A Transdisciplinary Decision-Making Approach to Food-Water-Energy Nexus

A GUIDE TOWARDS SUSTAINABLE DEVELOPMENT

Maryam Ghodsvali

Bouwstenen 334

A Transdisciplinary Decision-Making Approach to Food-Water-Energy Nexus

A Guide towards Sustainable Development

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“YOU CAN’T IMPROVE WHAT YOU DON’T MEASURE.”
— Peter Drucker

Dedicated to my family.
Thank you for supporting me!

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SUMMARY

Future availability of vital natural resources, i.e., food, water, and energy, has been a growing global concern during the past few decades. The increasing exploitation rates of these resources have spurred economic growth but have also led to sustainability and environmental challenges, such as resource depletion, climate change, and biodiversity loss. Many academic strategies thus far tended to approach the problem of resource efficiency from an integrated management perspective, understanding and quantifying interlinkages and trade-offs among the physical resource systems (i.e., food, water, and energy). There is also a recognition of social, economic, and environmental limits to resource efficiency. However, the real-world capacity to incorporate multiple natural resource systems and multiple socio-economic structures, including interaction and dynamics of multiple stakeholders, in multi-objective resource management agendas is limited.

Integrated, multi-level resource management can lead to coordinated strategies that are consistent with the degree of resource interconnectedness and, therefore, positively influence the long-term sustainability of the environment. Designing decision-making and policy mechanisms for such a multi-level issue require cooperation amongst competing systems and distinct interests of multiple stakeholders. This PhD research approached this problem in four steps: (1) understanding key drivers for an integrated system; (2) quantifying characteristics and indicators of the systems to be integrated; (3) identifying thresholds to multi-level actions in real-world; and (4) introducing a transdisciplinary decision support mechanism for innovations at the nexus of food, water, and energy systems via an online serious game.

Building on a systematic review of recent literature, this research has viewed the nexus of food, water, and energy systems through a biophysical, socio-economic, and governance lens. At the core of this aggregated perspective, there is a network of directly and indirectly interlinked components from the natural and human worlds. Heeding to the equal importance of these components in resource efficiency, this research developed an integrated multi-level assessment framework for guiding and improving robust decision-making on future urban developments. This novel ‘Nexus Social-Ecological Systems’ framework i) characterizes the ecological structure and socio-economic status of the interrelated food-water-energy systems to understand ‘what exists’; ii) uncovers synergies, detects detrimental trade-offs, and unveils unexpected consequences in order to identify capabilities of a system for a state of preservation, referring to ‘what we can do’; and iii) stresses the potential for practical resource management improvements by highlighting central drivers of social and ecological interactions that can respond to ‘what we need to do.’ The framework was tested empirically by using data from the city of Eindhoven, the Netherlands, with the result that it can support policymakers and resource

management professionals in organizing their analytical, diagnostic, and prescriptive capabilities to make robust urban development decisions.

Beyond understanding key food-water-energy nexus drivers and possible cross-sectoral feedback loops, changes are required in transdisciplinary decision-making practices. Poor engagement strategies, power inequity among stakeholders, and the absence of idea-sharing opportunities characterize existing resource management mechanisms, as evidenced by a qualitative multiple-case study of six diverse food-water-energy nexus-emphasized cities (i.e., Miami, United States; Southend-on-Sea, United Kingdom; Eindhoven region, the Netherlands; Gdansk, Poland; Uppsala, Sweden; and Taipei, Taiwan). This analysis underlines the value of the rapidly expanding area of information and communication technologies in designing transdisciplinary decision support tools for real-world integrated resource management practices.

In order to increase the effectiveness and efficiency of integrated resource management processes, this research developed a transdisciplinary food-water-energy nexus decision support tool (an online serious game) by integrating various innovative methodologies. This tool has been represented by means of a multi-player web platform that searches for optimal resource management solutions through a participatory scenario-building environment and incorporates elements of different perspectives into a single, comprehensive solution. The design of the tool relies on an innovative combination of methods capable of navigating decision-making through complex systems modelling and planning. This includes multi-objective spatial optimization and cooperative game theory in the frame of a serious gaming environment for real-world implementation. As a multi-dimensional model, the ‘Spatial Nexus Optimization Game’ model (S.N.O.G) can explain spatial and temporal features of an integrated food-water-energy system and formulate resource-effective strategies for optimizing resource productions and minimizing related environmental impacts. Trade-offs among social and ecological objectives, geographically concerned operational constraints, and the balance between human needs and preserving the environment are effectively evaluated. The tool can i) accommodate context-specific inputs; ii) generate results in a geographically understandable layout; iii) be simple from an analytical standpoint while providing a comprehensive insight into the situation; iv) test realistic options; and v) navigate uncertainties about future changes. The application of the model to a real-world food-water-energy nexus problem in Brainport Smart District (a smart city district in Helmond, Eindhoven region, the Netherlands) has demonstrated that the proposed methodology and tool can produce robust decision support outcomes. Its mathematical structure delivered the first building block of analytics for such complex, interconnected, and dynamic subsystems surrounded by constantly changing externalities. The outcomes serve as strategic guidelines for policymakers

and encourage effective decision-making related to maximizing socio-economic targets and minimizing environmental burdens.

Successful pathways in food-water-energy nexus in reference to the European Commission criteria for policy evaluation will only be possible in a transdisciplinary participative process that seeks social-ecological coherence. The developed integrated multi-level assessment framework supports cities for a food-water-energy nexus balance by taking into account the trade-offs between economic development and climate change and arranges inclusive monitoring and evaluation. The proposed S.N.O.G tool supports transdisciplinary food-water-energy nexus decision-making towards a successful resource management pathway by allowing stakeholders to investigate potential shared benefits and common interests among sectors in real-world practices.

This PhD research was situated in a larger JPI Urban European project called “CRUNCH” (2018-2021) which aimed to develop an integrated decision support system for addressing increasing challenges of the food-water-energy nexus. The outcome of this thesis is part of the CRUNCH’s general framework.

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INTRODUCTION

1.1 BACKGROUND & MOTIVATION

Real-world problems such as climate and environmental change cannot be addressed adequately from the perspective of any single scientific discipline. Combining knowledge from the multiple physical, biological, and social sciences is required to detect how environmental problems develop as well as to identify the key drivers of technological and behavior change needed to mitigate these problems (United Nations. Department of Economic and Social Affairs, 2016). However, too often, decisions on adapting to climate and environmental change are taken without the necessary coordination of different disciplines and regardless of the impact a decision in one activity may have on others (Medema, Furber, Adamowski, Zhou, & Mayer, 2016).

In this regard, there is a growing consensus on the importance of food, water, and energy nexus and the need to devise and implement relevant policies and actions in an integrated manner (Stirling, 2015). Food, water, and energy are essential resources for human life. In the current time of rapid population growth, economic development, and climate change, cities depend on larger quantities of these resources, while at the same time they become increasingly scarce (Hoff, 2011). By 2050, the world needs 60% more food, 55% more water, and 80% more energy (Nie et al., 2019). The urban setting thus represents a challenge and opportunity for understanding and steering the resources into more sustainable configurations (Webb et al., 2018). Although conventionally food, water, and energy are managed by different sectors of the economy, challenges facing their sustainable supply are highly interconnected due to the significant energy and water consumption in food production, the mutual footprint between energy and water provision, and the intertwined connections of the three sectors with the broader ecosystem (Stein, Pahl-Wostl, & Barron, 2018). This global warning points to a firm conclusion that silo approaches to resources management are no longer viable. The United Nations and World Economic Forum highly recommended integrated food, water, and energy resource management, additionally emphasizing the concerns for optimal social benefit of the resources, as well as environmental protection (Hoff, 2011). This shift in framing resource management suggests the emergence of a *nexus approach* in policymaking. As a policy frame, the nexus adopts holistic planning and management of interdependent natural systems, given policymakers the mandate to consider broader interdependence of human and environment and emphasizes trade-offs and complementarities among related subsystems (Harwood, 2018a; Howells et al., 2013).

Adopting the food-water-energy (FWE) nexus approach to manage these three crucial sectors requires innovative and cross-sectorial mechanisms of decision-making. Mechanisms that, for instance, address sustainable operation beyond a single-resource system-view, and towards understanding connections between FWE and the many intertwined social, engineering, and economic considerations that cut across the three resources (Bergendahl, Sarkis, & Timko, 2018). In recent years, analytical frameworks and tools to support systematic decision-making on FWE nexus have emerged. A number of frameworks have been developed for the modeling and assessment of the FWE resource systems performance (e.g., Daher & Mohtar, 2015; Howells et al., 2013). Another type of frameworks attempts to directly suggest optimal designs, plans, or operational strategies (e.g., WBCSD, 2014). The existence of different purposes has resulted in diverse boundaries for frameworks that have been developed at different levels — from a local level (e.g., Mohtar & Daher, 2019; Veldhuis & Yang, 2017) to a global level (e.g., Sušnik, 2018). This variety of frames of reference with different inputs, outputs, and analytical characteristics has its origin in the complexity of the nexus (McGrane et al., 2019). Cross-sectoral systems of decision-making for FWE nexus should have the capacity to accommodate the multiple interacting subsystems and the multiple stakeholders — including the public sector, the private sector, academia, and the community — in multi-objective agendas. Yet, a comprehensive analytical system that fully captures the multiplicity of the nexus nature and relevant decision-making processes to coordinate the actions of diverse stakeholders is missing (Howarth & Monasterolo, 2017). Therefore, the main topic of this thesis is to develop and test a comprehensive decision support system that draws integrated system assessment and cross-sectoral policy coordination on the rich engagement of stakeholders that interact in the nexus.

1.2 PROBLEM STATEMENTS

To inform effective FWE nexus interventions, researchers need to embed decision support frameworks and tools in a comprehensive knowledge management system that considers: defining the nexus problem at hand, defining data requirements, respective monitoring programs, visualization of outcomes, and communication of these outcomes to stakeholders (Daher, Saad, Pierce, Hülsmann, & Mohtar, 2017). One way to put such an approach into a broader perspective of the FWE nexus governance and bridge the science-policy gap in cross-sectoral knowledge and action coordination is making it part of the sustainable urban development outlook. Meaning that nexus decisions should be made considering not only the FWE resources performance, but also the further ecosystem, including spatial constraints, climate limitations, and social impacts of resource depletion. This leveraging of integration is a core aspect of transdisciplinarity. Transdisciplinarity seeks convergence of divergent viewpoints that may paralyze decision-making (Howarth & Monasterolo, 2017). It has been proposed as a frame of reference addressing complex problems that require input from multiple disciplines and must consider the needs of multiple stakeholders — its main output for the FWE nexus being the translation of sectoral solutions into coordinated policies that are consistent with cross-sectoral interdependencies and distinct interests of stakeholders (Bergendahl et al., 2018). Moreover, to enhance wider nexus-compliant practices, capacity building is required to engage current and future stakeholders. A major opportunity to accelerate progress in capacity building is through the utilization of opportunities provided by advances in information and communications technology (ICT). Research acknowledges the incorporation of ICT-supported methodologies into transdisciplinary approaches as promising solutions to the core argument of multi-stakeholder, multi-objective FWE nexus challenges.

There are significant theoretical innovations and advancements in understanding and recognizing the importance of ICT-supported transdisciplinarity in integrated management of the FWE nexus (e.g., Allouche, Middleton, & Gyawali, 2019; Bergendahl et al., 2018; Stirling, 2015). However, whilst this term is growing in use to capture the importance of the integration of approaches and stakeholders in solutions to FWE nexus, researchers urge caution about the risk of turning nexus into a matter for compromise where it remains a matter for competition (Cairns & Krzywoszynska, 2016). The prevailing technical nexus framing is inadequate for its operationalization (Howarth & Monasterolo, 2016). The challenging step is integrating innovative, ICT-based transdisciplinary methodologies to the analysis of coupled social-ecological nexus systems to develop effective solutions and inclusive decision-making processes (Covarrubias, Spaargaren, & Boas, 2019). It requires involving a spectrum of qualitative and quantitative methodologies, traditionally used for sector-specific analyses in different fields of nexus disciplines (e.g., natural science, social science, and mathematics), to be applied in innovative ways to complement and add value to each other’s results. However, no comprehensive decision support tool for transdisciplinary FWE nexus has been developed, which represents a clear gap in the literature.

With respect to the above discussion, there is a clear need to (i) improve scientific understanding of the transdisciplinary methodologies for food-water-energy nexus in a holistic way and applicable at a range of scales; and (ii) to develop a decision support tool, by means of a simple, easy-to-use collaboration technology, addressing the FWE nexus for a reasonable policy-relevant time dimension.

Therefore, the main topic of this thesis is to develop and test a transdisciplinary methodology, founded on information and communication technologies, that acknowledges the limitations of siloed and single-sector approaches and draws on the rich engagement of stakeholders that interact in the nexus. Such an approach will need to provide decision-makers with transparent and accessible results that enable them to gain a deeper understanding of the characteristics of the nexus, and how these develop complexities to cross-sectoral policy coherence. This drives the development of the goal of this thesis for operationalizing the FWE nexus through ICT-supported transdisciplinary approaches for integrated system assessment and cross-sectoral policy coordination.

The goal of this thesis is twofold: First, the transdisciplinary FWE nexus is conceptualized to evaluate the interplay between this scientific policy framing and policymaking. Second, based on empirical analysis of real-world needs, a decision support tool of the FWE nexus strategy implementation is developed. It supports understanding the negotiation of possible integration policies between a variety of stakeholders when considering if and how cross-sectoral policies and strategies can contribute to the sustainable configuration of resources and more climate-resilient developments.

A major new critique of the nexus approach in this PhD research offers insights into models for 'integrated social-ecological-technological nexus management,' such as the resilient city paradigm, as calls for both integrated resource management and transdisciplinary decision-making.

This PhD research contributed to a larger JPI Urban European research project called CRUNCH (Climate Resilient Urban Nexus Choices) which was conducted by an international consortium in the cities of Southend-on-Sea, Gdansk, Uppsala, Eindhoven, Miami, and Taipei. CRUNCH has shown how the FWE nexus can improve urban resilience and efficient use of natural resources in the participating cities. This PhD research contributed to CRUNCH by eliminating the existing knowledge and decision-making barriers and paving the way for the transdisciplinary planning necessary to realize the potential of the FWE nexus. The following sub-sections (1.3 and 1.4) present the way this PhD research has achieved this.

1.3 RESEARCH QUESTIONS & OBJECTIVES

To provide precise information for transdisciplinary FWE nexus planning, several crucial questions need to be answered. The main research question in this study is: *how can transdisciplinary decision-making processes support food-water-energy nexus in urban areas?* The transdisciplinary FWE nexus planning should incorporate all components from different sectors. An integrated assessment framework is the key to this approach and developing more sustainable living environments. To trace and quantify the interactions between systems involved and further come up with ideal future scenarios for nexus decision-making, four sub-questions need to be addressed:

1. What is the state-of-the-art for employing transdisciplinary approaches to food-water-energy nexus in urban areas?
2. What are key indicators of operationalizing the transdisciplinary FWE nexus in urban areas?
3. How are transdisciplinary approaches adapted to the current state of FWE nexus in selected urban contexts (i.e., Eindhoven region, the Netherlands; Gdansk, Poland; Miami, United States; Southend-on-Sea, United Kingdom; Taipei, Taiwan; Uppsala, Sweden)?

4. What methodologies of transdisciplinarity could be employed in developing an integrated, collaborative decision support system for FWE nexus in urban areas?

To answer these questions, several activities, below explained as research objectives, are undertaken. The main objective of this PhD research is *to develop and evaluate methods for integrating social, ecological, and technological systems of the FWE nexus into transdisciplinary decision-making processes in order to develop climate-resilient and resource-efficient urban strategies*. To achieve this objective, the following sub-objectives, each addressing a corresponding research sub-question, have been defined:

1. Reviewing the state-of-the-art on framing food-water-energy nexus by means of transdisciplinary approaches

A multiplicity of transdisciplinary concepts and applications are available for FWE nexus framing. To build on and upscale the existing knowledge on framing the multi-dimensional structure of the FWE nexus system with transdisciplinarity and to set the stage for innovations, a systematic review of what is appropriate in what context was still absent. This sub-objective addresses this gap (sub-question 1) by providing a systematic review of recent and contemporary approaches, indicators employed, and lessons learned from empirical cases with respect to sustainable development goals that could form a basis for further development of methods to frame nexus systems across contexts in the world.

2. Determining and analysing the integration of social, ecological, and technological indicators for framing a transdisciplinary perspective on food-water-energy nexus

Traditionally, resource management, and in particular food-water-energy nexus, has relied on ecological information. Within this sub-objective, the research departed from integrated social-ecological-technological information, which shows common transferability problems across systems. A framework of the multi-dimensional FWE nexus system is developed (sub-question 2) and tested with data from Eindhoven city in the Netherlands. The methodology builds on Social-Ecological Systems (SESs) theory, a synergistically integrated scheme that reveals central dynamics of the system components.

3. Mapping the diversity and knowledge need of transdisciplinary mechanisms experienced across food-water-energy nexus in selected Urban Living Labs across the world

Often, transdisciplinary approaches are seen as promising solutions to multi-stakeholder, multi-objective problems. However, there are considerable differences regarding transdisciplinarity within and across FWE nexus contexts. In order to address the diversity of such an approach, this PhD research analyses the capacity of Urban Living Lab (ULL), a sort of joint urban governance, of CRUNCH EU project (i.e., Eindhoven, Gdansk, Miami, Southend-on-Sea, Uppsala, and Taipei) and advanced socio-technical design methods to map locally specific types of transdisciplinary nexus actions (sub-question 3). A systematic approach is developed to capture the diversity of transdisciplinary nexus experiments with various social, administrative, and technological features that reflect different governance-related dimensions of such contexts. The outcome visualizes the diversity of operational guidelines FWE nexus contexts across cities have followed and obviates the need for information and communication technologies in designing transdisciplinary policymaking procedures for real-world nexus practices. The information and communication technologies enable new strategic guidelines that navigate policymaking through complex, multi-dimensional systems.

4. Developing an integrated decision-making methodology and tool that supports real-world transdisciplinary food-water-energy nexus for urban planning

The shifting policy focus in FWE nexus procedures from intra-disciplinary management towards transdisciplinary management has led to changes and needs. It has triggered a greater integration of social, ecological, and technological dimensions in advice and a stronger engagement of stakeholders in data collection, research, and decision-support processes. Understanding these complex needs of the FWE nexus systems leads to question the way different stakeholders and disciplines can be engaged, the mutual benefits of their engagement, and the suitability of existing policymaking structures to foster transdisciplinary approaches (sub-question 4). What is lacking is experience-based guidance and real-world approaches to operationalize transdisciplinary policymaking within and across nexus systems. In order to address this deficiency, this PhD research designs and develops an integrative decision-making methodology and tool, namely an online multi-player serious game (S.N.O.G.) based on spatial optimization of FWE nexus policies, suitable for incorporating the three FWE sectors and related social and ecological impacts of their integrated management into a general framework, and quantitatively investigating the complicated synergies to optimize nexus strategies from a holistic, multi-objective point of view. The S.N.O.G. tool offers an evaluation of different scenarios that could serve as the basis for enforcing innovative guided management strategies for the FWE nexus.

1.4 RESEARCH DESIGN

This thesis implies the use of multiple, quantitative and qualitative, methodologies to explore the scope and limitations of incorporating transdisciplinarity into food-water-energy nexus at local and city scales. While methodological choices of each chapter are separately justified, this section is devoted to how methodologies of each individual chapter fit together in response to the main research objective of the research. Fig. 1.1 presents the overall strategy of this thesis to address the research problem and objectives.

The work builds on the conceptualization of transdisciplinarity as a way to translate the particular social, ecological, and technological characteristics of urban systems into interpretive decision-making features so that they may be integratively identified and assessed in FWE nexus problems. This research commenced with a review of the state of the art in efforts of science to solve FWE nexus problems in ways acceptable to multiple disciplines and the society. A growing body of research seeks to investigate complex FWE nexus challenges from a transdisciplinary perspective (e.g., Bergendahl, Sarkis, & Timko, 2018; Bréthaut, Gallagher, Dalton, & Allouche, 2019; Yung, Louder, Gallagher, Jones, & Wyborn, 2019). Embedded within transdisciplinary research is the attention to the complexity of working across multiple disciplinary perspectives and professional knowledge. In view of this complexity, this PhD research first, explored the methods that allow the implementation of the FWE nexus through transdisciplinary approaches (see Chapter 2), then, assessed key drivers that characterize such an approach (see Chapter 3) and the way its integrated viewpoint on social, ecological, and technological systems can happen in practice (see Chapter 4), and thereafter, developed a tool, an online multi-player serious game (S.N.O.G.) based on spatial optimization method, in support of the real-world transdisciplinary FWE nexus decision-making processes implementation (see Chapters 5 and 6).

In the first phase of this research (Chapter 2), a comprehensive and systematic literature review of transdisciplinary methods in FWE nexus research is presented in order to further specify practical challenges and identify the knowledge needed for meeting those challenges in practice. Building on the theoretical findings, a conceptual framework is proposed that links the potentials and limits of such an approach with practice. This framework emphasizes the need for (i) a study of key drivers that characterize such an approach, and (ii) an understanding of knowledge needs for its successful implementation in real-world. The following phases of this research address these needs, respectively.

In the second phase of this research (Chapter 3), an integrated assessment framework, based on the integration of social, ecological, and technological nexus systems, is developed, and the results from its application to a Dutch smart-eco city, Eindhoven, is presented. This assessment proved advantages of social-ecological-technological integration in (i) revealing connections of natural resources and the cultural, regulating, and supporting services of nexus systems, and (ii) making practical recommendations for improved socio-ecologically-balanced nexus interventions.

In the third phase of this research (Chapter 4), a comprehensive comparison of transdisciplinary FWE nexus experiments in real-world is provided to get insights into its operational guidelines. Policymakers and other FWE nexus stakeholders are struggling with the implementation of transdisciplinary decision-making processes and seek guidance on potential improvements. This operational weakness is mainly due to a lack of evidence-based guidelines concerning how a transdisciplinary approach can best be organized and integrated into the local governance structure of nexus-emphasized cities. This phase of this research addresses this practical shortcoming through a critical reflection on the experience of FWE nexus projects in implementing transdisciplinarity to guide towards an effective route into collaborative innovations that meets context-based nexus challenges. Aiming for an improvement in practical gaps that exist in transdisciplinary FWE nexus, the following phase of this research proposes a methodological complementarity based on which a support tool for transdisciplinary decision-making and integrative nexus systems assessment is developed. It is believed that by means of decision support tools and the development of policy scenarios, cities can better understand how sustainability may be achieved by the optimal integration of the FWE sectors management strategies.

In the fourth phase of the research (Chapter 5), an integrated decision-support tool by means of an online multi-player serious game (S.N.O.G.) based on a spatial optimization method that searches for optimal resource management solutions through a cooperative scenario-building environment is developed. The design of the proposed tool relies on an innovative combination of methods capable of navigating decision-making through complex systems modeling and planning. This includes multi-objective spatial optimization and cooperative game theory in the frame of an online serious gaming environment for real-world implementation. Relying on such an algorithmic framework, this research enables forecasting nexus impact analyses based on socio-economic drivers of the demand for the resources, environmental carrying capacity, land management, and primary climate change drivers. The outcomes serve as strategic guidelines for policymakers and encourage effective decision-making related to maximizing socio-economic targets and minimizing environmental burdens.

Last but not least, in the fifth phase of the research (Chapter 6), an online web-based interface is designed and developed for the proposed serious game in order to aid stakeholders' deliberation of FWE nexus policy issues. It allows FWE nexus stakeholders to work with a large (spatial and temporal) set of social, ecological, and technological metrics and make scenarios for future resource planning and management. The online serious game, the transdisciplinary decision support tool, developed in this PhD project is tested on a use case, namely the Brainport Smart District (BSD) in Helmond, Eindhoven region, the Netherlands, for serving experimental purposes of implementing transdisciplinary FWE nexus decision-making processes. The rational for case selection is the availability of local knowledge and the required datasets on social, ecological, and technological characteristics of the context.

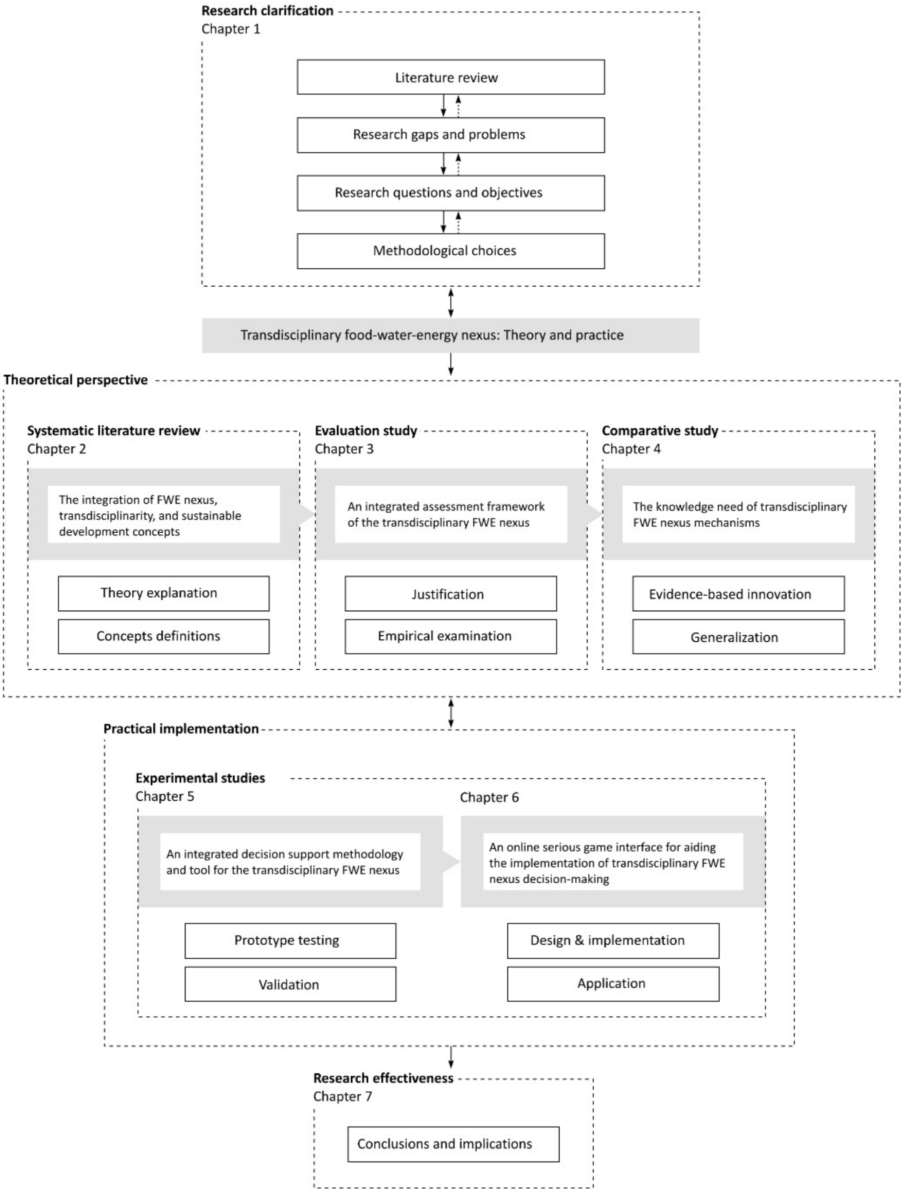

Fig. 1.1. Research design of this PhD thesis.

1.5 OUTLINE OF THE THESIS

Chapter 1 outlines the research scope of the thesis. It sets the motivation, the frame of reference addressed, the main objectives and questions of the research, and the overall strategy employed to integrate the different aspects of the study.

Chapter 2 reviews the existing body of literature on transdisciplinary approaches to food-water-energy nexus. This chapter builds an important base for understanding the foci of the following chapters. It presents an overview of the state-of-the-art in FWE nexus assessment and planning (scope and limitations) and explores which methods of transdisciplinarity and sustainability features have the potential to be transferred from one nexus context to another. In addition, it provides an overview of suitable methods to the complex, multi-dimensional FWE nexus contexts that might allow to upscale the information towards a larger-scale nexus systems inventory.

Chapter 3 explores the utility of integrated social, ecological, and technological indicators to map characteristics of interdependent nexus (sub)systems and develops a framework that is initiated in the Social-Ecological Systems theory to deliver information at more policymaking and planning relevant information type and level.

Chapter 4 combines the use of integrated social-ecological-technological indicators to map FWE nexus characteristics and dynamics with transdisciplinary mechanisms, which recently has been considered to show much better performances than the disciplinary isolation management approaches. The chapter explores measurements to advance transdisciplinary parameters, analyze the transferability across several cities worldwide, and employ information and communication technologies as the main transdisciplinary driving.

Chapter 5 explores to what extent the complex multi-objective, multi-stakeholder nature of the FWE nexus can be facilitated through an innovative combination of transdisciplinary methodologies. To navigate decision-making through the complex nexus systems modeling and planning, this research developed an integrated framework for a tool that considers the need of the interconnectedness of these essential resources. It offers an evaluation of different scenarios that could serve as the basis for enforcing innovative guided management strategies. Decision-makers are provided with choices of adjustable technological, environmental, and social policies to model and validate various possible scenarios for the FWE nexus process. Policies can be assigned in combination or individually to a location of desire, and possible implications in socio-ecological systems performance can be discussed simultaneously. Thus, optimal choices of nexus policies considering future implications can be made, along with a spatially validated action plan. In addition, the tool provides a collaboration platform designed to compile input from different groups of nexus stakeholders to reach a consensus on management goals. In this regard, the serious gaming approach is incorporated into the model as a basis for a cooperative decision-making environment. The application of the model to a local-scale nexus problem has demonstrated that the proposed approach can produce robust decision support outcomes. The tool delivers the first building block of analytics for such complex, interconnected, and dynamic nexus systems that are surrounded by constantly changing externalities.

Chapter 6 tests how the proposed tool, as an online web-based interface of a multi-player serious game based on a spatial optimization method, can support policymaking and strategy implementation for the complex, multi-dimensional FWE nexus systems.

Chapter 7 draws the main conclusions per research objective and relates them to mapping transdisciplinary FWE nexus approaches developed in the last years, reflects on the main scientific and societal contributions of this thesis and possible directions for further research on decision support tools for the evolving transdisciplinarity across FWE nexus contexts worldwide.

2

TRANSDISCIPLINARY FOOD-WATER-ENERGY NEXUS

A SYSTEMATIC LITERATURE REVIEW[1]

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2.1 INTRODUCTION

The food-water-energy (FWE) nexus is central to sustainable development (Bleischwitz et al., 2018). Demand for these resources (i.e., food, water, and energy) has been increasing rapidly for decades, causing severe risks to humans and ecosystems at different scales. Agriculture is the largest consumer of the world's freshwater resources, and more than one-quarter of the energy used globally is expended on food supply and production. The complex linkages among these critical domains and the fact that all the three sectors underpin several of the Sustainable Development Goals (SDGs) require a suitably integrated approach to ensure resources security and sustainable production systems worldwide (Endo et al., 2015). The recent debate on food, water, and energy resources nexus adopting transdisciplinary approaches addresses such needs of urban areas (Bleischwitz et al., 2018).

From the scientific viewpoint, the FWE nexus concept should be applied in a transdisciplinary manner across multiple scales. Transdisciplinarity can help in achieving regional and national sustainable development goals and promoting social inclusion in decision-making processes. This research believes that transdisciplinarity can align the FWE nexus research with public purposes, helping to overcome silo-thinking and reducing the risks of trade-offs across the SDGs.

The aims of this chapter are to examine the FWE nexus debates on transdisciplinarity and to develop a research perspective on how a better understanding of human relations with nature can be utilized to deliver SDGs in a novel integration. In this regard, a systematic literature review of relevant academic knowledge in this field is conducted to illustrate how current transdisciplinary nexus debates have been formulated in response to such interlinkages, and how they can be further improved. This chapter discusses the ability of a transdisciplinary FWE nexus approach to assess critical interlinkages across food, water, and energy and to enable sustainable resource planning and management pathways with respect to SDGs. The novel contribution is the clarification of recent FWE nexus perspectives, in particular towards the SDGs, and the conceptualization of the transdisciplinary FWE nexus from a policy-relevant perspective.

2.1.1 Perspectives towards delivering the SDGs

Sustainable development goals (SDGs) are linked and a nexus approach, by understanding key operational aspects that shape SDGs interconnections, encouraging trade-offs assessment, and identifying synergies across scales could support relating SDGs implementation (Bielicki, Beetstra, Kast, Wang, & Tang, 2019). Such transdisciplinary efforts encompass and integrate various disciplines and involve a wide range of stakeholders. The five areas of directionality, context dependency, governance dependency, technology dependency, and time-frame dependency shape interconnections among the SDGs (International Council for Science, 2017).

- The *directionality* describes ways SDGs interconnections occur. It can be unidirectional, a one-way interaction that between two SDGs only one influence the other (such as the need of health care services for electricity access while energy generation does not rely on health care services). Moreover, there are some bidirectional interconnections among SDGs, a two-way interaction that between two SDGs both influence one another (for instance, climate mitigation actions such as reducing the greenhouse gas emission could constrain transport access, and vice versa, providing more transport access causes more greenhouse gas emission and subsequently exacerbating climate change). Furthermore, some SDGs interact circularly, a loop-relationship that multiple SGDs affect the other in turn.
- The *context dependency* stands for geographical relationships across the implementation of SDGs and their outcomes. The geographical relationships are not limited to natural contexts and can comprise different aspects of social contexts such as social behaviors, economic activities, and political interests. This dependency clarifies how knowledge can be generalized to other contexts.
- The *governance dependency* refers to the extent to which institutions and rights are strong enough to avoid making decisions on any sectors of the economy regardless of its stakeholders and whatever their legal status is. Adequate governance reduces the likelihood of negative impacts on stakeholders.
- The *technology dependency* points out the significant influence of technology on the achievement of SDGs. Although there is a transition towards environmental-friendly technologies such as electric vehicles, at present, there exist conflicts (e.g., continues fossil fuel extraction, land use changes due to an increasing space demand for private vehicle parking) with climate change mitigations efforts.
- The *time-frame dependency* refers to the fact that the implications of some interactions may be limited to real-time, while others may have time lags. For instance, the increasing use of fertilizers may boost agricultural productivity over the short-term while might well have longer-term impacts on access to food, and poverty.

The integrated management of natural food, water, and energy resources (i.e., the FWE nexus approach) seems well-suited to the development of new pathways in the management of these aspects and the integrated achievement of SDGs (Bleischwitz et al., 2018). Although the FWE resources reflects mainly on interconnections between SDG2 on food (zero hunger), SDG6 on water (clean water and sanitation), and SDG7 on energy (affordable and clean energy), there are several direct and indirect linkages between nexus thinking and other SGDs (Pahl-Wostl, 2019). The

World Wide Fund for Nature organization presented the multiplicity of interlinkages between goals 2, 6, and 7 and the other SDGs (for more information see WWF-SA, 2017). In support of sustainability transition and delivering SDGs in an integrated manner from the lens of FWE nexus, transdisciplinary approaches are yet to be adapted (Allouche et al., 2019).

2.1.2 The need for more integrated, transdisciplinary approaches

The challenges of ensuring resources security while adapting human-made technologies to environmental change require the involvement of a range of disciplines and stakeholders. Issues such as climate change, water and energy use, agricultural management, and addressing ecological challenges are compounded by the need for socially and economically solutions (Harris & Lyon, 2014). These challenges require approaches that promote collaboration between multiple stakeholders from different disciplines, organizations, academic research, and practice. The stakeholder collaboration and the multiple disciplines coordination can be achieved through transdisciplinarity.

Transdisciplinarity allows challenges to be framed and viable solutions to be found at the outset in a broad and equal contribution of stakeholders (Stirling, 2015). This approach allows a more practical and problem-driven perspective to real-world challenges and complexities (Johnson & Karlberg, 2017). Drawing on the generation of knowledge from different stakeholders, transdisciplinarity provokes debates over the need for alternative perspectives and more socially accountable collaboration (Harris & Lyon, 2014). The engagement of a range of stakeholders from multiple disciplines and interests in problem identification, framing, and analysis is the exact need of the FWE nexus in shaping solutions to fit society's need and moving towards sustainability (Wyrwoll et al., 2018).

2.1.3 The transdisciplinary food-water-energy nexus

Given the variety of FWE nexus definitions among literature, it is not only the interactions within ecological sectors that describe the FWE nexus, but also the social actors whose behavior interrelates with environmental sectors define FWE the nexus (Bleischwitz et al., 2018; Endo, Tsurita, Burnett, & Orencio, 2017). A transdisciplinary perspective on the FWE nexus guides both the integration of knowledge from science and society, including local knowledge, and the problem orientedness of concerns that presents real-world situations of social-ecological interactions.

Regarding the overall notion presented in the literature, this chapter discusses three main elements that define the FWE nexus from a transdisciplinary perspective.

- *Key drivers for integration*: actions on the FWE nexus should form a problem-driven process accounting for the issue of concern, governance system, and stakeholders (Daher et al., 2017; Hamilton, ElSawah, Guillaume, Jakeman, & Pierce, 2015). Interdependencies between humans and nature mean that one environmental problem (e.g., low water quality, or extreme flood/drought) can cause other social and economic issues (e.g., lack of social equity, or low level of well-being) and vice versa. Such issues can be linked either directly, for instance, poor water quality often links to reduced river flows, or indirectly, for example the use of geothermal heat provides clean energy and food expenditures. The issues are defined depending on stakeholders and their position in a system (in terms of system governance) (Pahl-Wostl, 2007). The governance setting of the system, including both social and ecological contexts, refers to the degree of interventions carried out to enhance system process and stakeholders' interactions. Stakeholders can be individuals or interest groups associated with the sources of the problem, as well as those affected by the problem. Suh governance settings that involve stakeholders tend towards transdisciplinarity.

- *Characteristics of the systems to be integrated*: Given the interdependencies between social and ecological systems, a detailed understanding of each is essential for further improvements on their integration and sustainability achievements. The social system refers to all human-related aspects that influence or are influenced by the "issue of concern," and may include different sectors of economy, politics, and technology. These aspects depend on human behaviour towards all services provided by the natural system. Hence, in order to understand environmental problems and support intervention policies, it is essential to understand the underlying human drivers (Hamilton et al., 2015). The inclusive engagement of a wide range of stakeholders in nexus research and practice, which refers to the term transdisciplinarity, supports the required understanding of human drivers.

  The natural resources (e.g., food, water, and energy) are also on the other side of this interrelated system. Given the fact that natural resources do not operate in isolation, the recognition of their influences on one another is required. Resource flows in the environment where output(s) of one resource is treated as input(s) for another and the circular dependency among resources put a holistic perspective on the recognition of the natural system (Dyer et al., 2014). The engagement of multiple disciplines studying such ecological dependencies with nexus research has been ascertained through transdisciplinarity.

  In addition to interrelations within social and ecological systems, potential interactions among the two systems that can be recognized and monitored through actions require attention.

- Thresholds to actions: actions to the FWE nexus need incentives in order to address certain trade-offs, exploit synergies, and achieve resource optimization (Kurian, 2017). The distribution of risks to such achievements, in turn, defines thresholds to nexus actions. It is essential to understand how stakeholders shape thresholds to actions in decision-making and management processes

(Scott, Kurian, & Wescoat, 2015). Hence, the understanding of institutional capacity in order to respond to environmental risks, and externalities for the prioritization of decisions is essential to a comprehensive nexus perspective.

The three key transdisciplinary nexus elements highlighted above intend to capture both the integration of different sectors of social-ecological systems and the operational aspects related to incorporating different types of information, perspectives, and practices. Within the outline of these elements, it is apparent that the transdisciplinary FWE nexus perspective aside from interdependencies among different sectors of the economy targets risks that ecological and societal components may potentially pose to each other.

2.1.4 How does a transdisciplinary nexus perspective potentially support SDGs integration?

The sustainable development goals are interlinked, and the transdisciplinary FWE nexus plays a significant role in the achievement of these goals in an integrated manner (Biggs et al., 2015; Saladini et al., 2018; WWF-SA, 2017). Fig. 2.1 illustrates how transdisciplinary FWE nexus could potentially support SDGs integration.

- The variant *directionality* of sustainable development sectors may be under control if the human attitude towards services provided by the environment lies in the efficient use and climate-change mitigation skills (Kurian, Portney, Rappold, Hannibal, & Gebrechorkos, 2018). In case of training human in how to avoid throwing natural orders into disorder, such interactions among different sectors of sustainability stand stable. The transdisciplinary FWE nexus approach through controlling *human-related drivers of environmental risks* (e.g., deforestation, waste, pollutants) contributes towards cooperative interactions (Bergendahl et al., 2018). **Cooperative interactions** can be achieved through training purposes of transdisciplinarity.
- The *context dependency* of solutions to the integrated implementation of SDGs pushes policymakers towards **localized interventions** (Kurian et al., 2018). Urban areas are diverse in terms of natural resources availability, capacity to meet human demands, and the way users behave towards resource preservation. Significantly, any social-ecological related decision should be taken according to the related setting (Hoolohan, Larkin, et al., 2018). This context-based perspective is what the transdisciplinary FWE nexus emphasizes. The transdisciplinary nexus approach clarifies the *environmental, economic, and institutional status quo* through involving a range of relevant stakeholders, and subsequently, supports localized interventions (Allouche et al., 2019).
- The likelihood of SDGs integration in practice highly depends on *the extent to which stakeholders are involved in decisions and are influenced by actions* (International Council for Science, 2017). These dependencies are exactly what transdisciplinary FWE nexus targets for the integrity of ecosystems. From the

transdisciplinarity perspective, forming a **resilient alliance** among stakeholders and linking their ideas through their direct, continued, and equal involvement in decision makings support the *governance dependency* of sustainable development actions (Howarth & Monasterolo, 2017).

- Given the increasing role of *technology-based interventions* in sustainable development applications, the FWE nexus stresses on thresholds to actions (Kurian, 2017). The transdisciplinary perspective looks for **efficient resolutions** to adapt the use of technology for interrelated socio-ecological demands through building institutional capacity and managing externalities that may pose potential risks to the settings (Siegner, 2018).
- Given the variations of the implications of ecological performances over time, nexus emphasizes the need for comprehensive control over adverse conditions. It is essential to know *the extent to which stakeholders can adapt to the new situation or mitigate adverse consequences* (Howarth & Monasterolo, 2017; Wyrwoll et al., 2018). Transdisciplinarity contributes to the *time-frame dependency* of sustainable development through learning actions aiming **adaptive capacity**.

Fig. 2.1. The potential contribution of the transdisciplinary perspectives on FWE nexus to the achievement of SDGs in an integrated manner.
Sections of the inner circle illustrate different aspects that shape SDGs integration. Colored sections of the outer circle present different elements of the transdisciplinary FWE nexus that contribute to the management and control of aspects of SDGs integration. Dashed lines show how the two themes (i.e., transdisciplinary FWE nexus and SDGs integration) could be linked. The grey text boxes reflect on potential

outcome of such linkages among transdisciplinary FWE nexus elements and aspects of the SDGs integration.

Source: Adapted from Bazilian et al. (2011); Biggs et al. (2015); Bleischwitz et al. (2018); Daher et al. (2017); Davis and Andrew (2017); de Grenade et al. (2016); Endo et al. (2017); Harwood (2018); International Council for Science (2017); Kurian (2017); Pahl-Wostl (2019); Saladini et al. (2018); Schulterbrandt Gragg et al. (2018); Scott et al. (2015); WWF-SA (2017).

Though transdisciplinary FWE nexus may potentially be influential in the integrated management of sustainable development sectors, its critical engagement with empiricism is limited and challenging.

Given the coordination of information flows among multiple actors within the transdisciplinary nexus process, the key driving barriers are varying levels of knowledge, incompatibility of data from multiple sources, and data accuracy (Johnson & Karlberg, 2017; Kurian et al., 2018; Mohtar & Daher, 2019). Moreover, the availability of appropriate information across a variety of systems and actors is a concern over multi-stakeholder engagement (Basheer et al., 2018; Givens et al., 2018; Wolfe et al., 2016; Xue, Liu, Casazza, & Ulgiati, 2018). Concerning active interactions among multiple actors, incompatibilities within and between institutional and social network structures lead to undesired dynamics and low levels of communication (Bergendahl et al., 2018; Halbe, Pahl-Wostl, Lange, & Velonis, 2015; Pardoe et al., 2018; Treemore-Spears et al., 2016; Villamor, Guta, Djanibekov, & Mirzabaev, 2018). Furthermore, the availability of stakeholders, their willingness for collaboration, their power relations, and the timely inclusive decision- and policy-making add complexities to practical experience of transdisciplinary FWE nexus (Covarrubias et al., 2019; Howarth & Monasterolo, 2017; Kumazawa, Hara, Endo, & Taniguchi, 2017; Matthews & McCartney, 2018; Ziv et al., 2018).

Within the leading scientific nexus debates, the effective way to rise to the challenges of transdisciplinarity is rarely questioned but frequently discussed as a concept into the environmental resources' sustainability. This scientific shortcoming calls for a comprehensive review of, and critical reflection on, existing discussions of the transdisciplinary FWE nexus to guide towards an effective route into the empirical practices that enhance multi-stakeholder engagement, socially acceptable decisions, and sustainability outcomes. Hence, the authors deem it necessary to critically investigate transdisciplinary nexus approaches before further endorsing the FWE nexus solely as a resource governance framework regardless of probable reflections on stakeholders and its practicability towards sustainable development. Through conducting a systematic literature review adopting a discourse analysis technique, this chapter describes how scientific discourses have put transdisciplinary perspectives on FWE nexus performances towards sustainability.

The following sections describe how scientific discourses were selected for the systematic review of the transdisciplinary FWE nexus and how these documents were analyzed (Section 2.2). Next, in Section 2.3, the chapter presents its findings that characterize the diversity of transdisciplinary nexus approaches and methods in the reviewed discourses and derive key features of effective transdisciplinary actions from the body of the literature. The findings are at the forefront of the need for FWE nexus methods that advance scientific understanding of multiple stakeholders' collaboration, inclusive and legitimate policies, and sustainability outcomes. To support further development of transdisciplinary approaches to the FWE nexus, this chapter highlights empirical evidence of the FWE nexus debates for transdisciplinarity that explicitly address social and political contexts and deeply engage with multiple groups of stakeholders. Moreover, the required improvements for further practical developments of the transdisciplinary perspective on FWE nexus is emphasized.

2.2 METHODOLOGY

This chapter aims to systematically review the current transdisciplinary nexus debates from a qualitative standpoint. A systematic review is a detailed and transparent means of gathering, appraising, and synthesizing scientific evidence to answer a well-defined question (Boland, Cherry, & Dickson, 2014). The main question this review intends to answer is: what is the state-of-the-art for using transdisciplinary approaches within the FWE nexus to guide sustainable development. Given the qualitative perspective of this chapter on the review question, the study of numerical data from the reviewed literature (meta-analysis) is not included in the procedure of the systematic review.

Among several qualitative approaches that are optimal for systematic literature review (such as theme analysis, classical content analysis, and narrative analysis), the discourse analysis approach lends itself to a detailed identification of ideas, concepts, and categories through which researchers understand alternative interpretations and policy options (Onwuegbuzie & Leech, 2012). Discourse analysis is an interpretive research approach that helps to reveal multiple competing knowledge claims within leading discourses (Feindt & Oels, 2005). In the realms of environmental politics, discourse analysis raises awareness of the process through which policy challenges are constructed. It shows how a particular understanding of environmental issues gain dominance, and how its associated knowledge is legitimized while other ways of knowing are marginalized (Waitt, 2010). Apart from shaping environmental politics, discourse analysis also manifests in social practices and institutional capacities (Wiegleb & Bruns, 2018). Within the field of FWE nexus, discourse analysis can show how dominant perspectives on multi-stakeholder engagement emerge from particular knowledge and power relations, and how practice makes use of it.

To build a benchmark, this chapter took the discourse analysis approach to study international research and practices on the transdisciplinary FWE nexus. Following sub-sections (2.2.1 and 2.2.2) describe how the required corpora for the aimed discourse analysis were compiled and analyzed.

2.2.1 Corpus compilation

Intending to analyze scientific nexus discourses on transdisciplinarity, this chapter of the systematic literature review established a set of selection criteria that allows the detection of discursive structures within mostly relevant and leading academic literature (Appendix A: Table A.1). The inclusion of different online scientific databases, language, frequency of dominant keywords describing the subject of the study, and timeframe are the main selection criteria this chapter adopted for the discourse analysis stage. Documentary data were compiled in large text corpora under selection criteria reflecting the literature review question (Fig. 2.2). The final corpus includes 68 academic publications (Appendix A: Table A.3).

The academic publications for this systematic literature review were selected from three different online databases: Scopus, Web of Science, and ScienceDirect ensuring the comprehensiveness of the final text corpus (last accessed 22.07.2019). Selected publications included international academic literature in various document types comprising peer-reviewed articles, proceedings papers, books (chapters), and editorial materials. However, to ensure data quality, coherence, and comparability, this chapter only selected peer-reviewed papers and scientific books (or book chapter).

Within the online databases, this chapter used keywords *food*, *water*, *energy*, *nexus*, and *transdisciplinarity* for the relevant corpus compilation. Although the term food-water-energy nexus is dominant through current scientific debates, other possible combinations were also used of the three *food*, *water*, and *energy* words. In addition, multiple synonyms of the word *transdisciplinarity* such as *participation*, *governance*, and *collaboration* were included in the search string.

