the FOA is an innovative contribution, which allows for the complementary consideration of technical and nature-based solutions in engineering design. The application of the FOA method for social solutions is another contribution, as well as the subsequent modeling of functional flows through causal loop diagrams (CLDs), stock-and-flow diagrams and a system dynamics simulation model.

As part of this research, fuzzy cognitive mapping (FCM) was applied for the first time to vision modeling. As the method is able to handle a lack of empirical data and 'soft' variables (i.e., variables that are hard to conceptualize and quantify, such as 'wellbeing'), FCM has a high potential to become a central method in vision modeling. The application of system dynamics modeling as part of the VDAF constitutes one of the first attempts to apply this method in a vision modeling framework (see Chapter 2.3.1.4 for a thorough literature review on this topic). Only Iwaniec (2013) and Iwaniec et al. (2014) have applied system dynamics for vision modeling in an explicit way. However, their system dynamics model in the area of urban planning is a relatively simple model, and only limited information is available regarding the exact design and results of this modeling exercise. This might be due to the purpose of the model as a facilitation tool so that the model becomes more a byproduct of the process. Schmitt-Olabisi et al. (2010) did not use the term 'vision modeling' explicitly, but followed the general idea behind vision modeling, i.e., modeling a future system state. System dynamics was used to model different sustainability visions for the region of Minnesota, USA, in the year 2050 (Schmitt-Olabisi et al. 2010). However, the study does not provide details on the system dynamics model, so it remains unclear exactly how the system was modeled, such as the time steps and temporal boundaries. Thus, the system dynamics model of a renewable energy system vision developed in this research can be seen as the first focused attempt to apply this method for vision modeling. In comparison to the application of FCM, the application of system dynamics required more in-depth methodological reflection. FCM allows for the modeling of a dynamic system state, which is completely in line with the purpose of vision modeling. System dynamics modeling, however, is a continuous modeling approach, which at first seems to contradict the ambition to model a future system state. However, the clear separation between exploratory scenarios, backcasting scenarios and vision assessment scenarios allowed for the application of system dynamics in vision modeling by excluding aspects related to the implementation process from the model and selecting a long time-horizon to enable a comprehensive analysis of accumulation dynamics. The conceptualization of vision assessment scenarios is another contribution to knowledge. While explorative scenarios analyze how the future could unfold and backcasting scenarios examine potential pathways towards a desired future with appropriate policies and measures, vision assessment scenarios examine the design of a future system state and assess its sustainability performance through scenario analysis. The development of a specific methodological framework for vision modeling using system dynamics, including an in-depth investigation of the method's potential and limitations, is an important contribution of this research.

As mentioned before, a systematic approach to quality assurance in vision modeling and uncertainty handling was lacking in the literature. Several approaches to handle uncertainties in exploratory scenarios have been developed (e.g., Kwakkel, 2017). However, vision modeling and exploratory scenario analysis show profound conceptual differences, which necessitated further research on quality assurance and model testing specifically for vision models. To address this research gap, a detailed methodology was developed to test vision models using system dynamics. The methodology includes an integrated assessment approach, scenario analyses, global and local sensitivity analysis, model-to-model analysis and expert assessment. The Participatory Model Building Framework (PMBF) is part of the systematic approach for dealing with uncertainties by proposing a stepwise procedure towards the inclusion of stakeholders in modeling (addressing uncertainties stemming from value judgements and ambiguous system boundaries) and organizing long-term participatory modeling processes that foster social learning (addressing irreducible uncertainties through an iterative improvement of vision models). The PMBF also supports the analysis and design of the modeling process by addressing the socio-economic context and participating stakeholders. In this way, the PMBF is an innovative framework that combines participatory modeling with in-depth process and context analysis. The long-term orientation of the PMBF is also an innovative element that has not been systematically addressed by previous participatory model building frameworks. The PMBF therefore allows for the envisioning of institutional structures that support more sustainable resource management in the future.

The testing of the developed conceptual and methodological frameworks in four case studies allowed for an exploratory analysis of their potentials and limitations for different environmental issues and socio-economic contexts. In addition to the testing of concepts and methods developed in this research, the case studies also produced case-specific knowledge regarding environmental issues, solution strategies and future visions. The Québec case study demonstrated the various perspectives on achieving the goal of improved water quality in the Du Chêne watershed. Contributions to the social dimension of water management were also provided by initiating discussions between water managers and stakeholders in the scope of individual interviews. The subsequent group modeling process was the first time that stakeholders had discussed water issues in the du Chêne watershed in an active manner, which underscored the benefits of participatory modeling to structure discussions dealing with complex resource issues. The PMBF also supported the visioning of requirements for institutionalized participatory modeling in Québec, such as improvement of the water governance framework and advanced training in participatory modeling.

