An integrated decision support system for the urban food-water-energy nexus: Methodology, modification, and model formulation

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A B S T R A C T

Making cities more sustainable relies on opportunities to optimally integrate and manage food, water, and energy resources, among other essential requirements for the thriving of every society, in a synergistic manner. 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 natural resources. Although increasingly employed, the need remains for an integrative decision-making methodology and tool that supports the incorporation of food, water, and energy sectors and the corresponding environmental and social footprints into a general framework, and quantitatively investigating the complicated synergies to optimize nexus strategies from a holistic point of view. This research develops an integrated decision-support system by means of a spatial optimization game model that searches for optimal resource management solutions through a cooperative scenario-building environment. The design of the proposed system relies on an innovative combination of methods capable of navigating decision-making through complex systems modeling and planning. This includes multi-objective optimization and cooperative game theory in the frame of a spatial serious gaming environment for real-world implementation. Relying on such an algorithmic framework, this research provides the foundation for a spatial serious game that enables forecasting the impact of policy interventions 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.

1. Introduction

The rapid growth of world population, economic development, climate change, and environmental concerns, all play roles in magnifying or reducing the increasing stresses on the vital food, water, and energy resources (Vardoulakis & Kinney, 2019). Global projections indicate an alarming increase in demand for these resources over the next decades, while supply becomes unsecure. By 2050, the demand for energy will nearly double, and food and water demand is estimated to increase by over 50% (IRENA, 2015). Moreover, the nature of the food, water, and energy resources is intertwined which intensifies competition for limited resources. These warnings call for more integrative, systematic approaches towards the understanding and management of these resources. Integrated management strategies help to ease the current pressures on resources and the environment (Al-Saidi & Elagib, 2017).

The food-water-energy (FWE) nexus has emerged as a conceptual approach to better understand and integratively analyse the interactions between food, water, and energy, so that cities can manage the limited resources more sustainably (The World Economic Forum Water Initiative, 2011). In practical terms, it presents a more coordinated management of the natural environment, social system, and technical interventions across sectors and scales (FAO, 2014b). FWE nexus enables more integrated planning, decision-making, implementation, and monitoring.

In this context, the scientific arena has made progress in understanding and quantifying the challenges that lie ahead, but questions remain regarding how the knowledge can best be transferred to enable informed decisions in the policy/decision-making arena. Decision-makers lack effective tools that allow accounting for different resource management strategies and an understanding of the trade-offs between the different systems. Several tools exist that address specific aspects of the nexus. These include CLEWs (Howells et al., 2013), WEF Nexus tool 2.0 (Daher & Mohtar, 2015), WBCSD (WBCSD, 2014), MuSIASEM

(Giampietro, Mayumi, & Ramos-Martin, 2009), and DTI (Salman, 2013), among others. Each tool offers important advances over isolated resource management, as well as different methods for understanding and evaluating synergies among the FWE resources (Table 1). 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 modeling. MuSIASEM (Giampietro et al., 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 technical, perspective. Nonetheless, decision-makers are still not provided with comprehensive tools that at the same time: 1) are multi-sectoral and inclusive; 2) quantify and visualize interconnections among the food, water, and energy resources and with their surroundings; 3) support development of integrative strategies for systematic resource management and planning; and 4) provide feedback based on forecasted impact of policy interventions. The need remains for improvements that offer decision-makers a solid foundation for multi-dimensional debate, discussion, and action.

This paper introduces methodological advancements in nexus decision support tools. Governed by a comprehensive methodological framework, a decision-making system is developed that reflects the multi-dimensional, interdisciplinary nature of resource management. Specifically, the objectives of this paper are:

- To design a scenario-based, integrated methodological framework and, accordingly, to propose an application tool that quantifies the existent interdependencies among nexus components and affecting externalities, enables development of different strategies, and offers further examination of real-world practical implications.
- To evaluate the tool's performance based on its functionality and outcome.