To ensure consistency of the review approach, documents with the less frequent expression of keywords and no response to key components of the literature review question were excluded. The PICOSS framework identifies structures of scientific discourses based on key components of the literature review question (i.e., population, intervention, comparator, outcomes, study design, and setting) (Appendix A: Table A.2). Documents were screened automatically for the low-keywords-frequency exclusion and were screened manually based on the PICOSS framework.

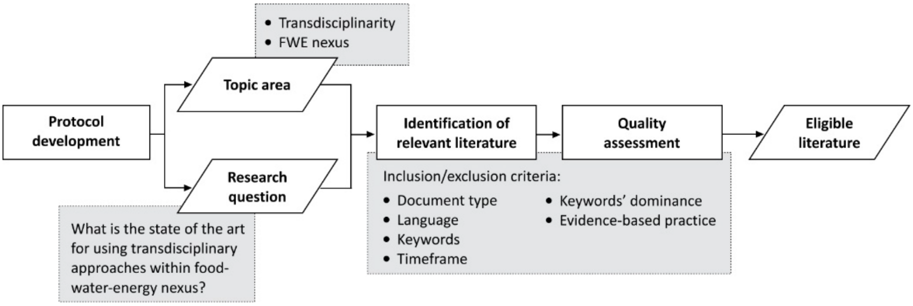

Fig. 2.2. Multiple phases of data selection for the systematic literature review about transdisciplinary approaches to food-water-energy nexus

Although this chapter compiled the final text corpus in a controlled, transparent, and comparative way through multiple online databases using all relevant combinations and synonyms of keywords, several limitations are associated with this approach. By restricting search results to only publications in English, discourses in other languages are disregarded for the interpretation. Moreover, by focusing solely on resources available online and publications in full-text format, the analysis may miss out on the most up-to-date evidence such as abstracts (Boland et al., 2014).

To compensate for the risk described above, discourse analysis adopts an in-depth interpretive research approach. The final 68 selected publications were analyzed to frame the structure of the FWE nexus discourses around transdisciplinary approaches, outline the development of international concerns about multiple stakeholder engagement within the FWE nexus research and practice over time, and compare debates.

2.2.2 The discourse analysis procedure

The in-depth analysis of the compiled discourses was carried out through coding within the qualitative software ATLAS.Ti. The coding was conducted initially based on known categories of concepts describing transdisciplinary FWE nexus debates and then was inductively complemented based on the interpretation of the reviewed publications. The final coding scheme focuses on four main questions:

First: “what are the underlying scientific trends in FWE nexus publications towards transdisciplinarity?”. This question investigates the extent to which the multi-stakeholder engagement purpose formed most legitimate knowledge on linking nexus and sustainability concerns. In this regard, the authors coded the compiled corpora as follow:

- Research scope for multiple stakeholder engagement (including community): Nominal engagement, little more than display only to give legitimacy to development plans and does not lead to any change; Instrumental engagement, a means towards the efficient use of the skills and knowledge of stakeholders; Representative engagement, giving stakeholders a voice in decision-making and implementation of policies that affect them; and Transformative engagement, focusing on the empowerment of involved stakeholders (S. C. White, 1996).

- Research sustainability concern (regarding Fig. 2.1, to explore the extent to which nexus research involves multiple stakeholders for sustainability purposes): Directionality, context dependency, governance dependency, technology dependency, and time-frame dependency.
- Research emphasis on different aspects of the FWE nexus transdisciplinarity (regarding Fig. 2.1, to identify the aspects of the FWE nexus application that most hosted the involvement of multiple stakeholders): Key drivers, systems characteristics, and thresholds to actions.

In addition, this stage also explores the geographical extent of the transdisciplinary FWE nexus discourses by analyzing the origins of knowledge production and destinations of their study in terms of case areas.

Second: "what are dominant concepts describing the transdisciplinary FWE nexus debates?". This question examines different interpretations of this conceptual term and its development direction. In this regard, the authors coded the compiled corpora based on the most frequent keywords appeared within the entire text (e.g., governance, policymaking, transdisciplinary, and stakeholders) to conclude leading conceptual descriptions of the transdisciplinary FWE nexus.

Third: "what methods have supported transdisciplinary nexus practices, and to what extent do they meet potential outcomes of links between FWE nexus and sustainable development (given Fig. 2.1, the grey boxes)?". This chapter identified dominant transdisciplinary methods that have been used within the reviewed publications (e.g., workshops, learning-based gaming, and participatory observation). Then, the compiled corpora were coded based on the identified transdisciplinary methods to explore their achievements in different contexts. Findings provide a deeper understanding of each method, their contribution to the transdisciplinarity concept, and the extent to which they support sustainability concerns within nexus applications.

Fourth: "what is the empirical evidence in transdisciplinary FWE nexus applications?". This question examines the key driving forces of the transdisciplinary FWE nexus practices. The authors pointed out experiments that addressed transdisciplinarity challenges and their associated solutions towards sustainable development. Addressing these questions is important since a deeper understanding of social inclusion within nexus thinking, in other words, the transdisciplinary FWE nexus application is gaining dominance.

2.3 THE STATUS QUO OF TRANSDISCIPLINARY FWE NEXUS

In recent years, to enhance multi-stakeholder engagement within the FWE nexus, the adoption of transdisciplinary approaches has attracted increasing attention. Initially, the concept of the transdisciplinary FWE nexus emerged within the realms of international politics under the influence of the United Nations (UN) (Bergendahl et al., 2018). Biggs et al. (2015), for instance, traces the transdisciplinary FWE nexus back to 2015, when the United Nations pushed forward new goals of the post-2015 sustainable development agenda to actions aimed at achieving sustainable water consumption, energy use, and agricultural practices, as well as promoting inclusive economic development. Messages from the Bonn2011 nexus conference added overarching principles to the aims of the sustainable development agenda: setting the right incentives, mechanisms for policy coherence, and local empowerment (Hoff, 2011). These international communities (the UN and the Bonn2011 nexus conference) set the tone for future debates by arguing that a transdisciplinary approach to the integrated management of FWE resources may better accomplish the SDGs.

2.3.1 The trend of transdisciplinary FWE nexus discourses

Since 2015, the significance of transdisciplinary approaches has emerged in the FWE nexus literature with exponential growth in the number of publications in 2018. The transdisciplinary nexus research has voiced growing concern over the integrated study of FWE nexus and sustainable development (Fig. 2.3). Scientific discourses have purposefully integrated social and political aspects of the FWE nexus along with environmental concerns (Wiegleb & Bruns, 2018).

The understanding of the social structure and political context helps to explore responsibilities of different stakeholders for the implementation of sustainability innovations and thereby provide critical reflection for the required governance system within nexus applications (Foran, 2015; Halbe et al., 2015; Keskinen, Someth, Salmivaara, & Kummu, 2015). Therefore, at early stages, the trending FWE nexus transdisciplinary research tried to unpack key drivers of the FWE nexus application and any likely threshold to their actions. Gradually, research has included more aspects of the FWE nexus and sustainable development in studies and subsequently, through multi-stakeholder engagement, in practice. Fig. 2.3 reveals that there has been a gradual increase in adopting higher levels of stakeholder engagement within nexus applications.

Stakeholders of the FWE nexus applications have been engaged variously in research and practice. Depending on the context and its associated challenges in taking advantage of knowledge and skills of the influenced population in making decisions and developing policies, research has involved stakeholders variously. From Fig. 2.3, it can be seen that the higher levels of engagement in terms of active stakeholders' involvement in making decision and empowering their skills for adaptive actions have become dominant recently.

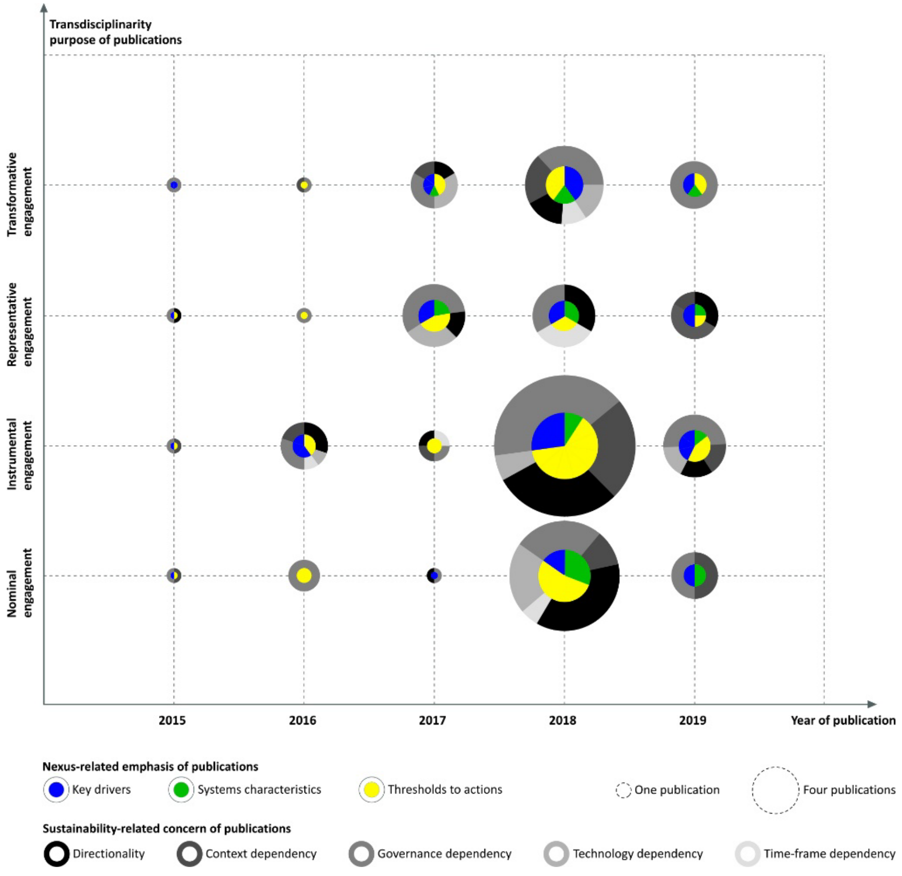

Fig. 2.3. The increasing trend of transdisciplinary FWE nexus publications (from Scopus, Science Direct, and Web of Science, last accessed 22.07.2019).

Any circle at the intersection of the X (date of publication) and Y (transdisciplinarity purpose of research) axes illustrates number of publications at that moment having the specific associated purpose (regarding size of the circle), the extent to which they emphasized the FWE nexus (regarding the inner colored circle), and the extent to which they concerned sustainability aspects (regarding the outer colored circle). The bigger the size of the circle and the more the number of its colored subdivisions, the more relevant the publication is to the purpose of linking nexus and sustainability concepts. In addition, the number of publications over the Y-axis illustrates that research has experimented with increasing inclusion of multiple stakeholders, including community, within nexus applications. The lower number of publications that adopted higher levels of stakeholder engagement compared with those adopted lower levels of stakeholder engagement indicates the existence of challenges in doing so.

Although the transdisciplinary research may bring about extensive knowledge integration, there are some limitations to the inclusion of multiple stakeholders in the FWE nexus practices. Given the geographical interpretation, the adoption of transdisciplinary approaches to the FWE nexus discourses may limit actions within specific geographies (for example, language barriers).

Transdisciplinary nexus practices depend on a common language between scientific communities and local stakeholders for knowledge sharing and collaborative discussion (Howarth & Monasterolo, 2016). More than 70 percent of actions that have been done in the field of transdisciplinary FWE nexus is situated within areas having linguistic commonalities with an author's location.

2.3.2 Conceptual description of the transdisciplinary FWE nexus

The ongoing debates on transdisciplinary FWE nexus serve multiple conceptual descriptions. First, it acts as a *sustainability transition concept* to support responsibilities of different stakeholders for the implementation of innovations in resource governance and sustainable development (e.g., Halbe et al., 2015; Karpouzoglou et al., 2017; Treemore-Spears et al., 2016; Xue et al., 2018; Ziv et al., 2018). Second, it serves as a *social inclusion concept* to facilitate negotiations over sustainable management of resources among multiple stakeholders from politics, academia, and private sectors to community (e.g., Bergendahl et al., 2018; Kumazawa et al., 2017; Mohtar and Daher, 2019). Third, it aims at a *transparency concept* to establish collaborations on trust and subsequently encourage stakeholders, especially non-experts, in their intention of collaborating in the nexus thinking and other related policy-making processes (e.g., Daher et al., 2019; Howarth and Monasterolo, 2017; White et al., 2017). Fourth, the transdisciplinary FWE nexus is employed as a *convergence thinking concept* to reach a consensus of opinions and ensure reliability and legitimacy of decisions (e.g., Johnson and Karlberg, 2017; Martinez et al., 2018; Wolfe et al., 2016).

Actions have operationalized the conceptual descriptions of the transdisciplinary FWE nexus variously depending on their purposes. Since the nexus concept emerged initially from a global point of view and most actions were taken on a global scale, the transdisciplinary nexus concept also had initially focused on the challenges of engaging stakeholders and converging their interests across geographical borders (R. Lawford et al., 2013). The argument of resource commonality across geographical borders makes the operationalization of the transdisciplinary nexus concepts more diverse (Daher et al., 2019). Some studies focused on the way stakeholders are engaged across the geographical borders (e.g., Al-Saidi and Hefny, 2018; de Strasser et al., 2016) while some emphasized the level of their engagement (e.g., Dombrowsky and Hensengerth, 2018; Soliev et al., 2015). Some researchers have also explored the necessity of active engagement of stakeholders from different areas of society in all phases of knowledge development for a real insight into needs (see Howarth and Monasterolo, 2016; Wolfe et al., 2016).

To overcome these concerns within the FWE nexus practices, proper transdisciplinary approaches are required.

2.3.3 Methods for transdisciplinary research on the FWE nexus

Several approaches have contributed to the development of the transdisciplinary FWE nexus. Among dominant statistical and environmental modeling approaches to the FWE nexus measurements, social approaches have recently contributed promisingly to the transdisciplinary aspect of nexus applications. Johnson and Karlberg (2017); Mochizuki et al. (2018); Sušnik et al. (2018) discussed that effective action to the transdisciplinary FWE nexus depends on how stakeholders frame the issue and interpret the knowledge. Within the FWE nexus research, several social methods emphasize the understanding of stakeholders' behavior, their way of thinking, and their ideas through direct observation or communication with participants. These methods include workshops, participants observations, gaming practices, and so forth.

Depending on research purpose and the scheme through which it serves multiple stakeholder engagement, nexus researchers have experimented with various methods. The systematic literature review in this chapter reveals key purposes of the FWE nexus research for adopting transdisciplinary methods as envisioning, experimenting, and learning.

An inspiring vision entails a narrative of the desired society based on shared principles of sustainable development and provides long-term guidance (Nevens, Frantzeskaki, Gorissen, & Loorbach, 2013). A process of envisioning engages and commits stakeholders with different perspectives. The envisioning purpose has been targeted frequently by FWE nexus researchers who have come up with the essential role of stakeholders in exploring the range of potential actions on the future of a transition pathway (e.g., Daher et al., 2017; Endo, 2018; Yung et al., 2019).

Following an inspiring vision, different experiments on how to realize the desired future situation can be outlined. Within the field of FWE nexus, practical experiments that link an established future vision with action, are developments of real-life alternative ways of thinking into the sustainability outcomes. Hoff et al. (2019); Vreugdenhil et al. (2012) discussed that practical experiments require an open and inclusive governance context in order to provide feedback and innovations to the policy. Several FWE nexus studies have conducted experiments in real-life contexts involving multiple stakeholders. For instance, Siegner (2018) offers experiments in educational contexts such as students gardening for placing resources sustainability at the forefront of human consciousness.

In order to initiate a sustainability transition, experiments have to be incorporated into stakeholders' behavior (Nevens et al., 2013). In that way, a learning perspective is needed. The lessons learned from envisioning efforts and practical experiments feed social capacity as well as the structure of knowledge for actions. Several studies enriched open and inclusive engagement of stakeholders within the nexus applications through learning. Agusdinata and Lukosch (2019) proposed gaming as a promising way to increase awareness of households about environmental issues and influence their behavior towards more sustainable practices.

The above-described purposes of the transdisciplinary nexus research have been covered by various practical schemes: information sharing, consultation, consensus building, decision-making, and partnership. These schemes identify the extent to which stakeholders are involved in the FWE nexus processes. Nexus research needs to know how and to what extent stakeholders are involved in the process (Stein et al., 2018). Stakeholders can potentially be involved in any of the three research purposes and their related schemes, although it is rare that they are involved in all. Fig. 2.4 presents dominant methods used for engaging multiple stakeholders within the FWE nexus research and practice. The methods used have different functionalities given the extent to which stakeholders are going to be involved in the process and the purpose of their involvement. Adapting from Stirling (2015), this chapter grouped the methods into two categories: 'analytic' or 'interactive.' Analytic methods involve a specific group of stakeholders to operate a specific shared activity. By contrast, interactive methods engage stakeholders in the process of implementing those methods in order to elicit the influences of variant values and commitments.

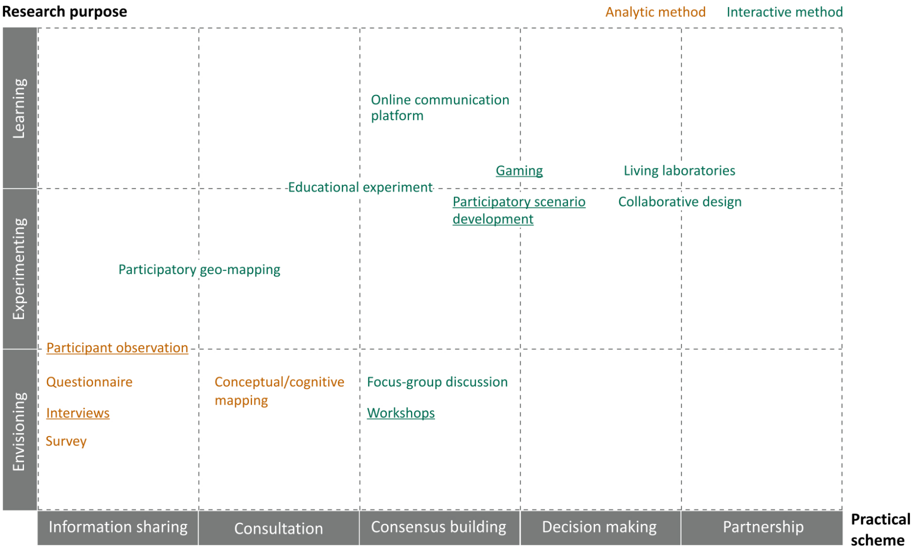

Fig. 2.4. Comparison of methods for the transdisciplinary FWE nexus.
This comparison illustrates how multiple stakeholder engagement within nexus research and practice have been carried out. Used methods have different functionalities given the extent to which stakeholders are going to be involved in the process and the purpose of their involvement. The brown and green colors distinguish whether a method tends to be 'analytic' or 'interactive' in practice. The analytic term refers to a category of methods that involve a specific group of stakeholders to operate a specific shared activity. By contrast, interactive methods engage stakeholders in their implementation process in order to elicit the influence of variant values and commitments (adapted from Stirling, 2015). The underlined methods have been used most frequently by the transdisciplinary FWE nexus research.

From the review, it is evident that interviews, workshops, participant observation, participatory scenario development, and gaming are respectively (from the highest to the lowest order) the most frequently used methods within the transdisciplinary FWE nexus research.

Interviews are one-on-one (in person or phone) conversations where several questions are put to pre-defined people. The FWE nexus research has adopted interviews in order to collect context-specific data about socio-ecological status quo of an environmentally challenging area for likely improvements. Some research discusses interviews for identifying stakeholders (e.g., White et al., 2017), some for setting intervention goals (e.g., Siegner, 2018), and several for identifying barriers to the implementation in practice (e.g., Bréthaut et al., 2019; Hoolohan, Larkin, et al., 2018; Pardoe et al., 2018). All these efforts let stakeholders get involved in envisioning the future of their living or working area and its potential development plans.

Workshops design an interactive and inclusive environment where several people can reach a consensus on what their future decision regarding a specific subject should be. The use of workshops has supported the FWE nexus in bringing together multiple stakeholders with an equal chance of incorporation and integrating ideas. Hoolohan, Soutar, et al. (2018); Treemore-Spears et al. (2016); Ziv et al. (2018) fostered integrative nexus brainstorming and envisioning through active stakeholder participation and a convergent idea space. During the workshops, participants from various groups (e.g., academia, institutions, policymakers) were asked to generate as many ideas as possible for preferred pathways towards sustainable resources management and prioritize important ones together. Moreover, pointing out the need for constructive dialogue between nexus stakeholders, Kumazawa et al. (2017); Yan and Roggema (2019) proposed experimental workshops. They provided a space for multiple stakeholders to actively challenge each other's view through creating connections between their ideas and related features in real-world.

Participant observation is a qualitative data collection method that helps researchers become known to individual behaviors and their activities. Given the importance of human behavior towards the use, storage, and conservation of natural food, water, and energy resources, several FWE nexus research have adopted the participant observation method. Siegner (2018) adapted the participant observation method, over six weeks, to capture the effectiveness of experimental learning strategies on students' behavior towards climate change and natural resources security. From her findings, the participant observation method affords opportunities for understanding informal interactions among nexus stakeholders, their behavioral norms, and all related variables of interest for understanding the interrelated socio-ecological performances. Moreover, Yung et al. (2019) explored the LIVES Cambodia project, which adopted the participant observation method for understanding uncertainties to stakeholder engagement within the FWE nexus performances. The participant observation method supported this project with knowledge of how stakeholders change their thinking in decision-making processes.

Games can provide an effective space in which stakeholders can exchange knowledge, increase their awareness, and learn skills. It is important for the FWE nexus that stakeholders acquire necessary skills for deliberative and pluralist policy making (Keshwani et al., 2017; Mochizuki et al., 2018a). There are several gaming experiments in the FWE nexus that involved various groups of stakeholders and explored multiple alternative solutions to complex resource management issues. Serious games and role-playing games are the most frequent gaming types used by the FWE nexus research through which players play the role of different stakeholders and address their interests. Agusdinata and Lukosch (2019) explored the effects of a role-playing game on households' behavior towards FWE resource consumption. They figured out that a gaming experience can connect its participants to the real context by building a shared narrative, providing learning opportunities, and encouraging problem-solving. In addition, Mochizuki et al. (2018) discussed several serious gaming experiments in the FWE nexus. Their finding highlighted the role of gaming in teaching nexus stakeholders to apply systemic thinking to making collective decisions and actions.

Participatory scenario development is a method for exploring with stakeholders various alternative storylines for the future (Voinov et al., 2016). The FWE nexus have adopted the participatory scenario development method extensively. The process of scenario development with multiple stakeholders supports the re-framing of nexus decision contexts towards more socially inclusive resource management (Colloff, Doody, Overton, Dalton, & Welling, 2019). For instance, Johnson and Karlberg (2017) explored the effect of such a participatory method on facilitating dialogue among nexus stakeholders with various levels of knowledge, experience, and interests. They emphasized the importance of local knowledge for a deep understanding of the FWE nexus issues in a particular context. Through their experience, stakeholders shared their local knowledge, and based on that, co-developed potential solutions for the future management of natural resources in Ethiopia.

2.3.4 Empirical evidence of the FWE nexus for transdisciplinarity

The transdisciplinary FWE nexus is more likely to succeed if active collaborations have happened among all groups of stakeholders including scientists, politics, industrials, and communities (Bergendahl et al., 2018). Inclusive stakeholder engagement is essential to create actionable information (Bierbaum et al., 2013; Kraftl et al., 2019). This engagement should be inclusive, frequent, two-way, and integrated across different development stages in order to support iteratively co-produced information (Ernst & Preston, 2017; Lemos, Kirchhoff, & Ramprasad, 2012; Liu, Gupta, Springer, & Wagener, 2008). Although multiple stakeholder engagement has long been the subject of FWE nexus debates, research has experienced difficulties at higher levels of collaboration in practice.

There are several limitations to the transdisciplinary nexus methods in real-world practical applications. The literature review in this chapter reveals these limitations as being context-, process-, or data- related constraints. This system of classification allows for the potential mixed adoption of various methods each addressing (a) specific limitation(s) (Hoolohan, Larkin, et al., 2018). The context-related limitations refer to the quality of communication (Daher et al., 2019; Halbe et al., 2015; Ziv et al., 2018), complexities in direct coordination among experts and non-experts (Bergendahl et al., 2018; Mochizuki et al., 2018a), varying levels of knowledge among stakeholders (Johnson & Karlberg, 2017), and context-sensitivity of transdisciplinary approaches to the FWE nexus performances (de Strasser et al., 2016; Howarth & Monasterolo, 2016). Given the process of the transdisciplinary FWE nexus, experiments have faced constraints in accordance with the timely decision- and policy- making process in a socially inclusive approach (Howarth & Monasterolo, 2017; Kumazawa et al., 2017). Moreover, incompatibility of data and variability in data availability across various groups of stakeholders are some data-related limitations to the transdisciplinary FWE nexus research (Basheer et al., 2018; Givens et al., 2018; Mohtar & Daher, 2019; Xue et al., 2018). Table 2.1 presents the extent to which these challenges influence the potential outcomes of the interlinked FWE nexus and sustainable development. Together these results provide important insights into principal concerns for conducting transdisciplinary research on the FWE nexus and potential innovations in practice for sustainability achievements.

Table 2.1

A critical review of challenges to practical experiences of the transdisciplinary FWE nexus, in terms of inclusive stakeholder engagement, and their influences on potential sustainability outcomes.

The potential contribution of inclusive stakeholder engagement to the FWE nexus sustainability	Challenges to the inclusive nexus stakeholder engagement
Higher levels of communication enhance the *capability* of different planning horizons. Daher et al. (2019)	The quality of communications. Daher et al. (2019)
Transdisciplinarity enables *inclusive stakeholder dialogue* at multiple spatial levels. Mohtar and Daher (2019)	The need for a *large amount of data* at multiple spatial levels. Givens et al. (2018)
A higher level of cooperation among multiple spatial scales helps to *maximize the benefits and minimize the costs* associated with the three FWE resources. Basheer et al. (2018)	The requirement of *extensive temporal and human resources* in bringing together individuals with different experiences. Sušnik et al. (2018)
Transdisciplinarity contributes to *raising awareness* and *building consensus* among stakeholders. Martinez et al. (2018)	Timely decision-making process. Howarth and Monasterolo (2017)
Stakeholder engagement ensures that benefits and costs of FWE nexus are *socially and environmentally acceptable*.	*Coordination of information flows* between actors at different scales. Karpouzoglou et al. (2017)

The potential contribution of inclusive stakeholder engagement to the FWE nexus sustainability	**Challenges to the inclusive nexus stakeholder engagement**
Matthews and McCartney (2018)	
Group discussion helps to *build social capital* between scientists and other stakeholders. White et al. (2017)	Complexities in *direct coordination* between scientists that developed the nexus concepts and the broader stakeholder community. Bergendahl et al. (2018)
Knowledge co-production increases *transparency* and *trust* among key nexus actors. Webb et al. (2018)	Identification of stakeholders and the way to avoid *undesired dynamics*. Halbe et al. (2015)
Transdisciplinary policymaking matches social scale with natural set up. Spiegelberg et al. (2017)	Varying level of knowledge and interest conflicts. Heitmann et al. (2019)
Participatory scenario building enables decisionmakers to *achieve more sustainable and equitable options* addressing resource allocation. Johnson and Karlberg (2017)	*A deal of time* to understand the constructed scenario building platform. Kumazawa et al. (2017)
Cross-sectoral collaboration may result in *policy coherence*. Pardoe et al. (2018)	Incompatibility of *institutional structures* and factors of political economy. Pardoe et al. (2018)

2.4 DISCUSSION

This chapter has shown the underlying scientific trend in adopting transdisciplinarity towards linking FWE nexus applications and sustainable development. Research has shaped the transdisciplinary FWE nexus by competing interpretations. Some researchers perceive this concept as a driving cause for the legitimacy of policies and development plans, while some draw on its participative management perspective and the potential for stakeholders' empowerment. The variation of interpretations highlights that the transdisciplinary FWE nexus is not uniform. It requires knowledge of navigating social transformation to shape collective behaviors and constructive dialogue among stakeholders (Mochizuki et al., 2018a).

The FWE nexus scholar mindset has recently experienced a slight shift towards social inclusion and the likely subsequent active collaboration among various stakeholders. From the environmental nexus perspective, social inclusion is the process of improving a community's opportunity to contribute to shaping climate-resilient development and gain new adaptive skills (Bergendahl et al., 2018). The social relations and dense connectivity among stakeholders can reduce transition costs that may impede the effective governance of resources.

FWE nexus research has been able to partly accomplish the desired transition towards resources governance and sustainable development through methods of transdisciplinary integration (given Fig. 2.1). In this regard, communities as the end-users of the natural resources need to be aware of the issues, be able to adjust to environmental changes, and have the willingness to taking improvement responsibilities (Blake et al., 2018). Raising community's awareness about the current socio-ecological challenges of their surrounding environment has been largely targeted by nexus debates (e.g., Agusdinata and Lukosch, 2019; Hannibal and Vedlitz, 2018; White et al., 2017). From the reviewed discourse and the structure of methods that have been used in this regard (e.g., field survey, questionnaire, and interviews), it is unlikely to observe active cooperation among FWE nexus stakeholders as a result of such awareness-raising practices. However, these practices are prerequisites to building the capacity of FWE nexus stakeholders to adjust to possible environmental changes (Mohtar & Lawford, 2016). Learning-based practices provide higher levels of communication among nexus stakeholders and subsequently allow them to consult each other about the issue and build consensus on potential solutions (Bierbaum et al., 2013). Learning-based methods such as educational experiments have contributed largely to enhance the ability of communities to adjust to environmental changes (Lotz-Sisitka et al., 2016).

Moreover, communities should take responsibility for sustainably developing their surrounding environment and making collective decisions for improvements. FWE nexus research has recently focused on the involvement of communities in decision-making processes. Gaming and participatory scenario development are such methods that nexus research has adopted in order to involve communities in decision-making processes and provide them with a sense of partnership. However, all these achievements are nascent and require more investigation to sustain practical defects.

Research has underlined the need for a balanced governance structure that incentivizes stakeholders' communication in practice and facilitates the collaborative development of new solutions. A particular impediment to this lies in unequal power relations and the structure of privilege within and between different groups of stakeholders (Stirling, 2015). The effective adoption of transdisciplinary nexus-related methods depends on nurturing capabilities that resist such inequalities. In addition, challenges of the FWE nexus are themselves created by diversities of natural settings, institutional sectors, and interests. Therefore, addressing these challenges requires relational diversities in methods and capabilities. However, as has been illustrated by the reviewed literature, there exists no unique way to express these various kinds of diversity. Nexus practices lie grounded in the specific context of research, particular disciplines, and stakeholders.

A further required capability is due caution in the contextualization of actions and the implications of generalization (Grafton et al., 2016; R. G. Lawford, 2019; Mohtar & Daher, 2019). Following statements present recommendations to achieve successful FWE nexus results in practice.

- The transdisciplinary process should be balanced in the sense of not giving too much power to one particular group of stakeholders over others even if that group leads the process. To do so, all groups of stakeholders should get involved from the very beginning of the process until the end. It may require research to employ multiple methods, for both envisioning and doing by learning, in order to realize equal contribution of stakeholders and their collective responsibilities. In case of achieving successful results in balancing power relations among nexus stakeholders, potential sustainability outcomes ‘cooperative interactions’ and ‘adaptive capacity’ would happen.

- The groups of transdisciplinary FWE nexus stakeholders should be representative to generate true sharing of knowledge and allow stakeholders to challenge different opinions. It is important to gather all relevant sectors and individuals around the table and let them learn from each other. The inclusive selection of stakeholders for nexus practices requires direct observation. It enables the involvement of voices from different groups of stakeholders (e.g., residents, local environmental mangers, development companies, and so forth) and subsequently would lead to ‘context-specific (localized) interventions.’
- The offer of the transdisciplinary perspective on the FWE nexus process should be timely. Stakeholders’ communication should start early at the beginning of the process. Specifically, the timely involvement of local stakeholders may be more satisfying than a sudden immersion in highly structured discussion meetings. If all stakeholders get involved at the same time, at the same level, and with equal power, ‘efficient solutions’ would be offered timely.
- The transdisciplinary FWE nexus process should avoid marginalizing any stakeholder. It should be ensured that all involved stakeholders express an opinion. In many cases, the role of communities in nexus projects is limited to providing local information. Securing their active engagement is essential to understanding and adjusting the way nexus practices should be taken. It would develop a new ‘resilient alliance’ among nexus stakeholders in response to environmental changes.
- The collaboration sessions should take place in locations with no connotations. It has been widely seen that collaboration sessions of nexus projects are held at universities, city council offices, or management companies that could have certain bias and may alter the development of the process. Public spaces like libraries that are open to every city actor may make a sense of ownership for less powerful stakeholders (e.g., local communities). Having a sense of ownership would then foster flows of comprehensive knowledge among stakeholders.

The interlinkages among transdisciplinarity, FWE nexus, and sustainable development shows that a consensus on political expectations is required. Policymakers need a clear elaboration of role distribution across actors, the currently implemented governance structure, and the measurement of actions in real contexts. A detailed understanding of these factors then supports optimal, acceptable, and implementable policies.

2.5 CONCLUDING REMARKS

FWE nexus can potentially support the integrated accomplishment of sustainable development goals if a transdisciplinary approach is taken. The existing literature on the FWE nexus shows that soaring research interests have been directed towards understanding, identifying, and qualifying the interrelationships among diverse stakeholders to inclusively involve nexus actors in the process and identify governance solutions. Although the underlying ideas of transdisciplinary nexus thinking have been widely accepted, there is no strong view of the understanding of its potentials and limits to practice. Concerning the varied interpretations of links between FWE nexus, sustainable development, and transdisciplinarity, this chapter proposed a framework of transdisciplinary FWE nexus conceptualization. It is believed that such an integrated conceptual development of the nexus issue can further explore its key factors and the way they interact in different contexts (see Chapter 3).

Methods pertaining to transdisciplinary nexus applications are still needed to realize inclusive, active, and equal collaborative management. Future transdisciplinary FWE nexus research should be directed towards the co-production of knowledge, cross-region communication mechanisms, co-development of decisions, and governance transition. The current experiments highlight the role of serious games in such a shift in the nexus research and practice direction. With a primary purpose of problem-solving, serious games combine learning strategies, knowledge and structures, and game elements to teach specific skills, knowledge, and attitudes. However, the governance regimes, with a high level of context-dependency, make the application of serious games in FWE nexus problems difficult. FWE nexus research should envisage likely circumstances for progress in future. First, extensive endeavors should be made to identify the key determinants of stakeholders' interactions, feasible communications, and procedures for advanced cooperative practices through real-world applications (see Chapter 4). Then, the potential of serious games in transdisciplinary FWE nexus should be realized in the real-world by simplifying the multi-stakeholder decision-making process into game elements to provide an implementation planning experience for an identified scenario or implementation endeavor (see Chapters 5 and 6).

3

AN INTEGRATED ASSESSMENT FRAMEWORK OF THE TRANSDISCIPLINARY FOOD-WATER-ENERGY NEXUS[2]

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3.1 INTRODUCTION

It is widely acknowledged that the implementation of the transdisciplinary FWE nexus arises at the intersection of complicated social and natural systems (Berkes, Colding, & Folke, 2003). Interests disputes, the cross-scale nature of nexus actions, and widespread social and ecological uncertainties demand new strategies. The best of transdisciplinary FWE nexus strategies should be turned toward social and ecological knowledge integration, aiming for an innovative governance approach that accommodates diverse views (Covarrubias, 2019). However, translating principles of the integrative social-ecological governance into transdisciplinary FWE nexus strategies and practices has remained a challenge.

A Social-Ecological Systems (SESs) approach to the FWE nexus frames linkages between humans and nature as part of a complex system with multi-scale dependencies and interactions (Maass, 2017). This approach provides insights into the multi-dimensional patterns and processes of the transdisciplinary FWE nexus, characterizing involved systems and key practical drivers.

In practical application, questions arise on how the SESs approach helps identify systems-level responses to FWE nexus? A comprehensive framework and also empirical approaches are lacking in the literature to support such a nexus responsive concern. This chapter addresses this concern by balancing the two thoughts of materialistic flows of the FWE resources and social flows into a social-ecological analysis. It does so by further conceptualizing the social-ecological interconnections among the FWE nexus systems. Specifically, this chapter offers an assessment framework that helps define and identify interconnections of the social and ecological flows shaping connections between the sectors of FWE and the actors facilitating these connections. The developed framework identifies key indicators for such an assessment. Moreover, this chapter applies an evidence-based approach via analyzing real-world data from a Dutch smart-eco city in order to prove the usability of the proposed framework. In the urban context, this chapter argues that it is in particular social interventions that lead the way towards more cross-sectorial provisioning of food, water, and energy and the transdisciplinary implementation of integrated resource management strategies.

The chapter is structured as follows. Section 3.2 provides background information into the literature on key drivers of the transdisciplinary FWE nexus, emphasizing social and ecological interconnections. Section 3.3 offers a conceptualization of a transdisciplinary FWE nexus approach from the integrative social-ecological systems perspective for improved strategies. To build this approach, different strands of the literature, including material flow analysis, environmental impacts, and the network of the society have been brought together in terms of an analytical assessment framework. Section 3.4, furthermore, illustrates these arguments through the employment of an example on FWE nexus in the Netherlands. The real-world examination sets the stage to support integrating thematic perspectives of FWE nexus, social-ecological balance, and transdisciplinarity in a multi-level analysis presented in a tabular form (Section 3.5). Results of this chapter are meant to support policymakers, management professionals, and scholars of FWE nexus to organize their analytical, diagnostic, and prescriptive capabilities so that urban sustainability interventions can be made on social-ecological balance. Section 3.6 concludes by reflecting on future developments of transdisciplinary FWE nexus strategies.

3.2 A SHIFTING PARADIGM FOR FOOD-WATER-ENERGY NEXUS

The FWE nexus has emerged as a concept to improve the sustainable use and supply of natural resources. It stands for cross-sectoral policymaking within FWE provisioning domains to overcome trade-offs and stimulate synergies in sustainable development. A key issue that it recently seeks to overcome is working in disciplinary isolation. Indeed, when it comes to resources governance, policymakers have continued to formulate policies in silos that do not guarantee coincident attainment of FWE security and social sustainability (Bhaduri, Ringler, Dombrowski, Mohtar, & Scheumann, 2015). It needs to go further into a more socially driven vision that focuses on the role of institutional arrangements, networks, and social meanings in shaping urban provisioning of FWE resources (Covarrubias, 2019).

However, such a social-ecological perspective is often ignored when analyzing interconnections among the FWE resources in cities (Covarrubias, 2019). Only a few studies have addressed the FWE resources governance from a more balanced social-ecological perspective (see Pahl-Wostl et al., 2013; Schiller et al., 2014; Scott et al., 2011).

At a societal level, Grant et al. (2002) presented a sociological approach, namely *quantified theory of Luhmann*, to couple societal aspects of natural resources management with material flow models. They quantified the impacts of societal constraints on environmentally relevant human actions. Quantitative representation of the social system in framing ecological problems is an advantage to nexus studies; however, it is rather a simplistic model that lacks the feedback of human action on social structure and the strength of the different social components on ecological decision-making.

At the level of organization, Binder (2007) introduced a structural agent analysis approach based on *Giddens structuration theory* that provides the understanding of social structures restricting or enabling strategies for managing ecological flows. This approach analyses the dynamics of social structure, including culture, studies interferences among agent groups (i.e., local communities, scholars, management professionals, and industries), and examines the different time scales of changes in social structure and ecological flows. However, in practice, this approach encounters some methodological issues regarding the weighting and operationalization procedures of factors.

At an individual level, psychological approaches such as *surveys* and *experiments* for explaining social agents' behavior affecting material flows in ecosystems and interventions for changing such behavior are mostly used. Hansmann et al. (2005); Jean et al. (2018) analyzed how game simulations of environmental and economic impacts of resources (e.g., water or food) consumption patterns influenced participants' subsequent behavior towards the use of the resources in an environmentally friendly manner. These approaches provide information about factors influencing human behavior towards natural resources consumption, although they are data and time intensive.

On closer inspection of how such approaches address the social dynamics of nexus systems, the result mainly reflects that the social dimension is not adequately conceptualized. Although those approaches provide a step forward in proposing methodologies for social-ecological analysis and perspectives, what is missing is an approach that understands the social significance of different nexus systems interactions and how they get configured through FWE resources governance. Recently, de Grenade et al. (2016); Maass (2017) introduced the *social-ecological systems (SESs) theory* to support encompassing the novel paradigm in FWE nexus although the gap yet exists in a lucid exposition of the SESs theory to nexus strategies. Therefore, this chapter posits the SESs theory as a suitable analytical perspective for emphasizing that the nexus is about the connectivity of resources flows and their embedded social relationships around FWE.

3.3 THE NEXUS SOCIAL-ECOLOGICAL SYSTEM FRAMEWORK (NEXSESF)

This chapter of the study used *social-ecological systems theory* as a base to address the FWE nexus from a more balanced social-ecological perspective. The SESs theory conceptualizes the uncertain and dynamic human-environmental systems and develops a systematic process for continually improving management policies and practices by evaluating alternative scenarios about the systems being managed and learning from operational plans outcomes (Petrosillo, Aretano, & Zurlini, 2015). A central aspect in dealing with nexus SESs is that they are characterized by cross-scale interactions, both spatial and temporal, and the same applies to their governance since decisions made on one location at a time can affect people at the same or another time living elsewhere. In this perspective, humans are considered as agents acting within nexus SESs rather than external drivers of natural systems, so that site-based, bottom-up, and transdisciplinary approaches are at the core of the nexus SESs research for sustainability.

To make the SESs theory fully operational for FWE nexus research, a right choice of social-ecological system frameworks, differing significantly in their goals and applicability, needs to be made to guide a more sustainable resource management. There are several existing frameworks for analyzing social-ecological systems that reflect the variety of research fields, and that can be applied according to the problem to be studied and how the social-ecological system is conceptualized (see Binder et al., 2013). A comparison of the frameworks' contextual and structural criteria concerning the goal of integrative FWE resources governance guides this research for selecting an adequate framework for the understanding of key transdisciplinary FWE nexus drivers (Table 3.1).

Table 3.1

A comparison of existing frameworks for analyzing social-ecological systems and a guide for selecting the adequate framework for evaluating and improving FWE nexus SESs performance.

Framework	Social scale	Spatial scale	Interaction type	Dynamics	Degree of equal S and E representation	Orientation
DPSIR Driver, Pressure, State, Impact, Response (European Commission & Eurostat, 1999)	Decision-makers	Any scale	S → E	Not conceptualized	Anthropocentric S > E	Action oriented
ESA Earth Systems Analysis (Schellnhuber & Wenzel, 1998)	Society	Global scale	S → E	Not conceptualized	Ecocentric E > S	Analysis oriented
ES Ecosystem Services (de Groot, Wilson, & Boumans, 2002)	Society	Any scale; favors regional, national scale	S → E	Not conceptualized	Ecocentric E > S	Analysis oriented
HES Human Environment Systems Framework (Scholz & Binder, 2003)	Includes all hierarchical levels	Any scale; favors regional, national scale	S ↔ E	Short- and long - term feedback loops between S and E	Anthropocentric S > E	Analysis oriented
MEFA Material and Energy Flow Analysis (Ayres, 1978)	Society	Any scale; favors regional, national scale	S → E	Not conceptualized	Ecocentric E > S	Analysis oriented
MTF Management and Transition Framework (Pahl-Wostl, 2009)	Includes all hierarchical levels	Any scale; favors regional, national scale	S ↔ E	Single, double, and triple loop learning of S as a reaction to changes in E	Anthropocentric S > E	Analysis oriented
SESF Social-Ecological Systems Framework (Ostrom, 2009)	Includes all hierarchical levels	Local and regional scale	S ↔ E	Feedback between the resource conditions and the rules determining	Anthropocentric S ≈ E	Analysis oriented

Framework	Social scale	Spatial scale	Interaction type	Dynamics	Degree of equal S and E representation	Orientation
				the consumption rates of the resource		
SLA Sustainable Livelihood Approach (Scoones, 1998)	Local stakeholders	Local and regional scale	E → S	Not conceptualized	Anthropocentric S > E	Action oriented
TNS The Natural Step (Burns, 1999)	Businesses or regions	Business and regions	S → E	Not conceptualized	Ecocentric E > S	Action oriented
TVUL Turners Vulnerability Framework (Turner et al., 2003)	Local communities	Local scale	E → S	Not conceptualized	Anthropocentric S > E	Action oriented

Note: The table presents key criteria of the several existing frameworks for analyzing social (in this table referred as S) and ecological (in this table referred as E) systems in different ways. These frameworks reflect the variety of research fields and can be applied according to the problem to be studied and the way in which social-ecological systems are conceptualized. This research made a comparison of the SES related frameworks based on a number of criteria namely: social scale (i.e., social system hierarchical levels), spatial scale (i.e., spatial scale of the ecological system, at which the framework can be applied), interaction type (i.e., the way interactions between S and E are conceptualized; S → E presents how human actions and resource needs affect the ecological system, E → S describe the influences of the ecological systems on the social systems , S ↔ E addresses the reciprocity between social and ecological systems), dynamics (i.e., the way in which SES change over time), degree of equal S and E representation (i.e., the extent to which S and E are treated equally with respect to analytical depth), and orientation (i.e., perspective of the framework; analysis-oriented frameworks provides a general language for formulating and approaching different research questions, and action-oriented frameworks act upon of intervening in a particular situation of an SES).
Source: Adapted from Binder et al. (2013).

Among the frameworks studied, SESF (Social-Ecological Systems Framework) (see Appendix: Fig. A.1) is the one that best serves the purpose of understanding FWE nexus systems' dynamics and interactions. SESF treats the social and ecological systems in almost equal depth and provides a frame for developing different degrees of specificity in analyzing the potential sustainable development of a social-ecological system. In SESF, the social system is conceptualized as resource users (actors) and the governance structure that affects the actors' actions, and the ecological system is conceptualized from an anthropocentric viewpoint as resource systems and corresponding resource units (Binder et al., 2013). Research revealed that longer-term sustainability of an SES depends on rules matching the resources systems, resource units, and actors' attributes. SESF contributes strongly to this multi-dimensional dependency. It helps to better understand the governance challenges that arise in nexus SESs and understand which governance arrangements effectively preserve the systems. The governance structure by defining rules as well as monitoring mechanisms and characterizing the kind of interdependence between users together set the condition under which action situations occur (Hinkel, Cox, Schlüter, Binder, & Falk, 2015).

Concerning FWE nexus principles and SESF fundamentals, this chapter introduces NexSESF (Nexus Social-Ecological Systems Framework) for nexus research to grasp the significance of a socio-ecological view on FWE systems (Fig. 3.1). Conceptually, the development of NexSESF is supported by adapting a generic data organizing structure for characterizing the intertwined nature of SES within FWE production systems. The scope of characterization includes food, water, energy supply and waste treatment as well as social and technological interacting components significant for nexus policies and practices. At the abstract level, an FWE system comprises several interrelated *components* each in turn encompasses one or more *processes* of transforming or generating *flows* and possibly changing *states* of components. NexSESF characterizes an FWE system with four different types of components:

Ecological components address food, water, and energy related ecosystems, including forest, wetlands, and heathlands. These components include ecological processes which although affect the availability of basic FWE resources, can, in turn, provide ecosystem services by means of raw material flows such as biomass for energy production.

Social components refer to the socio-economic structure encompassing social practices, networks, and power dynamics that go along through FWE material flows. These components focus on the role of policies, institutional arrangements, and social meanings in shaping urban provisioning of resources (Covarrubias, 2019). Incorporating social and material flows emphasizes that the FWE nexus policies and practices should rely on the connectivity of FWE resources flows and their embedded social relationships.

Technological components are principally human-made facilities that support processes for converting raw materials from ecological components into product flows; the treatment of waste and water; and the storage of resources. Such components interact well with each other through flows of FWE resources.

Demand components represent those components of the system that can receive flows that either process them to generate new flows or act as terminating points for flows, such as discharge or local consumption. These components may be of a social, ecological, or technological nature, but not fulfilling a function, merely representing a demand (Martinez-Hernandez, Leach, & Yang, 2017).

NexSESF couples the different components of an FWE system through direct input and output material and services flows among resources, indirect effects such as alteration of biogeophysical conditions or effects on stability and quality of ecosystem services, or indirect socio-economic impacts on the natural systems such as changes in resources availability conditions.

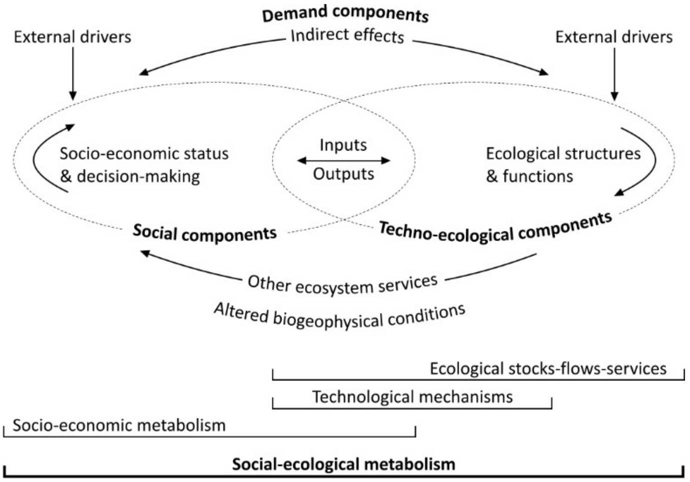

Fig. 3.1. NexSESF, a conceptual framework for research on coupling different components of an FWE nexus system.
Social, ecological, technological, and demand components are defined and coupled through direct input and output flows of interactions, indirect effects such as alteration of biogeophysical conditions or effects on stability and quality of other ecosystem services not related to the outputs, or indirect socio-economic impacts on the natural systems such as changes in resources availability conditions.