The case study in Southwestern Ontario provided an analysis of sustainable food systems from a whole system perspective comprised of production, distribution and consumption on multiple scales. Thereby, the VDAF addressed an important research gap, as most studies fail to address the complete organic food system (e.g., Strassner et al., 2015). Current studies mainly focus on the benefits and challenges of a singular system design rather than taking a multi-scale perspective (there are some notable exemptions, such as Barthel et al., 2013 or Rahmann et al., 2017). Research and policy-making have also followed a more polarized discussion on the superiority of local or global food systems. Such a polarized discussion was reflected in the stakeholder interviews, as food system designs from stakeholders were usually either based on local food, urban gardening or globalized commodity-chains (although some stakeholders combined a local food system with urban gardening). The model results demonstrated the overall benefits of a multi-scale food system that did not merely represent a combination of singular food systems, but included tradeoffs (e.g., space restrictions or water scarcity) and synergies (e.g., knowledge exchange between local farmers and urban gardeners) between system designs. As an example, the effects of such synergies could be seen in the higher income of local farmers in the multi-scale design compared to the local food system. The overall results indicated that the multi-scale design was the most promising with respect to sustainability indicators and scenario analyses. The assessment was, however, offset by the comparatively high carbon footprint of the multi-scale system. This aspect highlights that vision modeling must be embedded in a social learning process, in which such thought-provoking modeling results inspire new research questions and follow-up analyses (Robinson, 2003; Robinson et al. 2011). In this case, the modeling results suggest the need for a more detailed analysis of the carbon footprint of system designs, which could be carried out using other modeling approaches, such as system dynamics or resource allocation scenarios.

The case studies in Cyprus and Germany included system dynamics modeling to examine sustainability visions. In the Cyprus case study, system dynamics modeling was used for a functional flow analysis (FFA) to quantitatively analyze the interaction between technical, nature-based and social solutions. Due to the high abstraction level of system functions, the resulting system dynamics model had a relatively simple system structure. Nevertheless, the modeling approach was able to reveal synergies, such as the combined application of technical supply-side solutions (e.g., seawater desalination) and alternative sources (e.g., constructed wetlands) as well as specific trade-offs, such as overcapacities of water treatment due to water demand management. The Cyprus case study is the first application of system dynamics modeling for FFA according to the best knowledge of the author of this thesis. In addition, this study provides the first methodological framework to jointly consider technical, nature-based and social solutions in systems engineering design.

The case study in Germany showed that a vision of a fully renewable energy system for the supply of electricity and gas is possible through the use of PtG technologies, while the supply of liquid fuels through the use of PtL technologies can only be provided to a limited extent. The system dynamics model supported an integrated quantitative analysis of the consequences of this vision, such as impacts on greenhouse gas emissions, electricity and gas costs, amongst others. The energy system design would initially lead to a sharp reduction in greenhouse gas emissions, reaching an 85% reduction in the long-term. The model results showed an increase in electricity costs until 2040 (as a proxy, the Levelized Costs of Electricity were calculated), before the electricity costs levelled off to values similar to the beginning of the simulation period in 2019. The costs of SNG ranged between 14 and 16 €-cents/KWh (again levelized costs were calculated as a proxy). This was two to three-times the consumer price of natural gas in 2019; economic incentives to utilize green gas for heating and mobility are therefore quite low. These example results demonstrate the capability of system dynamics to produce specific quantitative results that can support decision-making. The system dynamics model from this research represents, to the best knowledge of the author of this thesis, the first detailed vision model using system dynamics as well as the first system dynamics model analyzing opportunities of a fully renewable energy system.

10.2 Overall study limitations

The focus of this research was related to the development, testing and application of conceptual and methodological frameworks, as as well as the further development of systems modeling methods. The case studies had different topics (i.e., food, energy and water supply) and geographical contexts (i.e., Ontario and Québec, Germany and Cyprus). On the upside, this allowed for the testing of the developed concepts and methods for different issues and contexts. On the downside, this diversity did not allow for a comparison of cases as well as the systematic identification of specific factors that supported or impeded the successful application of the frameworks.

The concepts and methods were developed over a time period of several years, and required an iterative application and testing in the case studies. Two ‘full cases’ are included in the thesis in which each step of the VDAF was applied (i.e., the case studies in Ontario and Germany). However, this was not conducted in a linear manner, such as a series of workshops over the course of several months. For instance, the FOA analysis and systems thinking method was initially tested in the Ontario case, before the in-depth analysis of system designs using FCM was conducted approximately two years later. The continuity of the process was stopped several times, as results had to be examined and subsequent methods had to be developed. This had a detrimental effect on the involvement of stakeholders, as only a low number of stakeholders (about eight) were involved throughout the process, while the majority of stakeholder were only included temporarily. This was an impediment for social learning in the case studies.