The remainder of the paper proceeds as follows. Section 2 demonstrates what the nexus among food, water, and energy sectors mean and what the important emelemnts are in integrated decision-making. Then, Section 3 first reviews the existing tools that support nexus decision-making processes and then describes the potential for possible methodological improvements. Fulfilling the requirements for the desired support of the nexus process, Section 4 presents a novel methodological framework and an application tool, namely S.N.O.G. (the Spatial Nexus Optimization Game). Section 5 demonstrates how the introduced methodology is applied to a local-scale Dutch case study (i.e., Brainport Smart District (BSD)) to achieve optimal integration of nexus management strategies and sustainable development plans in practice. The model performance analysis and discussion are presented in Section 6. Last but not least important, Section 7 draws some useful conclusions and announces some orientations for future work.

2. Integrated resource planning and decision-making

A 'nexus' among food, water, and energy commences with a holistic

Table 1
Review of a selection of available 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 modeling	• 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 Ecosystem Metabolism) (Giampietro et al., 2009)	To investigate synergies of food, water, and energy and their impacts on society.	A diagnostic and simulation framework	Possible for developers	Suitable for dissimilar geographies, but is resource-intensive	Multi-scale and multi-criteria analysis	National	• Resource flows in society • GHG emissions • 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 (2014a, 2014b); Giampietro et al. (2009); Howells et al. (2013); IRENA (2015); Salman (2013); WBCSD (2014).

quantification of interconnetions (Ghodsvali, Dane, & de Vries, 2022a). Besides ecological synergies, there exists trade-offs between urban spatiality, environmental conservation, social meaning, and technical infrastructutre. In this complex system of interconnections, decision-making can be challenging. Multiple sectors of the economy, multiple stakeholders, and multiple uncertainties are involved (Garcia & You, 2016). A thorough understanding of how these multiplicities is framed in the real world and how they are interconnected is key to effective decisions and intervenions. Ideally, the integration in nexus concerns trade-offs among multiple social, ecological, and technical components and their relations with potential externalities.

Fig. 1 demonstrates interconnections within a nexus system of the food, water, and energy resources. Energy is not only crucial to achieving economic development, it is a vital input to water management — and strengthens food production from farming systems (i.e, equipments) to food processing. Similarly, the water system underins energy generation and is fundamental to the growth of the food sector. Likewise bio-organic waste immense potential for green energy recovery.

Since the global aim is to lower the cost of FWE synergies while meeting the demand for now and future, understanding such interconnections and the impact of them on both society and environment helps decision-making being more informed and sustainable. The push for inclusive but fragmented policies in these sectors can lead to inadvertent adverse consequences; farmlands being converted to solar farms, crop production being diverted to biofuels threaten the food security. These dynamics of interdependencies for developments should be captured along with uncertainties of trade-offs (i.e., ecological, environmental, social, and technical benefits and sacrifices) (Rosales-Asensio, de la Puente-Gil, García-Moya, Blanes-Peiró, & de Simón-Martín, 2020).

3. Nexus decision-making tools: some current gaps and the potential for further improvements

Several tools, models and frameworks have been developed to guide decision-making through the complex FWE nexus systems. Table 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 nexus stakeholders (i.e., government, scholars, and community).

In principle, the ideal tool for integrative nexus management would allow the formulation of policies that improve the synergistic efficiency of the 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 nexus tools (presented in Table 2) since frequent capabilities show a consensus on vital while feasible elements in employing the nexus approach.