3.3.1 NexSESF operationalization and employment

Employment of NexSESF into a real-world FWE nexus locale is achieved by operationalizing the underlying drivers of the nexus components' dynamics and adopting an unsupervised learning algorithm, Principal Component Analysis (PCA), for quantifying the interrelated drivers. The structure of NexSESF operationalization is presented in Table 3.2. Concepts of the FWE nexus system components depicted by NexSESF were turned into measurable variables and indicators. Variables comprise predictability of the ecological system dynamics; resource units' flexibility, dependency, stability, efficiency, and accessibility; social network structure; operational rules; economic development; demographic trend; deliberation processes; and social and ecological performance measures. To quantitatively measure the variables, several indicators are defined for each, presented in Table 3.2. The selection of indicators was made based on multiple criteria: confirming international standards, considering biophysical limits, being limited in numbers (i.e., quantifying nexus drivers as numbers, even those of qualitative description), and considering data availability.

Table 3.2
NexSESF variables operationalization.

Dimension	Variable	Indicator
Ecological structures & functions	Predictability of system dynamics	Resource system size in terms of the total urban system area in ha, pollutant load on surface water (population equivalent), pollutant load on fresh water (population equivalent), volume of wastewater (m^3)), volume of tap water use by private households (m^3), total natural gas supplied (m^3), total electricity supplied (kWh)), average annual natural gas consumption of private households (m^3), electricity consumption of private households), total fertile cultivated land (ha), actual individual food consumption change (% annual volume change)).
	Resource units' flexibility	Gross wind energy end use in % of total energy consumption, gross solar energy end use in % of total energy consumption, gross biomass energy end use in % of total energy consumption.
	Resource units' dependency	Volume of natural gas supply to agriculture industry (m^3), volume of natural gas supply to water and waste management industry (m^3), amount of electricity supply to agriculture industry (kWh), amount of electricity supply to water and waste management industry (kWh), total tap water use by agriculture and food manufacture (m^3), tap water use by electricity and gas supply (m^3), tap water use by water supply and waste management (m^3), total groundwater use by agriculture and food manufacture (m^3), total groundwater use by electricity and gas supply (m^3), total groundwater use by water supply and waste management (m^3), total use of surface water for agriculture and food manufacture purposes (m^3), total use of surface water for electricity and gas supply purposes (m^3), total use of surface water for water supply and waste management purposes (m^3), total amount of households organic waste (kg per inhabitant).
	Resource units' stability	Average groundwater level (mm), the quantity of precipitation (mm), evaporation (mm), percentage of

Dimension	Variable	Indicator
		annual change of the total gross agricultural production (% annual production change),
	Resource units' efficiency	Economic values in terms of healthcare expenditure (euros per capita).
	Resource units' accessibility	Installed capacity of solar panels for all economic activities (kW), gross renewable energy consumption relative (in % of total energy consumption).
Socio-economic status & decision-making	Social network structure	Level of disciplinarity in socio-ecological projects (experts' scores of 1 to 0.25 with the highest to the lowest level of collaboration).
	Social capital	Motivation and attitude of actors in terms of the percentage of inhabitants that have been active in the past year to improve the ecological system of their living area (% of active inhabitants).
External drivers	Economic development	GDP (% annual change), average income per private household (x 1000 euros).
	Demographic trend	Population growth rate (%).
SES interactions effects and outcomes	Deliberation processes	Social cohesion (i.e., scale score measured based on citizens' attitudes relative to social relations - trust in other people, shared priorities with others, and diversity (for the case study of this chapter, social cohesion was calculated and provided on the official website of the City)).
	Social measures	Percentage of population overweight (%), drinking water quality in terms of total nutrients emission to water by private households (1000 inhabitant equivalents), annual volume of effluent wastewater discharged from urban wastewater treatment plants (1000 m^3), total capacity of urban wastewater treatment plants (1000 inhabitant equivalents).
	Ecological measures	Annual carbon dioxide (CO_2) emission by different sectors of private households, energy, agriculture, and waste and water treatment (million kg). Contribution of the use of different renewable energy types (i.e., solar energy, wind power, hydropower) in avoidance of CO_2 emission (in % of the total annual CO_2 emission), annual amount of household's residual waste (kg per inhabitant), installed capacity of solar panels on agriculture (kW), the amount of soil mineral excretion, including nitrogen, phosphate, and potassium, per hectare of cultivated land (kg/ha).

Note: This table presents the operationalization of variables depicting different social, ecological, technological, and demand components of an FWE nexus system, their dynamics, and interactions. The dependent variable of this study is the performance of integrative nexus systems governance, while the independent variables consist of economic and demographic development; predictability of the ecological system dynamics; resource units' flexibility, dependency, stability, efficiency, and accessibility; social network structure; operational rules; deliberation processes; and performance measures from both social and ecological perspectives. In the 'indicators' column, the parentheses represent units for the quantification of the indicators. See Appendix B: Table B. 1 for a detailed presentation of the indicators and their quantification measures for the case study of this chapter.

Source: Adapted from Arthur et al. (2019); Giupponi and Gain (2017); International Organization of Standards (2018); King and Carbajales-Dale (2016); Leslie et al. (2015); Maass (2017); Ostrom (2009); Ozturk (2015); Saladini et al. (2018); Wang et al. (2017).

The defined indicators represent a trend tracking the measurable changes in an FWE nexus system over time. Indicators need to draw upon a large set of data, possibly varying in scale, to quantify the latent or underlying relationships among components of an FWE nexus system and the key drivers of such relationships. Several challenges are associated with using large datasets for nexus research, including integrating data varying in scale, tricky process of converting large datasets into valuable insights, and complexity of managing data exploration and visualization. The employment of NexSESF which relies on a significant number of indicators and a large set of data requires a method that can overcome the challenges of working with high-dimensional datasets.

PCA, as one of the most widely used exploratory methods for data analysis, simplifies the complexities of high-dimensional data while retaining trends and patterns. Although dimensionality reduction normally comes at the expense of accuracy, the resulting simplicity is well worth it since smaller datasets are easier to explore and visualize. PCA transforms the data into fewer dimensions called *principal components (PCs)*, which act as best summaries of the dataset features (Lever, Krzywinski, & Altman, 2017). PCs are new uncorrelated variables constructed as a linear combination of the initial variables so that most of the information within the data is compressed into the first PCs. Geometrically speaking, PCs represent the directions of maximum variance in the data, having the first PC capturing the highest possible variance. The relationship between variance and information here is that the larger the variance carried by a line, the larger the distribution of the data points along it, and the larger the data distribution along a line, the more the information it covers.

This research took advantage of the PCA method to recognize central dynamics of FWE nexus changes, in a real-world context, over time. Python programming language and the Scikit-learn machine learning library were used to apply the PCA method to real-world employment of NexSESF (see Appendix B: Table B. 4 for a detailed illustration of the python code developed for the analysis). Retaining the most meaningful PCs representing the greatest variance of the data, the contribution of different indicators of NexSESF to changes in an FWE nexus setting was explored over time. Indicators with the greatest contribution are assumed to have robust linkages to change trajectories of the interrelated socio-ecological systems management.

The following section presents a case study to illustrate the real-world employment of NexSESF, using PCA, with respect to the role of the introduced framework in examining implications of transdisciplinary FWE nexus strategies.

3.4 AN ANALYSIS OF THE TRANSDISCIPLINARY FWE NEXUS IN A LOCAL SYSTEM USING NEXSESF

In this section, a case study to demonstrate the application of NexSESF is presented, by the following steps:

- Introducing the FWE nexus setting of the case study, including the objectives and the specific system components studied for the selected locale (Sub-section 3.4.1); and
- Presenting application results of the NexSESF on a system with synergistic relations (Sub-section 3.4.2).

3.4.1 Characterization of the case study

NexSESF was employed to analyze a nexus system comprising components considered for the Eindhoven smart-eco city in the Netherlands as part of a restructuring urban development plan. The plan considers a vision of integrated blue, green, and grey infrastructure that fully satisfies the food, water, and energy needs of the corresponding population (Hawxwell et al., 2018). To meet such needs, Eindhoven has integrated several social, ecological, and technological systems components and incorporated many nature-based features into re-development plans of the city. Developing gas-free districts, increasing permeable surfaces, creating greener areas, controlling stormwater, and encouraging citizens in local food production are examples of Eindhoven's SES incorporation activities. In addition, citizens have been challenged to discuss ecological problems of their living area and organize the exchanges with policymakers, management professionals, and scholars that provide solutions to the problem posed.

Here, the principal objective is to examine the various components of the local FWE systems and their interdependencies on the level of demand satisfaction in Eindhoven. The spatial scope of the study included the FWE systems available to the city, including residential, industrial, and ecosystem areas. The temporal scope is of 15 years from 2004 to 2018, which is a scale suitable to observe changes in ecological components due to the impact by social and technological components.

The local nexus system under study comprises multiple components of the food, water, energy nexus subsystems along with the main social and technological parameters required for evaluation.

Food subsystem component: The potential production of fresh vegetables, grains, fruit, meat, and dairy for local demand was considered in the Eindhoven food subsystem. Water, energy, and fertilizer requirements are compiled from the trend of resources consumption over time. The food components produce biomass as residues for which a waste processing is of need. The food subsystem also plays a role of assimilating excess nutrients available in the local system.

Water subsystem component: It includes wastewater treatment plant as a technological component and some aquifers set off to the city as ecological components in Eindhoven. The wastewater treatment plant treats the sewage water produced by inhabitants. The aquifers provide the locality with freshwater and introduce processes that may affect the water balance to this study to track the water level as an ecosystem state.

Energy subsystem component: It includes combined heat and power plants and roof-mounted solar panels on the houses as technological components. Heathlands are ecological components that provide biomass as an ecosystem service in Eindhoven which also significantly absorb CO_2 and excess nutrients but may be under threat from the current environmental and management conditions.

Demand component: Inhabitants are considered in this study as a demand component of the nexus system in Eindhoven which the overall production system should aim to serve by satisfying its food, water, and energy needs.

The interdependence of FWE nexus components in Eindhoven was considered through an exchange of flows among food, water, and energy subsystems and the demand component. These specifications for Eindhoven were generated based on the information available from CBS (Centraal Bureau voor de Statistiek), an online statistical database in the Netherlands, and the Eindhoven city planning documents (see Appendix B: Table B. 1 for a descriptive summary of the compiled data for Eindhoven and how it is used to cover each indicator, and Table. B. 3 for the raw data). Due to the different nature of the resources in a nexus system that integrates heterogeneous components, it is desirable to adopt a unifying quantity. In this study, exergy, defined as the available energy of a resource to do useful work, is used (Adapted from Leung Pah Hang et al., 2016). In delivering a service, exergy includes all types of resources required from extraction to the point where they are used. Moreover, exergy is a unifying quantity that can represent material, energy, and non-energetic streams.

Fig. 3.2 depicts how the food, water, and energy subsystems' components reflect the studied local nexus setting in a quantitative manner. The diagram demonstrates the FWE resources interdependence (in plot (a)) and their pairwise interaction on the level of demand satisfaction in Eindhoven, depicting 15 years of integrative environmental management from 2004 to 2018 (in plot (b)). It can be observed from Fig. 3.2(a) that in this integrated case of the FWE nexus system, the water subsystem is more directly dependent in the system, especially on energy, as is presented in Fig. 3.2(b). Although water and energy, in this case, are hardly dependent on direct input from the food subsystem, any changes in the food subsystem will affect the other two by changing water and energy utilization in the nexus.

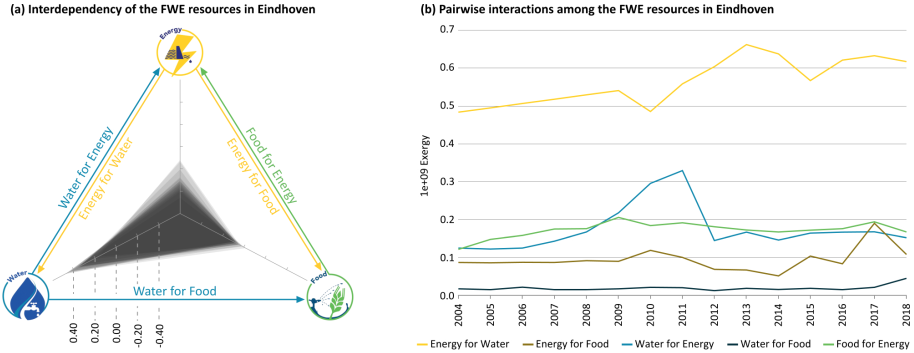

Fig. 3.2. Plots of (a) the FWE resources interdependence and (b) their pairwise interaction on the level of demand satisfaction in Eindhoven depicting 15 years of integrative environmental management from 2004 to 2018.

This information is based on the visualization of the unified quantity of NexSESF indicators (in exergy) for Eindhoven. In plot (a), all sources of food, water, and energy that contribute, to any extent, to the production of one another are concerned. The resources input-output relationships were overlayed over the years. The value zero shows the equality of input and output flows for a resource. Darker areas in plot (a) illustrate the most dominant material and production flows across resources over time. For instance, the water subsystem which has a dominant value close to 0.4 over years, receives more input from the other two resource subsystems than its outputs toward them. The line chart (b) displays the magnitude of changes in pairwise food, water, and energy relationships over time. It shows the total values across an almost coordinated trend. The values presented in the chart demonstrate the extent to which each resource is dependent on one another. For instance, over the studied 15 years of resources management in Eindhoven, the demand of water subsystem for energy is significantly high compare with other FWE relationships.

3.4.2 Analyzing the FWE nexus in a synergistically integrated scheme

Employing NexSESF, the FWE nexus analysis was evolved into a synergistically integrated scheme intended to reveal central dynamics of the system components. The role of PCA here is to offer NexSESF an exploratory tool that discovers the extent of the influence different variables exert on an FWE nexus system and its variant components interactions.

In this chapter, NexSESF using PCA discovered key variables that significantly influence the transdisciplinary FWE nexus in Eindhoven, as shown in Fig. 3.3 and Fig. 3.4. To minimize complexities and reflect clearly on visible trends in data, this study focused on the first two principal components which contribute significantly (i.e., ≈ 71%) to explaining the variance of the data. In a two-dimensional graph, Fig. 3.3 shows the distribution of NexSESF indicators across the selected PCs. Having PC1 as the horizontal x-axis and PC2 as the vertical y-axis, indicators with the highest absolute X and Y values (i.e., darker dots in Fig. 3.3) contribute more to the associated PC, therefore, have more influence on exploring the FWE nexus in Eindhoven. In this case, whether the value of an indicator across each PC is positive or negative corresponds to how it influences the subject of the analysis. Indicators with positive values correlate positively with the FWE nexus in Eindhoven, and vice versa, there are negative correlations between the FWE nexus in Eindhoven and the indicators having negative values of the PCs.

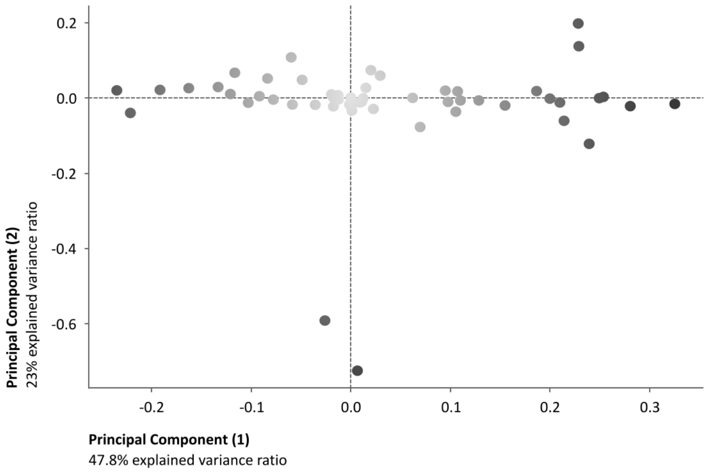

Fig. 3.3. Dispersion of NexSESF indicators across PC1 and PC2 of principal component analysis on FWE nexus data from Eindhoven.

The plot axes show the value of each indicator in each of the corresponding component. The dots represent NexSESF indicators and their color stands for their values, the darker the color the greater the value (see Appendix B: Table B. 2 for the numerical data of this figure). Having PC1 as the x-axis and PC2 as the y-axis and the zero value at the intersection of the two components, indicators with the highest absolute X and Y value contributes more to the associated PC. The indicators with high values (darker dots on this plot) have more influence on defining underlying drivers of nexus interactions and changes (a detailed explanation of such indicators is presented in Fig. 3.4). In addition, the positive values stand for a positive correlation between the indicator and the FWE nexus improvement in Eindhoven. The same applies to the negative values which show a negative correlation of corresponding indicators with the improvement of FWE nexus processes in Eindhoven. The values of the 'explained variance ratio' are percentages of variance explained by each of the selected principal components. PC1 explains almost 48% of the data variance, PC2 explains about 23% of the data variance, and cumulatively, they explain almost 71% of the data in this analysis.

From the data in Fig. 3.4, it is apparent that the transdisciplinary FWE nexus in Eindhoven needs to count on adapting techno-ecological solutions to overcome society's tendency for more resources. Technological advances in renewable energies such as solar panels, wind turbines, and thermal energy storage may support Eindhoven in balancing resources and reducing the CO_2 emission as a climate protective measure. Such developments have positive influences on the FWE nexus purpose of Eindhoven in preserving scarce natural resources. According to Fig. 3.4, there exist several drivers that influence the FWE nexus in Eindhoven negatively. From plot (a) in Fig. 3.4, the continuance in the supply of natural gas retards the success of nexus policies and plans in Eindhoven.

In addition to advanced technologies, some socio-economic aspects such as population growth and GDP (per capita) appear to correlate closely to food, water, and energy metrics in Eindhoven (Fig. 3.4(b)). Research expressed that areas with higher GDP generally withdraw more water, consume more food, and produce more energy (Sušnik, 2018). It is also acknowledged that cities cannot interfere in such socio-economic aspects for FWE nexus improvement. Therefore, along with the previously mentioned techno-ecological actions, Eindhoven needs to focus on the possible indirect drivers of such socio-economic changes.

In addition to PCs emphasizing key direct nexus drivers, PCA, by calculating highly significant correlations among NexSESF indicators, determines indirect drivers of the FWE nexus success (see Appendix B: Fig. B.4). In Eindhoven, level of disciplinarity in socio-ecological projects and the motivation and attitudes of nexus actors have significant indirect influences on FWE nexus progress.

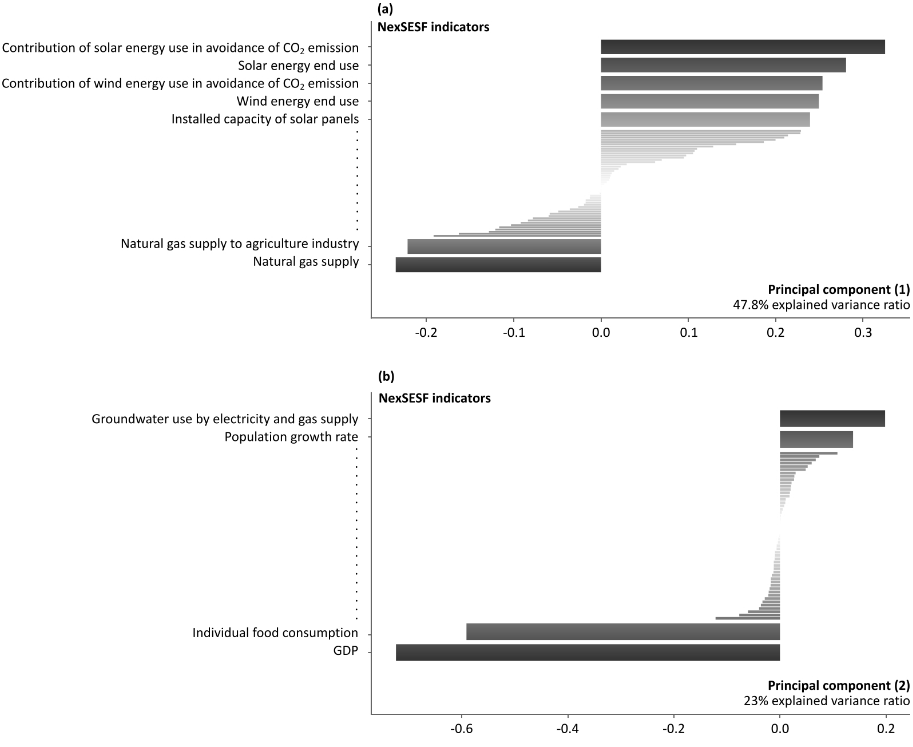

Fig. 3.4. Underlying Principal Components and the key variables describing FWE nexus in Eindhoven. Plots (a) and (b) respectively show key drivers of FWE nexus changes in Eindhoven across PC1 and PC2. In this case, whether the value of an indicator across each PC is positive or negative corresponds to how it influences the subject of the analysis. Indicators with positive values correlate positively with the FWE nexus in Eindhoven, and vice versa, there are negative correlations between the FWE nexus in Eindhoven and the indicators having negative values of the PCs. See appendix B: Fig. B.2 and Fig. B.3 respectively for the extended representation of NexSESF indicators across PC1 and PC2.

3.5 VERIFYING THE ROLE OF NEXSESF IN TRANSDISCIPLINARY FWE NEXUS STRATEGIES

This section verifies the role of NexSESF in transdisciplinary FWE nexus improvement by incorporating several intimate connections between key practical concepts of NexSESF, current FWE nexus concerns, and the goal of social-ecological balance. At the end of this section, further developments of the integrative NexSESF conceptual model are discussed (Section 3.5.1).

Based on the empirical examination in this chapter, the novel NexSESF framework presents a great reflection of *systematic*, *transdisciplinary*, *adaptive*, and *monitoring mechanisms* for FWE nexus concerns in practice. From a practical point of view, FWE nexus concerns how uncovering synergies, detecting detrimental trade-offs, unveiling unexpected consequences, and promoting integrated decision-making and governance. Table 3.3 illustrates the role of NexSESF, by means of its key practical concepts, in addressing such concerns over FWE nexus.

Systemic thinking entails considering FWE nexus as interrelated connections among multiple social, environmental, technological, and organizational scales, so that the synergistic effects and varying demands are identified (Wolfe et al., 2016). From our practical experience, NexSESF can support a systemic nexus thinking through (i) stressing variables that are most likely to change in response to systems dynamics (Fig. 3.4) and (ii) identifying synergistic effects and co-benefits that might otherwise be missed in complex production systems (Fig. 3.2). This perspective is particularly important in densely populated areas where benefits of more efficient resource consumption are high.

Transdisciplinarity frames FWE nexus as a process that starts with 'what exists', continuing with 'what we can do', moving towards 'what we want to do', and resulting in 'what we need to do'. The empirical examination of an FWE nexus system using NexSESF in this chapter shows that the proposed framework contributes greatly towards transdisciplinarity (see Table 3.2). It characterizes ecological structure (e.g., FWE demand profile) and socio-economic status (e.g., social network) of a nexus system to understand 'what exists'. In addition, by studying ecological functions (e.g., resources stability, efficiency, and accessibility) and decision-making processes (e.g., operational rules, and attitudes of actors), NexSESF identifies capabilities of a system for a state of preservation and referring to 'what we can do' and 'what we want to do'. Moreover, NexSESF stresses the potential for practical FWE nexus improvements by highlighting central drivers of social and ecological interactions that can respond to 'what we need to do'. Accordingly, NexSESF can help detect and minimize detrimental trade-offs through identifying context-specific solutions adapted to the respective resource scarcities (e.g., the right choice of irrigation systems for drier regions).

Adaptive governance supports the great deal of nexus uncertainties originate from mismatches between characteristics of environmental sectors and the way corresponding organizations are governed. NexSESF couples social and ecological metabolisms of a nexus setting through characterizing interconnections between ecological structures and socio-economic processing and organizational decision-making. It can, accordingly, assist in considering unexpected consequences of solutions to environmental management.

Monitoring mechanism acts to position assessment, reflection, and learning in empirical FWE nexus contexts. NexSESF, by bringing together different actors involved in FWE management and considering uncertainties involved in social-ecological interactions, can promote coordination and policy coherence, and help keep track of the impacts generated by policies. It draws attention to key variables that structure the most complex interactions in nexus systems and support the understanding of future trajectories.

Table 3.3
A thematic perspective on the role of NexSESF, by means of its key practical concepts, in addressing FWE nexus concerns.

		FWE nexus concerns				**Relevance to regaining social-ecological balance**
		Uncovering synergies	Detecting harmful trade-offs	Unveiling unexpected consequences	Promoting integrated governance	
NexSESF practical concepts	Systemic thinking	×	×	×		▪ Stability ▪ Cost of extraction ▪ Robustness against over-exploitation of resources
	Transdisciplinarity	×			×	▪ Transparency ▪ Willingness to collaborate
	Adaptive governance			×	×	▪ Coordination ▪ Cost of organization ▪ Integrated management decisions
	Monitoring mechanism		×	×	×	▪ Deterrence of free riders ▪ Adapted rules

Note: This table aims to verify the assessment of this study by incorporating several intimate connections between NexSESF, current FWE nexus concerns, and the goal of social-ecological balance. Systematic thinking, transdisciplinarity, adaptive governance, and monitoring mechanism are key concepts characterizing NexSESF from a practical point of view.
Source: Frey (2017); Ghodsvali et al. (2019); Howarth and Monasterolo (2016); Ostrom (2009); Virapongse et al. (2016).

3.5.1 Future developments of the nexus integrative framework

Through examining NexSESF application results, useful information for decision-making can be derived for the nexus situation in a particular locale. This is helpful, especially because the FWE nexus can manifest differently depending on the condition. As a framework mainly for studying integrative social-ecological nexus systems, NexSESF needs sufficient details of a locality to carry out meaningful assessments. As long as context-specific data is unavailable, the adoption of generic values for missing parameters could introduce inaccuracies to NexSESF outputs. Therefore, engagement with nexus scholars and local communities to develop context-specific datasets is crucial for successfully applying such a framework.

Although arguably less critical at local scales, NexSESF currently does not explain spatial variations of ecosystem components and will benefit from adding spatially explicit assessment capabilities. Moreover, the framework could be enhanced in aligning the FWE nexus studies at different resolutions. Given the multi-scale nature of FWE nexus challenges, it would be helpful to connect a framework that focuses on detailed assessment at a local level, such as NexSESF, with tools that address other levels.

3.6 CONCLUDING REMARKS

Addressing the need of the urban areas for understanding key operational drivers of the transdisciplinary FWE nexus, this chapter was concerned with providing an integrative social-ecological perspective by means of a novel assessment framework, namely NexSESF. An integrated social-ecological perspective on FWE nexus conceptualizes the uncertain and dynamic human-environmental systems and develops a systematic process for continually improving management policies and practices. NexSESF allows FWE nexus scholars to incorporate details and gain holistic insights into not only the interdependencies but also the dynamics in the social and techno-ecological systems and the opportunities of better managing the FWE nexus systems in real-world. It couples the different components of an FWE system through direct input and output material and services flows among resources, indirect effects such as alteration of biogeophysical conditions or effects on stability and quality of ecosystem services, or indirect socio-economic impacts on the natural systems such as changes in resources availability conditions. A novel aspect of the framework involves capturing the interactions and dynamics over time. This provides a cross-level approach allowing the study of interferences in processes of resources production, processing, and distribution. To achieve more efficient resource consumption and a better balance between demand and supply within a local system, the framework helps explore potential synergies between different technological components.

NexSESF is particularly useful in exploring potential improvement options for specific optimization strategies within a wider context of a local FWE nexus system. As a framework mainly for studying integrative social-ecological nexus systems, NexSESF needs sufficient details of a locality to be able to carry out meaningful assessments. Engagement with nexus scholars and local communities to develop context-specific datasets is crucial for successfully applying such a framework. From the use of the framework on a local nexus system in a Dutch smart-eco city, it was found that the synergistic assessment through a combination of clarifications on social responsibility, ecological balance, technological progress, and political participation suggested potential amendments to nexus practices.

From a practical FWE nexus viewpoint, the urban understanding of social and ecological systems interactions and dynamics needs to be combined with a sort of transdisciplinary governance mechanism. Changes are required in how practices and policies use this information and advance socio-eco-technical design methods of the transdisciplinary FWE nexus. This research contributes towards such practical changes by employing the findings of this chapter and the developed assessment framework, i.e., NexSESF, for a game-based transdisciplinary decision-making process design and implementation. The integration of social and ecological perspectives in nexus decision-making processes provides insight into how such multi-level interactions affect planning alternatives in future.

4

THE GOVERNANCE MECHANISM OF THE TRANSDISCIPLINARY FOOD-WATER-ENERGY NEXUS

LEASONS LEARNED FROM SIX URBAN LIVING LABS ACROSS THE WORLD[3]

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[3] This chapter has been accepted as:
Ghodsvali, M., Dane, G., & de Vries, B. (2022). The urban living lab as an adaptive governance mechanism for the transdisciplinary food-water- energy nexus: lessons learned from six local contexts. In Designing Sustainable and Resilient Cities: Small Interventions for Stronger Urban Food-Water-Energy Management. Routledge.

4.1 INTRODUCTION

As many cities worldwide try to restore the balance in trade-offs between the food, water, and energy sectors, it has gradually been discerned that, beyond the understanding of social-ecological interactions and the adoption of new technologies and infrastructure, changes are required in how practices and policies shift towards transdisciplinarity (Colloff et al., 2019; Gorddard, Colloff, Wise, Ware, & Dunlop, 2016). Human behavior regarding resource consumption is of central importance in ecosystems' integrity and the implementation of integrated solutions for the nexus of the FWE sectors (Ghodsvali et al., 2019). However, urban communities will not modify their consumption behavior while gaps exist regarding the awareness of the severity of the issue and the role of stakeholders at human scales (Yan & Roggema, 2019).

In response to these challenges, a new governance mechanism that shifts policies and practices towards communication, experimentation, and learning is emerging in the form of the Urban Living Lab (ULL). ULLs constitute a form of innovative, transdisciplinary governance mechanism whereby stakeholders that are in a value chain co-create ideas, plans, and service propositions, and experiment with solutions to urban sustainability challenges in a real-life environment (Bulkeley et al., 2016). The co-creation process, with its reliance on iterative consultation, suggests stakeholder involvement at multiple stages throughout the FWE nexus process (Davis & Andrew, 2017). The experimentation process, consisting of various participatory approaches, establishes new forms of collaboration among stakeholders, guides urban policies, and navigates the dynamics of urban transformation (Frantzeskaki, van Steenbergen, & Stedman, 2018; Nevens et al., 2013). For cities trying to maintain an ecological balance, ULLs appeal as an open form of collective urban experimentation towards transformative improvements.

However, policymakers and other FWE nexus actors are struggling with the implementation of ULLs, and are seeking guidance on their further development (Kraker, Scholl, & Wanroij, 2016). This operational weakness is mainly due to a lack of evidence-based guidelines concerning how a ULL can best be organized and integrated into the local governance structure of nexus-emphasized cities. This practical shortcoming calls for a critical reflection on the experience of FWE nexus projects in implementing ULLs to help guide others towards an effective route into transdisciplinarity innovations that meet local socio-ecological challenges.

This chapter aims to frame the understanding of how ULLs are being operationalized in urban governance for the nexus linking food, water, and energy in cities and the way such an approach contributes towards transdisciplinarity and the multi-stakeholder decision-making processes. After a thorough review of the literature on the characteristics of ULLs and their recent contribution to the transdisciplinary FWE nexus (Section 4.2), six local case studies of nexus ULLs were selected for further analysis (Sub-section 4.3.1). The empirical cases were part of an international FWE-nexus ULL project called Climate Resilient Urban Nexus CHoices (CRUNCH), which aimed to create an interconnected knowledge platform in support of the increasing challenges of food, water, and energy resources management. The selection of multiple case studies is supposed to broaden the potential rigor of the study by improving the validity and robustness of the results (Yin, 2009). This chapter assessed key operational characteristics of the selected ULLs and the likelihood of advancing their performance in terms of transdisciplinarity, multiple stakeholder engagement, and cross-sectoral policy coordination. The findings lay down guiding principles for the development of ULLs for such practical challenges of the transdisciplinary FWE nexus (Sub-section 4.3.2 and Section 4.4).

4.2 THE URBAN LIVING LAB (ULL) THROUGH THE LENS OF THE TRANSDISCIPLINARY FWE NEXUS

The essence of the transdisciplinary FWE nexus is about building capacity to inclusively gain more from less, in the context of the natural food, water, and energy sectors (Ghodsvali et al., 2019; Scott et al., 2015). Acting upon this concept requires *cooperative interactions*, *localized interventions*, a *resilient alliance*, *efficient resolutions*, and *adaptive capacity* (according to the conceptual framework developed in Chapter 2 of this thesis for the transdisciplinary FWE nexus) (Ghodsvali et al., 2019). The ULL approach is a way to put these theoretical propositions into practice (Baccarne, Logghe, Schuurman, & De Marez, 2016; Ghodsvali, Dane, & de Vries, 2022).

From the transdisciplinary FWE nexus perspective, ULLs perform beyond simply promoting learning and innovation. They undergo a structured process in which a wide range of nexus actors (i.e., civil society, academia, government, and industry) through implementing a combination of diverse participatory methodologies (e.g., co-creation workshops and focus groups) give shape to socio-ecological interventions and govern development resolutions in real-time (Bulkeley et al., 2016; Ghodsvali et al., 2022).

Empirical research on the transdisciplinary FWE nexus underlined four key peculiarities shared by ULLs (see, e.g., Almirall, Lee, & Wareham, 2012; Mulder, 2012; Nesti, 2017):

First, ULLs are founded on a network of relationships among their ***actors and users*** inspired by the quintuple helix model, i.e., collective interaction and exchange of knowledge between the political system, civil society, the natural environment, the economic system, and the education system (Carayannis, Barth, & Campbell, 2012). Along with the transdisciplinary nature of FWE nexus practices, ULLs forge an effective public-private-people partnership, placing people at the very center of the innovation process (Molinari, 2011). This relational structure in turn facilitates *cooperative interactions* as part of the transdisciplinary FWE nexus requirements through which different actors, organizations, and ecosystems are able to collaborate.

Second, ULLs enable the adoption of ***co-creation approaches*** for socio-ecological problems that are designed, prototyped, evaluated, and refined with participants in real-world settings (Pierson & Lievens, 2005). Through comprising of co-creation, a form of collaborative innovation, ULLs represent a remarkable shift from passive user engagement to a more active approach based on the dominant paradigm of iterative consultation and participatory knowledge production. They develop a knowledge-driven society, thereby potentially leveraging the knowledge circulating in the urban environment (Baccarne et al., 2016; Cardullo, Kitchin, & Di Feliciantonio, 2018). From the transdisciplinary FWE nexus perspective, the ULL approach, including experimentation and learning, explores the possibility of directing societal behavior change and optimizing the overall ecological impact of an FWE nexus approach implementation (Davis & Andrew, 2017; Lund, 2018). More specifically, it contributes towards the requirement of the transdisciplinary FWE nexus to characterize paradigms of *localized interventions* based on the collaborative knowledge of society.

Third, at the core of ULLs lies the concept of collective responsibility, from which stakeholders can form the basis for a concerted ***governance structure*** (Halbe et al., 2015; Voytenko, McCormick, Evans, & Schliwa, 2016). The basic idea is that instead of delegating responsibilities to specific stakeholders, such as politicians or certain businesses, ULLs make an effort to remain inclusive to all different stakeholders and to foster joint innovations (Chesbrough, 2003; Nesti, 2018). Within ULLs, participants are encouraged to brainstorm and discuss ideas for which the operational knowledge is diffused across society, and in turn practical solutions to FWE nexus challenges are offered by governments, scholars, and industrial coordinators together with communities. Hence a *resilient alliance*, in terms of concerted action across multiple actors (i.e., the FWE nexus quintuple helix system), is promoted through a continuous process of knowledge diffusion and the division of responsibilities. This concept of a coordination role is significant for a ULL to be effective within the transdisciplinary FWE nexus process since it underpins the ability of ULLs to build the *adaptive capacity* of the nexus social system to meet mutual challenges. It facilitates explicit learning among nexus participants, and allows for the refinement of developmental visions and how to better align them with the needs of the end-users (Voytenko et al., 2016).

Fourth, ULLs are characterized by their concern for ***socio-technical system design*** utilizing Information and Communication Technologies (ICT) (Nesti, 2017). Active collaboration with citizens often necessitates generating new content, instant sharing with others, and testing the outcomes of decisions. ICT provides great opportunities for active collaboration since it enables interactions at all times with lower costs of connection, and facilitates the transformation of thorough knowledge (Meijer, 2012). Communities utilizing ICT for inclusive and active collaborations benefit from empowerment and social progress. From a transdisciplinary FWE nexus perspective, ICT infrastructure supports ULLs with social progress through enabling mutual interactions, a continuous exchange of knowledge, and the transformation of expert knowledge into information that is comprehensible to all participants. This interlinked socio-technical systems design in turn particularly contributes to the FWE nexus' goal for an *efficient resolution* of socio-ecological transformations, which meet environmental changes with social progress.

Notwithstanding commonalities, there are apparent differences in the way that the ULL approach have been implemented in the practice of the transdisciplinary FWE nexus. The urban contexts of transdisciplinary FWE nexus practices vary in their social, institutional, and environmental aspects, and the ULL approach is implemented differently in accordance with this (Ghodsvali et al., 2019). Transdisciplinary FWE nexus practices need to modify the ULL approach with regard to context-based specifications and complexities. Research often depicts practical experiences as versatile guidelines which development operations can learn from, and if applicable, can adapt. Hence cities need to obtain adequate evidence in order to draw up operational guidelines for adopting the ULL approach in the context of the transdisciplinary FWE nexus.

The aim of this chapter is to collect sufficient evidence of the use of the ULL approach in transdisciplinary FWE nexus actions across the world and provide urban areas with empirical knowledge and operational guidelines. In doing so, a framework of the key components of a ULL for operationalizing the transdisciplinary FWE nexus is developed (Sub-section 4.2.1). The components are derived from the above-described peculiarities shared by ULLs in the practice of the transdisciplinary FWE nexus (i.e., actors and users, co-creation approaches, governance structure, and socio-technical system design). The framework developed proposes relevant variables through which cities can characterize, appraise, and test a ULL's performance in terms of the transdisciplinary FWE nexus. Next, in order to draw out further transdisciplinary FWE nexus developments on practical experiences, this chapter investigated the performance of six FWE nexus ULLs citing the proposed framework. The understanding of various ways through which FWE nexus ULLs are implemented in different socio-political contexts with varying ecological complexities can guide cities towards an adaptive governance mechanism for more inclusive, transdisciplinary environmental management protocols.

4.2.1 Key operational components for employing ULLs in the transdisciplinary FWE nexus

This sub-section addresses the defining characteristics of the ULL approach in operationalizing the transdisciplinary FWE nexus. Drawing conclusions from the insights from theoretical and empirical research (Section 4.2), four key operational components for implementing the ULL approach in the transdisciplinary FWE nexus can be identified: actors and users, co-creation approaches, governance structure, and socio-technical system design (Fig. 4.1). Each of these is comprehensively explored below.

- **Actors and users** provide the ULL's community with their specific wealth of knowledge and expertise, assisting in boundary-spanning knowledge transfer results (Bergvall-Kåreborn, Ihlström Eriksson, Ståhlbröst, & Svensson, 2009). The actors, whose participation in activities of an FWE nexus process are required, are at a minimum: end-users of the FWE sectors; in many cases citizens, knowledge institutes, private actors (e.g., companies, industry, and businesses), and public actors (e.g., governments and public organisations). These actors, in addition to their need for active and continuous participation in ULL activities, need to have the power to influence the process (Prahalad & Ramaswamy, 2004). The balance of power among all ULL actors enables their active partnership in innovations and development.
- **Co-creation approaches** represent methodologies and tools aimed at experimentation and learning (e.g., workshops, design thinking, and group discussions) that emerge as best practices within a ULL approach (Mulder, 2012). To qualify as co-creation, a transdisciplinary FWE nexus process that is highly dependent on stakeholder engagement needs the targeted actors and users of the ULL to be involved in all sorts of development phases and activities. In addition to being asked for their opinions, actors within FWE nexus ULLs should have power in decision-making processes (Steen & van Bueren, 2017). The development mechanism of ULLs is iterative, which implies that, after being created and designed, the prototypes of solutions to FWE nexus challenges are validated and tested by stakeholders. The evaluation and refinement gathered from these phases are employed in further developments and improvements.
- The **governance structure** stands for a collaboration setting that handles the way in which ULLs are organised on different operational or strategic levels in their FWE nexus activities (Molinari & Schumacher, 2011). The strategic level addresses several issues, such as the way in which ULL actors and users are involved concerning their responsibility and influence, the ownership of the ULL, and the way in which the management structure handles the delicate balance between leading and controlling. The operational level comprises aspects such as a road map to empirical practices, progress monitoring, and the way that

development strategies are validated and refined. It is crucial for nexus ULLs that ultimate responsibility for decisions and strategies lies with all its actors. For this to happen, governance models and the allocation of resources are of vital importance.

- Finally, the **socio-technical system design** component outlines the role of technology in facilitating new ways of transdisciplinarity innovations among ULL actors. A ULL is a context-based experience which is complicated to replicate in exactly the same way elsewhere. A combination of the ICT-based collaborative context, open innovation platforms, user-centred development methods, and public-private-people partnerships proposes potentially transformational effects on socio-ecological systems (Molinari, 2011).

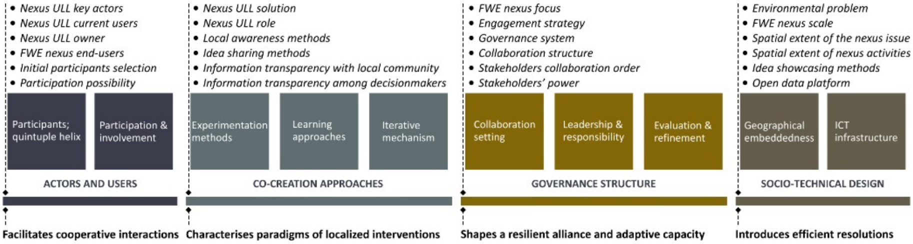


Fig. 4.1. The assessment framework for defining characteristics of Urban Living Labs (ULLs) in operationalizing the transdisciplinary food-water-energy (FWE) nexus.
Actors and users, co-creation approaches, governance structure, and socio-technical system design are the four key components that significantly contribute to practical innovations in the transdisciplinary FWE nexus. Each component, relying on multiple factors (colored text boxes), contributes towards a specific requirement for operationalizing the transdisciplinary FWE nexus concept in a real-life environment (linked via dashed lines). Nexus ULLs foster social, administrative, and technological innovations through supporting community-focused/led participation, running various sorts of experimental and learning methods, governing active involvements and shared responsibilities, and identifying a distinct spatial form of governance associated with desired digital platforms that support FWE nexus ULL activities. This framework offers a set of categorical variables (bullet points) based on which an online survey for the assessment of the characteristic of the selected ULLs in this chapter was conducted.
Source: Adapted from Baccarne et al. (2016); Chronéer, Ståhlbröst, and Habibipour (2019); Ghodsvali et al. (2019); Molinari (2011); Nevens et al. (2013); Steen and van Bueren (2017); Voytenko et al. (2016).

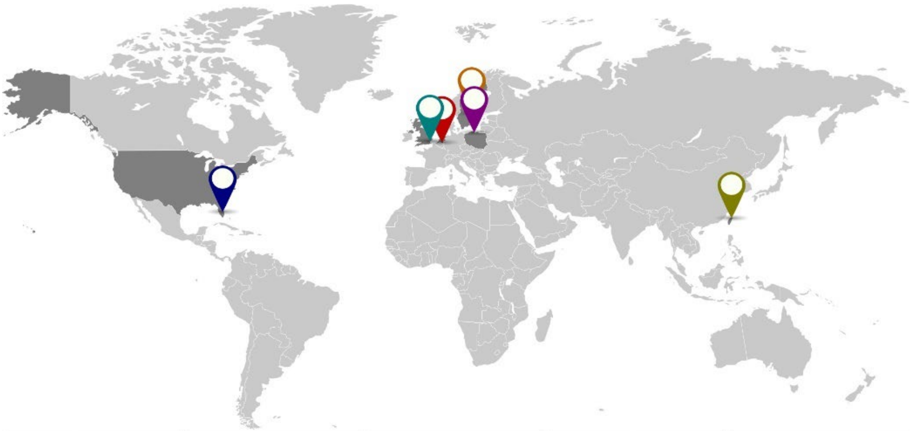
The framework developed not only signifies the most crucial components of a ULL in operationalizing the transdisciplinary FWE nexus but also enables the determining of bridges between existing FWE nexus ULLs. The multiplicity of aspects explained by this framework drives the design and development of future FWE nexus ULLs to learn from each other, benchmark the validation of actors' attitudes, adopt best practices, and interconnect similar ULLs in environment and approach. Hence, a real-life-practices assessment was conducted for a set of selected FWE nexus ULLs investigating the components defined in Fig. 4.1 (Given that this chapter, due to time and resources availability limitation, involved a small number of ULL actors for data collection, the framework should also be further validated on a larger scale).

4.3 ULLS IN THE PRACTICE OF TRANSDISCIPLINARY FWE NEXUS: INSIGHTS FROM SIX LOCAL EXPERIENCES

4.3.1 Case selection and research methods

This chapter employed a qualitative multiple-case-study method to obtain empirical evidence of six nexus-emphasized cities, namely Miami Beach, USA; Southend-on-Sea, UK; Eindhoven region, the Netherlands; Gdansk, Poland; Uppsala, Sweden; and Taipei, Taiwan for organizing and integrating the ULL approach into their local governance structure. The case selection criteria required that the ULLs must have links to the FWE nexus, innovate in a real-life environment, engage multiple stakeholders including people, and emphasise the role of actors and users in innovation. Moreover, the chosen cases reflect the diversity in FWE nexus ULLs, as they were driven by diverse types of actors. Fig. 4.2 presents an overview of the cases in general.

It can be seen from the data in Fig. 4.2 that many variations on FWE nexus themes can be put into practice. Carbon neutrality and circularity are instances of the studied FWE nexus ULLs themes linked to the concept of the transdisciplinary FWE nexus. Developing a carbon-neutral city, on closer inspection of the Miami Beach nexus ULL, refers to nature-based coastal blue-green infrastructures that support a mix of renewable energy harnessing and storage systems, organic food waste for biomass, hydroponics, and wastewater treatment strategies. Moreover, the circularity in Brainport Smart District (BSD) in Helmond, i.e., the Eindhoven region ULL, will be realised in conjunction with collaboration between humans and nature, and its resources combined with existing and future technology. In BSD, smart technologies for mobility, a strong social foundation, and clean energy generation; organic urban agriculture; and a circular water system for becoming hydrologically neutral are the means to support circularity and, in turn, the transdisciplinary FWE nexus.



Urban Living Lab	Geographical location	Main theme	Operational scale	Running time
Miami	Miami, USA	Carbon neutrality	City level	2017 - present
Southend High Street	Southend-on-Sea, UK	Green infrastructure	Street level	2018 - present
Brainport Smart District	Eindhoven region, Netherlands	Circularity	District level	2018 - present
Olivia Business Centre	Gdansk, Poland	Local micro-climate	Building level	2010 - present
Rosendal	Uppsala, Sweden	Socio-eco-techno integration	District level	2016 - present
Fudeken Envi. Restoration Park	Taipei, Taiwan	Ecosystems integrity	Neighbourhood level	2016 - present

Fig. 4.2. An overview of the selected ULL's operating in the practice of the transdisciplinary FWE nexus.

Data collection

Research data on the characteristics of the selected FWE nexus ULLs were collected through an online survey and an in-person focus group discussion. Thirty stakeholders in the case studies, including governmental authorities, scholars, industrial coordinators, technical specialists, and users provided research information. The selection of the participants was made based on the purposive sampling technique in order to reliably characterise and criticise the selected FWE nexus ULLs from the perspective of their key, well-informed actors. To ensure confidentiality, the identities of participants have been withheld. During the data collection, the participants were first asked to complete an online survey (Appendix C: Table C.1), and then to participate in a face-to-face focus group discussion.

Through the online survey, the association between the actors which an FWE nexus ULL may involve, mechanisms that best support their interactions, and the technical infrastructure that may facilitate a consensus of opinions on nexus solutions were explored. Multiple categorical variables, following the proposed framework (Fig. 4.1), formed survey questions encompassing 25 scaling and multiple-choice questions. The contribution of the research participants to the survey resulted in a set of qualitative data.