In addition to the application of vision modeling methodologies, it could have been worthwhile to test complementary methods, such as the graphical visualization of visions (e.g., collages) or the preparation of narratives (e.g., through storylines). The study’s focus on modeling might have supported the involvement of stakeholders who are more comfortable with qualitative and quantitative modeling, but at the same time also hindered the involvement of stakeholders who are more open towards visual or literary approaches to visioning.

Finally, a limitation was the late completion of the process design and analysis method, as part of the PMBF, near the end of this research. The visioning process in the case studies in Ontario and Germany was not analyzed in as much depth as would have been possible if the PMBF had been ready at the beginning of this research. Instead, the PMBF was applied to water quality management in the Québec case study, i.e., a focus was set on a specific goal in Stages 1 to 4 (‘water quality’ was selected as a start variable for the participatory modeling process), rather than an explicit focus on developing a broader sustainability vision. Nevertheless, a vision of more supportive institutional structures for stakeholder participation and institutionalized participatory modeling was developed in Stage 5 of the PMBF.

The process design and analysis approach of the PMBF is generally applicable to participatory processes irrespective of the goal of the process, such as developing a future vision or solving an environmental problem. The general focus of the article on the PMBF (Halbe et al., 2018) therefore supports a broad application of the framework in environmental management as opposed to explicit tailoring to vision modeling approach. The next step would be to combine both frameworks, i.e., the VDAF and the PMBF, towards a comprehensive framework that addresses vision modeling (VDAF) and the case-specific design, evaluation and analysis of the visioning process (PMBF). More details on future research needs are provided in the section below.

10.3 Recommendations for further research

The VDAF focuses on the design and assessment of visionary future system states (i.e., a vision modeling approach) instead of dealing with potential pathways towards a future vision (i.e., as it is done using an explorative modeling approach). Future research could test the sequential combination of these two modeling approaches. A vision modeling approach could thus be interpreted as a pre-study in which target knowledge is developed. After a desirable future system design is identified, an exploratory scenario approach could explore potential pathways towards the vision. There are two advantages of such a sequential application of both modeling approaches. First, modeling sustainability visions results in simpler models compared to pathway models, as implementation barriers and drivers are not considered. Applying vision modeling first could therefore require fewer resources. In the case that a vision turns out be incoherent or the expected sustainability benefits are not reached, a rethinking of the target can be conducted before a more extensive exploratory modeling approach is applied. Second, target knowledge can also guide the design of pathway models. Exploratory modeling could examine pathways towards a specific sustainability vision or a set of visions, rather than considering a wide array of future system states. Such a sequential application of vision modeling and exploratory modeling can result in simpler pathway models as both model purposes (i.e., generation of target and transformation knowledge) are not conflated but separated.

Another interesting conceptual research question relates to the positioning of the future visions produced by the VDAF into future-orientation categories. As mentioned in the introduction, Grunwald (2004) differentiates between four different future-oriented notions: *goals* (i.e., concrete aims), *Leitbilder* (i.e., more technical and plannable futures), *visions* (i.e., more far-reaching notions of the future that involve technical as well as social processes of change) and *fictions* (i.e., more creative and artistic pictures of the future without a serious claim of feasibility). As discussed in the introduction, this research specifically addresses future visions. The developed visionary system designs for food, energy and water supply are more comprehensive than Leitbilder, but are still considered feasible. However, future visions entail a gradient with different degrees of realism, feasibility and comprehensiveness. A detailed categorization of future visions could be developed based on a literature review in which visions stemming from the VDAF and other visions, such as the visions of the Global Scenario Group, could be sorted and compared.

As mentioned in Chapter 9.2, some elements of the PMBF, comprising process analysis, process design and envisioning of structures supporting a long-term continuation of the modeling process, are not explicitly considered in the VDAF. Further development of the VDAF could address this shortcoming by explicitly addressing process evaluation and long-term continuation. This could be accomplished by including process design and analysis as a preceding step in the VDAF before the actual modeling process starts. The analysis of requirements for a long-term continuation of the process could be a last step in the VDAF (i.e., after vision assessment). The combined application of both frameworks would require an in-depth case study that allows for long-term engagement in order to analyze the process' context, apply qualitative and quantitative vision modeling and monitor outcomes of the visioning exercises.

The full and in-depth application of the VDAF should be conducted in several case studies to allow for cross-case comparison. As mentioned in Chapter 9.2, the VDAF was iteratively developed across the duration of this research. The momentum of the stakeholder engagement process was lost several times, as the methodological framework had to be further developed before the next step could be accomplished. In addition, some case study applications only consisted of a single step of the VDAF (e.g., the Cyprus case study only consisted of the application of the functional analysis method). A full and long-term application of the VDAF in multiple case studies would support a more rigorous process evaluation and comparative assessment. This would result in further insights into the case study characteristics that favor or hinder the application of the VDAF.

10.4 References

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