A prevalent capability of nexus decision support tools is the understanding of systems complexity. Every 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, only avoid this problem in view of synergies simplification. Once the 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
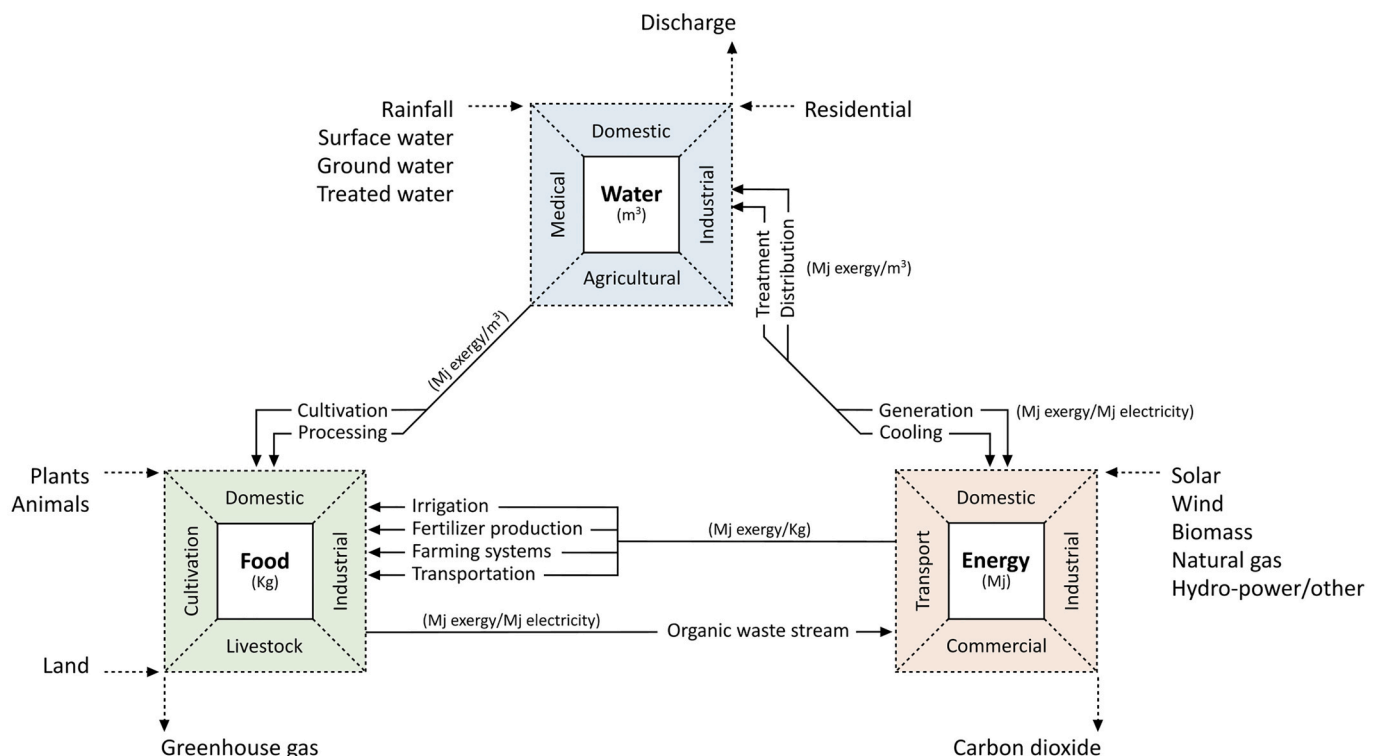

Fig. 1. Food-water-energy resource interconnections.

Table 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 • No future projections.
WEF Nexus tool 2.0	• Accessible web-based tool • No complex data requirements • Consider economic factors in nexus scenarios • Provides comparable policy alternatives	• 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 (2014a, 2014b); Giampietro et al. (2009); Howells et al. (2013); IRENA (2015); Salman (2013); WBCSD (2014).

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. Nexus tools vary according to their temporal functionalities. However, a comprehensive nexus tool 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 can contribute to increasing the use of a tool. A web-based tool offering *a user-friendly interface* eases accessibility for nexus analysts from different nations (Sušnik et al., 2018).

The existing 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.

3.1. 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. 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 3 presents some capabilities of various decision-making methods appropriate for the nexus process and allows the evaluation of desired combinations.

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

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 among 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 $X = [x_1, x_2, ..., x_n]$ subject to value limits $a_i < x_i < b_i$ $(i = 1, 2, ..., n)$ and equality constraints $g_k(X) \leq 0$ $(k = 1, 2, ..., q)$ to optimize objective functions $F(X) = [f_1(X), ..., f_m(X)]$.