Through the face-to-face focus group discussion, the likely challenges of practical FWE nexus experiences to the variant ULL approaches and environments across the case studies were linked. In the face-to-face group discussion, the research participants were first asked to define the core problem that their ULL faces in implementing the transdisciplinary FWE nexus in practice, and then to elaborate on the immediate and secondary causes and effects of the problem raised. This manner of issue mapping, i.e., problem tree, guides the activities for the effective development of the nexus ULLs concerning context specifications and the available capabilities of the political, social, ecological, economic, and education systems. Afterwards, the qualitative data collected were cross-checked with the participants to verify the key findings.

Data analysis

For analysing the data collected, this chapter followed a multi-phased analytical process, including Multiple Correspondence Analysis (MCA) for the survey data, and the Logical Framework Approach (LFA) for the group discussion data.

MCA is a multivariate statistical technique designed to explore underlying structures in a categorical dataset and is particularly a useful method for dealing with survey data (Abdi & Valentin, 2007). The general strategy of MCA is to look for the principal dimension explaining the variability of individuals (i.e., survey respondents), and to closely examine the links between variables (i.e., categorical variables forming the survey questions, see Fig. 4.1). Given that the data collected for this chapter is categorical, and the aim is to analyze the data for discovering variabilities of the selected FWE nexus ULLs, the MCA technique should prove useful to this research. Having J variables (i.e., the categorical variables that form the survey questions) each comprising of K categories (i.e., the response options to the questions), and I individuals (i.e., the 30 survey respondents in this study), MCA generates a Complete Disjunctive Table (CDT). The CDT represents individuals as rows and categories as columns, with binary values illustrating whether each category belongs to each individual or not (Zárraga & Goitisolo, 2011). Relying on the CDT, MCA creates a low-dimensional point cloud to explore relations between individuals and categories. The MCA dimensions separate individuals based on the categories that differentiate them extremely from the average. MCA uses the frequency distribution to distribute all of the categories across each of the computed dimensions, with categories with the lowest distance being considered those with the highest degree of similarity in the corresponding dimension (Rodriguez-Sabate, Morales, Sanchez, & Rodriguez, 2017). In MCA, the individuals are located in a K-J dimensional space, which gets bigger and bigger as the number of categories per variable increases. Therefore, even if the variables are firmly linked, the maximal percentage of inertia that can be in a given dimension (i.e., the percentage of each dimension's contribution towards defining the main subject of the analysis) is $J/(K-J) * 100$, which for this study is 14%. Based on the inertia value and Cronbach's alpha greater than 0.7, a measure of dimensions' reliability (Field, 2013), this study extracted the first two MCA dimensions yielding a total variance of 13.5% to interpret the results (see Appendix C: Table. C.2). Interpreting the MCA point cloud, individuals with a significant number of categories in common are located close to the origin of the point cloud, and those of which have rare common categories are located at the periphery of the point cloud. This interpretation applies to the categories as well. Rare categories are located away from the point cloud origin. Accordingly, the MCA technique enables the detection of relationships among the ULLs' actors, approaches, governance structures, and socio-technical design factors. Subsequently, the MCA result investigates the possibilities of adopting the ULL approach and the best way in which it can be organized for the transdisciplinary FWE nexus. In this study, the MCA method was performed using the "FactoMineR" package R.

LFA is a systematic and participatory technique of mapping out core problems, as well as their contributing causes-effects and means-ends relationships. This technique supports ULL actors to set clear and achievable goals and strategies for the best ways to attain them. An open brainstorming session is the first step in employing this participatory technique. In consultation with participants, employing visual methods, namely flipcharts or colour cards, a core problem and a hierarchy of its immediate and secondary causes and effects (i.e., the problem tree) are established. These arrangements can be useful in building a community's awareness of a nexus problem, the way that they contribute to the problem, and how the problem affects their living conditions. The second step is to reformulate the negative situations of the problem tree into positive solutions, presenting means-ends relationships (i.e., the objective tree). It is of central importance that all ULL actors are involved in the discussions, giving their feedback. The objective tree created provides an outline of the desired future situation, including effective means by which ends can be achieved. After creating the desired future situation, the third step is to form possible interventions. This step requires a balance to deal with different stakeholder interests. Through a group discussion session, this research analysed six problem trees, each created by representative actors of the selected FWE nexus ULLs. Subsequently, it developed a Logical Framework Matrix (LFM) as the main result of the LFA technique for possible operational guidelines for the FWE nexus ULLs.

4.3.2 Current status of the selected ULLs in operationalizing the transdisciplinary FWE nexus

This chapter aims at obtaining two main pieces of information about the nexus ULLs examined: 1) the defining operational characteristics of a FWE nexus ULL, and 2) the likelihood of advanced implementation levels of the transdisciplinary FWE nexus employing the ULL approach.

4.3.2.1 The defining operational characteristics of the FWE nexus ULL

The MCA determined the defining characteristics upon which the FWE nexus ULL approach has been employed in the different studied socio-ecological contexts. From the MCA dimensions obtained, there were clear differentiating values among the FWE nexus cases studied in employing the ULL approach (Appendix C: Table C.2

and Fig. 4.3). The variables stakeholder power, idea showcasing methods, and local awareness methods, which presented similar discrimination measures in both dimensions, contribute significantly to the variant performance of the selected FWE nexus ULLs.

On closer inspection of the power balance among the stakeholders of the ULLs studied, there are various kinds of operational commonality. A top-down governance system enabling collaboration among key FWE nexus stakeholders is the defining operational commonality across the studied ULLs (Fig. 4.3(A)). In Taipei, local government, in cooperation with academics, has significant power over the decisions that affect nexus-related actions in Fudeken Restoration Park (FRP). Likewise, the Olivia Business Centre (OBC) ULL in Poland operates under the great power of the municipality and academics. In both the FRP and OBC ULLs, the ultimate responsibility for nexus-based decisions lies with the public actors. People and local communities are solely considered as end-users of services that the ULL sites offer and are not automatically involved in the process of the ULL's development.

In comparison, BSD ULL of Helmond, Eindhoven region and Uppsala were the more promising of the six nexus ULLs in terms of a public-private-people partnership. The BSD ULL in Helmond, Eindhoven region and the Rosendal District (RD) ULL in Uppsala possess various characteristics of an effective FWE nexus ULL working towards transdisciplinarity. Although they have different approaches in co-creating the scope of the FWE nexus ULL and setting up the technical communication infrastructure, their main merit is the level of openness for cooperative interactions. By broadening the collaboration to the entire community (who are either directly or indirectly influenced by nexus-related problems, decisions, and development plans), the BSD and RD ULLs ascertained how transdisciplinarity boosts the effectiveness of FWE nexus practices. They both engage stakeholders from multiple disciplines, though by adopting different techniques and infrastructure. Opting for an ad-hoc infrastructure, as in BSD, stakeholders feel less restricted in testing out innovations that are linked to the thematic focus of the ULL. It is of vital importance that new ideas and solutions can be created and shared amongst every stakeholder when joining the ULL initiative. If RD had a mixed set of experimentation and learning tools, the possibility for seizing new opportunities for innovative ideas would have been higher.

Despite all the nexus ULLs studied having various commonalities in practice, Miami and Southend-on-Sea formed a distinct group. This difference may be due to the missing links in their value chains and the unequal contribution of stakeholders. For instance, the Southend High Street (SHS) ULL in Southend-on-Sea focused on green infrastructure though there was no thematic expert involved in executive decisions. This gap brought about missed opportunities for building more innovative services in that domain. A good variety of stakeholders is what Southend-on-Sea missed while setting up its nexus ULL. Regarding Miami, a clear narrowed-down thematic focus will lead to complementary motives for collaboration within the ULL, which, in turn, will benefit the community aspect and creation of new partnerships. Carbon neutrality includes various thematic focuses (e.g., renewable energy, hydroponics, wastewater treatment) that cause more accurate and comprehensive performance at the micro-level.

The fact that the nexus ULLs studied should emphasize most while developing their FWE nexus strategies is the balance of stakeholder power and responsibilities (Fig. 4.3(B)), although each should consider other conditions that need to exist for advanced performance (see Sub-section 4.3.2.2 and Fig. 4.4).

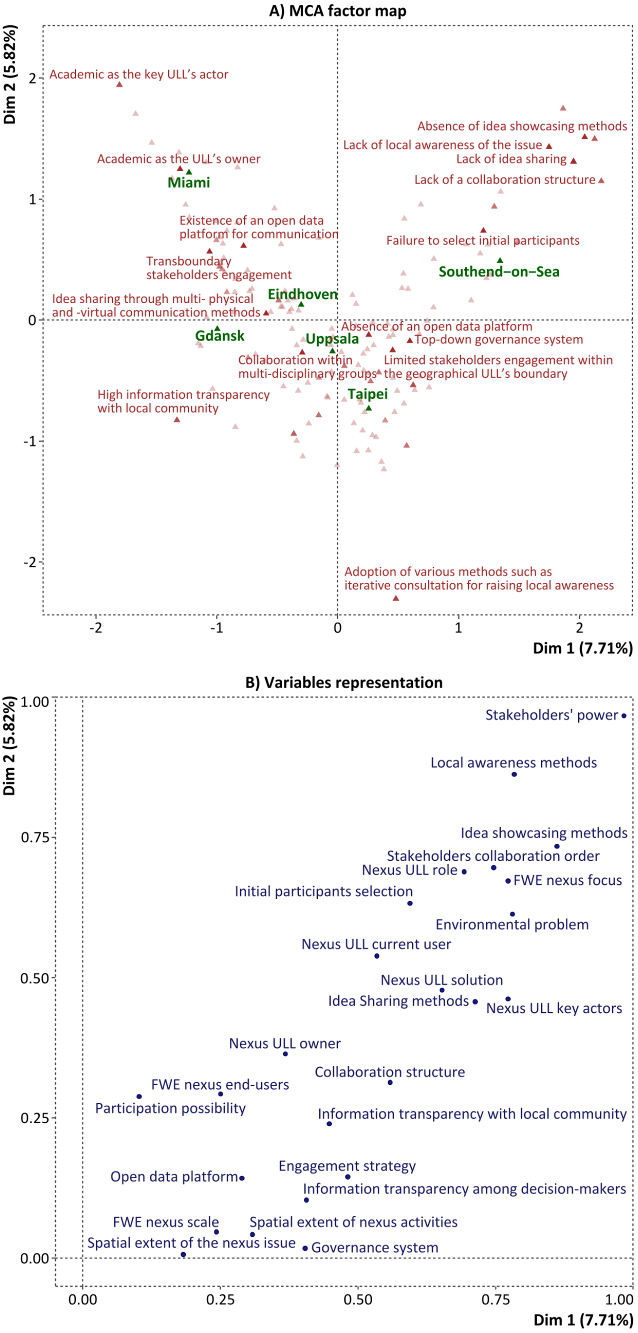


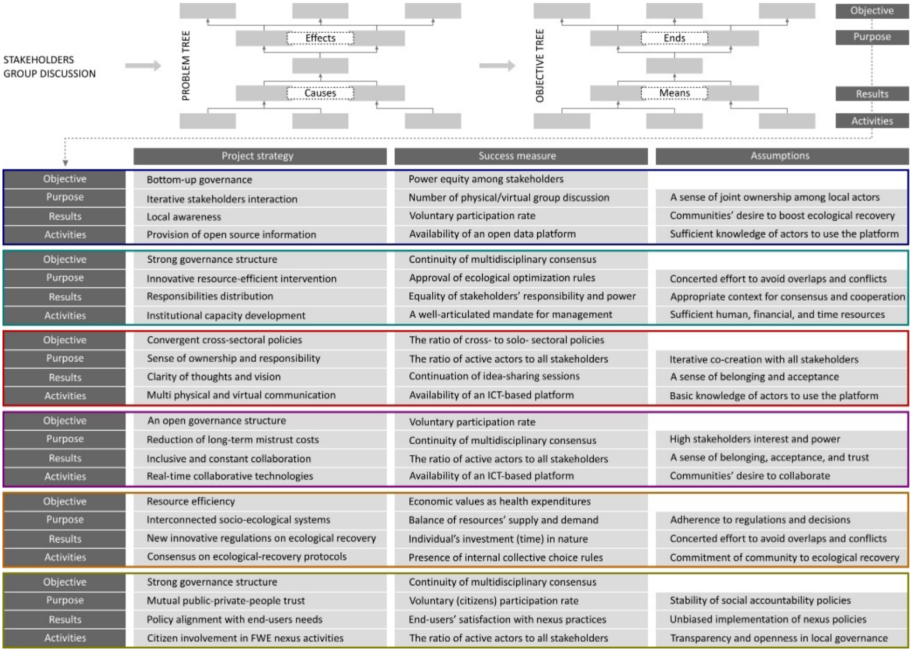
Fig. 4.3. Multiple Correspondence Analysis (MCA) of the ULLs studied on the transdisciplinary FWE nexus. Plots show A) how differently the ULLs studied operate in terms of the transdisciplinary FWE nexus, and B) what variables significantly contribute towards the effective operation of the transdisciplinary FWE nexus across the nexus ULLs examined. In plot (A), red triangles, along with their descriptive statements, represent MCA categories with the largest contribution in characterizing the ULLs examined which are visualized in green. The distance between two triangles shows how different or similar they are. The closer the categories are located to each other, the more similar their categorization pattern. The center of the plot represents the average characteristics of the nexus ULLs examined. Unique categorization patterns result in a triangle's location being further away from the center. Therefore, categories that are located close to the center represent the most common characteristics of the nexus ULLs studied. Plot (B) illustrates MCA variables (given Fig. 4.1) along the two extracted principal dimensions. The further a variable is placed from the center point of the plot, the greater the contribution it has for understanding the distinguishing characteristics of the FWE nexus ULLs studied.

4.3.2.2 The likelihood of advancing the FWE nexus ULL implementation

The LFA, based on the structures of the problem and objective trees, identified logical linkages between the strategic intent of the ULLs studied for operationalizing the transdisciplinary FWE nexus and the prerequisite activities and conditions for such development. The findings from the group discussion session (i.e., problem trees, see Appendix C: Fig. C.1), identifying negative aspects of the current FWE nexus ULL situations, established positive achievements that can contribute towards eliminating the problems which were subsequently used for the projects' strategy description in the Logical Framework Matrix (LFM). The LFM contains three items of information in this research: *project strategies* elaborating the strategic intent and alignment of each FWE nexus ULL project, *success measures* appraising the performance and signs of the nexus ULL projects’ improvement, and *assumptions* highlighting potential risks to functional prerequisites. Fig. 4.4 provides the sequential steps leading to the LFM development, which describes activities to be undertaken in order to reduce the impacts of barriers to the transdisciplinary FWE nexus through the ULL approach.

The structures of the problem trees show how the barriers identified impact the realization of transdisciplinarity in FWE nexus projects. Lack of community capacity and governance practices have directly affected people's inability to participate in FWE nexus projects. In addition, a lack of professional and technical competence in transdisciplinary engagement and the absence of adequate security caused the affected people to be unwilling to participate. Furthermore, scientific and technical knowledge issues limit the opportunity for nexus end-users and other indirectly affected people to participate in the development of the project, since the FWE nexus ULLs have been mostly founded on thorough expertise and ICT-based communication infrastructure. Therefore, inability, unwillingness, and a limited opportunity to participate can be considered as the main reasons for the lack of community participation in FWE nexus ULLs, and accordingly, the failure of the transdisciplinarity perspective.

Following the establishment of a means-ends relationship among a nexus ULL’s objectives, it becomes clear that to realize the transdisciplinary FWE nexus in practice, the affected community needs to be enabled to participate. For this to happen, the structure of the nexus community needs to be re-established, community ownership of the ULL ownership should be encouraged, and management for transition support, as well as social accountability opportunities, must be provided. From the findings of this study, a multimodal communication platform, relying on a common language supporting real-time collaboration in both physical and virtual spheres, is the potential benefit of the ULL approach for FWE nexus practices in order to overcome a disconnection between the general public and the concerns of politicians.



	Project strategy	Success measure	Assumptions
Objective	Bottom-up governance	Power equity among stakeholders	
Purpose	Iterative stakeholders interaction	Number of physical/virtual group discussion	A sense of joint ownership among local actors
Results	Local awareness	Voluntary participation rate	Communities' desire to boost ecological recovery
Activities	Provision of open source information	Availability of an open data platform	Sufficient knowledge of actors to use the platform
Objective	Strong governance structure	Continuity of multidisciplinary consensus	
Purpose	Innovative resource-efficient intervention	Approval of ecological optimization rules	Concerted effort to avoid overlaps and conflicts
Results	Responsibilities distribution	Equality of stakeholders' responsibility and power	Appropriate context for consensus and cooperation
Activities	Institutional capacity development	A well-articulated mandate for management	Sufficient human, financial, and time resources
Objective	Convergent cross-sectoral policies	The ratio of cross- to solo- sectoral policies	
Purpose	Sense of ownership and responsibility	The ratio of active actors to all stakeholders	Iterative co-creation with all stakeholders
Results	Clarity of thoughts and vision	Continuation of idea-sharing sessions	A sense of belonging and acceptance
Activities	Multi physical and virtual communication	Availability of an ICT-based platform	Basic knowledge of actors to use the platform
Objective	An open governance structure	Voluntary participation rate	
Purpose	Reduction of long-term mistrust costs	Continuity of multidisciplinary consensus	High stakeholders interest and power
Results	Inclusive and constant collaboration	The ratio of active actors to all stakeholders	A sense of belonging, acceptance, and trust
Activities	Real-time collaborative technologies	Availability of an ICT-based platform	Communities' desire to collaborate
Objective	Resource efficiency	Economic values as health expenditures	
Purpose	Interconnected socio-ecological systems	Balance of resources' supply and demand	Adherence to regulations and decisions
Results	New innovative regulations on ecological recovery	Individual's investment (time) in nature	Concerted effort to avoid overlaps and conflicts
Activities	Consensus on ecological-recovery protocols	Presence of internal collective choice rules	Commitment of community to ecological recovery
Objective	Strong governance structure	Continuity of multidisciplinary consensus	
Purpose	Mutual public-private-people trust	Voluntary (citizens) participation rate	Stability of social accountability policies
Results	Policy alignment with end-users needs	End-users' satisfaction with nexus practices	Unbiased implementation of nexus policies
Activities	Citizen involvement in FWE nexus activities	The ratio of active actors to all stakeholders	Transparency and openness in local governance

Fig. 4.4. The Logical Framework Matrix (LFM) of the studied transdisciplinary FWE nexus ULLs.
LFM is a recognition of activities into an ordered hierarchy of purposes and results, systematically culminating in the principal objective each project has. "Activities" refer to tasks and resources that, along with the existence of some other conditions (i.e., "assumptions") bring about some noticeable "results". The "results", referring to potential deliverables of activities, along with associated assumptions, lead to the project "purpose". The project "purpose", stating expected project changes, along with the existence of some other conditions, fulfills the project's "Objective". In general, the objective, purpose, result, and activities target the strategic intent of the project and answer the question of what the project is trying to accomplish and how. This matrix gives the nexus ULLs coherence across the various aspects of their main problem at hand and serves as a guideline for a nexus ULL's governance structure and activities. The logical framework analysis has been done for all of the six selected nexus ULLs in this study, distinguished by colored outlines in the matrix. The colors are assigned to the case studies as in Fig. 4.2. The LFM presented was developed based on the defining characteristics of the nexus ULLs studied presented in Fig. 4.1 and Fig. 4.2, the problem trees developed (see Appendix C: Fig C.1).

4.4 KNOWLEDGE NEED FOR IMPLEMENTING TRANSDISCIPLINARY FWE NEXUS ULLS

FWE nexus stakeholders require a platform and structure to communicate, negotiate, and integrate their perspectives. Such a structure is complicated to develop and manage since the FWE nexus challenges extend over multiple scales and dimensions. The ecological dimension of the FWE nexus is closely interwoven with the social, political, and economic dimensions. Consequently, FWE nexus projects are surrounded by various uncertainties and involve several interdependent stakeholders with often diverging interests and perspectives on the actual nature of the problem, as well as on possible ways to solve it. To acquire knowledge relevant to the management of such complex challenges, scientists need a structure of integrated approaches that involves multiple perspectives and various types of expertise (de Kraker, Kroeze, & Kirschner, 2011). Participatory modelling in FWE nexus ULL applications is a structured process conducted with stakeholders to evaluate the social, ecological, and economic dimensions of the complex FWE nexus problem and the impacts of policy choices.

Investigations into the role of ICT-based participatory modelling methods and tools suggest that they are advantageous for the multiplicity of spatial and temporal scales of environmental challenges, the complexity of interactions between the social and ecological systems, and the uncertainties around stakeholders' understanding of the system and its related challenges (de Kraker et al., 2011). A higher degree of local stakeholder involvement in the development of participatory models can raise the effectiveness of the process in the form of transdisciplinary tools, although this is resource- and time- intensive, and complicated to scale up.

A range of factors are of vital importance in identifying actionable policy options and instruments for engaging the transdisciplinary FWE nexus concept, ULL approach, and computer-supported participatory platform. Regarding the strategy for such engagement in the socio-ecological transition, the FWE nexus ULLs examined in this chapter have experienced multiple obstacles, including lack of transparency and complexity of participatory tools which often made direct stakeholder interactions impossible, a low degree of user-friendliness, and a lack of support for aligning feasible policy options with stakeholders' interests (either spatially or temporally) (Fig. 4.4). To surmount these obstacles, the use of participatory-supported models should be made using innovative geographical, semi-quantitative methods and tools that translate conceptual models to stakeholder perspectives and to simulation models. In addition, the tools and methods should be flexible in terms of the diversity of stakeholder interests and values, in other words, in terms of the alignment of different goal definitions. Moreover, the models should be more efficient in terms of iterative stakeholder interactions, which are often restricted due to limited time availability.

Various innovative tools and methods are offered to help with the likely instrumental obstacles to a governance mechanism with people at the very center of the process, potentially applicable to the ULL approach for the transdisciplinary FWE nexus (Ghodsvali et al., 2019). Instances include multi-player gaming experiments in a face-to-face or as a virtual reality setting (Agusdinata & Lukosch, 2019; Mochizuki et al., 2018a), creating interfaces between participants and computer models through participatory scenario development for exploration through alternative future storylines (Colloff et al., 2019; Johnson & Karlberg, 2017), and participatory geographic information systems potentially open to the multi-dimensional visualization of ecological changes for interactive decision-support experiences (Karpouzoglou et al., 2017; Kraftl et al., 2019).

An intensive participatory modelling approach may consequently increase the effectiveness and efficiency of the ULL approach in supporting an adaptive governance mechanism for the transdisciplinary FWE nexus. The following statements explore how the strategy of such an engagement between the transdisciplinary FWE nexus concept, the ULL approach, and a computer-supported participatory platform promotes requisites for a sustainable socio-ecological transition (see Fig. 4.1). The use of participatory modelling methods and tools, specific to contextual complexities, supports:

- ***Sociability*** *to facilitate cooperative interactions*

  Through the FWE nexus projects, direct and indirect stakeholders should regularly collaborate in order to cope with the uncertain challenges of socio-ecological transitions. Working as a team can support participants in learning from each other and exchanging useful information. Thus, the structure of the FWE nexus social networks and the capacity of individuals to interact with each other are of primary importance in constructing knowledge. In addition, a greater number of stakeholders are of potential benefit for progressing opportunities as it maximizes corrections and improvements, although it also raises additional concerns over the management of a more extensive collaboration. Virtual collaboration, along with face-to-face discussion, serves as a practical solution to extensive nexus collaborations. As an advantage, virtual collaboration operates across space, time, and organizational boundaries. Moreover, virtual collaboration overcomes the likely emotional states within face-to-face meetings and minimizes the risk of impeding the negotiation process.

- ***Knowledge co-production to characterise paradigms of localised interventions***

  In FWE nexus projects where all stakeholders have to collaborate as a team on new socio-ecological solutions, every stakeholder should have a chance to propose their experiences and democratically take the initiative. It means an all-together-decision-making that is a requisite for the transdisciplinary FWE nexus. Such decisions entail potential risks associated with the uncertainties of stakeholder engagement, consensus, and the future, which can be part of the creative process. Exploration of new ideas and experimentation with new solutions through participatory modelling tools involving local stakeholders may potentially contribute to a reduction in the nexus transdisciplinarity attendant risks.

- ***Corporate governance to shape a resilient alliance and adaptive capacity***

  Accountability, fairness, transparency, assurance, leadership, and stakeholder management are of primary importance in empowering a community for ecological-conservation purposes. The contextual design embedded in the participatory-supported ULL mechanisms attaches great importance to power dynamics in multi-stakeholder nexus processes (Ghodsvali et al., 2019). The contextual inquiry captures detailed information about how stakeholders affected by a nexus project interact with the environment in their normal life. In addition to the support for participatory modelling methods in distributing an equitable balance of power, it supports nexus stakeholders to understand others' interests, and in turn adjusts and prioritises their ideas and tasks.

- ***Socio-eco-techno integration to introduce efficient resolutions***

  Exploring innovative ideas, experimenting with different future scenarios, and learning adaptable responses to ecological changes are the collection of participatory-supported ULL mechanisms through which FWE nexus resolutions are controlled and operated. Best practice is to seek this through the integration of computer-supported participatory techniques into socio-ecological concerns. Although experiments vary significantly in objective and scale, they always rely on an iterative procedure and logical exploration. FWE nexus experimentation provides insight into cause-and-effect relationships by indicating which outcome occurs when a specific factor is manipulated. Experimenting with social innovation, including new technology, strategies, ideas, and institutions, enhances the capacity of social and ecological systems to help steer away from multiple FWE resource thresholds. The trial-and-error logic promotes the need of FWE nexus projects to experiment through iterative consultation and the subsequent mutual understanding among participants. Moreover, experimentation may provide nexus actors with a sense of joint ownership and raise opportunities for accountability.

By integrating the above-described potential benefits of participatory modelling methods into the FWE nexus ULL approach, FWE nexus projects might be able to end up with new context-specified solutions and operational concepts.

4.5 CONCLUDING REMARKS

The Urban Living Lab (ULL) approach can potentially support the accomplishment of the transdisciplinary FWE nexus if there is a well-balanced social-ecological-technological integration. From the literature and existing empirical evidence, there appear to be many requisites for making the ULL approach more effective and efficient as an adaptive governance mechanism for the transdisciplinary FWE nexus. However, a critical evaluation of these requisites and the best way to satisfy them have not been conducted so far, and no operational guidelines are available on how to adopt the ULL approach to effectively and efficiently support the transdisciplinary FWE nexus, emphasizing inclusive, active, and direct stakeholder engagement. This knowledge gap requires thorough studies of the interactions between the ULL approach and the varying related participatory settings and the transdisciplinary process in the FWE nexus. Thus far, evaluations of participatory techniques in FWE nexus ULLs have been characterized by limited attention to socio-technical design and the development of innovation processes (e.g., Molinari & Schumacher, 2011). This research suggests that such evaluations could greatly benefit from the fields of corporate governance, sociability, knowledge co-production, and in particular, from the rapidly expanding area of ICT-supported participatory modelling methods and tools. Studies show how the insights from ICT-supported participatory modelling are supportive in designing collaboration support tools, facilitating negotiation and learning processes, building consensus, and evaluating the effectiveness of jointly made decisions. This study expects, therefore, that integrating the fields of participatory modelling via ICT tools, the ULL approach, and the FWE nexus will considerably advance scientific capabilities in accomplishing the concept of transdisciplinarity for more sustainable environmental and natural resource management.

5

AN INTEGRATED DECISION SUPPORT SYSTEM FOR THE TRANSDISCIPLINARY FOOD-WATER-ENERGY NEXUS

S.N.O.G. MODEL FRAMEWORK[4]

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[4] This chapter is based on:
Ghodsvali, M., Dane, G., de Vries, B. An integrated decision support system for the urban food-water-energy nexus: methodology, modification, and model formulation. Computers, Environment and Urban Systems (under review).

5.1 INTRODUCTION

In recent times, several decision support tools in support of the transdisciplinary management and decision-making on FWE systems have been developed, aiming to address the FWE nexus challenges from varying perspectives. A number of these tools have been made to *model and assess* the FWE systems' performance (e.g., Daher & Mohtar, 2015; Howells et al., 2013). Another variety, with a nature of optimization, seeks to precisely *suggest optimal designs, plans, or operational strategies* (e.g., WBCSD, 2014). Some other tools have been carried out for *incorporating multiple disciplines* and providing a transdisciplinary environment that accounts for different interests and preferences (e.g., Salman, 2013). Nevertheless, FWE nexus processes still lack effective and comprehensive decision-making tools that combine elements of perspectives on integrative FWE nexus modeling, optimal operational strategies development, and transdisciplinary cooperation with real-world practice. There remains a need for a transdisciplinary decision support tool based on a robust and analytical methodology suitable for incorporating the three FWE sectors and related social and ecological impacts of their integrated management into a general framework, investigating the complicated synergies to optimize FWE nexus strategies from a holistic point of view, and facilitating stakeholder engagement throughout the decision-making process.

Given the deficiencies in transdisciplinary FWE nexus planning and strategy management, this research developed a spatial optimization model as a base for a web-based serious game tool, searching for optimal FWE nexus scenarios through a cooperative setting. The design of the proposed model relies on an innovative combination of methods capable of navigating decision-making through complex systems modeling and planning (with regards to the findings of Chapter 4, Section 4.4.). This includes optimization and game theory in the frame of a spatial serious gaming environment for real-world implementation. Relying on such an algorithmic framework, this chapter enables forecasting nexus impact analyses based on socio-economic drivers of the demand for the resources, environmental carrying capacity, land management, and primary climate change drivers (retrieved from Chapter 3). The outcomes offer strategic guidelines for the transdisciplinary FWE nexus practices and support decision-making appropriate to the goals.

The remainder of the chapter proceeds as follows. Section 5.2 first reviews the existing tools that support FWE nexus decision-making processes and then describes the potential for possible methodological improvements. Fulfilling the requirements for the desired support of the transdisciplinary FWE nexus process, Section 5.3 presents a novel framework and model, namely S.N.O.G. (the Spatial Nexus Optimization Game). Section 5.4 demonstrates how the introduced methodologies and the developed S.N.O.G. model are applied to a local-scale Dutch case study (i.e., Brainport Smart District (BSD)) to achieve optimal integration of transdisciplinary

FWE nexus management strategies and sustainable development plans in practice. The model performance analysis and discussion are presented in Section 5.5. Last but not least important, Section 5.6 draws some useful conclusions and announces some orientations for future work.

5.2 FWE NEXUS DECISION SUPPORT TOOLS: CURRENT GAPS AND THE POTENTIAL FOR FURTHER IMPROVEMENTS

In the context of the FWE nexus, decision-making can be complex due to the multi-sectoral, multi-scale, multi-stakeholder, and multi-uncertainty nature of the systems involved (Garcia & You, 2016). A thorough understanding of FWE nexus systems and the complexities they imply commences with a holistic quantification of the interconnections among the three resources. Given the complex aspects of the FWE interconnectedness, flexible and robust decision-making tools capable of capturing the dynamics against uncertainties associated with nexus systems should be adopted (Rosales-Asensio, de la Puente-Gil, García-Moya, Blanes-Peiró, & de Simón-Martín, 2020). In this regard, several models and frameworks have been developed to guide decision-making through the FWE nexus systems. Table 5.1 summarizes available decision-making tools and associated methods applied to address resource management challenges from the integrative nexus perspective, carry out evaluations at a wide-state level, and, to a considerable extent, be accessible for the use of developers and FWE nexus stakeholders (i.e., government, scholars, and community).

In principle, the ideal tool for integrative FWE nexus management would allow the formulation of policies that improve the synergistic efficiency of the social, ecological, and technological nexus systems (Kaddoura & El Khatib, 2017). However, limitations are always allied with capabilities while developing an integrated nexus decision support tool. This study identified capabilities and limitations of the available FWE nexus tools (presented in Table 5.2) since frequent capabilities show a consensus on vital while feasible elements in employing the nexus approach.

The review revealed that the FWE nexus decision support tools vary in levels of integration and granularities. The CLEWs framework (Howells et al., 2013) and the WEF Nexus Tool 2.0 (Daher & Mohtar, 2015) strongly emphasize the complexity of nexus systems interactions from a holistic perspective. WBCSD (WBCSD, 2014) specifies another concern regarding context-specific nexus modelling. MuSIASEM (Giampietro, Mayumi, & Ramos-Martin, 2009) and DIT (Salman, 2013) express the significance of alternative nexus perspectives to recognizing vital fundamentals that are impossible to understand when the nexus is viewed from a narrower, such as only technical, perspective.

A prevalent capability of nexus decision support tools is the understanding of systems complexity. Every decision support tool has an approach to address this complexity, for instance, MuSIASEM employed Complex Theory and the CLEWs framework adopted Reference Systems Diagrams. Attempts to deal with such complexity, however, often bring about extensive data requirements. Some tools, for instance, the Nexus Tool 2.0, avoid this problem in view of simplification of synergies. Once the decision support tool is evolved to handle specific socio-economic structures with complicated ecological systems, the complexity becomes more. Extensive data requirement is common to most modeling tools and is a key restriction on nexus modeling. The need remains for an innovative way to balance the trade-off between simplicity and comprehensiveness. Both the MuSIASEM and DTI nexus tools reveal the significance of the *simultaneous adoption of multiple nexus approaches* in response to the extensive data requirement challenge.

Comparing the tools, the importance of time scale on their functionality can be identified. On the one hand, short-term nexus planning is crucial in case of a need for an immediate change, for instance, the situation in which local rules need to be aligned with international regulation. On the other hand, long-term planning is needed for the primary nexus purpose of developing sustainable cities. FWE nexus tools vary according to their temporal functionalities. However, a comprehensive tool in support of the FWE nexus process should *reflect temporal variability* to consider short- and long- term implications of integrative decision-making (Kaddoura & El Khatib, 2017).

The vast majority of the studied tools were developed as conceptual frameworks for systematic nexus interactions analyses but not as simple user-friendly models for exploratory assessments. Improved accessibility to these models can contribute to increasing use of them as tools for integrated FWE decision making. A web-based tool offering *a user-friendly interface* eases accessibility for nexus analysts from different nations (Sušnik et al., 2018).

Table 5.1
Review of a selection of available FWE nexus decision-making tools.

Nexus Tools	**Purpose**	**Practicality**	**Analytical Characteristics**				
			Accessibility	Generalizability	Comprehensiveness		
					Decision-making method	Scale	Desired outputs
CLEWs (Climate, Land-use, Energy, and Water systems) (Howells et al., 2013)	To explain synergies and trade-offs within the CLEW sectors for decision-making on how to achieve future development goals	A framework, not an actual and useable modeling tool	Possible for developers	Suitable for dissimilar geographies, but is resource-intensive	Integrated modelling	• Global • National	• Energy balance • Water balance • Use of irrigation technologies, fertilizers, and farming machinery • GHG emission • Land-use
WEF (Water, Energy, Food) Nexus tool 2.0 (Daher & Mohtar, 2015)	To quantify the flows among the three nexus areas and allow comparison between various development scenarios	A web-based tool	Possible for developers and accessible online to the public, researchers, and policymakers	Can be applied to different geographies	Scenario building	National	• Water demand • Land requirement • Energy demand • Carbon footprint • Financial cost
WBCSD (the World Business Council for Sustainable Development) Nexus tool (WBCSD, 2014)	To understand the nexus linkages at varying levels and develop co-optimized policy and technology options to address the challenges.	A spreadsheet-based model	Possible for developers, future graphical user interface	Suitable for different geographies	Mathematical optimization	• Global • National • Regional • Local	• Nexus systems trade-offs • Food production • Land for food production
MuSIASEM (the Multi-Scale Integrated Analysis of Societal and	To investigate synergies of food, water, and energy	A diagnostic and	Possible for developers	Suitable for dissimilar	Multi-scale and multi-criteria analysis	National	• Resource flows in society • GHG emissions

Nexus Tools	**Purpose**	**Practicality**	**Analytical Characteristics**				
			Accessibility	Generalizability	Comprehensiveness		
					Decision-making method	Scale	Desired outputs
Ecosystem Metabolism) (Giampietro et al., 2009)	and their impacts on society.	simulation framework		geographies, but is resource-intensive			• Economic costs and values added • Land-use
DTI (the Diagnostic, Financial, and Institutional Tool for Investment) in water for agriculture and energy (Salman, 2013)	To provide an insight into the relationship of components of the nexus system with economic development.	A user-friendly web-based interface	Possible for developers	Can be applied to different geographies, but resource-intensive	Index-based strategy modeling	National	• Resource accessibility and security • Investment needs for agriculture • Cultivated land

Source: Daher and Mohtar (2015); FAO (2014); Giampietro et al. (2009); Howells et al. (2013); IRENA (2015); Salman (2013); WBCSD (2014)

Table 5.2
Capabilities and limitations of the reviewed nexus decision-making tools.

Nexus Tools	Capabilities	Limitations
CLEWs	• Studies nexus complexity • Adopting a system thinking approach	• Extensive data requirements • Incapable of addressing economic aspects • No practical toolkit
WEF Nexus tool 2.0	• Accessible web-based tool • No complex data requirements • Consider economic factors in nexus scenarios • Provides comparable policy alternatives	• No future projections. • Simplified synergies, e.g., agriculture is only considered for food production regardless of food supply from ruminant or poultry products
WBCSD Nexus tool	• Diagrammatic representations of land based on GIS characterization of the water needed for food and energy	• The technical and complex data structure of the output
MuSIASEM	• Provides an insight into the society's demand profile • Allows analysis of various scenarios from the feasibility, viability, and desirability point of view	• The complex nature of its mathematical method • The need for multi-disciplinary collaborations to obtain valuable multi-scale data • Forecasts are not possible • No cost and benefit calculation • The need for its combination with conventional tools
DTI in water for agriculture and energy	• Highlights the importance of institutional capacity • Suggests different policies • Provides an accessible, user-friendly web-based tool • Allows for multi-temporal investment planning	• No technical forecasting • Partial consideration of nexus system components bounded to the water sector • The need for extensive technical and economic data

Source: Daher and Mohtar (2015); FAO (2014); Giampietro et al. (2009); Howells et al. (2013); IRENA (2015); Salman (2013); WBCSD (2014).

The existing FWE nexus tools show that further consensus needs to be developed on a complementary combination of appropriate decision-making methods for the progress of nexus modeling.

5.2.1 Potential methodological improvements

The right choice of combining multiple decision-making methods should offer the basis for any discussion about the systemic nexus management strategies needed. On the one hand, the model should be designed in a way that highlights knowledge diversity, understands sources of conflict, and maximizes engagement and understanding of nexus interactions. From this viewpoint, ease of communication and interpretation is important in selecting the most appropriate decision-making methods. On the other hand, the model should focus on multi-disciplinary knowledge about the system and allow scenarios to be developed for future resource planning and that support thorough exploration of the implication of different decision scenarios. Some methods may contribute towards further advantages that exceed matters of effectiveness and efficiency. For instance, for a true engagement of the nexus stakeholders (i.e., government, scholars, and community) in the decision-making process, the model needs to be transparent and easy to manipulate based on the stakeholders' needs. The ideal approach to nexus decision-making may be a combination of methods, thus considering their mutual compatibility is desirable. Table 5.3 presents some capabilities of various decision-making methods appropriate for the nexus process and allows the evaluation of desired combinations.

Table 5.3

Some capabilities of various decision-making methods appropriate for the nexus approach, rated from Low (L) to Medium (M) to High (H). All values are relative to the suit of methods considered and assumed that each method is considered in the context of a similar problem with approximately the same level of detail and complexity. A rating of "L" means that a method is less able to produce outputs regarding the desired capability than is a method rated "H" on the same capability.

Decision-making capabilities	**Decision-making methods**										
	Qualitative		Semi-quantitative			Quantitative					
	Serious (role-playing) game	Decision tree analysis	Scenario building	Fuzzy cognitive mapping	Game theory	System dynamics	Geographic information systems	Optimization	Cost-benefit analysis	Agent-based modeling	Integrated modelling
Spatial representation	M	L	L/M	L	L	L	H	H	L	H	H
Temporal representation	L	L/M	H	L	L	H	L	H	L/M	H	H
Prediction	L/M	L/M	H	L/M	L	H	L	H	L/M	H	H
Ease of communicating results	H	M	H	M/H	M/H	M	H	L/M	M/H	M	L
Transparency	H	M/H	M/H	M/H	H	M	M	M	M/H	L	L
Ease of modification	H	H	H	H	H	M	H	L/M	M/H	M	L
Feedback loops supported	L	L	M	H	H	H	L	H	L	H	H
Handling uncertainties	L	L	H	L	M/H	H	L	H	L	H	M

Source: Albrecht, Crootof, and Scott (2018); Endo et al. (2015); Ghodsvali, Krishnamurthy, and de Vries (2019); Namany et al. (2019); Voinov et al. (2018, 2016).

To navigate decision-making through the complex nexus systems modeling and planning, this chapter proposes the innovative methodological combination of spatial optimization and game-theoretic models in the frame of a serious gaming environment. These methods have shown their capability to encourage efficiently informed decision-making when combined (see Namany, Al-Ansari, & Govindan, 2018; Namany et al., 2019).

Optimization is one of the most frequently used decision-making methods employed to improve the performance of complex systems and thus to accomplish desired outputs within optimum conditions (Xiao, Shao, Gao, & Luo, 2015). It relies on a mathematical design of realistic problems that detects a choice amongst various alternatives. In the realm of FWE nexus, involving diverging objectives, multi-objective optimization (MOO) has proven its usefulness in improving technical aspects of the system under both stable and uncertain conditions (Namany et al., 2019). Mathematically, MOO seeks design variables $\mathrm{X} = [x_1, x_2, \dots, x_n]$ subject to value limits $a_i < x_i < b_i \quad (i = 1,2, \dots, n)$ and equality constraints $g_k(X) \leq 0 \quad (k = 1, 2, \dots, q)$ to optimize objective functions $\mathrm{F(X)} = [f_1(\mathrm{X}), \dots, f_m(\mathrm{X})]$.

Game theory is the science of interactive decision-making for independent and competing stakeholders in a strategic setting (Rasmusen, 2006). It studies how interacting choices of stakeholders generate solutions concerning their preferences. As for the multi-stakeholder and multi-objective nature of the FWE nexus, game theory exhibits a prominent ability to assess the attainability of the system's optimal solutions with due attention to individual self-optimizing behaviors (Garcia & You, 2016). By means of mathematics, the model of an m-player game (considered as G) includes a set of strategies available for each player, expressed with $S_1, S_2, \dots, S_m$, and their associated payoffs represented by $U_1, U_2, \dots, U_m$. A matrix of payoffs summarizes solutions of several scenarios considered by each player, showing how the cooperative behavior affects the decision-making of the natural resources of interest (Zamarripa, Aguirre, Méndez, & Espuña, 2013).

From the game theory perspective, the multi-objective optimization problem has similar features to the decision-making problem in the game (Sohrabi & Azgomi, 2020). Each of the optimization objectives can be considered as a game player having their benefits calculated as the values of the corresponding objective function. The optimization design variables, X, can be defined as the game player's strategy space $S_1, S_2, \dots, S_m$. Constraints in the game can be determined similar to the optimization constraints. So, the game of a multi-objective problem can be formulated as $\mathrm{G} = \{S_1, \dots, S_m;\ f_1, \dots, f_m\}$. $f_1, \dots, f_m$ stand for m-design objectives. $\mathrm{S}_1 = \{x_i, \dots, x_j\}, \dots, \mathrm{S}_m = \{x_k, \dots, x_l\}$ represent strategy sets of an m game players and fulfill $S_1 \cup \dots \cup S_m = X;\ S_a \cap S_b = 0\ (a, b = 1, \dots, m; a \neq b)$. Interactions of nexus systems', simulated through multi-objective optimization models, could be evaluated using game-theoretic rules to have a reasonable perception of relationships among stakeholders from different economic sectors.

Serious games coupled with Geographic Information Systems (GIS), by creating realistic simulations, offer the nexus optimization game a cooperative environment to test the potential cross-sectoral and multi-temporal implications of decisions. Such an environment combines nexus systems' structures and strategies with game elements in a real-world spatial representation manner to teach specific skills, knowledge, and attitudes to stakeholders and decision-makers. Serious games function as space for players (i.e., nexus stakeholders) to cooperatively seek alternative solutions to complicated resource management problems. GIS is instrumental in applying game-theoretic algorithms to nexus spatial optimization.

Taking advantage of the potential improvement possibilities such methodological combination may offer development of new models and tools for FWE nexus decision-making, therefore, this chapter developed a model for an integrated decision support tool called S.N.O.G. (the Spatial Nexus Optimization Game) that can offer a holistic and dynamic approach to address FWE resources management problems. The proposed model is a function of time and space, and considers the uncertainties, synergies, and trade-offs among the three FWE sectors and with the community.

5.3 THE S.N.O.G MODEL: INNOVATION IN GUIDING INTEGRATIVE NEXUS DECISION-MAKING

The S.N.O.G. (Spatial Nexus Optimization Game) model is proposed to address some of the gaps previously identified—its main contribution towards the nexus approach being the assessment of fundamental requirements for a balanced, holistic system combined with a number of particular policy actions on social and environmental implications of uncontrolled resource use (see Fig. 5.5). The provided model can (i) accommodate context-specific inputs; (ii) generate results in a geographically understandable layout; (iii) be simple from an analytical standpoint while providing a comprehensive insight into the situation; and (iv) test realistic options.

Through S.N.O.G. model based serious game tool, decision-makers are provided with adjustable technological, environmental, and social policies to model and validate various possible scenarios for the nexus process. Policies can be assigned in combination or individually to a location of desire, and possible implications in socio-ecological systems performance can be discussed simultaneously. Thus, optimal choices of nexus policies considering future implications can be made, along with a spatially validated action plan.

5.3.1 Methodology development

The core methodology for developing the proposed S.N.O.G. model consists in a modified version of *Non-dominated Sorting Genetic Algorithm II (NSGA-II)* and a *coalition game* model (Fig. 5.1).

NSGA-II, proposed by Deb, Pratap, Agarwal, and Meyarivan (2002), is one of the state-of-the-art multi-objective genetic algorithms that aims to produce non-dominated solutions by simulating the natural selection process. Key advantages of using NSGA-II over other MOO algorithms in this study are: i) a widely accepted approach that leads to fast convergence; ii) an efficient ranking scheme that provides the most optimal set of trade-off solutions; and iii) a crowded comparison operator that keeps diversity in solutions. Since nexus optimization is a spatial process and requires representing spatial attributes and areas, this study developed an enhanced form of the NSGA-II algorithm, incorporating two geometric operators, so that the spatial rationality can be strengthened.

Coalition game is one of the cooperative game-theoretic models in which players, based on Pareto protocol, aim to maximize their mutual payoffs (Ilavendhan & Saruladha, 2018). In the Pareto protocol, a visual representation of all possible strategies and associated payoffs is made (i.e., the payoff matrix) through which players negotiate how to allocate in some fair way the payoffs among their diverging objectives supporting nexus decision-making in equilibrium.

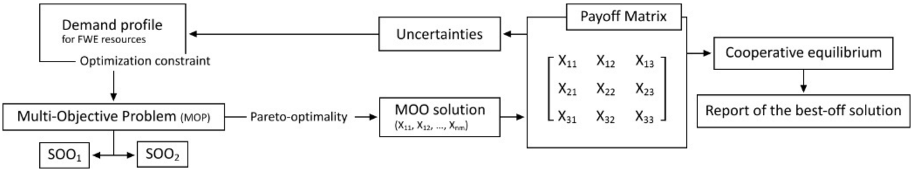

Fig. 5.1. Methodological framework of the proposed Spatial Nexus Optimization Game (S.N.O.G.). Based on local characteristics, the nexus problem of the study area should be described in the form of several single optimization objectives. Through the optimization model, nexus stakeholders and decision-makers can consider the possible optimal nexus development scenarios. In order to choose the most optimal scenario (action plan), the model provides users with a cooperative game environment allowing trade-offs comparison and discussions. In the Figure, SOO refers to Single Optimization Objectives, MOO describes the multi-objective optimization solutions, and X_{ij} presents the possible development scenarios (solutions) to be compared and discussed through the cooperative game environment.

The proposed methodology implies the following procedure:

Step 1: formulation of objective and constraint functions for optimization

To formulate sustainable nexus strategies, decision-makers must hedge against adverse impacts that synergies within the FWE sectors may have on the environment while adhering to social objectives. The nexus approach formulation herein consists in discovering the most optimal spatial layout of nexus policies so as to simultaneously attain two objectives: i) minimization of ecological stress in terms of a set of processes and activities for meeting demands of society for FWE resources, and ii) maximization of social acceptance in terms of how satisfactory choices of nexus optimization actions are for the society.

Suppose that the area under consideration is divided into a regular grid with N rows and M columns. There are K different policies available to be implemented within this area. A binary variable P_{ijk} is defined where P_{ijk} equals 1 when policy K is assigned to cell (i,j). Otherwise, P_{ijk} equals 0. B_{ijk} is determined as a parameter of the different policies that relies on the characteristics of the area and the objectives themselves.

The process of accomplishing optimization of the two stated objectives can be formulated as follows:

Minimize $\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M}\beta_{ijk}\,P_{ijk}$ 1)

Where $\mathrm{P}_{ijk}\in\{0,1\},\forall K=1,\dots,K; i=1,\dots,N; j=1,\dots,M$

For ecological stress minimization, β_{ijk} is defined as the total cumulative exergy consumption (CExC) of cell (i,j) when policy K is selected. In view of the heterogeneous FWE components composing the nexus system, Sciubba and Wall (2007) advised the use of a unifying quantity such as exergy; considered as the available energy of a resource to carry out useful work. This research proposes the use of CExC for FWE nexus studies which quantifies the total amount of exergy destroyed while collecting, processing, and consuming all the needed resources. Considering the availability of local and external resources in an area and the population demand for respective products and services, CExC serves as processes and activities that need to be undergone to satisfy such demands under the condition of minimizing exergy.

For social acceptance maximization, $-\beta_{ijk}$ is defined as a criteria weight of policy K representing how satisfactory it is for the society with respect to other policies when it is assigned to cell (i,j).

The bi-objective optimization problem stated herein is subject to some constraints:

Practical compatibility of policies with different land-use types (LU_t)

$$\beta_{ijk}=\begin{cases}0, & k \text{ compatible with } LU_t\\ 1, & k \text{ incompatible with } LU_t\end{cases} \qquad 2)$$

Where policy K can be compatible with multiple types of land-use without causing problems for the usual functionality of the land. Attributes of different land-use types are key to implementing nexus policies in an area. For instance, agriculture is land demanding and shapes the antagonism within land-uses. Nexus policies that target improvements in agricultural activities are not compatible with land-uses else than agriculture. Other self-sufficiency policies aiming for household-scale implications, such as on-site wastewater purification or solar power generation, can consider various kinds of land-use such as residential and commercial.

Feasible spatial adjacency of policies; observing a minimum Euclidean distance of standard

$$\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(q_{ij}-p_{ij}\right)^{2}}-D_{qp}\ \geq 0 \qquad 3)$$

Where p and q are centers of two cells in Euclidean $i*j$-space, and D is the minimum standard distance between two specific policies for real-world implementation. The

Euclidean distance between centers of the cells that two policies are assigned to should be at least equal or greater than the standard distance determined by literature and authorities for implementing the two policies in adjacency of each other in the real world.

A minimum total amount for the FWE resources production

$$Q_s - Q_d \geq 0 \qquad 4)$$

Where the supply capacity, Q_s, should meet the quantity of demand, Q_d, for each of the resources.

A maximum total land available for resources production, regarding the characteristics and requirements of the context of the study.

To give equal importance to all constraints, constraints values were normalized regarding an average value for each derived from a large (e.g., 500) number of random iterations. Meaning that the model has randomly generated 500 times distribution of policies throughout the area in question, values of each constraint has been calculated, and the average of the generated values was used for the normalization $\overset{\text{m}}{=} g_k(X)_i/\overline{g_k(X)_\imath}$ where g stands for the value of a constraint calculated for a set of finite policies $\ni \{k_1, k_2, \dots, k_k\}$ chosen as a design solution X to the problem.

Step 2: optimization model formulation

In the proposed model, a grid-based design owing to computation simplicity of regular territorial units (i.e., squared cells) and its great applicability to various spatial scales is employed. Possible solutions to the optimization problem are presented by a chromosome (i.e., the operational element of any genetic algorithm) (García, Rosas, García-Ferrer, & Barrios, 2017), hereafter referred to as the map grid. Every cell of the map grid, the chromosome gene, in theory, derives its value from the possible set of policies. Since land-use can place restrictions on real-world implementation of nexus policies, the generated cells have their corresponding land-use type attached. Therefore, policies that are applicable to a land-use type can be allocated to the entire valid subset of that land-use unless it is limited by the optimization constraints. The optimal size of the cells is therefore subject to a set of parameters, including computational cost, (land-use) information loss, and model impracticability from a user perspective. The lower the values of the parameters, the more optimal the spatial resolution of analysis and, therefore, the more accurate the spatial allocation of policies.

Initialization

Spatial rationality in nexus planning and the improvement of the currently implemented policies is subject to two main issues: policy actions compactness and the land size needed per policy. Accordingly, to form rational initial chromosomes, an improved process was designed through which the initial population of solutions can be generated and further enhanced (see appendix D: Fig. D.1 for a detailed demonstration of the population generation procedure of the NSGA-II algorithm in this study). The initialization process is reliance upon a random cell agglomeration of pre-defined nexus policies. The allocation of policies to cells expands until the maximum population demand for resources is reached. As a topological structure, valid subsets of different policies can share their dimensions, partially or entirely, in a map based on the territorial capacity of different land-use types for more than one policy. Hence, the desirable spatial extension of a policy may not be achieved as other policies can crowd its valid subset. In addressing this issue, the unallocated map grid cells will be filled by policies in deficit until their demand target is fulfilled. Initialization assures diversity and the compactness of policy actions throughout the map grid. Appropriate allocations will subsequently be enhanced through evolutionary operations.

Model operators

The S.N.O.G. model operators are categorized as evolutionary and geometric operators as follows.

A. Evolutionary operators

Evolutionary operators, including selection; crossover; and mutation, encourage the diversity of offspring by means of reproduction iterations over the population for further optimal solutions provision.

Selection operator. During the execution of the NSGA-II algorithm, the *selection operator* chooses members of a population with greater suitability for mating. Mathematically, the suitability is measured regarding the value of the objective functions.

Crossover operator. Conventionally, population recombination through crossover depends on exchanging genes between two chromosomes derived from the renewed population by the selection operator. As soon as a chromosome (parent) set is determined for recombination, two of them are picked at random with a high probability (e.g., 90%) to crossover as follows (illustrated in Fig. 5.2):

1) Overlapping stage: matching cells of the two selected parents having equal policies assigned to their positions (overlapped cells) are precisely transmitted to their desirable offspring if geometrically positioned within their valid subsets. Corresponding cells holding distinct policies remain empty.
2) Local search: a local search is applied across valid subsets of each policy in order to fill the empty cells. For this, each parent is evaluated regarding the value of the objective functions per policy into minimization function OU (Equation (5)). Comparing the result across the parents, the policy with minimum value is then assigned to the empty cells of the two offspring alternatively if the above-described optimization constraints are satisfied (Equations (2)-(4)). Thus, the

offspring receives the best distribution of policies that has a high probability of containing good solutions between two parents.

$$\text{Minimize } OU\text{: } \sum_{j=1}^{M}\left(U_{ij}^{max} - U_{ij}(x)\right)/\left(U_{ij}^{max} - U_{ij}^{min}\right) \qquad 5)$$

Where M represents the number of the model's objective functions from j to M; $U_{ij}(x)$ is the value of a current policy from i to K evaluated at the jth objective for parent (x); and U_{ij}^{max} and U_{ij}^{min} are the maximum and minimum values obtained from the initial population set evaluated for the ith (current) policy K at the jth objective function.

3) Filling-in process: misplaced cells that contain policies outside their valid subsets experience a filling-in process through which they are replaced with valid but deficient policies. The process initiates with the random, geometrically valid allocation of deficit policies, beginning from the one with the highest deficit, while reaching the lower action limit for the current policy. If the offspring lacks more than one policy type, the process begins with the least need policy, provided the constraints are completely met. As for urban development strategies, nexus policies do not necessarily have to cover the whole area (cells). However, since the spatial NSGA-II works in a way that all cells are being assigned to the solution, an additional policy called 'empty policy' was defined that helps the model to fill the cells that do not match with any other policy. The crossover process ends as soon as no empty cell remains in the offspring.

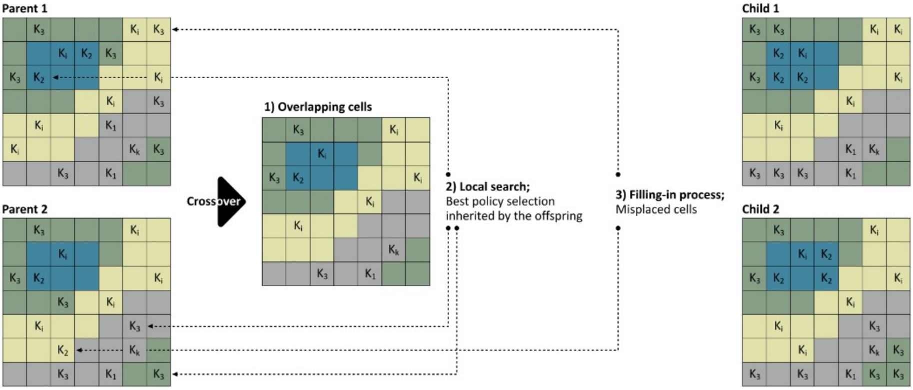

Fig. 5.2. Illustration of S.N.O.G. crossover operator.

Mutation operator. This evolutionary operator evaluates whether the solutions meet the constraints; thus, some specific policies which steer the overall solution toward an improved change are chosen (see Fig. 5.3). With the aim to maintain diversity among individuals, the mutation operator in this study relocates policies outside their valid subset cells following the procedure indicated below:

1) Identifies cells of a land-use subset containing invalid policies.

2) Replaces the invalid policies with the most frequent policy that exists within their corresponding land-use subsets if still needed.

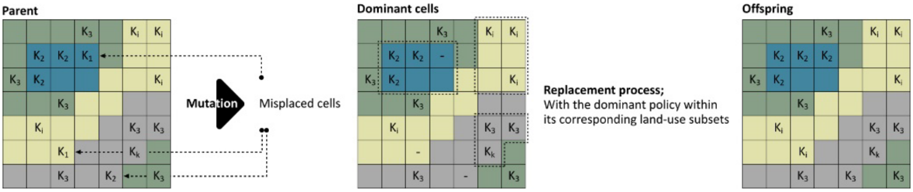

Fig. 5.3. Illustration of S.N.O.G. mutation operator.

B. Geometric operators

To enhance FWE nexus policies' compactness and maintain the required land size, two geometric operators have been adopted in this research (Fig. 5.4). Key elements for improving the spatial allocation of nexus policies are the boundaries of their corresponding land-use subsets. A two-step boundary analysis, as a means of chromosome correctness, is incorporated into the proposed modified spatial NSGA-II algorithm that performs after the evolutionary operators to erase infeasible solutions from the population.

1) The spatial dispersion operator (SDO) was developed to improve policies' compactness. The SDO recognizes whether policies are allocated within their valid land-use subset. When recognized, unfeasible policies change into the most recurrent policy in their adjacent cells. The spatial dispersion stated herein lies on one or maximum two neighbouring cells whose policies are dissimilar to other adjacent cells. The spatial dispersion control continues until no more infeasible solution remains in the grid.

2) The proportion steering operator (PSO) controls the land size assigned to each policy type while maintaining the demand. Initially, the operator recognizes unbalanced policies, either being in deficit or surplus to requirements. Those types of policies that have the highest deficit and the highest surplus are selected. Then, the spatial boundary analysis indicates if both policy types are adjacent. In the case of policies having common boundaries, changes are essential only in cells contributing to the constraints; therefore, the deficit/surplus could be balanced. This process repeats until the required number of cells for each policy is fulfilled or until no neighbour remains between unbalanced policies, provided that the spatial constraints are fulfilled.

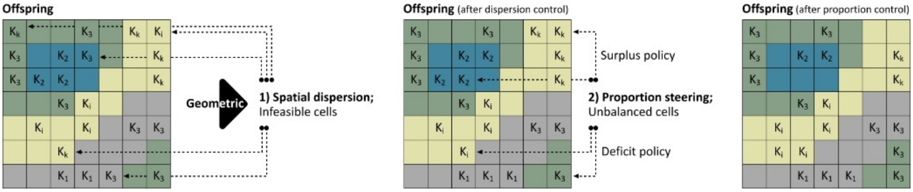

Fig. 5.4. Illustration of S.N.O.G. geometric operators.

Following the evolutionary and the geometric operators respectively redressing diversity and compactness of solutions, the offspring is assessed by objective functions, and the process iterates until all generations are completed, therefore providing the associated non-dominated set of solutions.

Termination criteria

For every optimization model, it is required to determine some conditions that must be reached to end the execution of the algorithm (Blank & Deb, 2020). This study implemented the termination based on a couple of criteria explaining movements in the design space (i.e., here as the spatial grids) and the convergence in the constraint and objective spaces. The greatest shift from a solution to its nearest neighbor is monitored over generations, and once it falls below a specific value, the algorithm is said to have reached convergence. In the objective space, however, the algorithm monitors the boundaries and uses them, when they have settled down, for termination. In addition, to make the termination more robust, a maximum number for the function evaluations or generations is considered.

Step 3: game model construction

For every decision-making in the nexus, it must be determined which set of alternatives provides the best solution. This study uses a payoff matrix associated with the information of several strategy alternatives (i.e., the derived non-dominated solutions from optimization) that compete for the optimal integration of nexus systems to summarize preferences considered by each player (from the viewpoint of the different optimization objectives) and gradually build a consensus on the best solution (i.e., Pareto optimal). Considering the coalition game represented in Table 5.4, let player one (i.e., the first optimization objective) be the row and player two (i.e., the second optimization objective) the column.

1) Strategy S dominates a strategy $\acute{S}$ if
    - it makes higher payoffs for all players than $\acute{S}$, i.e., $\mathrm{U}(S) \geq U(\acute{S})$ for all players,
    - it makes a higher payoff at least for one player than $\acute{S}$, i.e., $U_i(S) > U_i(\acute{S})$ for at least one player.
2) Strategy S is the best response to the optimization objectives if no other strategy dominates it, i.e., $U(S) \geq U(\acute{S})$ for every strategy $S \neq \acute{S}$ available to all players.

Table 5.4
Payoff matrix for coalition game model. In this table, rows and columns list strategies of each player and the cells display their payoffs such that the row player's payoff is listed first. In this study, players are considered as two different groups of nexus stakeholders each follows one of the optimization objectives. Strategies with dominant payoffs for each player are optimal equilibrium solutions, and the best solution is the strategy that gives both players less loss. S And $\acute{S}$ are considered as non-dominated strategies derived from the optimization model, and $\mathrm{U}(S)$ and $U(\acute{S})$ are the payoffs each player receives from the implementation of each strategy.

		Player i	
		S	$\acute{S}$
Player j	S	$\mathrm{U}(S), \mathrm{U}(S)$	$\mathrm{U}(S), U(\acute{S})$
	$\acute{S}$	$U(\acute{S}), \mathrm{U}(S)$	$U(\acute{S}), U(\acute{S})$

Such an incentive mechanism can promote cooperation between stakeholders and positively impact the nexus process.

5.4 APPLICATION EXAMPLE OF THE S.N.O.G

5.4.1 Overview of the synthesis example system

The presented S.N.O.G. model is employed in describing a synthetic example FWE system in order to illustrate its applicability. The system studied in this chapter represents an adaptive urban ambition in the Netherlands, namely Brainport Smart District (BSD)[5], to realize a sustainable, circular, and socially cohesive neighbourhood that benefits from joint food production, water management, and energy generation subsystems. Fig. D.2, in Appendix D, illustrates components and interactions of the FWE nexus subsystems in BSD. It is crucial for BSD to design a system with low energy demand and minimize the use of raw materials considering locally available and environmentally friendly resources. The system vision includes solar and wind power to generate electricity, both requiring water from different sources (i.e., groundwater, surface water, treated water). The generated energy serves both the FWE systems interdependencies (i.e., to treat water and for food production) and socio-economic demands. Similarly, the food production and processing system requires both water and energy (in the form of electricity in this study). Moreover, carbon dioxide (CO_2) is emitted by electricity generation, food productions, and water purification processes. It is also important to collect feedback on how the FWE system works so that the neighbourhood can function optimally. S.N.O.G. proposes an iterative feedback system measuring FWE performance and having a transparent information network to BSD to keep the FWE system running properly and efficiently.

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[5] BSD is the Urban Living Lab (ULL) from Helmond, Eindhoven region within the CRUNCH project.

The aim is to make an effective selection of context-specific nexus policies and to determine their optimal spatial allocation that will minimize resource intensity (measured by CExC in this study) and maximize the community's acceptance of the management plans under strict social, ecological, and technical constraints (Equations 2-4) for meeting the local FWE demand.

The S.N.O.G. model operational design for BSD, using the Pymoo library in Python (Blank & Deb, 2020), is performed over a time period of 30 years in line with real-world nexus policies (to access the code repository see Ghodsvali (2021)). The data used in this study is collated from available literature and BSD project reports (Centraal Bureau voor de Statistiek, 2009; Geudens & Grootveld, 2017; M. Geurts, van Bakel, van Rossum, de Boer, & Ocké, 2016; Leung Pah Hang et al., 2016; UNStudio, Felixx Landscape Architects & Planners, Metabolic, UNSense, & Habidatum, 2019; van der Bie, Hermans, Pierik, Stroucken, & Wobma, 2012; Voedingscentrum, 2019) (see Appendix D: Table D.1 and Table D.2 for a detailed description of all parameters and data used in the S.N.O.G. model design for BSD). In general, the data includes information on local characteristics of the BSD area given the field of the FWE nexus. It includes available capacity of food, water, and energy resources; demand of its future population (over 30 years) for food, water, and energy; and the work required for the extraction, productions, transportation of demanded products and services for use (see Appendix D: Table D.1 for a detailed description of all parameters and data used in the S.N.O.G. model design for BSD). These data, based on the lowest possible computation cost, least information loss, and best practicability from users' perspective, were converted to a 21×14 grid with a resolution of 100×100 meters, considering the system boundary.

Fig. 5.5 shows the structure of the model performance citing the example of BSD. Key components of the model, i.e., objectives, constraints, and policies are retrieved from NexSESF, the assessment framework introduced in Chapter 3. Following the analytical structuring of the model, the operation modules of the model are designed based on our findings of the systematic transdisciplinary nexus literature review. The possibility of spatially implementing policies and evaluating the implications of different actions through a simulation of real-world situation addresses the need of FWE nexus stakeholders for cross-sectoral, multi-criteria decision-making. Having determined the FWE subsystems' interconnections and based on the information that describes local characteristics of the case study, the practical application starts with a preliminary optimum scenario developed automatically by the model, followed by possibilities of the strategy adjustment to the varying users' interests. The preliminary scenario is developed by the optimization model selecting and spatially allocating the pre-defined resource management policies throughout the grided area. Then, using a control module in respect of manual spatial adjustments, the tool enables the development of various scenarios by removal, addition, or relocation of policies, on the basis of the preliminary optimal scenario, over the grids.

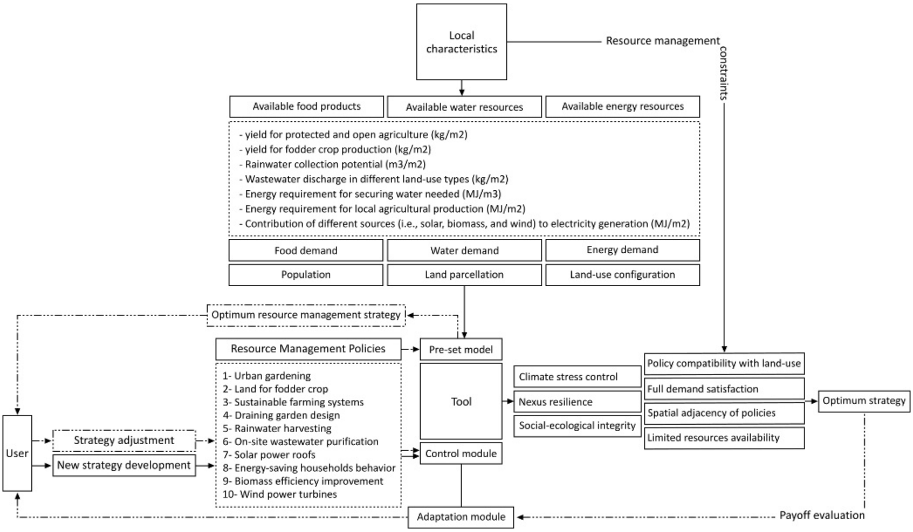

Fig. 5.5. Model structure and the practical application for BSD.

The multi-dimensional character of the model necessitates advanced investigation and interpretation of the results. Although the tool is structured generically, the results ought to be specific to the area in question. Viewpoints on results of a specific scenario may vary across different decision-makers, thus each needs to provide its respective input. The importance and sensitivity of the model parameters vary from one area to another. Local viability of a scenario can be accomplished through the calculation of strategic performance measures, in this study, including 1) climate stress control in terms of scenarios contribution towards CO_2 emission reduction versus the business-as-usual scenario, 2) nexus resilience characterized by system relations and physical capacities, and 3) social-ecological integrity as concerns the extent to which the scenarios maintain the delicate balance of the system.

5.4.2 Design analyses: illustration with some performance indicators

In this study, optimal solutions to the FWE nexus operation in BSD were discovered consistent with the two set objective functions (see Equation 1) using NSGA-II and the concept of Pareto Front. Fig. 5.6 shows the set of 550 optimal solutions, known as Preto Front, that provides deeper insights into the trade-off among the optimization objectives and many choices for nexus implementation in BSD throughout 2020-2050. Point A represents the ecological optimal solution, while point D indicates the social optimal solution. Closer to point A (e.g., group B), optimal solutions were more likely to minimize ecological stress output; in contrast, solutions nearby point D (e.g., group C) sacrificed ecological output for social acceptance. Fig. 5.7 illustrates the most optimal solution, compromising all the situations equally.

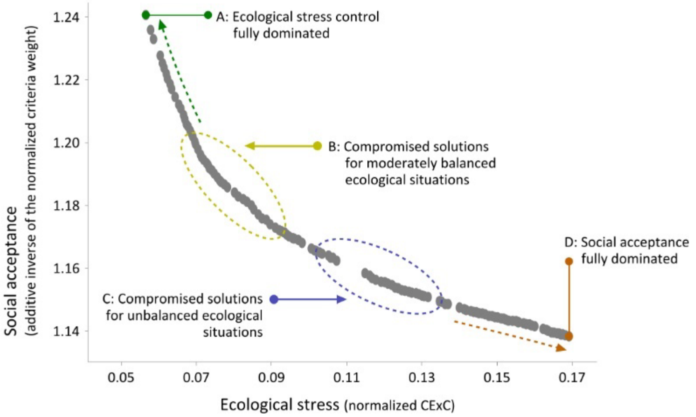

Fig. 5.6. Pareto Front of the S.N.O.G. optimization model for an optimum nexus process of 30 years during 2020 and 2050 in Brainport Smart District.

Based on land-use configuration and availability of resources in BSD, the optimum spatial allocation of the pre-defined nexus policies (presented in Fig. 5.5), either in combination or individually, was made through the simulation of long-term operation (Fig. 5.7). Real-world implementation of the developed optimal nexus scenario, BSD can achieve both the optimization objectives and resolve all the local ecological, social, and technical constraints.

To fully investigate advantages of the S.N.O.G. model, two other alternative scenarios were developed (Fig. 5.8). The first scenario, termed 'self-sufficiency,' created a local design of the FWE subsystems regardless of synergies with external sources. The food subsystem is designed considering solely local urban gardening. The water subsystem is intended only to satisfy the needs of the residential, commercial, and mixed-use sectors for water. It involves only the use of available water sources within the area, such as groundwater, rainwater, and treated wastewater. Moreover, the energy subsystem is also considered to exclusively satisfy the local electricity demand, regardless of heat recovery possibilities among the FWE subsystem, but enabling the use of various eco-friendly sources (e.g., solar and wind power). The second scenario termed 'eco-conscious consumerism' assumes that all the local demands of BSD for food, water, and energy were met by environmentally friendly sources considering local availabilities.

For evaluating the model performance and analysing the reliability of the results, this study investigated hypervolume and constraint violation, key performance indicators of optimization models. Hypervolume is known to be Pareto-compliant and is based on the volume between a reference point (which should be larger than the maximum value of the Pareto front) and the solution provided. The hypervolume indicator in this study shows that the model performance improves gradually over function evaluations. Constraint violation evaluates the model performance with respect to the extent to which it could resolve the optimization constraints (i.e., reaching a value less than or equal to zero). For this study, the model was able to find an optimum solution for the nexus process in BSD that has no constraint violation (Fig. 5.7). The results revealed that the optimal solution performed better than the other two alternative scenarios when resolving all constraints during the optimization procedure. The alternative scenarios, in line with sub-nexus purposes, adopt a limited number of policies and accordingly may not resolve all the constraints comprehensively, although the objectives are considerably attained. Game theory plays an important role in this regard, which will allow model-based tool's users to evaluate and discuss alternative scenarios collaboratively and reach a consensus on the most timely-appropriate solution.

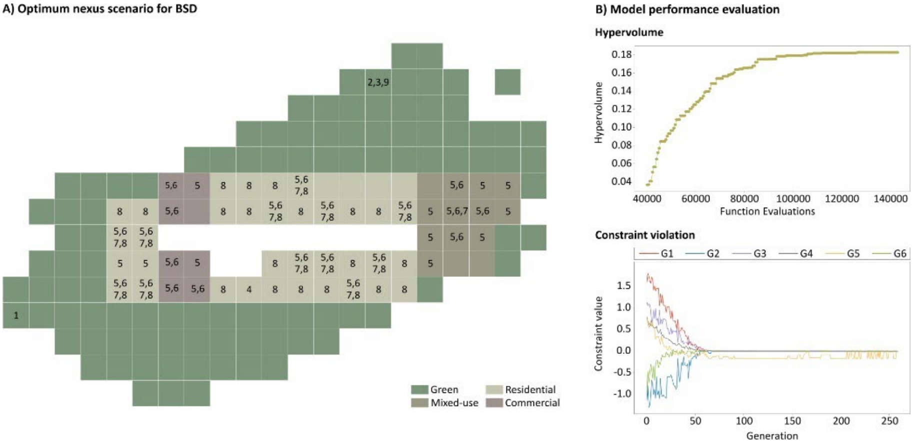

Fig. 5.7. Illustration of the optimum nexus scenario developed by S.N.O.G. for BSD and the model performance evaluation.

A) presents the most optimum spatial allocation of the pre-defined nexus policies in this study concerning land-use configuration and in a way that all the optimization objectives and constraints are met. See Fig. 5.5 for descriptions associated with each policy number 1, …, 9. B) shows the evaluation of model performance using two indicators, hypervolume and constraint violation. For hypervolume, the larger the calculated value, the closer the solution is to the minimization target; in other words, the further the solution is from the maximum value of the Pareto front. For constraint violation, the closer the Gs (constrains) value to zero or below it, the better the model performance in resolving the optimization constraints. G1 stands for policy compatibility with land-use, G2 refers to the full satisfaction of the local vegetable demand, G3 represents land availability for agricultural production, G4 considers the spatial adjacency of the policies, G5 refers to land availability for energy generation, and G6 stands for the full satisfaction of the local electricity demand. The values for Gs in the constraint violation charts are normalized to give equal importance to each of them (see Sub-section 5.3.1. for the normalization procedure).

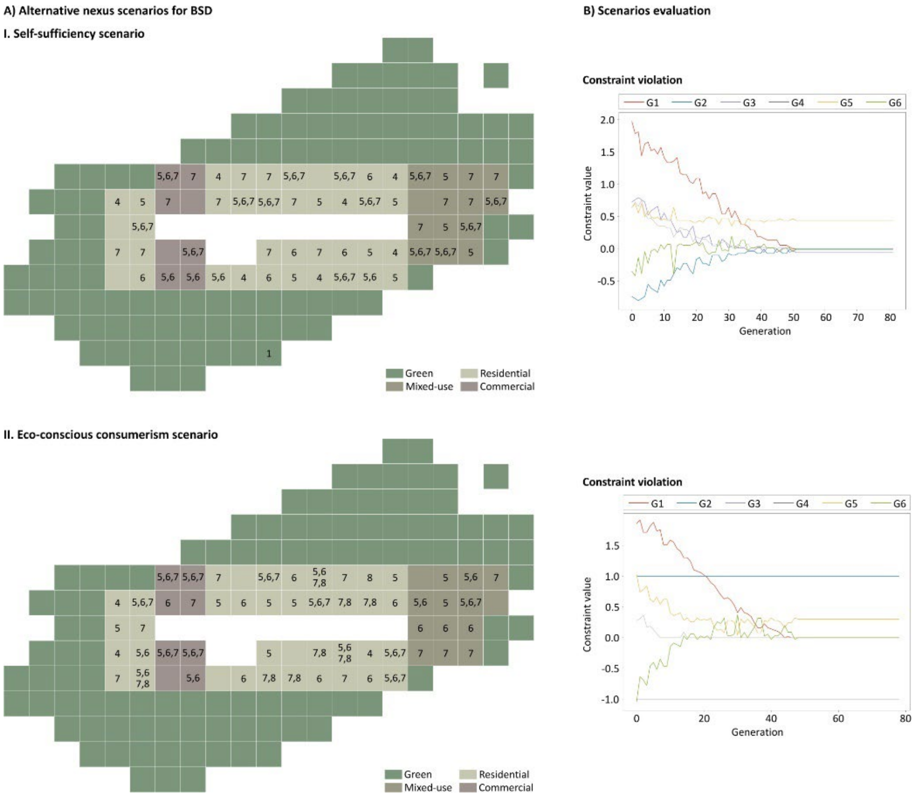

Fig. 5.8. Illustration of alternative nexus scenarios for BSD.
Each scenario employs particular policies in support of a specific purpose, and their evaluation. Unsurprisingly, due to the limited use of the policies in these scenarios, they could not effectively resolve all constraints (i.e., reaching a value less than or equal to zero), though they are constructive in nexus management in general.

Employing the game theory, S.N.O.G. provides users with a possibility to compare the alternative scenarios quantitatively and agree on the one that suits all their concerns collectively. On the basis of the two example alternative scenarios developed for BSD, Table 5 demonstrates the payoff matrix for the coalition game model. The scenario that gives both players less loss is the best solution for nexus strategy in BSD. This can be discussed in a group discussion environment, such as the serious gaming platform that is based on the S.N.O.G. model, to be discussed in the next chapter.

Table 5.5

Payoff matrix for a coalition game model based on the sample alternative scenarios developed for BSD. In this table, players one and two respectively stand for the optimization objectives one and two of this study. Rows and columns list strategies of each player and the cells display their payoffs such that the row player's payoff is listed first. Strategies with dominant payoffs for each player are optimal equilibrium solutions, and the best solution is the strategy that gives both players less loss.

		Player 1	
		Sc 1	Sc 2
Player 2	Sc 1	0.64, 1.07	0.64, 1.2
	Sc 2	0.46, 1.07	0.46, 1.2

Note: Data regarding objective values of the two scenarios used in this table are presented in Appendix D: Fig. D.3.

5.4.3 Model assumptions

The model design for BSD rested on several assumptions to control the following complexities of the nexus problem studied herein:

- Dynamic parameters used in this study (listed in Appendix D: Table D.1) are uncertain owing to the absence of information on future socio-economic conditions in BSD. Local data, for instance, on water supplies, local agricultural production, and energy demand would produce reasonably accurate results. For nexus systems that are explored in areas with an existing population, this study recommends the integration of the Agent-Based Modelling technique to the S.N.O.G. model for more reliable simulations.
- Future projections of the local characteristics are not incorporated into the current design of the tool. It simulates a design and builds scenarios on known characteristics of the area in 2050, regardless of possibilities for further developments over the years.
- Input from multiple disciplines, including scholars, policymakers, and communities is essential for the scenario adjustment step. A group discussion involving a mix of all relevant stakeholders is suggested to develop well-founded and socially relevant policies while facilitating active communication.

5.5 S.N.O.G. EVALUATION: OVERALL MODEL PERFORMANCE AND LIMITATIONS

To support the optimal integration and management of FWE nexus systems, this study developed a decision support model called S.N.O.G. The S.N.O.G. model sets the base for a web-based serious game (is described in Chapter 6) in order to support policymakers and communities to collaboratively formulate effective strategies and decisions from a social-ecological resilience perspective. The S.N.O.G. model is able to address the complicated interactions of the nexus food, water, and energy components from a comprehensive point of view (see Appendix D: Fig. D.2). Trade-offs among social and ecological objectives, geographically concerned operational constraints, and the balance between human needs and preserving the environment are effectively evaluated. As a multi-dimensional model, S.N.O.G. can explain spatial and temporal features of a nexus system and formulate resource-effective strategies for optimizing FWE productions and minimizing related environmental impacts (i.e., carbon dioxide emission). Although the presented model in this study is adapted to the BSD case area and includes only renewable energy types, the S.N.O.G. model is capable of including more types of energy sources by designating supplementary policies and decision variables, while the model structure remains unchanged. From the operational perspective, S.N.O.G. is appropriate for practical applications at varying spatial scales owing to its algorithmic efficiency regarding computation power and implementation accuracy. Decision-makers can simply form context-specific applications of the S.N.O.G. model based on their operational policies priorities and management purposes.

The S.N.O.G. approach to nexus challenges has some limitations. An FWE nexus system can be extremely complex in general, and the S.N.O.G. model does not provide a comprehensive illustration of all the possible components and processes linked to the nexus management such as cultural, territorial, and security-related issues. This chapter's primary aim was to develop a decision support tool that can address FWE nexus issues at multiple scales in a collaborative setting. Thus, key nexus attributes, including FWE supply and demand, resources interactions, socio-economic status of the context in question, and the spatial constraints on the integrated resource management, are merely incorporated into the S.N.O.G. model. All the model parameters are definite. In the future, uncertainties related to the model and the parameters can be thoroughly examined employing stochastic simulation approaches such as agent-based modelling (ABM). Effective nexus management requires the evaluation of the decisions derived from support tools against such modelling uncertainties, and these types of analyses should be added to the S.N.O.G. model for further improvements. Climate resilience principles are not directly included in the S.N.O.G. model and are only considered as strategic performance measures of the developed scenarios. In real-world implementation, local knowledge is required as it more accurately describes the site-explicit specifications of the nexus system, including both social, ecological, and technological components.

The S.N.O.G. examination provided herein was conducted for a synthetic example nexus system that should be adequate to validate the real-world applicability of the model. In the next chapter, this research intends employing S.N.O.G. to guide a real-life FWE nexus practice.

5.6 CONCLUDING REMARKS

Food, water, and energy resources are considerably interconnected, and their interconnections require to be considered in decision-making and planning realms that govern the management of these resources. Modelling of urban development scenarios and the use of such models for the application of decision support tools involving inputs from local stakeholders is crucial to proper resource planning and management. To navigate decision-making through the complex nexus systems modeling and planning, this research developed an integrated methodology for a model that considers the need of the interconnectedness of these essential resources. Methodologically, the presented model is developed based on a combination of multi-objective mathematical optimization programing and the coalition game theory technique that incorporates various components of the nexus management. It offers an evaluation of different scenarios that could serve as the basis for enforcing innovative guided management strategies. When S.N.O.G. model is used as a base for a serious game tool, decision-makers are provided with choices of adjustable technological, environmental, and social policies to model and validate various possible scenarios for the nexus process. Policies can be assigned in combination or individually to a location of desire, and possible implications in socio-ecological systems performance can be discussed simultaneously. Thus, optimal choices of nexus policies considering future implications can be made, along with a spatially validated action plan. In addition, the tool provides a collaboration platform designed to compile input from scholars, policymakers, and associating communities to reach a consensus on management goals. In this regard, serious gaming and GIS are incorporated into the model as a basis for a cooperative decision-making environment (see Chapter 6). The application of the model to a synthetic nexus example problem has demonstrated that the proposed approach can produce robust decision support outcomes. The Spatial Nexus Optimization Game (S.N.O.G.) model and the mathematical structure deliver the first building block of analytics for such complex, interconnected, and dynamic subsystems that are surrounded by constantly changing externalities. The demonstration of the S.N.O.G. model as a base for a web-based serious game tool is explained in the next chapter.

6

FOOD-WATER-ENERGY NEXUS GAME DEVELOPMENT

S.N.O.G. ONLINE SERIOUS GAME[6]

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[6] This chapter is based on:
Ghodsvali, M., Dane, G., de Vries, B. An online serious game for aiding decision-making on food-water-energy nexus policy issues: Design, implementation, and test. Sustainable Cities and Society (under review).

6.1 INTRODUCTION

The inherent complexity of food-water-energy (FWE) nexus makes stakeholder engagement in decision-making processes essential (Bielicki et al., 2019). Following an early call by Rio Declaration (United Nations, 1992) and more recently by the European Union (European Parliament, 2021), stakeholder engagement has become almost routine in many environmental policy arenas (Hage, Leroy, & Petersen, 2010). Experience has shown that the involvement of stakeholders can delineate the space for agreement or compromise, take into account local concerns, bring new options to light, increase public awareness, and, not least, enhance the credibility of public policies (see Mochizuki, Magnuszewski, & Linnerooth-Bayer, 2018).

Many tried-and-tested methodologies to facilitate stakeholder engagement in the complex FWE nexus policy issue are available (see Ghodsvali, Krishnamurthy, & de Vries, 2019), yet grounding these practices in state-of-the-art FWE nexus modeling techniques raises challenges. Foremost, content coherence is a consideration when expanding stakeholder geography to encompass interested actors across policy arenas and those who are in decision-influencing positions (Mochizuki et al., 2018b). Moreover, learning and capacity building among researchers, resource managers, and resource users are central to the engagement of stakeholders in FWE nexus decision-making processes in order to find sustainable solutions for nexus policy implementations (Sušnik et al., 2018). Furthermore, the underlying features for integrated FWE nexus decision-making (e.g., techno-ecological synergies, socio-technical networks, and cross-sectorial implications) may be less developed than for singular sectoral issues, which will mean more uncertainty and complexity for participating stakeholders. An emerging conceptual solution is influenced by knowledge derived from geospatial technologies. By integrating the exploration of stakeholders' ideas with direct, simultaneous evaluation of design solutions, geospatial technologies have been potential supports for urban challenges for years (Lee, Dias, & Scholten, 2014). Conceptually, the framework of Geo-design has connected the transdisciplinary decision-making opportunities for multi-sectoral spatial planning challenges. Methodologically, the translation of complex modeling results into interactive virtual simulations, in particular, a computer-based serious gaming approach, can offer the operationalization of such a conceptual solution to the integrated physical-spatial-social-technological nexus challenge (Barreteau, Le Page, & Perez, 2007). Computer simulations can include both the techno-physical complexity—the underlying physical/spatial elements of the system and its uncertainties—and the socio-political complexity—the strategic interactions between stakeholders in the policy domain.

Serious games, by combining computer simulations with a multi-stakeholder decision-making objective, offer FWE nexus modeling approaches a tool for collaboration, learning outcomes, and behavior change (Sušnik et al., 2018). Initially developed for research and teaching purposes, serious games are now played to create awareness and inform multi-stakeholder decision-making in a broad range of policy domains such as climate change mitigation and adaptation (see Juhola, Driscoll, Mendler de Suarez, & Suarez, 2013), and flood risk management (see Khoury et al., 2018). Towards multi-stakeholder decision-making, serious games provide experimental, rule-based, interactive environments where players learn by taking actions and by experiencing their effects through feedback mechanisms (Mayer, 2009). The assumption is that any learning that occurs from playing serious games is transferable to the world outside the game (J. L. A. Geurts, Duke, & Vermeulen, 2007).

While scientific calls exist for a more systematic assessment of FWE nexus stakeholders' engagement through serious games (e.g., Sušnik et al., 2018), its development on a practical level is challenging. On a practical level, data gathering and analytics occur in an interactive setting that introduces many challenging variables regarding gaming experience, learning experience, and usability (Moizer et al., 2019). Serious games should also be appropriately targeted to a wide range of users and convey clear policy-relevant messages and information based on the latest scientific understanding. The lack of consensus on how grounding serious games in state-of-the-art FWE nexus modeling techniques has made it difficult to employ (Mochizuki et al., 2018b).

With respect to the above discussion, there is a clear need to develop a serious game that (i) is grounded in robust methods and analysis using state-of-the-art FWE nexus models, (ii) enables stakeholders to learn about the medium and long-term implications of FWE nexus policy decisions, and (iii) allows the design and exploration of scenarios of a possible future state of the social and environmental systems under the nexus consideration. This chapter introduces the design, implementation, and test phases of a state-of-the-art online serious game, namely Spatial Nexus Optimization Game (S.N.O.G.), embedded in a state-of-the-art nexus optimization model (presented in Chapter 5), which deals with science-policy-society interface across FWE nexus issues. It increases an understanding of the FWE nexus issue across various stakeholders and the long-term implications of different policies that may be implemented. In an interactive and entertaining way, players learn about the complex interplay of social and ecological aspects, and the impacts of integrated resource management on social inclusion and nature conservation. Thus, S.N.O.G. aims at bridging the gap between FWE nexus modeling and stakeholder engagement. A spatial optimization model of S.N.O.G. simulates the complex feedbacks and interrelations of FWE resources management. The game serves as a training tool, which encourages systemic thinking and discovering the nature of nonlinear cause-effect relations. The S.N.O.G. online serious game was launched in 2021 (Eindhoven University of Technology, 2021).

This chapter presents the overview of serious games in the context of FWE nexus, the concept and implementation of S.N.O.G., as well as the evaluation of the first user survey. Finally, further improvements and utilization of S.N.O.G. are discussed.

6.2 OVERVIEW OF SERIOUS GAMES IN FOOD-WATER-ENERGY NEXUS

Serious games offer potentially transformative capabilities to strategic decision support tools to provide better management of the complex FWE systems compared to purely technical simulation or optimization methods that have difficulty in conflict resolution. Conflicts often arise in relation to FWE nexus due to multiple economic and environmental objectives, as well as the multitude of conflicting goals and perspectives held by multiple stakeholders. A concept of shared vision planning which requires engaging stakeholders in developing and experimenting with interactive simulation models has been an effective way of conflict resolution in the serious gaming approach (UNESCO & European Commission, 2021). Shared vision planning combines FWE nexus modeling and assessment methodologies with innovations such as structured public participation and the use of collaborative modeling. This results in a complete understanding of complexities for FWE nexus solutions. A serious game, together with interactive simulation models and a shared vision planning concept, can be considered an integrative decision support tool for the implementation of FWE nexus policies.

A number of serious games for FWE nexus have been reported in the literature or can be found online (e.g., *Nexus Game* (Centre for Systems Solutions, 2019), *Nexus! Challenge* (Centre for Systems Solutions, 2018), *SIM4NEXUS* (Sušnik et al., 2018)). They have demonstrated that serious gaming is a valuable technique for making various stakeholders aware of the socio-ecological-technological issues related to managing complex food, water, and energy systems integratively. The increasing number of references appearing in the last few years also indicates that serious games are tools that FWE nexus researchers and practitioners are becoming aware of and are starting to embrace.

The *Nexus Game* is an integrated simulation board-game of the socio-ecological interrelations of food, water, and energy systems, addressing a complex transboundary resource management process (Centre for Systems Solutions, 2019). As a simple representation of reality, the game represents the challenges facing a transboundary river basin. It is designed to simplify many aspects of real-world problems, such as urban-to-rural water diversion and different agricultural production systems. As such, the game falls short of providing a comprehensive representation of nexus issues (i.e., integrated social and ecological interactions), nor in-depth technical details of nexus solutions (i.e., spatial and temporal (context-specific) characteristics of formulated policies). Extensive scientific information on these topics is available from more conventional means, such as integrated assessment models and technological feasibility studies (Conway et al., 2015; Entholzner & Reeve, 2016). Despite these limitations, the key value of the *Nexus Game* lies in its negotiation process through which players experience and learn not only potential technological solutions but also relational challenges to reducing food, water, and energy footprints. When a system is complicated though reducible to a few key relationships, achieving the optimal solution is a matter of knowing all parameters and functional forms (Mochizuki et al., 2018b). Diverse preferences and worldviews, as well as social dynamics make it challenging for participants to agree on a joint strategy. The gameplays shed light on social elements, largely ignored by conventional technological assessments. The more value-laden aspects of collective decision problems are needed in the design of the FWE nexus serious games.

The *Nexus! Challenge* is a serious board game that lets its participants stand in the shoes of decision-making authorities who jointly shape an economy that has to provide food, water, and energy to its cities. The game aids players in better understanding the interconnected FWE nexus challenges and exploring opportunities for different decision-making authorities (e.g., companies, governments, NGOs) to alleviate stress between stakeholders and build resilience among them. It provides a crash course in identifying when collaboration is required and shows the value of understanding the systems in which players operate. The rules of the game are not fixed and evolve during the game. This puts players in a position where they need to deal with uncertainty, similar to the real world. At the same time, the process and mechanism of negotiation, coordination, and collaboration are flexible and open to trial and error. This flexibility is one of the important mechanisms in which not only players learn to simulate open-ended negotiations of FWE nexus issues, but researchers make reservations on players' communication, collaboration, and decision-making styles. In spite of these strengths, the key shortage of the *Nexus! Challenge* lies in impact assessment models that are not provided to players while developing different scenarios for the future. This adds uncertainties to the game for making robust and accurate decisions. The incorporation of impact assessment models into the FWE nexus decision-making domain is a means of estimating accurately the largest possible extent to which interventions or actions achieve their objectives.

The *SIM4NEXUS* is an online serious game that tries to aid learning about the FWE nexus by helping stakeholders to explore interactions with the resource management process under a climate change context (Sušnik et al., 2018). The game enables players to implement policies in a computer gameplay environment and to explore how policies impact different FWE nexus components. It is built upon system dynamics models, and the problem is divided into manageable interventions in order to allow players to learn by doing. However, the game needs further improvements in terms of spatial representation of the problem. On correct spatial representation, better information will be generated for policy and decision making with results more accurately expressing on-the-ground situations.

These findings formed the basis of the S.N.O.G. serious game design and development, which has the following core idea: players step into the role of a decision-maker who controls the resilience of food, water, and energy sectors against overexploitation and mismanagement in a particular virtual area by various spatially explicit cross-sectoral policy implementations. In each round, players decide on spatial interventions in any combination of policies, in terms of a nexus scenario, based on which the climate stress control is estimated, and the level of resource management resilience and social-ecological integrity are calculated. Climate stress control shows the contribution of each scenario towards limiting carbon footprint and the avoidance of carbon dioxide emissions. Resource management resilience indicates the extent to which equilibrium is achieved between the supply of food, water, and energy to meet the local demand. The social-ecological integrity evaluates the extent to which the human impact on FWE resources security has been reduced. The S.N.O.G. serious game links decisions on these strategic measures of the FWE nexus with spatially-explicit policy implementation and a feedback mechanism that characterizes dynamics of the integrated socio-environmental nexus systems. The S.N.O.G. serious game is designed to offer the field of FWE nexus an appealing graphical user interface to positively affect the gaming experience and support learning on FWE sectoral impacts on climate stress control, resource management and social-ecological integrity.

6.3 S.N.O.G. SERIOUS GAME DEVELOPMENT

The S.N.O.G. serious game is featured in scenario planning, performance measurement, and knowledge cooperation and communication. The game enables FWE nexus stakeholders to develop and plan possible scenarios of the future state of the FWE resources and to explore how different social and environmental components of the systems involved can be influenced. Scenarios can be developed using different policies available in the game. A strategy map facilitates the comparison of policy impacts in different regions and allows users to make decisions regarding implementation of policies in certain domains of FWE (e.g., interventions of urban gardening, rainwater harvesting, and solar panels). In addition, as a web-based (online) platform, the game supports policymakers, management professionals, scholars, and resource end users by creating a common language and understanding that can facilitate transdisciplinary communication.

The game is designed for a smart-eco case study, the Brainport Smart District (BSD), in the Netherlands as an urban living lab that aims to realize the ambition of developing a sustainable, circular, and socially cohesive living environment through joint and balanced food production, water management, and energy generation under transdisciplinary circumstances.

6.3.1 Study context

Brainport Smart District (BSD), an adaptive urban ambition, has been designed to realize a sustainable, circular, and socially cohesive neighborhood that benefits from joint food production, water management, and energy generation. It will be an attractive living environment where self-sufficiency, organic development, and co-creation with end-users are paramount, and collaboration between humans and nature, including its resources, is combined with technology. Over the next ten years, 1,500 new houses and a 12-hectares business park will be built in BSD based on the needs of people living and working in the area. Regarding the joint food, water, and energy management, the starting point was mapping the demand of the future residents of BSD. Therefore, BSD has made an initial estimate of the need for water, food, and energy.

It is crucial for BSD to design a system with low energy demand and minimization of the use of raw materials. As soon as the demand for raw materials has been limited as much as possible, it is time to look at the exchange of residual flows. For example, if a building or sewer produces residual heat, it would be ideal for storing that heat and using it on site. It is especially important to take into account locally available resources (such as rainwater or heat from local water bodies) and raw materials. Once the possibilities for synergy have been exhausted, it is time to look at how the remaining demand can be met with clean, renewable, and otherwise environmentally-friendly sources. Local resources are preferable, as their impact is usually smaller, and efficiency is higher. It is also important to collect feedback on how the system works so that the neighborhood can function optimally. The S.N.O.G. serious game provides BSD with such an iterative feedback system measuring performance and having a transparent information network to keep the system running properly and efficiently.

6.3.2 Game design implementation

The core function of the S.N.O.G. online serious game is to provide a multi-objective constraint-based predictive model with a reduced number of state variables, which get input from a spatially explicit map representing land-use and compatibility of FWE nexus policies. The spatial explicitness of the model, represented by cells in a regular grid (100*100 meters), allows incorporating aspects of socio-technical nexus configuration. For details on the underlying S.N.O.G. quantitative model, see Chapter 5. To access the code repository see Ghodsvali (2021).

The main content in S.N.O.G. serious game is provided both through the interface and the logic that the game contains, as well as through the system-wide impact of each action implemented under a specific scenario. This content is divided into three main parts:

1. Core experience: what do players experience while playing the game?

The core experience is to play the role of decision-makers in food, water, and energy management. Over the course of playing the game, players will be encouraged to develop scenarios that consider an integrated nexus-compliant policy implementation and decision-making. In the S.N.O.G. serious game, nexus-compliance refers to the degree to which policy choices made by players tend to lead towards/away from policy objectives for that case study (in this research BSD), as elucidated by both the detailed policy analysis work in the game and by relevant FWE nexus policies as indicated by stakeholders (i.e., the municipality of Helmond and apart from the stages of this research) during the case study formulation.

2. Base mechanics: what do players do?

Players will have a target at the start of each round of the game, and they will have to implement policies to try to reach their target. Given their individual perception of the FWE nexus issue, the target strategic measures could emphasize the balanced synergies and trade-offs across the FWE sectors, the incorporation of the social system into nexus decisions, and climate-resilient urban developments. The round ends when the player has decided on the policies to be implemented to achieve their target. The game will compute the policies simultaneously, and an analysis of the decisions will be presented. By ending the game, the player will have to select their best-developed nexus scenario by comparing their contribution towards their target.

3. Penalties and reward system: what actions within the game are encouraged or discouraged?

Integrated nexus-wide decision-making is encouraged within the game. For every round of the game, players are encouraged to look at policies for interventions in all sectors and consider them to achieve a holistic target. There are some scores for players which indicate how successful they are at applying nexus-compliant scenarios to achieve their strategic targets in the game. The scores are computed for all indicators (presented in Chapter 3; Table 3.2, and Appendix D; Table D.1), explaining three themes (i.e., (i) climate stress control, in terms of the contribution of the developed scenario to limiting carbon footprint and the avoidance of carbon dioxide emission; (ii) resource management resilience, in terms of the extent to which equilibrium is achieved between the supply of food, water, and energy to meet the local demand; and (iii) social-ecological integrity, in terms of the extent to which the human impact on FWE resources security has been reduced through the developed scenario), and per policy area, making clear on which areas to focus on in order to make improvements. Emphasis is placed on maximizing beneficial cross-sectoral impacts from a given policy choice. Thus, the scoring system can serve as a basis to advise players and explain opportunities to improve their performance in FWE nexus management.

Being a basis for a multi-stakeholder FWE nexus decision-making game comes along with the requirements for the underlying model. To support the players' perception and understanding of state variables, indicators in the model are normalized. For an exciting gaming experience, variations between gameplays are ensured. Therefore, an optimized solution to the nexus problem of the area is incorporated in the model, with which every solution (i.e., a combination of FWE policies) that players find is compared (for more information on the optimized solution provided by the game model see Chapter 5; Fig. 5.7). Thereby, players not only try to come up with a solution that corresponds to their perception of the situation, in every round of their gameplay they try to improve their solutions compared to the given optimized solution.

The game can be played in different modes. It can be used by a single player, controlling all policy options. It also can be used for playing the game in sessions led by a trainer or group facilitator, where participants play roles of policymakers in particular nexus domains and their game results are then shared for further discussions and joint decision making.

6.3.3 Gameplay

Each S.N.O.G. game starts with a sample of an optimized solution to FWE nexus policies implementation for the study area and the option for players to develop new solutions either by adjusting the sample solution to their personal vision or by starting from scratch. Players can provide solutions in two ways: i) dragging and dropping the desired policy card from the policy control panel (Fig. 6.1, label 2) to the desired location on the map (Fig. 6.1, label 1), or ii) clicking on each grid cell on the map and selecting the possible policies for implementation from the displayed list. By implementing different nexus policies, the player determines ecological and social change and modifies FWE nexus measures.

The objective of the game is to achieve a balance between social and ecological conditions, i.e., a closer approach to climate change, social engagement in environmental concerns, and resource resilience. To achieve this goal, the player has to carefully observe changes in FWE nexus strategic measures and the map for better policies combination and spatial distribution in each round of the game. Furthermore, the player may study additional information provided as help text for each policy card. Social-ecological balance may increase or decrease based on the profit obtained from renewable production and exploration sources and determine opportunities for management decisions in the next action or round. A successful strategy results in a high number of score points collected after each action. Score points calculation takes into account the current state of FWE resources, environmental quality (i.e., carbon dioxide emission), and the level of social integration with environmental concerns and plans.

6.3.4 Design of the graphical user interface

The S.N.O.G. serious game was developed to give a broad target group, namely the public sector, the private sector, academia, and local stakeholders, an understanding of integrated FWE resource management. The game design should therefore be attractive and also comprehensible for all user groups, regardless of their scientific or practical expertise in the field of the FWE nexus. The graphical user interface (GUI) of the game offers an interactive feedback system, which provides help based on the current course of the game. Regarding the technical side of the GUI development, JavaScript programming language, in particular Lit (i.e., a simple library for building fast, lightweight web components without a framework), was used. This development was supported by Geodan B.v. in the Netherlands. Fig. 6.1 shows the S.N.O.G.'s GUI consisting of six key elements: (1) the land-use map, (2) policy implementation controls, (3) a scenario planning panel with feedback relationships, (4) the policies compatibility map, (5) various strategic measures of the state of play, and, (6) the temporal scope of the delivered innovation implementation in real-world (visit the S.N.O.G. serious game webpage for in-depth experiences (Eindhoven University of Technology, 2021)).

The land-use map with a legend (Fig. 6.1, label 1) illustrates the current/planned land-use configuration of the study area (i.e., BSD) in cell grids (100*100meters), which affects the functionality of various policies. It helps players to introduce changes to FWE nexus policies spatially. As soon as the player assigns any policy card to a location on the map, the core model recalculates changes. To visualize the player-driven changes applied via policy cards, colored dots, representative of FWE policy sectors and associated actions, are added to specific player-defined locations on the map. Within this, players can reveal the consequences of their decisions and the resulting FWE nexus strategy change. With the ten policy cards (Appendix E; Table E.1, explains each policy card in detail) located on the bottom side of the map (i.e., the policy implementation controls) (Fig. 6.1, label 2), players decide on policy implementations to govern the FWE nexus in the area and trigger changes on the map and the indicators.

The complex system of policy functions (see Fig. 6.1, label F) and their interrelations are shown in a simplified panel (i.e., scenario planning) next to the map (Fig. 6.1, label 3). Each policy is represented by a slide bar and a numeric label (Fig. 6.1, label A), which displays the use frequency of each policy card in the current round of the game. A circular percentage chart (Fig. 6.1, label B) on the left side of each policy slide bar shows the temporal changes of the associated sector (i.e., food, water, or energy) in terms of a balanced supply and demand chain. These charts offer an in-depth analysis of the inter- and cross- sectoral dynamic patterns, explaining which policy actions influence the particular sector significantly. Players can change the numbers in order to explore the extent to which each policy influences the changes. Additionally, a number above the policy cards (Fig. 6.1, label C) supports assessing the current status of the use of a given policy. Besides this more technical way of displaying the current state of the socio-ecological nexus system, the status is illustrated by a compatibility map (Fig. 6.1, label 4).

The complex interrelations within the nexus system and compatibilities with the current development plans of the area impose severe restrictions on the spatial allocation of policies. All policies are not compatible with all land-use types. In addition, some policies need to be allocated within a specific distance from each other. Moreover, only some policies can be combined. In order to implement these restrictions in the game, grids have been given different colors (i.e., green: valid; yellow: moderately valid; red: invalid) in accordance with each policy to alert players to the validity of their choices of actions (Fig. 6.1, label 4). Different policy cards can be clicked, and further information on the current compatibility status is obtained. Additionally, each grid of the map can be selected and associated policies with further information on the changes in the last action is displayed. The game also supports an interpretation of results and understanding of changes caused by every action on integrated FWE resource management by showing the strategic target measures.

The overall game score is displayed as three-line charts, where different segments present core strategic measures of the FWE nexus (i.e., climate stress control, resource management resilience, and social-ecological integrity) in each round of scenario development (Fig. 6.1, labels 5 and D) (see Section 6.3, the explanation of the game's penalties and reward system). Different scenarios of the FWE nexus can be developed and then compared through the strategic measure charts to better understand the importance of how to combine and where to implement the policies within the area of study. Additionally, three gauge charts help players to improve their performance by calculating the extent to which their current gameplay (scenario) is better or worse than the provided optimized solution by the core game model (Fig. 6.1, label E). Moreover, a bar chart representing the temporal scope of the implementation of policy actions that players have selected is visualized (Fig. 6.1, label 6). This chart shows the time period that takes the required action to be activated and the time representing the action's longevity (detailed information on this is available to players through description boxes of each policy card (see Fig. 6.1, label F)).

In addition to this result-related feedback, the GUI also offers action-related feedback by the presence of some guiding pop-ups, which accompany players during the game and facilitate their interactions with game elements. The S.N.O.G. serious game also provides a tutorial that explains possible steps during the game and describes interactive interface elements.

When applied, this policy takes **0.5** years to build and become active (semi transparent area on the 'temporal scope of the implementation' chart). From that moment, the policy will go on for **10** years. During all that time, the same policy cannot be applied to the same area.

Fig. 6.1. Graphical user interface and key elements of the S.N.O.G online serious game.
The game is currently developed for Brainport Smart District in Helmond, Eindhoven region, the Netherlands. Yellow-colored labels are assigned to different elements of the game (explanation of each is provided in Sub-section 6.3.4). Accessible via https://snog.beta.geodan.nl/viewer/#game.

6.4 TEST AND EVALUATION RESULTS

In addition to being scientifically sound and robust, the S.N.O.G. serious game needed feedback from the user community. Therefore, this research developed a two-phased testing and evaluation process in order to test the usability of the S.N.O.G. serious game. The process enabled this research to receive user experience feedback from a set of players that represent the target group of the game.

The first phase of the S.N.O.G. testing and evaluation process was online rounds of individual playtests to assess the initial gameplay experience and examine the role of such a serious game in FWE nexus decision-making processes. A database of the potential game user community, including experts in FWE nexus field; the urban development team members of the study area (i.e., BSD); and laymen with no knowledge either on the FWE nexus field or the study area, was created and volunteered players (hereinafter referred to as 'players') were asked to participate. The playtest was carried out by 30 individuals (i.e., 7 FWE nexus experts, 9 BSD development team members, and 14 laymen) in the form of individual online sessions over a period of several weeks supported by a facilitator (i.e., this PhD researcher) who guide players through the procedure in an identical way to ensure consistency of user experience across groups of players. For each test session, the facilitator first gave the player a comprehensive explanation of game instructions, and then the player was asked to play and develop different scenarios for the nexus of the food, water, and energy in BSD.

After the first phase of the game testing and evaluation, feedback was gathered regarding the experience of end-user participants utilizing an online survey. The survey was conducted immediately after the gaming (during the first playtest phase) was completed. In order to evaluate the playtest feedback, the online survey (see Appendix E; Table E.2) consists of various questions examining three main dimensions, including gaming experience, usability, and learning experience. Gaming experience identifies the ability of players to take actions in the game successfully and concerns the skills development of players, which is central to a game play (Moizer et al., 2019). A positive gaming experience needs the serious game to be useable for all sorts of players. The characteristics of usability include ease of use of the game interface, user control within the gaming environment, and satisfaction with the game's interactive features (Moreno-Ger, Torrente, Hsieh, & Lester, 2012). Moreover, the skill development of players within serious games is very much associated with their learning experience. Serious games ought to provide players with clear goals to help them focus on the gaming tasks and with feedback used to bring an opportunity for learning (Le Marc, Mathieu, Pallot, & Richir, 2010). Game feedback allows players to reflect on experiences to create knowledge and then be applied in the real world. It is important for learning that players receive immediate feedback from the game-generated ongoing results.

Survey included questions related to ease of use of the game interface, user control within the gaming environment, and satisfaction with the game’s interactive features and the learning experience of the game with respect to FWE nexus. These questions were measured as various multiple-choice, Likert-scale, open-ended, and polar survey questions to obtain feedback on the S.N.O.G. gameplay. Moreover, observations from the playtest facilitator and open questions within the online gameplay sessions added further insight to support the game refinement. Finally, the data from the gameplay sessions were also analyzed in terms of the policy cards chosen and their relations with the game objectives. Data from all the 30 players was collected and analyzed, and the results formed the basis for adaption and revisions to the S.N.O.G. game and learning content.

6.4.1 Survey results

In order to assess the role of the S.N.O.G. serious game in implementing transdisciplinary FWE nexus decision-making, a comprehensive analysis of results from the survey of the gameplay was undertaken. Table 6.1 summarizes the results and compares the mean ratings (as well as the standard deviation of the answers) given by players to items pertaining to the serious game playtest. For each of the three dimensions that formed the survey (i.e., gaming experience, usability, and learning experience), a number of attributes were identified (i.e., challenging, competence, flow, and tension for the gaming experience dimension; interface, and interaction for the usability dimension; learning goal, feedback, and extensibility for the learning experience dimension) and used as a basis for developing measurement items for the playtest evaluation. In addition, for each attribute across all the three dimensions, statements were developed to form measurement items for the instrument used to evaluate the S.N.O.G. gameplay among the players. Some statements were associated with the survey Likert Scale questions and some with polar questions. For the Likert-Scale-based statements, a five-point Likert scale was employed to evaluate players' level of agreement with each statement (where 1 = 'strongly disagree' and 5 = 'strongly agree'). Mean and Standard deviation were the mathematical observations used in this regard. The mean identifies a central value in the distribution of the dataset and the standard deviation is a summary of the differences of each observation from the mean (Field, 2013). Together, they show the extent of variability among players in understanding and revealing the underlying mechanisms and elements of the game. For the polar-based statements, proportion percentage was calculated to show the extent to which players were agreed with the statement. Table 6.1 categorizes the survey measurement items, the associated statements, and the descriptive statistic (including the mean and standard deviation for Likert Scale statements and proportion percentage for polar statements) used for each dimension of the game-test evaluation.

Based on the survey feedback and the identified measurement items (Table 6.1), it was assessed how players experienced the S.N.O.G. serious game. Overall, the game was perceived positively (see Table 6.1, the proportion percentage of 93 for the ‘tension’ attribute). Easy access to information on the underlying feedback mechanism of the game resulted in high value for categories of 'competence', 'feedback', and 'extensibility' which received an average response above 4.0 with a lower variation. Moreover, the 'flow', 'tension', and 'learning goal' attributes of the game received the agreement of more than 87% of the players on the facts that the goals of the game are achievable, the overall experience of the game is positive, and the learning goal of the game is clear.

Regarding the graphical user interface, results (a mean score of 3.6 for the item 'the user interface was easy to use') indicated that majority of the users found the interface easy to use, however, evidently improvements were needed to the appearance of the game. A helpful feature to the understanding of the user interface elements was a tutorial video of the game that most of the player found that clear and helpful (according to the mean score of 4.3 for the corresponding item of the interaction attribute).

There is a clear indication that perceptions of how challenging the game is, varied significantly among players, which show that there is high variability in understanding and revealing the underlying mechanisms of the game. Some players felt satisfied with their understanding achieved during the game, some players did not (see Table 1, the mean score of 3.0 and the standard deviation of 0.97 for the item 'the experience was challenging'). This feedback can be due to the high diversity of players from various fields of knowledge and expertise. It should also be considered that players who experienced the game positively might be over-represented in the survey as successful players might be more willing to complete a survey questionnaire after the game. It should be noted that there were some players that did not grant this study permission for the data gathered from their survey to be used in publications or any research outcomes on the S.N.O.G. serious game. A higher number of participants in this evaluation procedure might reduce the uncertainty of understanding the extent to which the game is challenging. In addition, some players indicated that they had difficulties in understanding how certain options were available or not during the game. In S.N.O.G., every game action is dependent on previous actions taken by the player in the game. Some policy cards may be available to be allocated to a certain spatial location at the beginning of the game, while it may not be possible to choose if an incompatible policy card is allocated in their surroundings. Players need to figure out these challenging aspects of the game during their gameplay. Therefore, each players' perception of how challenging the game is, is different and is mainly based on the way they play the game each time.

Overall, the game was perceived positively. The evaluation of the gameplays was useful for comparing perceptions of the game and provided various suggestions for further improvements of the prototype. These improvements are suggested mainly on understanding the challenge of the game, possible options with respect to policy cards and user interface.

Table 6.1
A summary of S.N.O.G. playtests survey feedback and the mean ratings of the results.

Dimension	Attribute	Survey item#	Playtest, Mean	Standard Deviation	Proportion percentage
Gaming experience	Challenging	The experience was challenging[7]	3.0	0.97	
	Competence	I found the game stimulating[5]	4.1	0.93	
	Flow	I was able to achieve the goals set in the game[3]			87%
	Tension	The overall experience was positive[10]			93%
Usability	Interface	The user interface was easy to use[8]	3.6	0.75	
	Interaction	The user manual and tutorial video were clear[OPS]	4.3	0.79	
		The survey aided my reflection on the game[OPS]	3.6	0.75	
Learning experience	Learning goal	The learning goal of the game was clear[3]			87%
	Feedback	The game provided opportunities to receive feedback[11]	4.2	0.85	
	Extensibility	I recognize the value of the game as a tool for transdisciplinary decision-making[12]			83%

Note: the # superscripts indicate the question number that presents the corresponding survey item. See Appendix E, Table E.2 for survey questions and their numbering.

The table includes two different types of statements given the type of survey questions they are representing. Some statements were associated with the survey Likert Scale questions and some with polar questions. For the Likert-Scale-based statements (i.e., questions # 5, 7, 8), a five-point Likert scale was employed to evaluate players' level of agreement with each statement (where 1 = 'strongly disagree' and 5 = 'strongly agree'). Mean and Standard deviation were the mathematical observations used in this regard. The mean identifies a central value in the distribution of the dataset and the standard deviation is a summary of the differences of each observation from the mean. A low standard deviation indicates that the values tend to be close to the mean of the dataset, while a high standard deviation indicates that the values are spread out over a wider range. Together, they show the extent of variability among players in understanding and revealing the underlying mechanisms and elements of the game. For the polar-based statements (i.e., questions # 3, 10, and 12), proportion percentage was calculated to show the extent to which players were agreed with the statement.

OPS stands for 'open playtest session' and presents questions that were discussed with players during the online playtest sessions. Players answered these questions with Yes or No, and the results for this table were calculated similarly to the dichotomous questions analyzed from the survey questionnaire. For question #11 of the survey, choices of answers were categorized regarding the fact they highlighted. For instance, for analyzing the perspective of players on the 'feedback' attribute of the 'learning experience' dimension, 4 of the choices of answers to question #11 were selected and analyzed (i.e., I learned key drivers of sustainable and climate-resilient urban development, I learned the fact that policies of different sectors of the economy can block or negatively influence each other, I learned differences between short-term and long-term planning, and I learned that the efficient spatial distribution of policies across the area is as important as my choices of best policies for implementation).

6.4.2 Gameplay results

In addition to evaluating the S.N.O.G. gameplay experience among the players (Subsection 6.4.1), the gameplay results, going from choices of FWE nexus policies to spatial scenario development, have been analyzed. It is crucial to understand whether the game can play a role in FWE nexus decision-making processes and whether it supports the development of future scenarios from different perspectives. Fig. 6.2 presents a graphical evaluation of the S.N.O.G. gameplay results of the 30 players. Players' choices of the FWE nexus policy cards have been visualized across different planning perspectives and land-use types.

The results point out that having different perspectives on the FWE nexus issue is as important as attributing different planning thresholds to different land-use types for policy implementation. The game is capable of viewing the FWE nexus issue from different perspectives. Players have developed different scenarios from variant nexus development perspectives (e.g., climate neutrality, short-term management, and low social impact). These perspectives vary in terms of the use of FWE nexus policies and their spatial placement for implementation. However, from the results presented in Fig. 6.2, it is apparent that in this game, different nexus perspectives are slightly limited to the same level of performance in different types of land-use, particularly in residential lands which comprise a large extent of the study area, i.e., BSD. For residential land-use type, the FWE nexus and the holistic combination of policy cards from all different sectors of the economy was more apparent. For mixed land-use type, players did not take social impacts and the temporal scope of their management plan into account. Overall, choices of policy cards were more dependent on land-use type rather than the one's possible planning perspective (i.e., climate neutrality, self-sufficiency, eco-conscious consumerism, low social impact, integrated urban design, and short-term management). This is due to the fact that S.N.O.G. is developed based on some general nexus- and context- specific thresholds to actions, regardless of the fact that different planning perspectives require different thresholds of actions at different land-use types. For instance, making FWE nexus decisions based on a climate-neutral perspective requires extensive focus on the way the living population in residential lands consumes energy and produces waste. This needs an adaption of the game prototype.

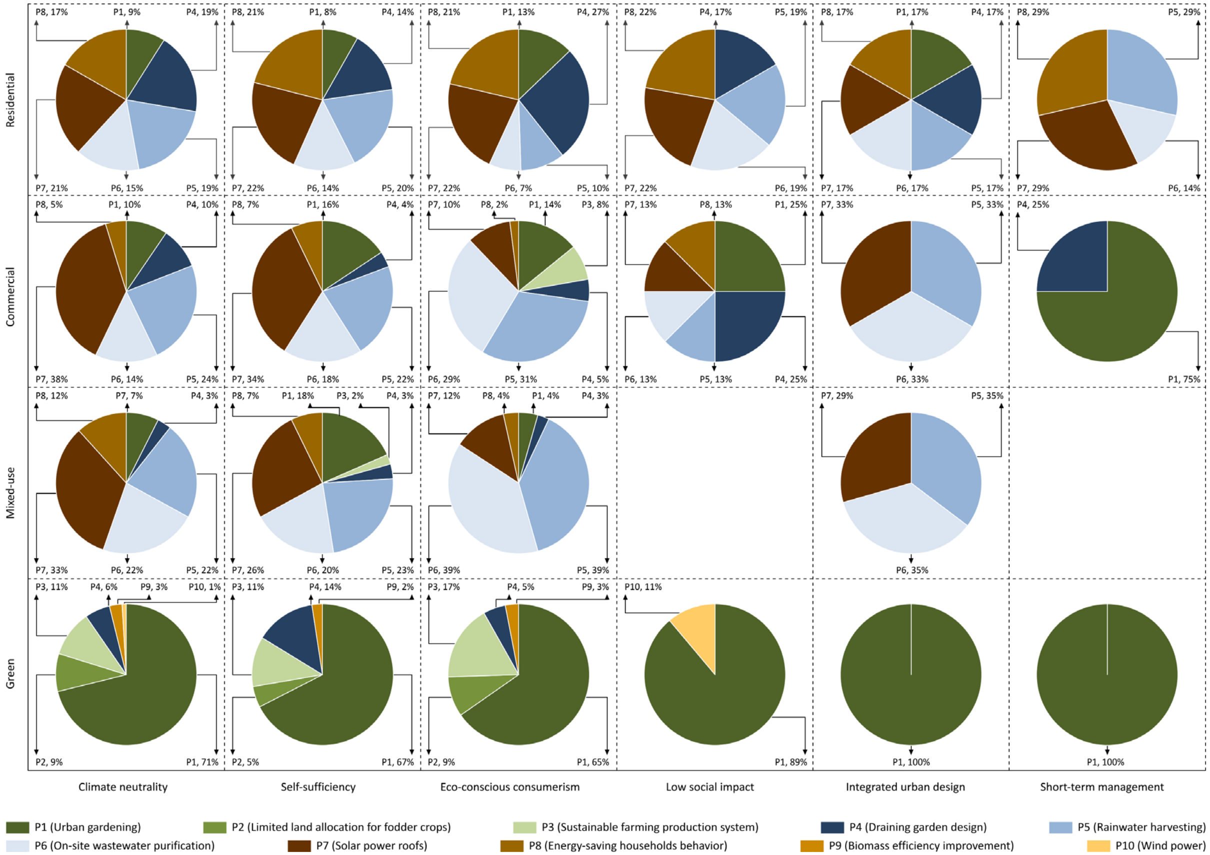

Fig. 6.2. Results of the playtest illustrating players' choices of FWE nexus policy cards across different planning perspectives and land-use types.
The horizontal axis of the figure presents the planning perspectives of the players for FWE nexus scenario development, and the vertical axis presents land-use types of the study area (i.e., BSD). The Pie charts show the percentage each policy card has been used to develop a solution to FWE nexus problem from every specific perspective (i.e., climate neutrality, self-sufficiency, eco-conscious consumerism, low social impact, integrated urban design, and short-term management) and within every single type of land use. The colors are associated with each policy card, numbered in the legend from 1 to 10 according to their order visualized on the game user interface (presented in Fig. 6.1., label 2).

Besides land-use, the results indicated a common tendency among players to use mostly some specific policies in developing FWE nexus scenarios from different perspectives (see Fig. 6.3). For instance, within climate-neutral nexus scenarios, players used the 'solar power roof' policy (i.e., p7) the most, as expected, given its significant contribution to the avoidance of carbon dioxide (CO_2) emissions. From both social and ecological perspectives, the 'urban gardening' policy (i.e., p1) was used considerably among players. The 'draining garden design' policy (p4) was also used frequently within different nexus planning perspectives. There were also some policies that players rarely used in their scenarios. For instance, the 'wind power' policy (i.e., p10), although it can provide sufficient energy for the area sustainably, it is associated with negative effects that wind turbines might have on the environment and the social community. The fact that all players had a common tendency in using some specific policies for developing nexus scenarios, although from different perspectives, indicates the S.N.O.G.'s competence in framing the game elements and defining the content of the game.

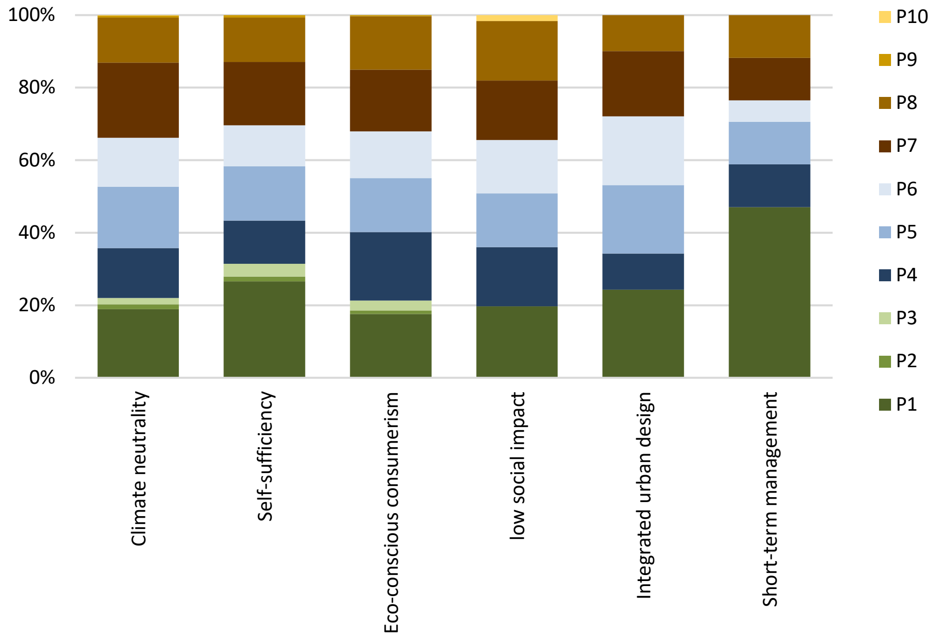

Fig. 6.3. The contribution of each policy card in the development of FWE nexus scenarios from the specified different planning perspectives.
The colors are associated with the type of resource (either food, water, or energy) that the policy belongs to. The policies are numbered from 1 to 10 according to their order visualized on the game user interface (presented in Fig. 6.1., label 2).

6.5 DISCUSSION

6.5.1 S.N.O.G. as a base for multi-stakeholder decision-making purposes of food-water-energy nexus

Results of the playtest evaluation suggest that the online S.N.O.G. serious game attracts decision-making attention and stimulates transdisciplinary discussions. In S.N.O.G., the issues of managing integrated social-ecological systems are coded sufficiently complex for keeping the player attracted to identifying various interactions of a complex food-water-energy and land system. On the other hand, the complexity is not challenging. Players operate in an environment where the disassociation from error consequences enables low-cost experimentation. This setting of the S.N.O.G. serious game supports experimental learning where knowledge is generated from action. Scenario development allows players to step into the decision-making process of natural resources in real-world and try different possibilities for future developments from their own perspectives. The findings of this chapter suggest that the S.N.O.G. serious game has the potential to be used for transdisciplinary decision-making, integrated social-ecological planning, stakeholder meetings, or learning purposes.

6.5.2 Further development

According to the game playtest results and survey feedback results, S.N.O.G. has implemented helpful features in transdisciplinary decision-making processes, which make it easier for FWE nexus stakeholders to reveal interacting mechanisms in the complex systems involved. Nevertheless, the results highlighted some areas of improvement which can follow three directions: a) to start the game with perspective-specific initial conditions, b) to further develop the game interface by taking advantage of the in-game tutorial assistant, c) to improve the game functionality and model extensions in order to incorporate finer spatial units, more sophisticated representation of the space, and a wider range of measures while limiting levels of complexity, and d) to promote the transdisciplinarity aspect of the decision-making procedure within the game using a communication option to provide a multi-player game through which players can make groups regarding their planning perspectives (e.g., eco-conscious group, liberals, etc.).

a) The initial conditions, as well as specific feedback, can be adapted to players' planning perspectives, such as additional policy options (i.e., policy cards) and supplementary standard target lines on feedback charts that donate the ideal value of that specific perspective. This would offer customized starting conditions to players, which could qualitatively be closer to real-world situations. To foster links to real-world situations, players can start the game by specifying the perspective from which they aim to play, and accordingly, the game provides them with additional relevant policy options and target lines on feedback charts given their specified planning perspective. For a mixed audience, the list of perspectives that needs to be implemented in the game can be pre-defined by a random sample of potential players. This keeps up players' interest in playing the game for more than one round and also takes up different information from the survey (e.g., a less challenging and a more interactive game (given the statements identified for these game attributes in Table 6.1)). Much more important is the fact that this way of game adaptation, the S.N.O.G. serious game is able to illustrate (within the playtest feedback results) the mechanism of how different perspectives of decision-making authorities can influence the environment and the social system differently. A computer-based serious game like S.N.O.G. is an ideal platform for illustrating different planning perspectives and potentials for multi-objective decision-making processes design.

b) The game could become more attractive to players by implementing an in-game tutorial assistant which exemplifies certain processes much clearer. This also concerns the barrier of technology as an external limiting factor for players and the consistency of their gameplay. For a mixed audience, an in-game tutorial assistant may be appropriate for S.N.O.G. which aims at players with different skills, different levels of knowledge about the FWE nexus issues, and different expertise. Although the results from the survey indicated that the game manual and the tutorial video provided within the game were clear to most of the players (see Table 6.1, the mean of 4.3 for the item 'interaction'), a step-by-step guide during the game may be more appropriate.

c) Acknowledging that such a serious game is just one — but very promising — element of decision-making, this research underlines the clear need for development of the game functionality in terms of a more sophisticated representation of the space and a wider range of measures. From a spatial planning point of view and in case of further developing the game for larger scales, the spatial S.N.O.G. model (see Chapter 5 for a detailed explanation of the model) is relatively simple as it only includes a satellite image of the area and square grids of the land-use. Future development of the spatial game model could incorporate finer spatial units and the ability to model a wider range of spatial measures in a 3-dimensional (3D) space. This certainly would have to be done carefully so as to limit the resulting increase in complexity. Having a 3D visualization of the spatial game elements, the game can better, more realistically, support resource management and potentially offer local residents more opportunities for participation in decision-making.

d) The game could facilitate transdisciplinary decision-making processes even more using a communication panel for players that allows them to chat with other online players and discuss different aspects of their gameplay and share ideas. Such as multi-player option is now only available within the game if players play the game in the same place physically. The online possibility of communication among players is an advantage to the game that can make it more suitable for real-world situations, such as the current world-wide COVID-19 pandemic situation. This also concerns the barrier and difficulty of bringing different stakeholders in the same location at the same time. Moreover, the communication panel because of the fact that players have access to each other's game results, can motivate players to play in rounds and develop more scenarios in order to reach a consensus (in groups). This way, the game can support convergence between different stakeholders of real-world problems.

Finally, the design of the S.N.O.G. serious game, which is presently attracting increased interest, could scale very well to other complex urban problems with thousands of variables. The mathematical optimization model developed for the S.N.O.G. serious game (see Chapter 5) is capable of being adapted to any other themes of urban decision-making and spatial scale.

6.6 CONCLUSION AND PERSPECTIVES

Multi-stakeholder decision-making processes, although they can delineate the space for convergent thinking on potential FWE nexus solutions, they can be challenging due to the complexities of aligning diverging interests, competing objectives, and variant perspectives. Collaboration, learning, capacity building, and behavior change are central to the engagement of multiple stakeholders in decision-making processes, particularly within problems of multiple dimensions such as the FWE nexus. State-of-the-art FWE nexus decision support models lack a promising approach to the engagement of stakeholders and the provision of coherent content for stakeholders with different levels of knowledge, skill, and expertise. Serious games illustrate how a visually rich socio-ecological informatics application with an intuitive user interface can help non-experts approach a solution to the problem that previously was only achieved by experts employing sophisticated optimization models. Serious games provide experimental, rule-based, interactive environments where players learn by taking actions and by experiencing their effects through feedback mechanisms.

A conceptually simple but computationally elaborate serious game for FWE nexus system analysis, design, and evaluation was presented in this chapter. The S.N.O.G. serious game has the main goal of finding an optimized design for the problem of integrated food, water, and energy management, for which the serious game environment takes the computational and visualization burden away from the simulation tool and the player. The game deals with the clear challenge of integrative, multi-stakeholder decision-making in FWE nexus processes. It works as a strategic card game (online) that puts the most powerful scientific modeling data at players' fingertips. The game engine and the user interface provide fully interactive manipulation, simple spatial visualization, and a database facility that stores players' performance during the game. This application is novel and provides a new, active, and personalized way of solving resource management problems within an interactive and motivating environment capable of providing immediate feedback. Through the application of the S.N.O.G. serious game, decision-makers can:

a) learn about the complexity of integrated food, water, and energy resources management problems;
b) experiment safely using a computer model of a real system;
c) understand conflicting objectives (i.e., minimization of ecological stress in terms of a set of processes and activities for meeting demands of society for FWE resources, and maximization of social acceptance in terms of how satisfactory choices of nexus optimization actions are for the society); and
d) develop strategies for coping with complexities without being a burden on real-world resources and the society.

The S.N.O.G. serious game has been evaluated by multiple stakeholders (n=30) of a real-world FWE nexus problem (i.e., Brainport Smart District (BSD) in Helmond, Eindhoven region, the Netherlands) in which a high degree of engagement was observed among players. In addition, a significant improvement in learning has been observed in how players attempted to identify solutions that satisfy the pressure criteria for the nexus problem in BSD.

Besides the quantitative analysis of feedback through the survey of players, the S.N.O.G. application as a decision-support tool in BSD provides a wide range of qualitative feedback for further development and future applications. The playtest results indicate that the game initiates integrative social-ecological thinking among players and quickly introduces various crucial aspects of sustainable resource management and appropriation, such as the effects of land-use on resource consumption pattern change, the intensity difference of resource management policies between different land-use types, the trade-off between resource conservations and societal demand satisfaction. Thus, S.N.O.G. can serve as a core element of transdisciplinary decision-making.

Online accessibility and the use of regular web browsers have given S.N.O.G. distinct advantages. It is independent of operating systems, broadly available, easily accessible, and supported by the possibility of embedding relevant information such as related webpages on the topic FWE nexus and video materials for the gameplay.

In summary, S.N.O.G. has acted as an innovative decision-support tool illustrating general characteristics of complex interrelations among FWE nexus, land-use planning, and social inclusion. The scenario-based structure allows players to explore specific interactions in a stepwise practice. This serious game contributes to bridging the gap between science and practice in the field of integrated resource management and transdisciplinary decision-making applications.

7

CONCLUSION AND DISCUSSION

7.1 INTRODUCTION

In this research, a transdisciplinary food-water-energy nexus framework-based decision support system has been proposed to solve the increasing environmental footprint of food production, water use, and energy generation from the viewpoint of socio-ecological integrity. This decision support system is characterized by its comprehensiveness and innovativeness in multi-objective problem formulation, cross-sectoral disciplines incorporation, multi-stakeholder engagement, and spatial optimization. It has shown the potential as a useful tool for the integrated management of natural resource systems and the implementation of transdisciplinary decision-making processes. The research process for achieving this end-result has been formulated as four sub-objectives, starting with 'what exists' (Chapter 2), continuing with 'what we want to do' (Chapter 3), moving towards 'what we need to do' (Chapter 4), and resulting in 'what we can do, and how' (Chapters 5 and 6).

7.1.1 Main conclusions per research objective

I. Conclusions on Sub-Objective 1 (Chapter 2)

Capturing the state-of-the-art on framing food-water-energy nexus by means of transdisciplinarity

When aiming at capturing the state-of-the-art on framing FWE nexus through transdisciplinarity (i.e., crossing disciplinary boundaries), presented in Chapter 2, it became apparent that limited knowledge on characteristics of key FWE nexus drivers across disciplines exists. The existing body of knowledge shows that FWE nexus systems share specific characteristics: they are interdependent networks of humans and nature; have multiple stakeholders each with distinct interests; and are often threatened by competing social, economic, and environmental factors (e.g., climate change, expanding population, and economic development). Concerning the management of such complex systems in mechanisms of knowledge integration, there is no general agreement on the most suitable method(s). Many methods have been developed in the past decade that, to some extent, allow crossing disciplinary boundaries and managing FWE nexus systems more integratively (see Endo et al., 2015). The most promising methods that can be applied and/or transferred across FWE nexus problems are based on an integration of i) analytical and ii) interactive perspectives. A thorough analytical perspective on FWE nexus allows the integration of knowledge across multiple social, economic, ecological, institutional, and technological dimensions. Combining such an informative perspective on key FWE nexus operationalization drivers with an interactive decision-making approach facilitates stakeholder engagement, and certainly, the attempt to balance competing interests. However, very few comparative studies exist that developed and implemented such a method that is transferable and robust in support of the transdisciplinary FWE nexus in the real-world. Looking at these studies, it can be concluded that the main hindrance observed is the absence of a comprehensive framework for the assessment of the key FWE nexus drivers across time and locations. Most developed methods facilitate low levels of disciplinary incorporation. This research gap calls for an integration with SESs (Social-ecological Systems) paradigm (Maass, 2017), producing higher levels of information on key operationalization drivers of the transdisciplinary FWE nexus, including social, economic, ecological, institutional, and technological domains (addressed in Chapter 3).

II. Conclusions on Sub-objective 2 (Chapter 3)

Determining and analyzing key operationalization drivers of the transdisciplinary FWE nexus

Chapter 3 focused on identifying and analyzing key operationalization drivers of the transdisciplinary FWE nexus using the SESs paradigm. Chapter 3, by developing an integrated assessment framework, addressed the quantification of structural and functional differences of FWE nexus systems in terms of socio-economic status, techno-ecological services, and the indirect effects of bilateral relations between the two sets. At the abstract level of the SESs paradigm, an FWE system comprises several interrelated ecological, social, and technological *components* each in turn encompasses one or more *processes* of transforming or generating *flows* and possibly changing *states* of the components. Concepts of the FWE nexus system components depicted in this chapter were turned into measurable variables and indicators. Variables comprise predictability of the ecological system dynamics; resource units' flexibility, dependency, stability, efficiency, and accessibility; social network structure; operational rules; economic development; demographic trend; deliberation processes; and social and ecological performance measures. The utility of employing both the socio-economic and the techno-ecological variables for the development of a transferable method for the analysis of FWE nexus systems is rather limited, due to the heterogeneity of relevant components.

Employing a unifying quantity, i.e., exergy, that can represent material, energy, and non-energy streams (Leung Pah Hang et al., 2016) is the main contribution of this study besides a framework for the quantification of systems characteristics. This would allow providing meaningful information to inform FWE nexus decision-making processes. Another encountered advantage of such an integrated, standardized method is its transferability to other scales and locations.

The application of the developed assessment framework to a local FWE nexus system in a Dutch smart-eco city, Eindhoven, presents a great reflection of systematic, transdisciplinary, adaptive, and monitoring mechanisms for FWE nexus concerns in practice. The results concern how FWE nexus problems can uncover synergies, detect detrimental trade-offs, unveil unexpected consequences, and promote integrated decision-making and governance.

Although arguably less critical at local scales, such frameworks do not explain spatial variations of the FWE nexus ecosystem components and will benefit from adding spatially explicit assessment capabilities. Changes are required in how practices and policies use this information and advance socio-eco-technical design methods of the transdisciplinary FWE nexus. This calls, first, for an understanding of what already is available to FWE nexus processes for the transdisciplinary decision-making processes implementation, and second, for a tool that can further facilitate the process. This research contributes towards such practical changes by employing the findings of this chapter and the developed assessment framework for a game-based transdisciplinary decision-making process design and implementation. The integration of social and ecological perspectives in FWE nexus decision-making processes provides insight into how such multi-level interactions affect planning alternatives in future.

III. Conclusions on Sub-objective 3 (Chapter 4)

Mapping patterns of transdisciplinary mechanisms experienced by food-water-energy nexus problems across the globe and levels of operational requirements for further improvement

Chapter 4 departed from the idea that Urban Living Labs (ULLs) as a sort of joint urban governance mechanism provides opportunities, created by the integration of multiple disciplines and multi-stakeholders (i.e., the quintuple helix approach, including the collective interaction and exchange of knowledge between the political system, civil society, the natural environment, the economic systems, and the education system), to address the operationalization of the transdisciplinary FWE nexus process. Therefore, Chapter 4 framed the general characteristics of ULLs, analyzing whether real-world experiments across the globe would allow the mapping of such characteristics for a joint urban governance mechanism. For the understanding of the ULLs' characteristics, qualitative literature-based information was combined with ground-based information that was gathered from the existing empirical evidence of ULLs practices of transdisciplinary FWE nexus around the world. The employed combined approach allowed to evaluate how differently ULLs operate across the world in terms of the transdisciplinary FWE nexus and to classify the significant variables that support such operations in real-world situations. However, such a structure is not transferable across FWE nexus contexts because ULLs characteristics and practices are locally specific and require qualitative ground understanding. Therefore, a detailed questionnaire was designed and combined with several focus group discussion sessions in order to collect the necessary information for evaluating ULLs characteristics and practices.

The mapping of the studied FWE nexus ULLs (i.e., Miami, the United States; Southend-on-Sea, the United Kingdom; Eindhoven, the Netherlands; Gdansk, Poland; Uppsala, Sweden; and Taipei, Taiwan) showed patterns of transdisciplinarity and levels of differences. The diversity of the studied transdisciplinary mechanisms across FWE nexus ULLs indicated that such a governance mechanism reveals the real extent of FWE nexus operationalization in complex urban environments. Lack of transparency and the absence of collaboration platforms for FWE nexus stakeholders to get involved in decision-making processes are the main and common obstacles that the studied ULLs have experienced. This calls for the development and use of ICT tools that allow the engagement of social actors by supporting their communication and collaboration, with FWE nexus systems and translate conceptual models to stakeholder perspectives and to simulation models.

IV. Conclusions on Sub-objective 4 (Chapter 5 and Chapter 6)

Developing an integrated decision-making methodology and tool that supports the operationalization of transdisciplinary mechanisms for food-water-energy nexus processes

Grounding on the utility of the SES paradigm (Chapter 3) and of an optimized ULL structure (Chapter 4), in Chapter 5, an optimization-based spatial serious game provided via a web platform showed successful transdisciplinary FWE nexus performances in terms of bridging disciplinary boundaries, transferability across ULLs and case areas, and being transparent to stakeholders. The development towards using interactive decision-support methodologies is very promising to FWE nexus compared to classical simulation and analytical models, e.g., when dealing with heterogeneous spatial components and diverse development objectives in complex FWE nexus problems. To navigate decision-making through the complex FWE nexus systems modeling and planning, in this chapter, an integrated decision-support methodology for a model that considers the need for the interconnectedness of the FWE nexus systems and components (retrieved from Chapter 3) is developed. Methodologically, the model is developed based on a combination of multi-objective mathematical optimization programing and the coalition game theory technique that incorporates various components of the FWE nexus management. It offers an evaluation of different scenarios that could serve as the basis for enforcing innovative guided management strategies.

In order to offer a tool for transdisciplinary FWE nexus processes that supports collaboration, communication and learning outcomes, the proposed integrated model was used as a base for an online serious game tool (S.N.O.G.). For the development of the proposed serious game, quantitative context-based information was combined with qualitative narratives of local stakeholders (the game was tested in a local small scale FWE nexus context; the Brainport Smart District (BSD), in Helmond, Eindhoven region, the Netherlands). The S.N.O.G. game provides decision-makers with choices of adjustable technological, environmental, and social policies to model and validate various possible scenarios for the issue of the FWE nexus. Policies can be assigned in combination or individually to a location of desire, and possible implications in socio-ecological systems performance can be discussed simultaneously. Thus, optimal choices of FWE nexus policies considering future implications can be made, along with a spatially validated action plan. In addition, the tool provides a collaboration platform designed to compile input from scholars, policymakers, and associating communities to reach a consensus on management goals. In this regard, the serious gaming approach and the Geographic Information System are incorporated into the model as a basis for a cooperative decision-making environment (see Chapter 6). The application of the model to a synthetic nexus example problem (i.e., BSD) has demonstrated that the proposed approach can produce robust decision support outcomes.

The developed serious game has been evaluated by multiple stakeholders (n=30) of the case study area (i.e., BSD) in which a high degree of engagement was observed among players. In addition, a significant improvement in learning has been observed in how players attempted to identify solutions that satisfy the pressure criteria for the FWE nexus problem in BSD. Besides the quantitative analysis of feedback through the survey of players, the game application as a decision-support tool in BSD provides a wide range of qualitative feedback for further development and future applications. The playtest results indicated that the game initiates integrative social-ecological thinking among players and quickly introduces various crucial aspects of sustainable resource management and appropriation, such as the effects of land-use on resource consumption pattern change, the intensity difference of resource management policies between different land-use types, the trade-off between resource conservations and societal demand satisfaction. Thus, the game can serve as a core element of transdisciplinary decision-making in the field of FWE nexus. Online accessibility and the use of regular web browsers have given the game distinct advantages. It is independent of operating systems, broadly available, easily accessible, and supported by the possibility of embedding relevant information such as related webpages on the topic FWE nexus and video materials for the gameplay.

In summary, the developed serious game has acted as an innovative decision-support tool illustrating general characteristics of complex interrelations among FWE nexus, land-use planning, and social inclusion. The scenario-based structure allows players to explore specific interactions in a stepwise practice. This serious game contributes to bridging the gap between science and practice in the field of integrated resource management and transdisciplinary decision-making applications.

7.2 REFLECTIONS

This section reflects on the main findings of the research and gives some potential outlook for further research in the field of operationalizing transdisciplinary FWE nexus with integrated decision-support tools and methodologies.

7.2.1 Main scientific contributions

Operationalizing transdisciplinary mechanisms for FWE nexus is, in many aspects, challenging. State-of-the-art FWE nexus simulation models employed for crossing disciplinary boundaries have limitations in terms of examining multi-dimensional interdependencies, balancing competing objectives, and engaging multiple stakeholders. In addition, interactive decision support methods have similar limitations and different experts might have different views on what is transdisciplinarity depending on the local contexts (Bergendahl et al., 2018). In general, the integration of analytical models into interactive decision support methodologies allows providing information in a more systematic, comprehensible manner, potentially covering large stakeholder engagement. In this context, this thesis contributed to the development of an integrated transdisciplinary approach in three main aspects, i.e., conceptual, methodological, and with respect to applications.

On a conceptual level, the research showed that FWE nexus problems share specific characteristics which allow them to be addressed by transdisciplinary methodologies that cross many disciplinary boundaries. However, urban contexts are diverse and understanding their FWE nexus problems under a homogenous category of characteristics is oversimplifying the on-ground realities. Therefore, this research argues for a systematic conceptualization of the structural, governance, and technological characteristics of such problems before starting any operationalizing activities. Only a few studies have been acknowledging the diversity of FWE nexus contexts but did not analyze them using an integrated analytical-interactive decision support methodology. Towards filling this scientific gap, given the complex multi-dimensional nature of the FWE nexus, this research adopted a generic data organizing structure for characterizing the intertwined nature of social-ecological systems within FWE production systems, including food, water, energy supply and waste treatment as well as social and technological interacting components significant for nexus policies and practices. The different components of an FWE system have been coupled through direct input and output material and services flow among resources, indirect effects such as alteration of biogeophysical conditions or effects on stability and quality of ecosystem services, or indirect socio-economic impacts on the natural systems such as changes in resources availability conditions. Turning generic concepts of the FWE nexus system components (i.e., ecological structure and functions, socio-economic status and decision-making, external institutional drivers, systems interaction effects and outcomes) into measurable variables and indicators allow nexus scholars to incorporate details and gain holistic insights into not only the interdependencies but also the dynamics in the social and techno-ecological system and the opportunities of better managing the FWE nexus systems. Moreover, the integrated assessment of the FWE nexus systems helps to explore potential synergies between different technological components in order to plan more efficient resource consumption and a better balance between demand and supply within the system.

On a methodological level, this research showed the utility of comprehensive analytical frameworks in addition to interactive decision-making methods. To combine analytical and interactive requirements of the FWE nexus operationalization, spatial optimization algorithms are of high utility, being able to deal with a large number of input features, multiple objectives, and multiple stakeholders. When working on multiple objectives and competing features, their balance and an optimal solution selection are relevant to reduce conflicts. Optimal solution selection can be made based on game theory models (Madani, Darch, Parra, & Workman, 2015). Within this research, the SES paradigm was used as an efficient way to understand the most significant FWE nexus drivers, which allows quantifying their importance. To overcome the multiplicity of the FWE nexus dimensions, multi-objective non-dominated sorting genetic algorithms allowed the aggregation of diverse features into optimal solutions, which also could be adapted and transferred to different nexus contexts. In order to engage stakeholders in FWE nexus decision-making and facilitate them to make consensus on an optimal solution, game theory was combined with the optimization algorithm and the general model was visualized through an online serious gaming interface. To date, there has been no such holistic approach yet to FWE nexus problems, and this holistic research has been the first one that introduces mixed methods approaches and ICT tools to a nexus problem.

With respect to application level, this research focused on methods that have the potential to engage a broad range of stakeholders in shaping joint decisions and coherent policies. Many studies used relatively small groups of stakeholders, often municipal authorities, for showing the application potential of a specific methodology, not addressing whether this methodology could be applied to operationalize the transdisciplinary FWE nexus with a broader range of stakeholders, including local communities that have limited knowledge of the filed. Thus, this research stressed methodologies that have practical application potentials in support of multi-stakeholder, multi-objective decision-making processes. Such methodologies should meet four main requirements. First, the methodology should be transferable across different FWE nexus systems. This research highlighted the transferability of the proposed mixed methodology by proposing generic SES-based FWE nexus features which can be adapted to other spatial contexts with different structural and functional characteristics of nexus components. Second, the granularity level of the output should be meaningful for all stakeholders.

Accordingly, this research showed the utility to transform the optimization-based outputs into comprehensible game features using the serious gaming approach. Third, to capture possible solutions to FWE nexus that deliver reliability and performance, this research emphasized the development of an online web-based interface. Such an innovative methodological combination gives an understanding of integrated FWE resource management to a broad target group, namely the public sector, the private sector, academia, and local stakeholders. Moreover, this research combined the gaming experience with a survey feedback approach which results indicated that the game developed in this research created awareness among participants on FWE nexus and consequences of scenarios they developed for integratively managing the social and ecological components of an example FWE nexus problem (i.e., the BSD).

The main strength of S.N.O.G., an online (spatial) optimization-based serious game interface in operationalizing the transdisciplinary FWE nexus is its ability to go beyond the often very heterogeneous social, ecological, technological, and institutional features and to show multi-stakeholder, multi-objective decision-making across their boundaries but also showing relations between statistical data and the local community's perception of the issue. Furthermore, interrelated social and ecological dynamics can be much better and more frequently captured by interactive simulation models than purely statistical-based models. In this research, information from interactive simulation models is coupled with information from stakeholders to develop locally relevant indicators and verify outputs, but also to understand dynamics and their underlying drivers. The developed online optimization-based serious game (S.N.O.G.), through participatory scenario development, allows FWE nexus stakeholders to increase their awareness, share knowledge and build consensus.

7.2.2 Societal contributions

According to the application of the transdisciplinary FWE nexus decision support system in real practice, the results of this research provide the following societal contributions:

I. The integrated SES-based FWE nexus assessment framework provides a comprehensive view of key operationalization nexus drivers at the city level. It incorporates details and provides holistic insights into not only the interdependencies but also the dynamics in the social and techno-ecological nexus systems and the opportunities for better managing the FWE nexus process. The results can support policymakers and management professionals of the FWE nexus to organize their analytical, diagnostic, and prescriptive capabilities to make development decisions on urban resilience and ecological balance.

II. S.N.O.G. (the online (spatial) optimization-based serious game) provides decision-makers with choices of adjustable technological, environmental, and social policies to model and validate various possible scenarios for the FWE nexus process. The model combines elements of perspectives on integrative nexus modeling, optimal operational strategies development, and transdisciplinary cooperation with real-world practice. Its outcomes serve as strategic guidelines for policymakers and encourage effective decision-making related to maximizing socio-economic targets and minimizing environmental burdens. In addition, S.N.O.G. provides a collaboration platform designed to reach a consensus on management goals.

III. In an interactive and entertaining way, the designed and implemented online interface offers potentially transformative capabilities to the developed optimization-based decision-support tool. Through online gaming, players learn about the complex interplay of social and ecological aspects and become aware of the impacts of integrated resource management on the social system and nature conservation for a more sustainable built environment. This way, cities can act on climate change more effectively. Compared to classic ways of decision-making, citizen engagement and raising their awareness of the interrelated social and ecological challenges have a positive effect in terms of climate change adaptation. The fact that sustainability and climate adaptation are in need of extensive integrated socio-ecological interventions is a window of opportunity to implement transdisciplinary-based technologies, such as the serious game developed in this research, to better address future climate change-related food, water, and energy challenges.

7.2.3 Limitations encountered within this research

Throughout this research, several challenges and limitations have been encountered. Access to data was one of the challenges. Development of the integrated SES-based FWE nexus framework required time-series data (for the case area studied in this research, Eindhoven city in the Netherlands in Chapter 3). Through several meetings with responsible authorities from the municipality and using freely available online data portals, the required data for the framework assessment was collected and merged for the use of this research. In addition, understanding transdisciplinary mechanisms that have been experienced for operationalizing the FWE nexus needs empirical data. Due to spatial dispersion of the selected cases (i.e., Miami, the United States; Southend-on-Sea, the United Kingdom; Eindhoven, the Netherlands; Gdansk, Poland; Uppsala, Sweden; and Taipei, Taiwan) and the challenge of visiting all these cases for empirical data collection, the required data had to be collected using resources that were available or could be collected within the discussion sessions that partners from all these case areas were present. As all selected cases were involved in a larger international project, namely CRUNCH, the required data was collected through one of the consortium meetings held by this research team. It was important to understand different views on the potential benefit, but also potential threats associated with different transdisciplinary mechanisms in operationalizing FWE nexus processes. The advantage of such consortium meetings was that all participants had an understanding of the FWE nexus field. However, they were all from the scientific community and the citizen and political groups of nexus stakeholders were missing in the data collection process. Moreover, when aiming at validating the research result, the challenge of data collection continued as the developed game had to be tested by different users in order to represent all potential groups of FWE nexus stakeholders. The game was tested by 30 players from i) FWE nexus experts, ii) local decision-makers, and iii) laymen as potential users. Due to the COVID-19 pandemic situation and related measures in the Netherlands, it was impossible to gather all volunteered players in one location and ask them to play and discuss in groups for making a consensus on a best-off FWE nexus solution for their desired district (i.e., the Brainport Smart District, in Helmond, Eindhoven region, the Netherlands). The only way to collect the required information for the validation stage of this research was to hold individual online meetings. Although this way may increase the risk of insufficient data collection or statistically insignificant results, this research tried to orient the analysis of the data in a way that lowers such risks, for instance, by conducting a more qualitative-based analysis (see Chapter 6).

7.2.4 Recommendations for further research

The future improvement of this research can introduce more advanced methodologies for the decision-support tool development. What has not been covered within this research is the simulation of temporal FWE nexus systems dynamics, which is important to support natural resource management. FWE nexus decision-making processes can be complex and dynamic. However, the multi-temporal simulation of such complex systems is methodological challenging besides data demanding. In this regard, the transferability of methods and key operationalization drivers are crucial. Moreover, the modeling of stakeholder behavior using agent-based models is a contribution to overcoming the need for dynamic decision-making in FWE nexus systems. It exploits the flexibility associated with stakeholders to simulate real-world decisions. The further combination of system dynamics and agent-based models with the proposed spatial optimization game is of great potential to overcome the lack of temporal and dynamic information when working with large scale nexus problems and also possibilities for deeper analysis of the scenarios developed by players as their potential desire solutions to the issue.

In this research, different multi-sectoral, multi-stakeholder, and multi-objective decision-making features have been employed for operationalizing the transdisciplinary FWE nexus, however, further features might be explored that relate to the unique characteristics of such systems. For instance, qualitative information about operational rules, network structure, and leadership could increase assessment accuracies and would be useful to further refine the capturing of the diversity of transdisciplinary FWE nexus mechanisms characteristics. More research is required to provide information retrieved from the state-of-the-art integrated systems assessment techniques to support decision-making and planning processes, planning professionals but also local stakeholders dealing with development projects in urban areas.

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APPENDICES

APPENDIX A. SUPPLEMENTARY DETAILS OF CHAPTER 2

Table A. 1
Selection criteria for the eligibility assessment of publications to be reviewed

Selection criteria		**Justification**
Database	Scopus, Web of Science, and ScienceDirect	Comprehensive coverage of scientific publications allows systematic literature review and ensures comparability of the larger text corpora.
Document types	peer-review paper, and scientific book (chapter)	Selection of publication in accordance with scientific standards for a systematic literature review that ensures data coherence.
Language	English	Focusing on international scientific publications ensures data comparability.
Keywords	Food, water, energy (in terms of food-water-energy, food-energy-water, water-energy-food, water-food-energy, energy-food-water, and energy-water-food), nexus, and transdisciplinarity (along with synonyms as participation, governance, and collaboration)	Inclusion of all content-related keywords to identify scientific debates around transdisciplinary practices within FWE nexus.
Keywords' dominance	Frequency greater than the standard deviation of all datasets (i.e., 5)	Frequent expression of a keyword in a scientific text ensures significant relevance of the document to the subject of the study. Standard deviation quantifies the amount of variation of keywords' frequency throughout all documents.
Timeframe	All years	All relevant literature with no time limitation was compiled to explore scientific trends in debates and the gradual development of the subject over time.
Evidence-based practice	PICOSS framework (Table C.2)	Document screening relying on the PICOSS framework ensures careful selection of most relevant scientific discourses to the research question.

Table A. 2
PICCOS framework identifying key components of the research question

Review question	What is the state of the art for using transdisciplinary approaches within food-water-energy nexus?
Population	Stakeholders of the food, water, and energy resources
Intervention	Social inclusion. Any transdisciplinary approach that has the potential for multi-stakeholder engagement within the FWE-nexus management that target sustainable development
Comparator	No comparison
Outcomes	Any positive or adverse transdisciplinary-oriented sustainable resource management-based outcomes
Study design	A conclusive research relying on a combination of qualitative and quantitative methods using primary and secondary data. Primary data collection based on qualitative methods as interviews, focus groups, and observation. Secondary data collection and analysis based on qualitative-quantitative methods as case studies, statistical and spatial analysis.
Setting	Any urban or rural areas, with different scales.

Table A. 3
Overview of the reviewed publications

Year	Author	Title	Source Name
2015	Scott, Christopher A., Kurian, M., Wescoat, James L.	The Water-Energy-Food Nexus: Enhancing Adaptive Capacity to Complex Global Challenges	Governing the Nexus
2015	Biggs, Eloise M., Bruce, E., Boruff, B., Duncan, John M.A., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J., Haworth, B., Duce, S., Imanari, Y.	Sustainable development and the water–energy–food nexus: A perspective on livelihoods	Environmental Science & Policy
2015	Stirling, A	Developing 'Nexus Capabilities': towards transdisciplinary methodologies	University of Sussex
2015	Foran T.	Node and regime: Interdisciplinary analysis of water-energy-food nexus in the Mekong region	Water Alternatives
2015	Halbe, J., Pahl-Wostl, C., Lange, MA., Velonis, C.	Governance of transitions towards sustainable development - the water-energy-food nexus in Cyprus	Water International

Year	Author	Title	Source Name
2015	Keskinen M., Someth P., Salmivaara A., Kummu M.	Water-energy-food nexus in a transboundary river basin: The case of Tonle Sap Lake, Mekong River Basin	Water
2015	Soliev I., Wegerich K., Kazbekov J.	The costs of benefit sharing: Historical and institutional analysis of shared water development in the Ferghana Valley, the Syr Darya Basin	Water
2016	de Grenade, R., House-Peters, L., Scott, CA., Thapa, B., Mills-Novoa, M., Gerlak, A., Verbist, K.	The nexus: reconsidering environmental security and adaptive capacity	Current Opinion in Environmental Sustainability
2016	De Strasser L., Lipponen A., Howells M., Stec S., BrŽthaut C.	A methodology to assess the water energy food ecosystems nexus in transboundary river basins	Water
2016	Grafton, R. Quentin; McLindin, Mahala; Hussey, Karen; Wyrwoll, Paul; Wichelns, Dennis; Ringler, Claudia; Garrick, Dustin; Pittock, Jamie; Wheeler, Sarah; Orr, Stuart; Matthews, Nathanial; Ansink, Erik; Aureli, Alice; Connell, Daniel; De Stefano, Lucia; Dowsley, Kate; Farolfi, Stefano; Hall, Jim; Katic, Pamela; Lankford, Bruce; Leckie, Hannah; McCartney, Matthew; Pohlner, Huw; Ratna, Nazmun; Rubarenzya, Mark Henry; Raman, Shriman Narayan Sai; Wheeler, Kevin; Williams, John	Responding to Global Challenges in Food, Energy, Environment and Water: Risks and Options Assessment for Decision-Making	ASIA \& THE PACIFIC POLICY STUDIES
2016	Howarth C., Monasterolo I.	Understanding barriers to decision making in the UK energy-food-water nexus: The added value of interdisciplinary approaches	Environmental Science and Policy
2016	Lotz-Sisitka H., Ali M.B., Mphepo G., Chaves M., Macintyre T., Pesanayi T., Wals A., Mukute M., Kronlid D., Tran D.T., Joon D., McGarry D.	Co-designing research on transgressive learning in times of climate change	Current Opinion in Environmental Sustainability

Year	Author	Title	Source Name
2016	Mohtar R.H., Lawford R.	Present and future of the water-energy-food nexus and the role of the community of practice	Journal of Environmental Studies and Sciences
2016	Treemore-Spears L.J., Grove J.M., Harris C.K., Lemke L.D., Miller C.J., Pothukuchi K., Zhang Y., Zhang Y.L.	A workshop on transitioning cities at the food-energy-water nexus	Journal of Environmental Studies and Sciences
2016	Wolfe M.L., Ting K.C., Scott N., Sharpley A., Jones J.W., Verma L.	Engineering solutions for food-energy-water systems: it is more than engineering	Journal of Environmental Studies and Sciences
2017	Kurian, Mathew	The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development	Environmental Science & Policy
2017	Karpouzoglou, T., Pereira, Laura M., Doshi, S.	Bridging ICTs with governance capabilities for food–energy–water sustainability	Food, Energy and Water Sustainability
2017	Davis, A., Andrew, J.	Co-creating Urban Environments to Engage Citizens in a Low-carbon Future	Procedia Engineering
2017	Daher, B., Saad, W., Pierce, SA., Hülsmann, S.	Trade-offs and Decision Support Tools for FEW Nexus-Oriented Management	Current Sustainable …
2017	Ernst, Kathleen M., Preston, Benjamin L.	Adaptation opportunities and constraints in coupled systems: Evidence from the U.S. energy-water nexus	Environmental Science & Policy
2017	Berga, H., Ringler, C., Bryan, E., ElDidi, H., Elnasikh, S.	Addressing transboundary cooperation in the Eastern Nile through the Water-Energy-Food Nexus: Insights from an E-survey and key informant interviews	The Center for Development Research (ZEF)
2017	Howarth C., Monasterolo I.	Opportunities for knowledge co-production across the energy-food-water nexus: Making interdisciplinary approaches work for better climate decision making	Environmental Science and Policy
2017	Johnson O.W., Karlberg L.	Co-exploring the water-energy-food nexus: Facilitating dialogue	Frontiers in Environmental Science

Year	Author	Title	Source Name
		through participatory scenario building	
2017	Keshwani D.R., Anderson R.D., Keshwani J., Subbiah J., Guru A., Rice N.C.	Educational immersive simulation game design to enhance understanding of corn-water-ethanol-beef system nexus	ASEE Annual Conference and Exposition, Conference Proceedings
2017	Kumazawa, T., Hara, K., Endo, A., Taniguchi, M.	Supporting collaboration in interdisciplinary research of water-energy-food nexus by means of ontology engineering	Journal of Hydrology: Regional Studies
2017	Pereira L.M., McElroy C.A., Littaye A., Girard A.M.	Food, energy and water sustainability: Emergent governance strategies	Food, Energy and Water Sustainability: Emergent Governance Strategies
2017	Spiegelberg M., Baltazar D.E., Sarigumba M.P.E., Orencio P.M., Hoshino S., Hashimoto S., Taniguchi M., Endo A.	Unfolding livelihood aspects of the Water–Energy–Food Nexus in the Dampalit Watershed, Philippines	Journal of Hydrology: Regional Studies
2017	White D.D., Jones J.L., Maciejewski R., Aggarwal R., Mascaro G.	Stakeholder analysis for the food-energy-water nexus in Phoenix, Arizona: Implications for nexus governance	Sustainability
2018	Ziv, G., Watson, E., Young, D., Howard, David C., Larcom, Shaun T., Tanentzap, Andrew J.	The potential impact of Brexit on the energy, water and food nexus in the UK: A fuzzy cognitive mapping approach	Applied Energy
2018	Endo, A.	Introduction: Human-Environmental Security in the Asia-Pacific Ring of Fire: Water-energy-food Nexus	The Water-Energy-Food Nexus
2018	Siegner, AB.	Experiential climate change education: Challenges of conducting mixed-methods, interdisciplinary research in San Juan Islands, WA and Oakland, CA	Energy research & social science
2018	Hannibal, B., Vedlitz, A.	Throwing it out: Introducing a nexus perspective in examining citizen perceptions of organizational food waste in the US	Environmental science & policy
2018	Basheer M., Wheeler K.G., Ribbe L., Majdalawi M., Abdo G., Zagona E.A.	Quantifying and evaluating the impacts of cooperation in transboundary river basins on the Water-	Science of the Total Environment

Year	Author	Title	Source Name
		Energy-Food nexus: The Blue Nile Basin	
2018	Bergendahl J.A., Sarkis J., Timko M.T.	Transdisciplinarity and the food energy and water nexus: Ecological modernization and supply chain sustainability perspectives	Resources, Conservation and Recycling
2018	Blake W.H., Rabinovich A., Wynants M., Kelly C., Nasseri M., Ngondya I., Patrick A., Mtei K., Munishi L., Boeckx P., Navas A., Smith H.G., Gilvear D., Wilson G., Roberts N., Ndakidemi P.	Soil erosion in East Africa: An interdisciplinary approach to realising pastoral land management change	Environmental Research Letters
2018	Dombrowsky I., Hensengerth O.	Governing the water-energy-food nexus related to hydropower on shared rivers-the role of regional organizations	Frontiers in Environmental Science
2018	Brouwer, F., Vamvakeridou-Lyroudia, L., Alexandri, E.	The Nexus Concept Integrating Energy and Resource Efficiency for Policy Assessments: A Comparative Approach from Three Cases	Sustainability
2018	Villamor, GB., Guta, DD., Djanibekov, U., Mirzabaev, A.	Gender specific perspectives among smallholder farm households on water-energy-food security nexus issues in Ethiopia	The Center for Development Research (ZEF)
2018	Givens J.E., Padowski J., Guzman C.D., Malek K., Witinok-Huber R., Cosens B., Briscoe M., Boll J., Adam J.	Incorporating social system dynamics in the Columbia River Basin: Food-energy-water resilience and sustainability modeling in the Yakima River Basin	Frontiers in Environmental Science
2018	Gragg, Richard Schulterbrandt; Anandhi, Aavudai; Jiru, Mintesinot; Usher, Kareem M.	A Conceptualization of the Urban Food-Energy-Water Nexus Sustainability Paradigm: Modeling from Theory to Practice	FRONTIERS IN ENVIRONMENTAL SCIENCE
2018	Hoff H.	Integrated SDG implementation-how a cross-scale (vertical) and cross-regional nexus approach can complement cross-sectoral (horizontal) integration	Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals: Monitoring and Implementation of Integrated Resources Management

Year	Author	Title	Source Name
2018	Hoolohan C., Soutar I., Suckling J., Druckman A., Larkin A., Mclachlan C.	Stepping-up innovations in the water-energy-food nexus: A case study of anaerobic digestion in the UK	Geographical Journal
2018	Hoolohan, C., Larkin, A., McLachlan, C., Falconer, R., Soutar, I., Suckling, J., Varga, L., Haltas, I., Druckman, A., Lumbroso, D., Scott, M., Gilmour, D., Ledbetter, R., McGrane, S., Mitchell, C., Yu, D.	Engaging stakeholders in research to address water-energy-food (WEF) nexus challenges	Sustainability Science
2018	Kurian M., Portney K.E., Rappold G., Hannibal B., Gebrechorkos S.H.	Governance of water-energy-food nexus: A social network analysis approach to understanding agency behaviour	Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals: Monitoring and Implementation of Integrated Resources Management
2018	Martinez P., Blanco M., Castro-Campos B.	The water-energy-food nexus: A fuzzy-cognitive mapping approach to support nexus-compliant policies in Andalusia (Spain)	Water
2018	Matthews N., McCartney M.	Opportunities for building resilience and lessons for navigating risks: Dams and the water energy food nexus	Environmental Progress and Sustainable Energy
2018	Mochizuki J., Magnuszewski P., Linnerooth-Bayer J.	Games for aiding stakeholder deliberation on nexus policy issues	Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals: Monitoring and Implementation of Integrated Resources Management
2018	Pardoe, J., Conway, D., Namaganda, E., Vincent, K., Dougill, AJ., Kashaigili, JJ	Climate change and the water-energy-food nexus: insights from policy and practice in Tanzania	Climate Policy
2018	Webb, R., Bai, X., Smith, MS., Costanza, R., Griggs, D.	Sustainable urban systems: Co-design and framing for transformation	Ambio
2018	Stein C., Pahl-Wostl C., Barron J.	Towards a relational understanding of the water-energy-food nexus: an analysis of embeddedness and governance in the Upper Blue Nile region of Ethiopia	Environmental Science and Policy

Year	Author	Title	Source Name
2018	Sušnik J., Chew C., Domingo X., Mereu S., Trabucco A., Evans B., Vamvakeridou-Lyroudia L., Savi, D.A., Laspidou C., Brouwer F.	Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: The SIM4NEXUS approach	Water
2018	Wyrwoll, P.R., Grafton, R.Q., Daniell, K.A., Chu, H.L., Ringler, C., Lien, L.T.H., Khoi, D.K., Do, T.N., Tuan, N.D.A.	Decision-Making for Systemic Water Risks: Insights from a Participatory Risk Assessment Process in Vietnam	AGU publications
2018	Xue J., Liu G., Casazza M., Ulgiati S.	Development of an urban FEW nexus online analyzer to support urban circular economy strategy planning	Energy
2019	Pahl-Wostl, Claudia	Governance of the water-energy-food security nexus: A multi-level coordination challenge	Environmental Science & Policy
2019	Allouche, J., Middleton, C., Gyawali, D.	The Knowledge Nexus and Transdisciplinarity	Routledge
2019	Bréthaut C., Gallagher L., Dalton J., Allouche J.	Power dynamics and integration in the water-energy-food nexus: Learning lessons for transdisciplinary research in Cambodia	Environmental Science and Policy
2019	Colloff M.J., Doody T.M., Overton I.C., Dalton J., Welling R.	Re-framing the decision context over trade-offs among ecosystem services and wellbeing in a major river basin where water resources are highly contested	Sustainability Science
2019	Covarrubias M., Spaargaren G., Boas I.	Network governance and the Urban Nexus of water, energy, and food: Lessons from Amsterdam	Energy, Sustainability and Society
2019	Daher B., Hannibal B., Portney K.E., Mohtar R.H.	Toward creating an environment of cooperation between water, energy, and food stakeholders in San Antonio	Science of the Total Environment
2019	Agusdinata, DB., Lukosch, H.	Supporting Interventions to Reduce Household Greenhouse Gas Emissions: A Transdisciplinary Role-Playing Game Development	Simulation & Gaming

Year	Author	Title	Source Name
2019	Heitmann, F., Pahl-Wostl, C., Engel, S.	Requirements Based Design of Environmental System of Systems: Development and Application of a Nexus Design Framework	Sustainability
2019	Hoff, Holger; Alrahaife, Sajed Aqel; El Hajj, Rana; Lohr, Kerstin; Mengoub, Fatima Ezzahra; Farajalla, Nadim; Fritzsche, Kerstin; Jobbins, Guy; Ozerol, Gul; Schultz, Robert; Ulrich, Anne	A Nexus Approach for the MENA Region - From Concept to Knowledge to Action	FRONTIERS IN ENVIRONMENTAL SCIENCE
2019	Jeffrey M. Bielicki, Margaret A. Beetstra, Jeffrey B. Kast, Yaoping Wang and Shaohui Tang	Stakeholder Perspectives on Sustainability in the Food-Energy-Water Nexus	Front. Environ. Sci.
2019	Lawford R.G.	A design for a data and information service to address the knowledge needs of the Water-Energy-Food (W-E-F) Nexus and strategies to facilitate its implementation	Frontiers in Environmental Science
2019	Mohtar R.H., Daher B.	Lessons learned: Creating an interdisciplinary team and using a nexus approach to address a resource hotspot	Science of the Total Environment
2019	Kraftl, P., Balastieri, JAP., Campos, AEM.	(Re) thinking (re) connection: young people, “natures” and the water–energy–food nexus in São Paulo State, Brazil	Transactions of the …
2019	Yan, Wanglin; Roggema, Rob	Developing a Design-Led Approach for the Food-Energy-Water Nexus in Cities	URBAN PLANNING
2019	Yung, Laurie; Louder, Elena; Gallagher, Louise A.; Jones, Kristal; Wyborn, Carina	How Methods for Navigating Uncertainty Connect Science and Policy at the Water-Energy-Food Nexus	FRONTIERS IN ENVIRONMENTAL SCIENCE

APPENDIX B. SUPPLEMENTARY DETAILS OF CHAPTER 3

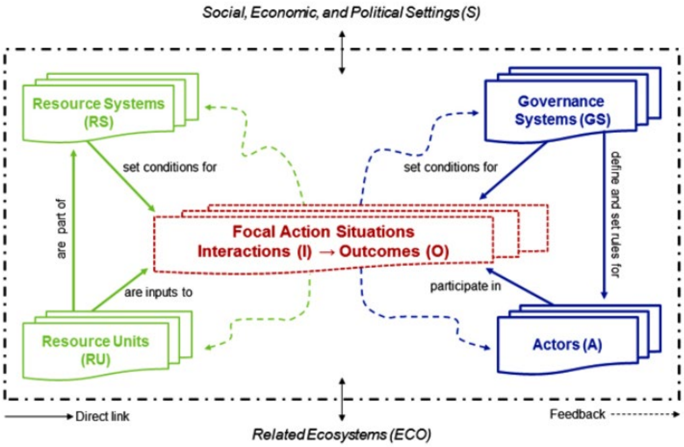


Fig. B. 1. Social-ecological systems framework (SESF). Resource Systems, Resource Units, Governance Systems, and Actors are the highest-tier categories of the model that include ranges of variables at lower tiers. Action Situations describes all the actions of actors that takes place on resource units. Dashed arrows indicate feedback from action situations to each of the top-tier categories. The line that surrounds the interior elements of the figure shows that the focal SES can be considered as a logical whole, but that external influences from related ecological systems or social-economic-political settings can affect any component of the SES. From "Social-ecological system framework: initial changes and continuing challenges", by Michael D. McGinnis and Elinor Ostrom, 2014, Ecology and Society, 19(2), art30, p. 4 (http://dx.doi.org/10.5751/ES-06387-190230). Copyright 2014 by Michael D. McGinnis and Elinor Ostrom.

Table B. 1
NexSESF indicators description and the descriptive statistics of the compiled dataset for Eindhoven.

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
1	GDP	Volume changes of gross domestic product	% annual changes	-4.3	4.1	2.8	2.28	2.36
2	Inhabitant income	Average income per private household (i.e., one or more persons who live together in a living space and provide daily necessities for themselves).	X €1000	26.25	37.4	32.3	3.57	0.38
3	Population growth rate	Population growth in the selected period per 100 inhabitants at the beginning of the selected period.	%	0.25	1.14	0.73	0.003	0.00
4	System area	Total area of the urban system.	ha	8884	8890	8884	2.21	0.98
5	Surface water load	The amount of oxygen-binding substances that ends up in the surface water and fresh national water. This is equal to the sum of the direct discharges and the residual discharges of treated wastewater from sewage treatment plants. It is measured regarding the oxygen consumption of the pollutants in wastewater that is discharged on average per inhabitant per day.	1000 population equivalents	193.4	493.8	337.95	92.65	15.98
6	Fresh water load			32.7	52.1	42.325	6.15	0.21
7	Wastewater supply	The amount of wastewater discharged.	1000 m^3	301695	330245	312769.3	7498.02	8667.58
8	Tap water use by private households	Total use of water from the tap of either drinking water quality that is purified or treated groundwater or surface water and transported through a network of pipes.	million m^3	781.8	805.3	788.8978	6.59	6.80
9	Natural gas supply	Natural gas supplies from the public grid.	1000 m^3	77368.86	271907.9	171812	62746.12	11479.14
10	Electricity supply	Electricity supplies from the public grid.	1000 kWh	951645	1031367	1014935	25146.92	28254.73
11	Natural gas consumption of	The average annual natural gas consumption of private households, as calculated from the connection registers of the energy network	m^3	1150	1853.333	1550	252.01	116.56

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
	private households	companies. In the calculation, homes with very low or even zero consumption are included if there is district heating. As a result, the average natural gas consumption of homes is low in areas where district heating is available.						
12	Electricity consumption of private households	The average annual consumption for electricity on individual connections of private households, as calculated from the connection registers of the energy network companies. The own generation of electricity, for example with solar panels, is not included in the calculation of this indicator.	KW.h	2550	3364.4	3050	266.74	119.46
13	Cultivated land	Cultivated land on which animal manure can be applied. This includes permanent and temporary grassland and arable land except fallow. The area is given in measured size, i.e., the net cultivable area, including furrows and paths necessary for cultivation.	1000 ha	334.89	617	436	77.52	49.35
14	Individual food consumption	Concerns the acquisition of goods and services by households calculated as consumer spending by households, plus final consumption expenditure by non-profit institutions at benefit of households, plus individual consumption by the government.	% annual volume change	-1.1	2.4	1.011538	1.07	1.11
15	Organic waste	Total amount of organic waste collected from households by or on behalf of the municipalities.	Kg per inhabitant	67.32198	98	80	8.99	1.85
16	Wind energy end use	Gross final consumption of renewable wind, solar, or biomass energy as a percentage of the total gross final energy consumption, calculated as the sum of the energy end-use of the end-use sectors	In % of total energy consumption	0.28	1.26	0.79	0.31	0.04

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
17	Biomass energy end use	(industry, households, services, agriculture, fisheries and transport); transport losses of electricity and heat; and own consumption the producers of electricity in the production of electricity.	In % of total energy consumption	1.49	4.449758	3.16	0.89	0.19
18	Solar energy end use		In % of total energy consumption	0.04	0.14	0.07	0.04	0.02
19	Natural gas supply to agriculture industry	This concerns natural gas deliveries from the national natural gas network to arable farming, livestock breeding and the production of other plants and animals on an agricultural holding or in the natural habitat.	1000 m^3	130	710	445	188.16	164.90
20	Natural gas supply to water/waste management	This concerns natural gas deliveries from the national natural gas network to extraction and distribution of water, waste treatment and recycling systems.	1000 m^3	205	489	389.80	80.56	80.04
21	Electricity supply to agriculture	This concerns electricity supplies from the national electricity grid to arable farming, livestock breeding and the production of other plants and animals on an agricultural holding or in the natural habitat.	1000 KW.h	132.51	6263	1626	1582.9	153.67
22	Electricity supply to water/waste management	This concerns electricity supplies from the national electricity grid to extraction and distribution of water, waste treatment and recycling systems.	1000 KW.h	20867.09	29049	24988	2955.26	2000.56
23	Tap water use by agriculture & food manufacture	Total tap water of either purified groundwater or surface water being transported through a network of pipes or (tap) water network used by agriculture and food manufactures.	million m^3	96.1	113.5	105.2	5.10	3.24

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
24	Tap water use by electricity and gas supply	Total tap water use by electricity and gas supply systems.	million m^3	2.3	9.2	3.7	2.07	2.07
25	Tap water use by water supply and waste management	Total tap water use by water supply; sewage, waste management and remediation activities.	million m^3	3.3	6.6	4.8	1.06	0.81
26	Groundwater use by agriculture and food manufacture	Total use of water pumped or otherwise abstracted from underground formations that may be fresh water but can also be brackish or salt water for the use of agriculture and food manufacture.	million m^3	103.2	153.2	120.3	16.08	15.89
27	Groundwater use by electricity and gas supply	Total use of abstracted groundwater for electricity and gas supply purposes.	million m^3	0.6	6.07	4	1.95	1.19
28	Groundwater use by water supply and waste management	Total use of abstracted groundwater for water supply; sewage, waste management and remediation activities.	million m^3	754.7	779.7	763.6	7.32	7.36
29	Surface water use by agriculture and food manufacture	Total use of water abstracted from inland waters such as rivers, lakes, canals (except for groundwater), and transitional waters for agriculture and food manufacture purposes.	million m^3	113.2	235	192.9	27.28	28.18
30	Surface water use by electricity and gas supply	Total use of abstracted surface water for electricity and gas supply purposes.	million m^3	9044.6	10999.4	10202.1	620.27	479.48
31	Surface water use by water supply and waste management	Total use of abstracted surface water for water supply and waste management purposes.	million m^3	921	1069.2	1001.1	36.50	37.00

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
32	Ground water level	Average groundwater level	mm	1615	1922	1811.002	75.30	95.85
33	Precipitation	The quantity of precipitation, including rain, snow, hail, sleet, dew and frost per day which is the number of mm that falls between 8.00 hrs in the morning and 8.00 hrs the following morning, measured with a pluviometer.	mm	833	1033	952	51.17	51.04
34	Evaporation	Transition of liquid water (in soil and plants) into vapor, Calculated from the average day temperature and solar radiation.	mm	564	612	585.33	13.94	15.73
35	Volatility on agricultural production	The percentage of annual total gross agricultural production change that also includes the part of production that for some reason is unsuitable for its original purpose. This only applies if the crop can still be used for other purposes (for example, potatoes which can only be used for animal feed).	% per year	-3.31	91.58	2.22	29.03	0.28
36	Renewable energy end use	Gross final consumption of renewable energy as a percentage of the total gross energy consumption, calculated as the sum of the energy end-use of the end-use sectors (industry (excluding refineries), households, services, agriculture, fisheries and transport), transport and distribution losses of electricity; and the self-consumption of electricity producers in the production of electricity.	in % of total energy consumption	2.05	7.41	4.52	1.53	0.25
37	Health expenditures	Total expenditure on medical and long-term care providers including provision of services and goods.	€ per capita	2962	4462	3987	480.64	118.06
38	Installed capacity of solar panels	The installed capacity of solar panels at the end of the reference year for all economic activities.	kW	1000	36915	1800	10690.5	242.89
39	Level of disciplinarity in	Score of the disciplinarity in socio-ecological projects from experts' perspectives (collected	from 1 to 0.25 with the highest to the lowest	0.5	1	0.75	0.19	0.07

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
	socio-ecological projects	through some interviews with relevant experts from the City)	level of collaboration					
40	Motivation and attitude of actors	Percentage of inhabitants that have been active in the past year to improve the ecological system of their living area.	% of inhabitants	14.5	24	19	3.09	0.95
41	Social cohesion	Scale score measured based on citizens' attitudes relative to social relations - trust in other people, shared priorities with others, and diversity (for the case study of this chapter, social cohesion was calculated and provided on the official website of the City)	scale score	5.5	6	5.73	0.13	0.13
42	Wastewater discharge	The annual volume of effluent wastewater using data on concentrations and quantities of pollutants in treated wastewater (effluent) discharged from urban wastewater treatment plants.	1000 m^3	301695	343211	314191	10855.22	10855.22
43	Capacity of sewage treatment plants	The total capacity of all urban wastewater treatment plants expressed in inhabitant equivalents which is determined on basis of: one inhabitant equivalent = 54 g BOD (Biological Oxygen Demand).	1000 inhabitant equivalents	3934.3	4496	3999	133.18	120.90
44	Nutrients emission to water	Total emission of nutrients that are necessary for the growth of crops and plants (such as phosphorus and nitrogen) to water. A too high concentration of phosphorus and nitrogen in the surface water is bad for the quality of the surface water. The emissions are converted to nutrient-equivalents and then added up.	1000 inhabitant equivalents	19795.95	20558.52	20177.23	246.06	64.98
45	Population overweight	Percentage of persons with a BMI of 25.0 kg/m^2 and above. BMI is the quotient of the weight in kilograms and the square of the height in meters	%	28.1	56.6	46.7	9.02	3.01

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
		[kg/m^2]. It is a generally accepted measure of underweight and overweight. This concerns the population of 19 years or older.						
46	CO_2 emission by private households	The total annual emission of CO_2 in air by one or more persons who live together in a living space and provide for the daily necessities for themselves.	million Kg	17570	25400	21490	2063.15	1604.47
47	CO_2 emission by energy sectors	The total annual emission of CO_2 in air by energy sectors including extraction of petroleum and natural gas, petroleum industry, and energy companies.	million Kg	58720	70860	65630	3572.24	2620.34
48	CO_2 emission by agriculture	The total annual emission of CO_2 in air by agriculture and services for agriculture.	million Kg	7060	10370	8370	878.66	797.70
49	CO_2 emission by waste and water treatment	The total annual emission of CO_2 in air by waterworks and waste management.	million Kg	15570	18400	17040	791.09	722.76
50	Contribution of hydropower energy use in avoidance of CO_2 emission	Avoided emissions of carbon dioxide as a percentage of the total context-based CO_2 emissions according to the IPCC guidelines by the energy generated by falling or flowing water.	in % of total CO_2 emission	0.03	0.041212	0.03	0.00	0.00
51	Contribution of wind energy use in avoidance of CO_2 emission	Avoided emissions of carbon dioxide as a percentage of the total context-based CO_2 emissions according to the IPCC guidelines by the energy generated by a windmill or wind turbine.	in % of total CO_2 emission	0.58	2.624909	1.52	0.65	0.09
52	Contribution of solar energy use in avoidance of CO_2 emission	Avoided emissions of carbon dioxide as a percentage of the total context-based CO_2 emissions according to the IPCC guidelines by the energy generated by solar collectors or solar cells.	in % of total CO_2 emission	0.03	0.23	0.07	0.08	0.04

#	Indicator	Description	Unit	Minimum	Maximum	Mean	SD	RMSE
53	Household residual waste	The amount of not-separately collected household waste per inhabitant per year.	Kg per inhabitant	198	219	203.2	6.54	5.15
54	Installed capacity of solar panel on agriculture	The installed capacity of solar panels in kW at the end of the reference year used for the agriculture sector.	KW	24.7	45	34	6.89	1.97
55	Soil mineral excretion	The amount of mineral excretion, including nitrogen, phosphate, and potassium, per hectare of cultivated land.	Kg/ha	68	165	114	23.11	19.78

Notes: SD stands for standard deviation and represents a measure of variability around the mean.
Data source: Centraal Bureau voor de Statistiek (2019); Eindhoven Municiaplity (2019)

Table B. 2
NexSESF indicators across PC1 and PC2 of principal component analysis on nexus data from Eindhoven.

#	Indicator	PC1	PC2
1	Contribution of solar energy use in avoidance of CO_2 emission	0.325394	-0.01537
2	Solar energy end use	0.280658	-0.02134
3	Contribution of wind energy use in avoidance of CO_2 emission	0.253688	0.003288
4	Wind energy end use	0.249516	-0.0001
5	Installed capacity of solar panels	0.239365	-0.12154
6	Population growth rate	0.22899	0.137879
7	Groundwater use by electricity and gas supply	0.22838	0.198276
8	Electricity supply to agriculture	0.214131	-0.06036
9	Renewable energy end use	0.209902	-0.01167
10	Biomass energy end use	0.199879	-0.0014
11	Level of disciplinarity in socio-ecological projects	0.186536	0.018697
12	Installed capacity of solar panel on agriculture	0.154859	-0.0196
13	Motivation and attitude of actors	0.128451	-0.00623
14	Contribution of hydropower energy use in avoidance of CO_2 emission	0.110005	-0.00641
15	Health expenditures	0.107177	0.01795
16	Groundwater use by agriculture and food manufacture	0.105385	-0.03611
17	Inhabitant income	0.097567	-0.01009
18	Electricity supply to water/waste management	0.094855	0.019988
19	Surface water use by agriculture and food manufacture	0.069555	-0.07676
20	Soil mineral excretion	0.061989	0.000622
21	CO_2 emission by agriculture	0.029431	0.059719
22	Precipitation	0.022555	-0.02875
23	Tap water use by electricity and gas supply	0.020099	0.0742
24	CO_2 emission by waste and water treatment	0.015016	0.027081
25	Nutrients emission to water	0.012253	-0.00064
26	Social cohesion	0.010846	-0.00957
27	Surface water use by electricity and gas supply	0.010152	-0.00944
28	Groundwater use by water supply and waste management	0.009162	-0.01168
29	GDP	0.006578	-0.72426
30	Wastewater supply	0.003838	-0.01174
31	Surface water use by water supply and waste management	0.000974	-0.03307
32	System area	0.00023	-4.7E-05
33	Evaporation	-0.00019	0.001411
34	Wastewater discharge	-0.00138	-0.01716

#	Indicator	PC1	PC2
35	Capacity of sewage treatment plants	-0.01249	-0.00341
36	Electricity supply	-0.01286	0.007732
37	Tap water use by agriculture & food manufacture	-0.01755	-0.02194
38	Ground water level	-0.0176	0.001166
39	Household residual waste	-0.01948	0.009928
40	Individual food consumption	-0.02609	-0.59129
41	CO_2 emission by energy sectors	-0.03577	-0.0177
42	CO_2 emission by private households	-0.04897	0.048444
43	Tap water use by private households	-0.05876	-0.01712
44	Volatility on agricultural production	-0.05994	0.108298
45	Electricity consumption of private households	-0.07794	-0.004
46	Tap water use by water supply and waste management	-0.0837	0.05221
47	Organic waste	-0.09192	0.005053
48	Cultivated land	-0.1031	-0.01232
49	Natural gas supply to water/waste management	-0.11662	0.067403
50	Fresh water load	-0.12109	0.010793
51	Natural gas consumption of private households	-0.12838	0.029481
52	Population overweight	-0.16288	0.026472
53	Surface water load	-0.19176	0.021795
54	Natural gas supply to agriculture industry	-0.22152	-0.03944
55	Natural gas supply	-0.23515	0.020575

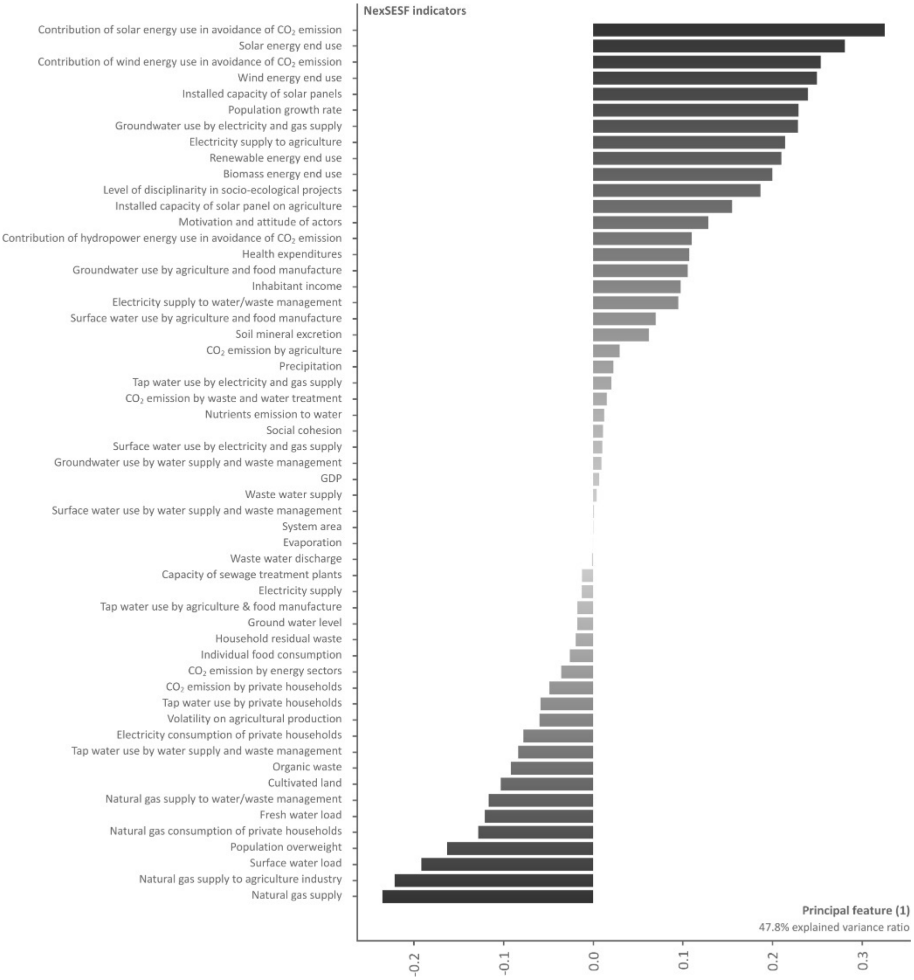


Fig. B. 2. Extended representation of the NexSESF indicators contribution to FWE nexus governance regarding the first feature of PCA on Eindhoven dataset. This information is shown with rectangular bars with heights proportional to the extent each indicator correlates with PCA feature (1).

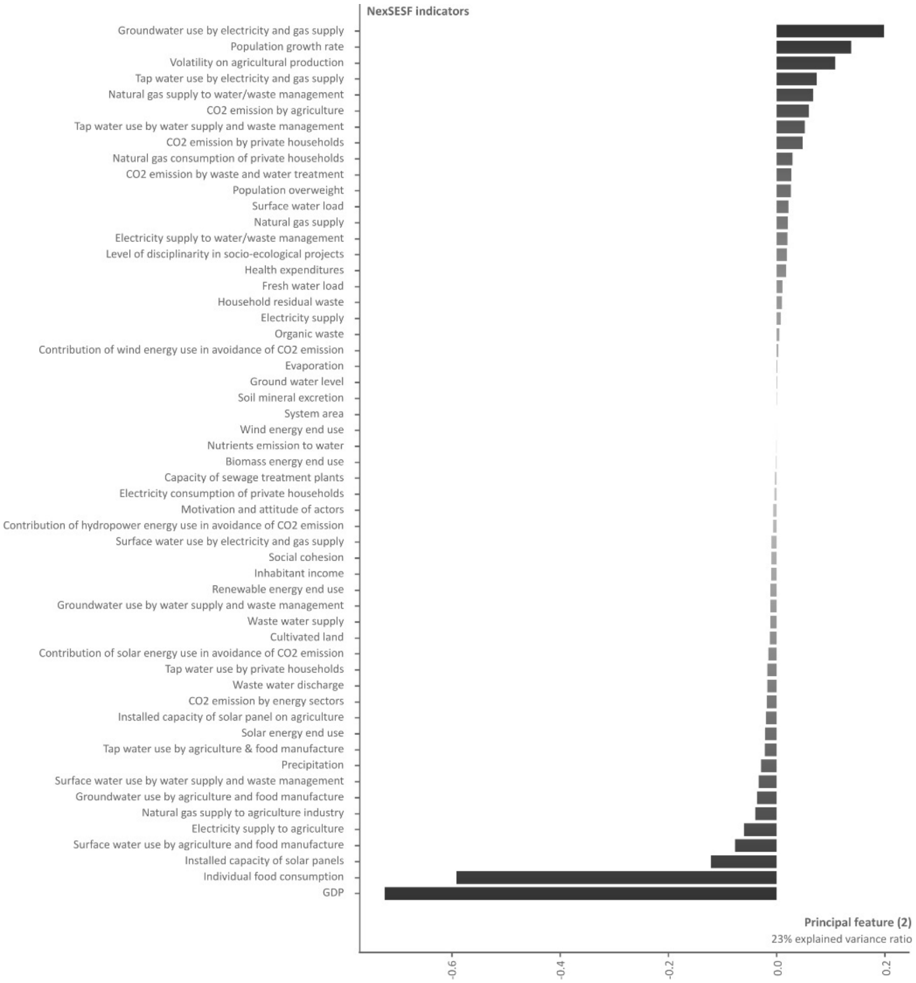


Fig. B. 3. Extended representation of the NexSESF indicators contribution to FWE nexus governance regarding the second feature of PCA on Eindhoven dataset. This information is shown with rectangular bars with heights proportional to the extent each indicator correlates with PCA feature (2).

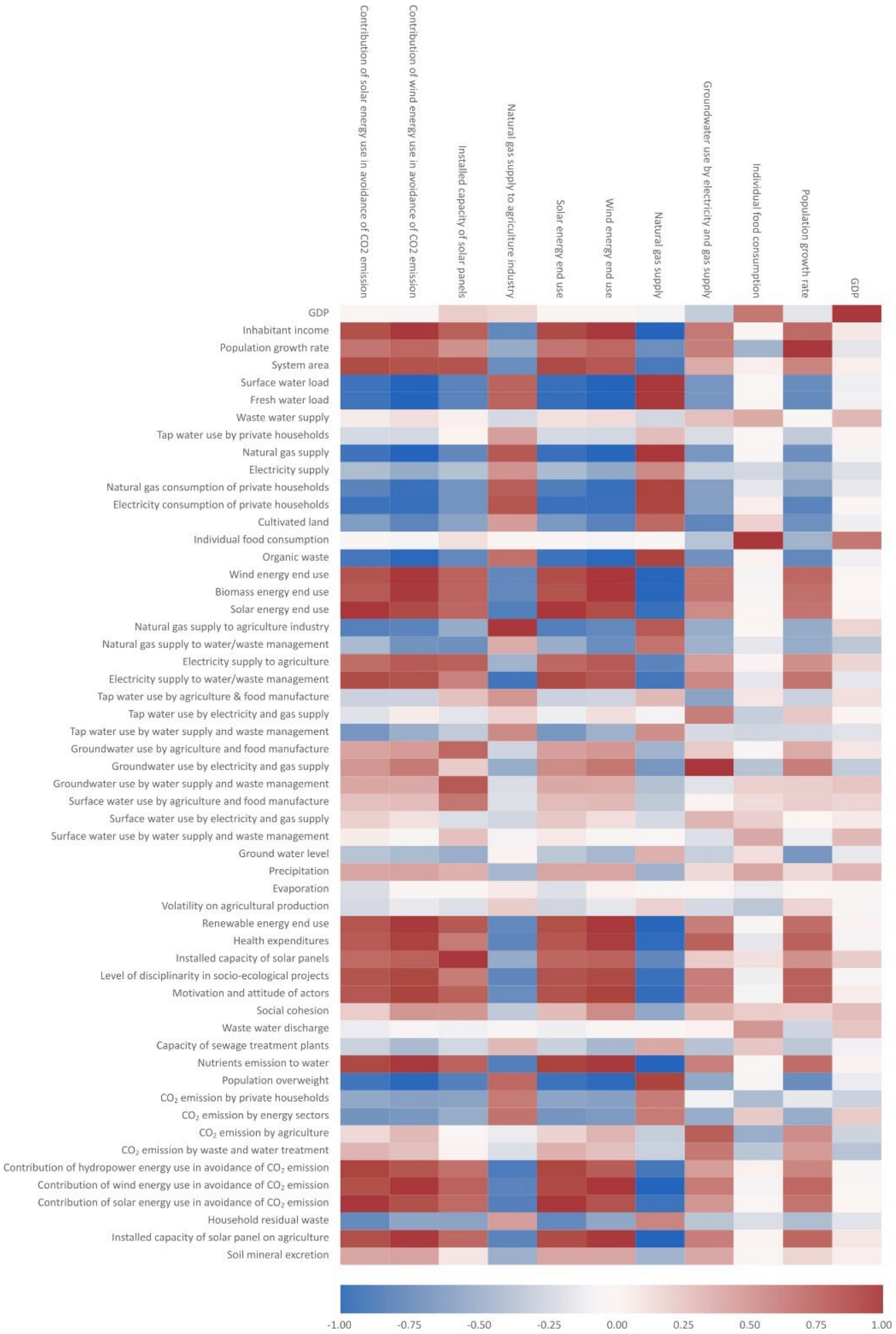


Fig. B. 4. Correlation heatmap, illustrating correlations among NexSESF indicators with the key drivers of FWE nexus in Eindhoven retrieved from PC1 and PC2

Table B. 3

Raw data, from Eindhoven, used in the real-world application of the NexSESF framework.

	GDP	Inhabitant income	Population growth rate	System area	Surface water load	Fresh water load	Wastewater supply	Tap water use by private households	Natural gas supply	Electricity supply	Natural gas consumption of private households	Electricity consumption of private households	Cultivated land	Individual food consumption
2004	1.7	26.25	0.28	8884	493.8	52.1	311696	12.5	271908	1023839	1853	3364	617	2.3
2005	3.1	27.05	0.34	8884	461.85	50.575	312054	12.3	258012	1020871	1801	3309	521	0.3
2006	4.1	27.84	0.25	8884	418.6	48.9	312412	12.4	244117	1017903	1749	3253	521	2.2
2007	2.8	28.64	0.3	8884	420.55	47.825	312769	12.2	230221	1014935	1696	3197	436	2.1
2008	1.8	29.44	0.92	8884	411.2	46.6	308780	12.1	216325	1011967	1644	3142	473	-0.1
2009	-4.3	30.23	0.73	8884	379.25	45.075	301695	11.9	202430	1008999	1592	3086	451	-1.1
2010	3.3	31.03	1.04	8884	358.6	43.7	323320	11.8	204599	990884	1700	3100	362	0.5
2011	3.5	32.30	0.55	8884	337.95	42.325	318395	11.6	171812	1019174	1350	3050	364	1.2
2012	-0.6	32.50	0.56	8887	317.3	40.95	330245	11.5	153181	1018250	1400	3000	424	1
2013	-0.9	32.90	1.14	8887	296.65	39.575	305555	11.5	150397	1020946	1550	2700	398	-0.6
2014	1.9	34.50	1.04	8887	276	38.2	313545	1.5	115530	958988	1150	2550	436	1.2
2015	3.4	34.50	0.69	8887	255.35	36.825	314687	11.8	108835	973887	1190	2810	444	2.4
2016	3.6	35.80	0.94	8887	234.7	35.45	323984	12.0	105978	951645	1230	2690	363	1.8
2017	3.7	37.00	1	8890	214.05	34.075	307157	11.7	108862	1031367	1190	2760	349	1.01
2018	2.2	37.40	1.1	8890	193.4	32.7	316703	12.6	77369	982287	1210	2610	335	1.01

Data source: Centraal Bureau voor de Statistiek (2019); Eindhoven Municiaplity (2019)

Table B. 3 (continued)

	Organic waste	**Wind energy end use**	**Biomass energy end use**	**Solar energy end use**	**Natural gas supply to agriculture industry**	**Natural gas supply to water/waste management**	**Electricity supply to agriculture**	**Electricity supply to water/waste management**	**Tap water use by agriculture & food manufacture**	**Tap water use by electricity and gas supply**
2004	98.0	0.28	1.49	0.04	654	454	133	20867	0.1069	0.0049
2005	94.2	0.33	1.88	0.04	621	441	292	21447	0.1019	0.0049
2006	87.1	0.42	2.10	0.04	588	428	557	22027	0.0996	0.0054
2007	89.2	0.51	2.42	0.04	555	415	717	22608	0.0985	0.0066
2008	87.4	0.62	2.55	0.04	522	403	1142	23188	0.0949	0.0086
2009	84.6	0.75	3.12	0.05	489	390	1267	23768	0.1011	0.0120
2010	80.0	0.70	2.79	0.05	710	319	1301	21444	0.0938	0.0178
2011	81.3	0.79	3.22	0.07	445	279	1997	24988	0.0914	0.0197
2012	79.7	0.81	3.28	0.09	209	405	1947	26624	0.0842	0.0066
2013	75.0	0.88	3.16	0.13	249	489	1628	29049	0.0878	0.0079
2014	77.8	0.99	3.67	0.10	130	286	1626	28626	0.0897	0.0064
2015	73.4	1.05	3.87	0.11	290	361	3106	25081	0.0914	0.0075
2016	71.5	1.12	4.06	0.12	253	300	2370	27829	0.0934	0.0079
2017	69.8	1.19	4.26	0.13	433	287	6263	28410	0.1036	0.0084
2018	67.3	1.26	4.45	0.14	191	205	3892	27970	0.1047	0.0075

Data source: Centraal Bureau voor de Statistiek (2019); Eindhoven Municiaplity (2019)

Table B. 3 (continued)

	Tap water use by water supply and waste management	Groundwater use by agriculture and food manufacture	Groundwater use by electricity and gas supply	Groundwater use by water supply and waste management	Surface water use by agriculture and food manufacture	Surface water use by electricity and gas supply	Surface water use by water supply and waste management	Ground water level	Precipitation	Evaporation
2004	0.0113	0.1184	0.0013	1.6542	0.0690	21.84	2.29	1848	910	569
2005	0.0099	0.1173	0.0017	1.6437	0.0428	20.96	2.15	1840	873	591
2006	0.0118	0.1970	0.0017	1.6696	0.0640	19.85	2.26	1833	867	601
2007	0.0105	0.1056	0.0034	1.6465	0.0484	20.10	2.14	1826	1033	581
2008	0.0141	0.1105	0.0036	1.6351	0.0430	19.36	2.06	1819	943	576
2009	0.0118	0.1572	0.0099	1.6296	0.0418	20.69	1.97	1811	833	612
2010	0.0131	0.1996	0.0113	1.6334	0.0615	20.75	2.20	1615	901	590
2011	0.0103	0.1897	0.0113	1.6203	0.0662	23.40	2.20	1922	962	585
2012	0.0122	0.1000	0.0107	1.6161	0.0289	20.56	2.11	1872	973	564
2013	0.0075	0.1777	0.0103	1.6360	0.0512	22.25	2.17	1782	934	565
2014	0.0075	0.1302	0.0086	1.6253	0.0469	22.18	2.10	1785	952	607
2015	0.0071	0.1649	0.0086	1.6452	0.0619	23.55	2.14	1793	958	585
2016	0.0079	0.1208	0.0079	1.6690	0.0430	22.22	2.22	1760	963	585
2017	0.0092	0.2077	0.0084	1.6779	0.0486	20.58	1.94	1768	968	585
2018	0.0109	0.4824	0.0084	1.7692	0.1645	18.99	2.44	1674	974	585

Data source: Centraal Bureau voor de Statistiek (2019); Eindhoven Municiaplity (2019)

Table B. 3 (continued)

	Volatility on agricultural production	Renewable energy end use	Health expenditures	Installed capacity of solar panels	Level of disciplinarity in socio-ecological projects	Motivation and attitude of actors	Social cohesion	Wastewater discharge	Capacity of sewage treatment plants	Nutrients emission to water
2004	7.60	2.05	2962	1000	0.5	14	5.67	314191	4496	19796
2005	-12.73	2.5	3071	1000	0.5	15	5.68	306224	3999	19891
2006	-3.31	2.8	3247	1100	0.5	16	5.70	310240	3950	19905
2007	7.36	3.32	3422	1200	0.75	16	5.71	343211	3950	19960
2008	91.57	3.61	3651	1300	0.75	17	5.73	308780	3994	20014
2009	2.22	4.28	3777	1400	0.75	18	5.8	301695	4002	20069
2010	-1.85	3.92	3907	1500	0.75	19	5.7	323320	4002	20016
2011	3.36	4.52	3987	1800	0.75	19	6	318395	4002	20177
2012	-7.53	4.68	4107	1997	0.75	19	5.7	330245	4002	20232
2013	7.07	4.73	4160	4699	1	20	5.5	305555	4002	20348
2014	7.54	5.48	4208	7319	1	23	5.9	313545	4002	20345
2015	-33.12	5.74	4205	11878	1	20	5.8	314687	3997	20396
2016	-6.96	5.93	4284	16685	1	22	5.9	323984	3997	20450
2017	41.32	6.6	4346	24351	1	24	5.9	307157	3997	20504
2018	-22.68	7.41	4462	36915	1	24	5.9	315817		

Data source: Centraal Bureau voor de Statistiek (2019); Eindhoven Municiaplity (2019)

Table B. 3 (continued)

	Population overweight	**CO_2 emission by private households**	**CO_2 emission by energy sectors**	**CO_2 emission by agriculture**	**CO_2 emission by waste and water treatment**	**Contribution of hydropower energy use in avoidance of CO_2 emission**	**Contribution of wind energy use in avoidance of CO_2 emission**	**Contribution of solar energy use in avoidance of CO_2 emission**	**Household residual waste**	**Installed capacity of solar panel on agriculture**	**Soil mineral excretion**
2004	56.6	22460	70860	7250	17230	0.03	0.58	0.03	202	25	68
2005	54.5	21750	69650	7580	16170	0.03	0.68	0.04	204	26	113
2006	52.6	21990	64370	7060	16160	0.03	0.86	0.04	210	28	106
2007	46.7	19850	66110	7670	15570	0.03	1.05	0.04	214	29	116
2008	46.7	22190	66070	8630	16430	0.03	1.30	0.04	219	31	110
2009	46.7	22090	65630	8750	17140	0.03	1.50	0.05	211	32	96
2010	46.7	25400	68310	10370	18400	0.03	1.35	0.05	203	34	103
2011	46.7	20220	63970	9300	16870	0.03	1.52	0.07	209	35	120
2012	43.8	21490	60730	9290	18050	0.04	1.74	0.13	204	34	165
2013	38.4	22730	59710	9100	18240	0.04	1.92	0.23	198	38	121
2014	36.4	17570	63090	7860	16470	0.04	2.05	0.16	201	43	116
2015	34.4	18630	67680	8280	17100	0.04	2.19	0.17	198	43	114
2016	28.1	19360	66080	8230	17040	0.04	2.33	0.19	200	43	147
2017	30.4	18930	61810	8370	17110	0.04	2.48	0.20	198	43	140
2018	28.4	18860	58720	8460	16940	0.04	2.62	0.22	198	45	94

Data source: Centraal Bureau voor de Statistiek (2019); Eindhoven Municiaplity (2019)

Table B. 4

Python code used for the PCA analysis.

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from sklearn.decomposition import PCA
from sklearn.preprocessing import MaxAbsScaler, Normalizer
from sklearn.pipeline import make_pipeline
import scipy

df = pd.read_excel(<path.xlsx>)

data = df.iloc[:,1:].values
years = df.iloc[:,0].values
scaler = MaxAbsScaler()
normalizer = Normalizer()
pca = PCA()

pipeline = make_pipeline(scaler, pca)
features = pipeline.fit_transform(data)

components = pca.components_

plt.bar(range(pca.n_components_), pca.explained_variance_ratio_)
plt.xlabel('PCA components')
plt.ylabel('variance')
plt.xticks(range(pca.n_components_))
plt.show()

fig = plt.figure()
variable = df.columns.tolist()[1:]
df2 = pd.DataFrame({'variable': variable, 'value': list(components[0,:])})
df2 = df2.sort_values('value', ascending = False)
plt.bar(df2['variable'], df2['value'])
plt.xlabel('Variables')
plt.ylabel('PC1')
plt.tick_params(labelsize=5)
plt.xticks(df2.variable.tolist(), rotation=90)
plt.show()

fig = plt.figure()
df3 = pd.DataFrame({'variable': variable, 'value': list(components[1,:])})
df3 = df3.sort_values('value', ascending = False)
plt.bar(df3['variable'], df3['value'])
plt.xlabel('Variables')
plt.ylabel('PC2')
plt.tick_params(labelsize=5)
plt.xticks(df3.variable.tolist(), rotation=90)
plt.show()

fig = plt.figure()
pcs = pd.merge(df2, df3, on = 'variable')
pcs.columns = ['variable', 'pc1', 'pc2']
fig = plt.figure()
plt.scatter(pcs['pc1'], pcs['pc2'])
plt.xlabel('pc1')
plt.ylabel('PC2')
plt.show()

corr = np.empty(len(variable)*len(variable)).reshape([len(variable),len(variable)])
sig = corr.copy()

perform = lambda i,j: scipy.stats.pearsonr(data[:,i],data[:,j])
for i in range(len(variable)):
    for j in range(len(variable)):
        corr[i,j] = perform(i,j)[0]
        sig[i,j] = perform(i,j)[1]
set1 = [0, 2, 13, 26]
set2 = [8, 15, 17, 18, 37, 50, 51]
subcorrelation = corr[set1+set2,:]
subsig = sig[set1+set2,:]
subcorrelation_condition = pd.DataFrame(subcorrelation)
subcorrelation_condition.columns = variable
subcorrelation_condition.index = [variable[i] for i in set1+set2]
subcorrelation_condition = subcorrelation_condition.replace(0,np.nan)
subcorrelation_condition = subcorrelation_condition.applymap(lambda x: round(x,3))
subcorrelation_condition = subcorrelation_condition.dropna(how = 'all',axis = 1)
subcorrelation_condition = subcorrelation_condition.dropna(how = 'all',axis = 0)
```

APPENDIX C. SUPPLEMENTARY DETAILS OF CHAPTER 4

Table C. 1
Questions of the online survey conducted on the design, processes, and practices of the selected ULLs.

1- What are the environmental problems your city deals with?

☐ Densification ☐ Biodiversity loss ☐ pollution ☐ Heat stress
☐ Water scarcity ☐ Flooding ☐ Lax food security ☐ Other:

2- What is the focus of the nexus project in your city? (one or more choice)
☐ Strategic planning ☐ Policy interventions ☐ Analytical approach ☐ Development actions ☐ Other:
Please explain your choice in detail.

3- What is the scale of the nexus project in your city?
☐ City scale ☐ Neighborhood scale ☐ Building scale

4- What is the relevance of the designed Urban Living Lab in relation to the aim of the nexus project in your city?
☐ Studying existing governance structure and processes ☐ Assessing existing state of the challenges in your city
☐ Increasing co-creation and participation ☐ Testing the usefulness of the ULL approach ☐ Other:

5- What are the solutions that proposed ULL explores?
☐ Repurposing existing areas ☐ Densification of existing urban areas ☐ Creation of mixed-use areas
☐ Development of innovative solutions on green/blue infrastructure ☐ Increasing awareness through participation
☐ Other:
Please explain your choice in detail.

6- To what degree following stakeholders are involved in the proposed ULL?

	1 (low)	2	3	4	5 (high)
Academic/University					
Municipality					
Industry/Professional					
Local community					

7- Who are defined as current users in the proposed location of the ULL?

8- Who are defined as end-users in the nexus project of your city?
☐ Existing group of users ☐ Future users ☐ Proxy (through a representative)

9- Who are the key actors in the proposed ULL?
☐ Governmental actors ☐ Industry ☐ Financial actors
☐ Local community ☐ Academic ☐ Other:

10- Please select the collaboration order of stakeholders within proposed ULL.

	Government	Industry	Academic	Local community	Financial actors
1 (first) – 5 (last)					

11- Does the issue go beyond the administrative borders of your city/municipality?
☐ Yes ☐ No ☐ Maybe

12- At which level of administrative boundary are the nexus activities of the proposed ULL managed?
☐ National ☐ Regional ☐ Local

13- How was the ULL's engagement strategy identified geographically?
☐ Within the ULL area ☐ Beyond the ULL area
If "beyond the ULL area", please identify the extent.

14- What is the governance system of the proposed ULL?
☐ Top-down ☐ Bottom-up ☐ Top-down and bottom-up

15- How was the selection of initial participants from the community made?
☐ Open to everyone (self-selection) ☐ stakeholder representative ☐ demographically representative
☐ specific individuals ☐ Other:

16- Is it possible for all community members to participate in the ULL?

☐ Yes, within the ULL boundary ☐ Yes, from outside the ULL boundary ☐ No

17- How do different actors collaborate in the ULL?

☐ Working individually ☐ Within multi-disciplinary groups ☐ In groups of similar backgrounds ☐ Other:

18- How does the ULL approach raise local awareness about the nexus concerns?

☐ Information sharing ☐ Consultation ☐ Collaboration ☐ Empowerment ☐ Other:

19- How do the ULL actors share ideas?

☐ one-way physical communication (e.g., post) ☐ One-way virtual communication (e.g., media, advertising) ☐ Two-way physical communication (e.g., workshops, booths) ☐ Two-way virtual communication (e.g., apps, remote attendance) ☐ Multi-model sharing (combination of physical and virtual methods)

20- Is there an open data platform that all different actors of the ULL have access to?

☐ Yes ☐ No

If yes, please add the link.

21- How transparent is the knowledge sharing within the proposed ULL?

	1 (low)	2	3	4	5 (high)
Between decision makers and local community					
Between decision makers					

22- Please identify methods used to showcase ideas between decision makers and community through the proposed ULL?

☐ Gamification ☐ 3D model ☐ Rendering and images ☐ Discussing examples of current studies ☐ Other:

23- Who is the owner of the proposed ULL in your city?

☐ Local government ☐ The Municipality ☐ Industry ☐ Local community ☐ Other:

24- Please identify policy barriers your city faces that prevent the integrated resource management in your city?

Please explain your answer.

25- How aligned are current political interests to the interest of local community in the context of nexus challenges in your city?

Please explain your answer.

Table C. 2

MCA dimensions discrimination measures.

Categorical Variables	**MCA dimensions**	
	Dimension 1	**Dimension 2**
Stakeholders' power	0.983	0.966
Idea showcasing methods	0.861	0.734
Local awareness methods	0.791	0.862
Nexus ULL key actors	0.783	0.462
Environmental problem	0.780	0.613
FWE nexus focus	0.772	0.672
Stakeholders’ collaboration order	0.746	0.696
Idea Sharing methods	0.726	0.460
Nexus ULL role	0.693	0.688
Nexus ULL solution	0.652	0.478
Initial participants selection	0.594	0.632
Collaboration structure	0.558	0.313
Nexus ULL current user	0.534	0.538
Engagement strategy	0.481	0.145
Information transparency with local community	0.448	0.240

Categorical Variables	**MCA dimensions**	
	Dimension 1	**Dimension 2**
Information transparency among decisionmakers	0.406	0.104
Governance system	0.404	0.016
Nexus ULL owner	0.368	0.364
Spatial extent of nexus activities	0.308	0.033
Open data platform	0.289	0.143
FWE nexus end-users	0.250	0.293
FWE nexus scale	0.243	0.028
Spatial extent of the nexus issue	0.182	0.005
Participation possibility	0.102	0.288
Active total	12.955	9.773
Percentage of variance	7.712	5.817

Fig. C. 1. Problem trees of the nexus ULLs selected for this research. Teams of multiple stakeholders from each ULL, through a focus group discussion, debated the main problem of their nexus ULL and defined its associated causes and effects. The problem trees were analyzed for a logical strategic guideline (see Fig. 4.4).

APPENDIX D. SUPPLEMENTARY DETAILS OF CHAPTER 5

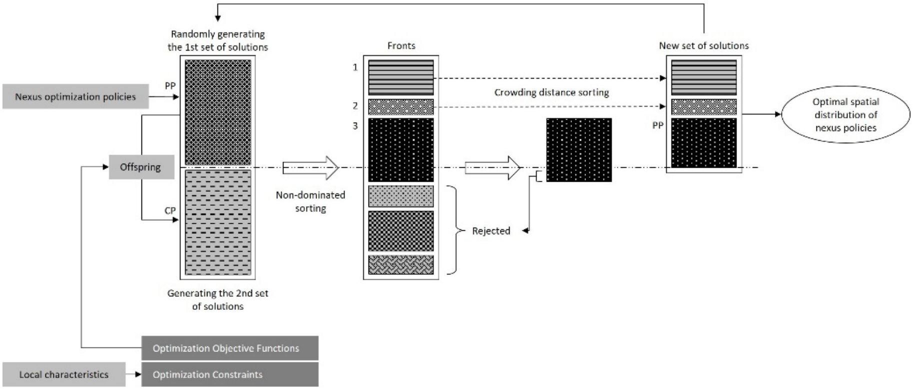


Fig. D. 1. Procedure of the NSGA-II operations for the generation of a population of solutions

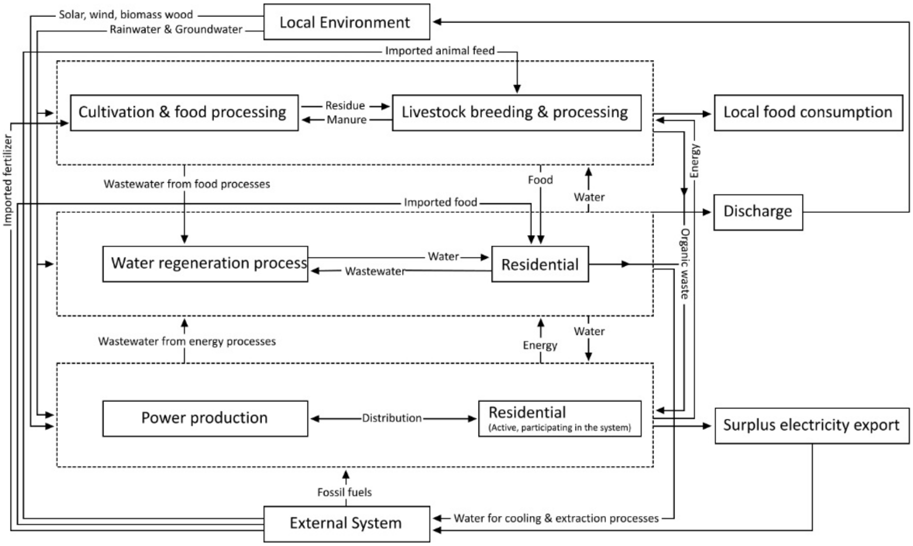
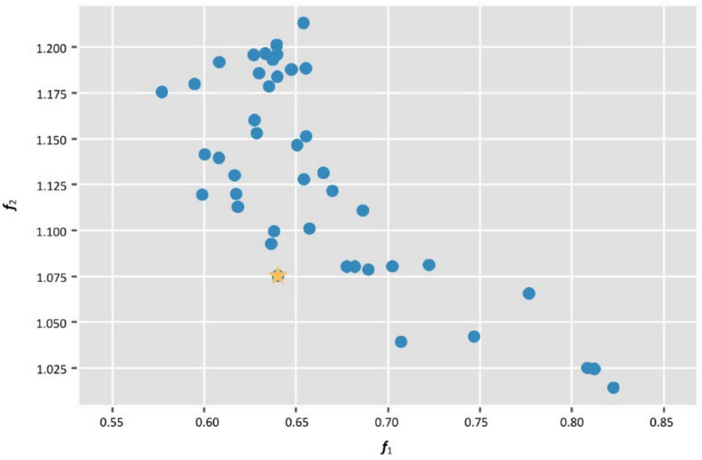


Fig. D. 2. Superstructure for integrated food, water, and energy subsystems in BSD.

I. Self-sufficiency scenario



II. Eco-conscious consumerism scenario

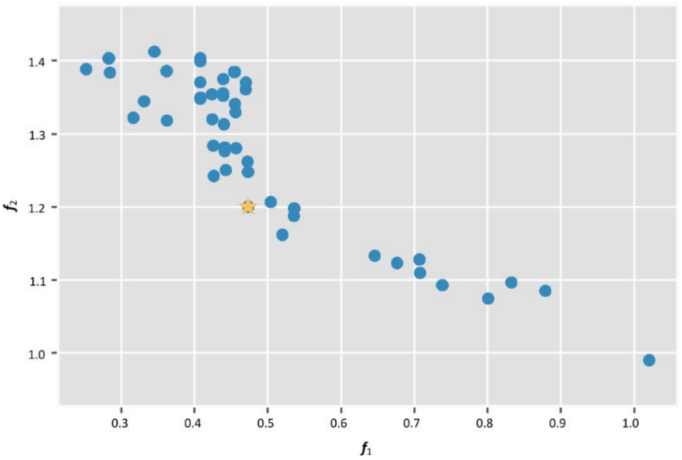


Fig. D. 3. Objective spaces of the two sample alternative scenarios developed for BSD, using the S.N.O.G. model. Data in the charts represents normalized values of the two optimization objectives for BSD, and the stared point is the most optimum solution from the Pareto Front set for each scenario.

Table D. 1
Illustration of all parameters and data used in the S.N.O.G. model design for BSD.

Nexus management policy		**Optimization parameters**			**Mathematical formulation**	
		Specificities		Value	Objective function (1)	Objective function (2)
K=1	Local urban gardening	$CExC_{veg}$	Cumulative exergy consumption for local vegetable production	$2.37\,\frac{Mj\,exergy}{kg\,(veg)}$	$\mathrm{f}_1^{k_1}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{veg} * Q_{ij}^{S}(veg) * G^2$	$\mathrm{f}_2^{k_1}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_1}^{f_2} * G^2$
		e_{veg}^{wat}	Specific cumulative exergy of water per unit vegetable cultivation and processing	$1.75\,\frac{Mj\,exergy}{kg\,(veg)}$	$CExC_{veg}$: $e_{veg}^{wat} + e_{veg}^{fer} + e_{veg}^{Nit} + e_{veg}^{elc}$	
		e_{veg}^{fer}	Specific cumulative exergy of fertilizer per unit vegetable cultivation	$0.01\,\frac{Mj\,exergy}{kg\,(veg)}$		
		e_{veg}^{Nit}	Specific cumulative exergy of mineral nitrogen residue per unit vegetable production	$0.01\,\frac{Mj\,exergy}{kg\,(veg)}$		
		e_{veg}^{elc}	Specific cumulative exergy of electricity per unit vegetable irrigation	$0.59\,\frac{Mj\,exergy}{kg\,(veg)}$		
		$Q^{S}(veg)$	Local vegetable production per m²	$25\,\frac{kg\,(veg)}{m^2}$		
		$B_{k_1}^{f_2}$	The social acceptance criteria weight for K=1	0.086		
K=2	Limited land allocation for fodder crops	$CExC_{fodd}$	Cumulative exergy consumption for local fodder crop production	$509.71\,\frac{Mj\,exergy}{kg\,(fodd)}$	$\mathrm{f}_1^{k_2}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{fodd} * Q_{ij}^{S}(fodd) * G^2$	$\mathrm{f}_2^{k_2}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_2}^{f_2} * G^2$
		e_{fodd}^{wat}	Specific cumulative exergy of water per unit fodder crop cultivation and processing	$65.51\,\frac{Mj\,exergy}{kg\,(fodd)}$	$CExC_{veg}$: $e_{fodd}^{wat} + e_{fodd}^{fer} + e_{fodd}^{Nit} + e_{fodd}^{elc}$	
		e_{fodd}^{fer}	Specific cumulative exergy of fertilizer per unit fodder crop cultivation	$339.14\,\frac{Mj\,exergy}{kg\,(fodd)}$		
		e_{fodd}^{Nit}		$98.97\,\frac{Mj\,exergy}{kg\,(fodd)}$		

Nexus management policy		Optimization parameters			Mathematical formulation	
		Specificities		Value	Objective function (1)	Objective function (2)
		e_{fodd}^{elc}	Specific cumulative exergy of mineral nitrogen residue per unit fodder crop production	$6.09\,\frac{Mj\ exergy}{kg\ (fodd)}$		
		$Q^S(fodd)$	Specific cumulative exergy of electricity per unit fodder crop irrigation	$12\,\frac{kg\ (fodd)}{m^2}$		
		$B_{k_2}^{f_2}$	Local fodder crop production per m²	0.035		
			The social acceptance criteria weight for K=2			
K=3	Sustainable farming production systems	$CExC_{sust-sys}$	Cumulative exergy consumption for sustainable farming production system using organic waste to generate electricity for movement	$0.58\,\frac{Mj\ exergy}{Mj\ elc}$	$\mathrm{f}_1^{k_3}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{sust-sys} * Q_{ij}^{elc} * G^2$	$\mathrm{f}_2^{k_3}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_3}^{f_2} * G^2$
		$Q_{m^2}^{elc}$	Required electricity for one-meter movement of the farming vehicle	$1.8\text{e-}5\,\frac{Mj\ elc}{m^2}$		
		$B_{k_3}^{f_2}$	The social acceptance criteria weight for K=3	0.093		
K=4	Draining garden design	$CExC_{soil}$	Cumulative exergy consumption for clay soil improvement for minor drainage issues	$0.01\,\frac{Mj\ exergy}{volume\ (soil)}$	$\mathrm{f}_1^{k_4}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{ij}^{soil} * G^2$	$\mathrm{f}_2^{k_4}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_4}^{f_2} * G^2$
		$B_{k_4}^{f_2}$	The social acceptance criteria weight for K=4	0.08		
K=5	Rainwater harvesting	$CExC_{rain}$	Cumulative exergy consumption for rainwater storage	$2.67\,\frac{Mj\ exergy}{m^3\ (rain)}$	$\mathrm{f}_1^{k_5}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{rain} * Q_{ij}^{rain} * G^2$	$\mathrm{f}_2^{k_5}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_5}^{f_2} * G^2$
		$Q_{m^2}^{rain}$	Possible amount of rainwater harvesting per m²	$0.81\,\frac{m^3\ (rain)}{m^2}$		
		$B_{k_5}^{f_2}$	The social acceptance criteria weight for K=5	0.119		

Nexus management policy		**Optimization parameters**			**Mathematical formulation**	
		Specificities		Value	Objective function (1)	Objective function (2)
K=6	On-site wastewater purification	$CExC_{wastewat}$	Cumulative exergy consumption for local wastewater purification	1.4e-3 $\frac{Mj\ exergy}{kg\ (waste)}$	$\mathrm{f}_1^{k_6}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{l=0}^{2} CExC_{wastewat} * Q_{ijl}^{wastewat} * G^2$	$\mathrm{f}_2^{k_6}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_6}^{f_2} * G^2$
		$Q_{res\ (m^2)}^{wastewat}$	Wastewater discharge in residential lands	5.84e-2 $\frac{kg}{m^2}$		
		$Q_{mix\ (m^2)}^{wastewat}$	Wastewater discharge in mixed-use lands	0.87 $\frac{kg}{m^2}$		
		$Q_{comm\ (m^2)}^{wastewat}$	Wastewater discharge in commercial lands	0.22 $\frac{kg}{m^2}$		
		$B_{k_6}^{f_2}$	The social acceptance criteria weight for K=6	0.052		
K=7	Solar power roofs	$CExC_{solar}$	Cumulative exergy consumption for local electricity generation from solar power	2.23 $\frac{Mj\ exergy}{elc}$	$\mathrm{f}_1^{k_7}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{solar} * Q_{ij}^{elc} * G^2$	$\mathrm{f}_2^{k_7}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_7}^{f_2} * G^2$
		$Q_{m^2}^{elc}$	Possible electricity generation by solar panels per m²	0.017 $\frac{Mj\ elc}{m^2}$		
		$B_{k_5}^{f_2}$	The social acceptance criteria weight for K=7	0.264		
K=8	Energy-saving households' behaviour	$B_{k_8}^{f_2}$	The social acceptance criteria weight for K=8	0.278	$\mathrm{f}_1^{k_8}(\mathrm{X}) = 0$	$\mathrm{f}_2^{k_8}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_8}^{f_2} * G^2$
K=9	Biomass efficiency improvement	$CExC_{biomass}$	Cumulative exergy consumption for biomass contribution to electricity generation	5.34 $\frac{Mj\ exergy}{Mj\ elc}$	$\mathrm{f}_1^{k_9}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{biomass} * Q_{ij}^{elc} * G^2$	$\mathrm{f}_2^{k_9}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_9}^{f_2} * G^2$
		$Q_{m^2}^{elc}$	Possible electricity generation by biomass per m²	0.41 $\frac{Mj\ elc}{m^2}$		
		$B_{k_9}^{f_2}$	The social acceptance criteria weight for K=9	0.048		

Nexus management policy		Optimization parameters			Mathematical formulation	
		Specificities		Value	Objective function (1)	Objective function (2)
K=10	Wind power	$CExC_{wind}$	Cumulative exergy consumption for wind power contribution to electricity generation	$1.42\,\frac{Mj\;exergy}{Mj\;elc}$	$\mathrm{f}_1^{k_{10}}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} CExC_{wind} * Q_{ij}^{elc} * G^2$	$\mathrm{f}_2^{k_{10}}(\mathrm{X}) = \sum_{i=1}^{N}\sum_{j=1}^{M} B_{k_{10}}^{f_2} * G^2$
		$Q_{m^2}^{elc}$	Possible electricity generation by wind turbines per m^2	$0.014\,\frac{Mj\;elc}{m^2}$		
		$B_{k_{10}}^{f_2}$	The social acceptance criteria weight for K=10	0.026		

Note: In this Table, ‘G’ represents the model spatial resolution, that is 100×100 meter. The social acceptance criteria weights for the different policies, in comparison with one another, are calculated employing the Analytical Hierarchy Process (AHP) method. This study only considers vegetable production to represent the local food subsystem in BSD. The different land-use types are identified as ‘L’ in this study; l=0: residential, l=1: commercial, l=2: mixed-use, and l=3: green. As policy number 8 has a social perspective on nexus process improvement, zero exergy consumption is considered if this policy is chosen for action. See Table D.2 for the detail of exergy values calculation (column ‘value’). To access the code repository see Ghodsvali (2021).

Source: Centraal Bureau voor de Statistiek (2009); Geudens and Grootveld (2017); Geurts, van Bakel, van Rossum, de Boer, and Ocké (2016); Leung Pah Hang, Martinez-Hernandez, Leach, and Yang (2016); UNStudio, Felixx Landscape Architects & Planners, Metabolic, UNSense, and Habidatum (2019); van der Bie, Hermans, Pierik, Stroucken, and Wobma (2012); Voedingscentrum (2019)

Table D. 2

Details of the exergy values calculation

Optimization parameter		Mathematical calculation	Source
$\boldsymbol{e_{veg}^{wat}}$	Specific cumulative exergy of water per unit vegetable cultivation and processing	$29253.8 \frac{Liter\ water}{1000\ kg\ (veg)} * 0.06 \frac{Mj\ exergy}{kg\ (water)} = 1.75 \frac{Mj\ exergy}{kg\ (veg)}$	Food and Agricultural Organization of the United Nations (2001)
$\boldsymbol{e_{veg}^{fer}}$	Specific cumulative exergy of fertilizer per unit vegetable cultivation	$136.6 \frac{Kg\ (manure\ N)}{ha\ (farm)} * 5.33 \frac{Mj\ exergy}{kg\ (manure\ N)} / 58.9 \frac{1000\ Kg\ (veg)}{ha\ (farm)} = 0.01 \frac{Mj\ exergy}{kg\ (veg)}$	Centraal Bureau voor de Statistiek (2022); Yildizhan (2017)
$\boldsymbol{e_{veg}^{Nit}}$	Specific cumulative exergy of mineral nitrogen residue per unit vegetable production	$200 \frac{Kg\ (N)}{ha\ (farm)} * 5.33 \frac{Mj\ exergy}{kg\ (N)} / 58.9 \frac{1000\ Kg\ (veg)}{ha\ (farm)} = 0.01 \frac{Mj\ exergy}{kg\ (veg)}$	Biemond (1995); Centraal Bureau voor de Statistiek (2022)
$\boldsymbol{e_{veg}^{elc}}$	Specific cumulative exergy of electricity per unit vegetable irrigation	$142 \frac{MJ\ (electricity)}{1000\ Kg\ (veg)} * 4.17 \frac{Mj\ exergy}{MJ\ (electricity)} = 0.59 \frac{Mj\ exergy}{kg\ (veg)}$	Gołaszewski et al. (2012)
$\boldsymbol{e_{fodd}^{wat}}$	Specific cumulative exergy of water per unit fodder crop cultivation and processing	$15.41 \frac{litr\ (water)}{Kg\ (beef)} * 0.42 \frac{1000\ Kg\ (beef)}{cattle/day} / 13.38 \frac{Kg\ (fodder)}{cattle/day} * 0.06 \frac{MJ}{Kg\ (water)} * 2.25 \frac{avg\ (cultivating\ days)}{year} = 65.51 \frac{Mj\ exergy}{kg\ (fodder)}$	Centraal Bureau voor de Statistiek (2009)
$\boldsymbol{e_{fodd}^{fer}}$	Specific cumulative exergy of fertilizer per unit fodder crop cultivation	$7.8 \frac{Kg\ (manure)}{Kg\ (cattle).\mathrm{year}} / 13.38 \frac{Kg\ (fodder)}{cattle/day} * 750 \frac{Kg\ (cattle)}{cattle} * 5.33 \frac{MJ}{Kg\ (manure)} * 6.87 \frac{avg\ day\ (harvesting)}{year} = 339.14 \frac{Mj\ exergy}{kg\ (fodder)}$	
$\boldsymbol{e_{fodd}^{Nit}}$	Specific cumulative exergy of mineral nitrogen residue per unit fodder crop production	$0.007 \frac{Kg\ (N)}{Kg\ (\mathrm{manure})} * 7.8 \frac{Kg\ (manure)}{Kg\ (cattle).\mathrm{year}}\ 750/13.38 \frac{Kg\ (cattle).year}{Kg\ (fodder)} * 32.34 \frac{MJ}{Kg\ (fodder)} = 98.97 \frac{Mj\ exergy}{kg\ (fodder)}$	
$\boldsymbol{e_{fodd}^{elc}}$	Specific cumulative exergy of electricity per unit fodder crop irrigation	$0.142 \frac{MJ\ (electricity)}{Kg\ (\mathrm{fodder}).\mathrm{day}} * 4.17 \frac{MJ\ exergy}{MJ\ (\mathrm{electricity})} * 10.28 \frac{avg\ day}{year} = 6.09 \frac{MJ\ exergy}{Kg\ (\mathrm{fodder})}$	

Note: This Table presents how exergy values, the ‘value’ column in Table D.1, were calculated for this research.

Source: Centraal Bureau voor de Statistiek (2009); Geudens and Grootveld (2017); Geurts, van Bakel, van Rossum, de Boer, and Ocké (2016); Leung Pah Hang, Martinez-Hernandez, Leach, and Yang (2016); UNStudio, Felixx Landscape Architects & Planners, Metabolic, UNSense, and Habidatum (2019); van der Bie, Hermans, Pierik, Stroucken, and Wobma (2012); Voedingscentrum (2019)

APPENDIX E. SUPPLEMENTARY DETAILS OF CHAPTER 6

Table E. 1
Explanation of policy cards available in the S.N.O.G. web-based serious game tool.

	Sector of the economy	Policy	Action plan	Attributes
1	**Food**	Urban gardening	The implementation of local gardens in order to locally satisfying the food demand of the population.	When applied, this policy takes 0.5 years to build and become active. From that moment, the policy will go on for 10 years.
2		Limited land allocation for fodder crop production	Limited allocation of land for fodder crop production in order to reduce size of herd in local agricultural systems.	When applied, this policy takes 0.5 years to build and become active. From that moment, the policy will go on for 30 years.
3		Sustainable farming production system	The implementation of sustainable farming production system in order to save greenhouse gases and reduce their emissions in the air.	When applied, this policy takes 1 years to build and become active. From that moment, the policy will go on for 20 years.
4	**Water**	Draining garden design	The implementation of on-site wastewater purification in order to decentralize the wastewater treatment system in living areas.	When applied, this policy takes 1 years to build and become active. From that moment, the policy will go on for 10 years.
5		Rainwater harvesting	The implementation of rainwater harvesting system for residential zones in order to conserve water resources and cut down on waste.	When applied, this policy takes 1 years to build and become active. From that moment, the policy will go on for 15 years.
6		On-site wastewater purification	The implementation of on-site wastewater purification in order to decentralize the wastewater treatment system in living areas.	When applied, this policy takes 5 years to build and become active. From that moment, the policy will go on for 40 years.
7	**Energy**	Solar power roofs	The implementation of solar panels on building roofs in order to increasing self-sufficiency of the area in meeting the energy demand.	When applied, this policy takes 1 years to build and become active. From that moment, the policy will go on for 30 years.

8	Energy-saving households' behaviour	The increase of households' awareness in regards of the energy consumption and possibilities for saving energy.	When applied, this policy takes 2 years to build and become active. From that moment, the policy will go on for 15 years.
9	Biomass efficiency improvement	The improvement of biomass use in order to provide users with a cleaner alternative feedstock for energy production.	When applied, this policy takes 3 years to build and become active. From that moment, the policy will go on for 30 years.
10	Wind power	The implementation of wind turbines in order to generate clean and renewable energy.	When applied, this policy takes 5 years to build and become active. From that moment, the policy will go on for 50 years.

Table E. 2

Questions of the online survey conducted on the playtest evaluation of the S.N.O.G. serious game tool.

A survey of the S.N.O.G serious game experiments

Managing food, water, and energy sustainability requires our better understanding of how these resources work together. This research, as part of a PhD project within the Faculty of the Build Environment at TU Eindhoven (Netherlands), with this need in mind, designed a serious game, implemented as an online web tool, to encourage better choices and collaboration for the management of natural resources (i.e., food, water, and energy). Brainport Smart District (BSD), a smart city district in Helmond, the Netherlands, has been chosen for the real-world application of this game.

This questionnaire aims to identify the role of technologically supported serious gaming in support of a successful decision-making process for the food, water, and energy resource management through assessing your game experience and evaluating the gameplay.

If you register for this survey, you agree to participate in this research and the processing of your data collected in this research. We will take great care to protect your privacy. The survey data will only be used for the purpose of this research and will be stored until the end of this research period (September 2022). Any concerns can be communicated to Maryam Ghodsvali (m.ghodsvali@tue.nl).

Consent for participation in the survey

Name: Please enter here the name with which you registered for the game.

I grant permission for the data generated from this survey to be used in publications on this topic.

☐Yes ☐No ☐I grant permission under the following conditions: ………………

Questions

Please answer following questions regarding your game experience.

1. What were your criteria for the BSD plan design?
   ☐Climate neutrality ☐short-term management ☐self-sufficiency
   ☐Eco-conscious consumerism ☐Other: ………………
2. What were your selection criteria for choosing the best design?

☐Food-water-energy supply and demand balance ☐Climate stress control
☐Resource resilience ☐Social and ecological systems integration
☐Other: ………………

Please answer following questions regarding the usability of the game.

3. Was the aim of the game clear to you?
☐Yes ☐No

4. What did you miss in the game?
Click or tap here to enter text.

5. How fun was the game for you to play?

Boring	☐	☐	☐	☐	☐	Fun
	1	2	3	4	5	

6. Which aspect of the game make it fun to play?
☐The interactive map ☐Beating the optimized design
☐Improving your former designs
☐Selection of the policy type and required number ☐Spatial positioning of policy cards
☐Other: ………………

7. How easy was the game for you to play?

Easy	☐	☐	☐	☐	☐	Difficult
	1	2	3	4	5	

8. How easy was the user interface for you to use?

Difficult	☐	☐	☐	☐	☐	Easy
	1	2	3	4	5	

9. What kind of analytical aspect did you miss in your state-of-play?
Click or tap here to enter text.

Please answer following questions regarding the content of the game and your learning experience.

10. The principle social aim of this game is to raise awareness among resource users and policy managers of food-water-energy nexus. Do you think this has been achieved?
☐Yes ☐No ☐To some extent: Please explain.

11. What did you learn from playing the game?
☐The extent to which food, water, and energy are interconnected.
☐Key drivers of sustainable and climate-resilient urban development.
☐Differences between short-term and long-term planning.
☐The importance of social aspects in resource management.
☐The efficient spatial distribution of policies across the area is as important as our choices of best policies for implementation.
☐The fact that policies of different sectors of the economy can block or negatively influence each other.
☐Policy integration helps our cities to perform better in terms of natural resource conservation.
☐Other: ………………

12. We aim to share game results with users and invite them to a discussion group session for consensus making. Do you think that this would be sufficient to achieve transdisciplinarity in resource management issues?
☐Yes ☐No ☐If you have any suggestion in this regard: Please explain.

CURRICULUM VITAE

Maryam Ghodsvali was born in Kerman, Iran. Trained as an urban planner and Geo-information specialist, she received her Bachelor's degree in Urban Planning and Development (2012) and her first Master's degree in Urban Planning (2015) at Tehran University of Art, Iran. Maryam Ghodsvali did her second MSc in Geo-Information Science and Earth Observation at the University of Twente, the Netherlands, in 2018. Between 2014 and 2016, she worked as a GIS specialist at the Municipality of Tehran, Iran. In 2018 she started a PhD project at the Technical University of Eindhoven (Eindhoven, NL), of which the results are presented in this dissertation. Since January 2022, Maryam Ghodsvali has been working as a Postdoctoral Researcher at the Faculty of Built Environment Department of the Technical University of Eindhoven. Her main research focus is the design and implementation of transdisciplinary urban decision-making processes via digital tools.

LIST OF PUBLICATIONS

Ghodsvali, M., Krishnamurthy, S., de Vries, B. (2019). Review of transdisciplinary approaches to food-water-energy nexus: A guide towards sustainable development. Environmental Science & Policy, 101, 266–278. https://doi.org/10.1016/j.envsci.2019.09.003.

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Ghodsvali, M., Dane, G., & de Vries, B. (2022). The urban living lab as an adaptive governance mechanism for the transdisciplinary food-water-energy nexus: Lessons learned from six local contexts. In A. Melis, J. Brown, & C. Coulter (Eds.), Designing Sustainable and Resilient Cities: Small Interventions for Stronger Urban Food-Water-Energy Management (pp. 27–57). Routledge. https://doi.org/10.4324/9781003112495-11.

Ghodsvali, M., Dane, G., de Vries, B. An integrated decision support system for the urban food-water-energy nexus: methodology, modification, and model formulation. Computers, Environment and Urban Systems (under review).

Ghodsvali, M., Dane, G., de Vries, B. An online serious game for aiding decision-making on food-water-energy nexus policy issues: Design, implementation, and test. Sustainable Cities and Society (under review).

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Future availability of vital natural resources, i.e., food, water, and energy, has been a growing global concern during the past few decades. The increasing exploitation rates of these resources have spurred economic growth but have also led to sustainability and environmental challenges, such as resource depletion, climate change, and biodiversity loss. Many academic strategies thus far tended to approach the problem of resource efficiency from an integrated management perspective, understanding and quantifying interlinkages and trade-offs among the physical resource systems. There is also a recognition of social, economic, and environmental limits to resource efficiency. However, the real-world capacity to incorporate multiple natural resource systems and multiple socio-economic structures, including interaction and dynamics of multiple stakeholders, in multi-objective resource management agendas is limited.
Integrated, multi-level resource management can lead to coordinated strategies that are consistent with the degree of resource interconnectedness and, therefore, positively influence the long-term sustainability of the environment. Designing decision-making and policy mechanisms for such a multi-level issue require cooperation amongst competing systems and distinct interests of multiple stakeholders. This PhD research approached this problem in four steps: (1) understanding key drivers for an integrated system; (2) quantifying characteristics and indicators of the systems to be integrated; (3) identifying thresholds to multi-level actions in real-world; and (4) introducing a transdisciplinary decision support mechanism for innovations at the nexus of food, water, and energy systems via an online serious game.

DEPARTMENT OF THE BUILT ENVIRONMENT

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