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 $S_1, S_2, ..., S_m$, and their associated payoffs represented by $U_1, U_2, ..., U_m$. 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, an MOO 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 $S_1, S_2, ..., S_m$. Constraints in the game can be determined similar to the optimization constraints. So, the game of a multi-objective problem can be formulated as $G = \{S_1, ..., S_m; f_1, ..., f_m\}$. $f_1, ..., f_m$ stand for m-design objectives. $S_1 = \{x_i, ..., x_j\}$, ..., $S_m = \{x_k, ..., x_l\}$ represent strategy sets of an m game players and fulfill $S_1 \cup ... \cup S_m = X$; $S_a \cap S_b = 0$ $(a, b = 1, ..., m; a \neq b)$. Interactions of nexus systems', simulated through MOO 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

Table 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 modeling
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, Al-Ansari, and Govindan (2019); Voinov et al. (2018, 2016).

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 such methodological combination may offer nexus decision-making, this research developed an integrated decision support tool called S.N.O.G. that can offer a holistic and dynamic approach to address FWE resources management problems. The proposed tool is a function of time and space, and considers the synergies and trade-offs among the three FWE sectors and with the community.

4. The S.N.O.G. model: innovation in guiding integrative FWE nexus decision-making

The S.N.O.G 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. 6). The provided 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; and (iv) test realistic options.

Through S.N.O.G., 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.

4.1. 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. 2).

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.

The proposed methodology, openly accessible on GitHub (Ghodsvali, 2021), implies the following procedure:

4.1.1. 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
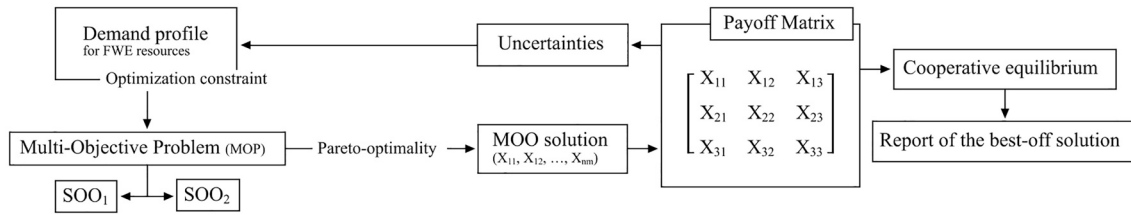
Fig. 2. Methodological framework of the proposed Spatial Nexus Optimization Game (S.N.O.G.). Based on local characteristics, the nexus problem of the study area should be described in the form of several single optimization objectives. Through the optimization model, nexus stakeholders and decision-makers 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.

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:

$$Minimize \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{M} \beta_{ijk} P_{ijk} 0 \text{ where } P_{ijk} \in \{0,1\}, \forall K = 1, \ldots, K; i = 1, \ldots, N; j = 1, \ldots, M \tag{1}$$

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:

i. practical compatibility of policies with different land-use types (LU_t)

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

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.

ii. feasible spatial adjacency of policies; observing a minimum Euclidean distance of standard

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

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.

iii. a minimum total amount for the FWE resources production

$$Q_s - Q_d \geq 0 \tag{4}$$

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

iv. 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, we normalize constraints values 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 $\frac{m}{g_k(X)_i}/\overline{g_k(X)_i}$ where g stands for the value of a constraint calculated for a set of finite policies $\ni \{k_1, k_2, \ldots, k_k\}$ chosen as a design solution X to the problem.

4.1.2. 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.

4.1.3. 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, we designed an improved process through which the initial population of solutions can be generated and further enhanced (see appendix: Fig. A.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.

4.1.4. 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. 3):

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* (Eq. (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 (Eqs. (2)–(4)). Thus, the offspring receives the best distribution of policies that has a high probability of containing good solutions between two parents.

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

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 *j*th 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 *i*th (current) policy *K* at the *j*th 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,
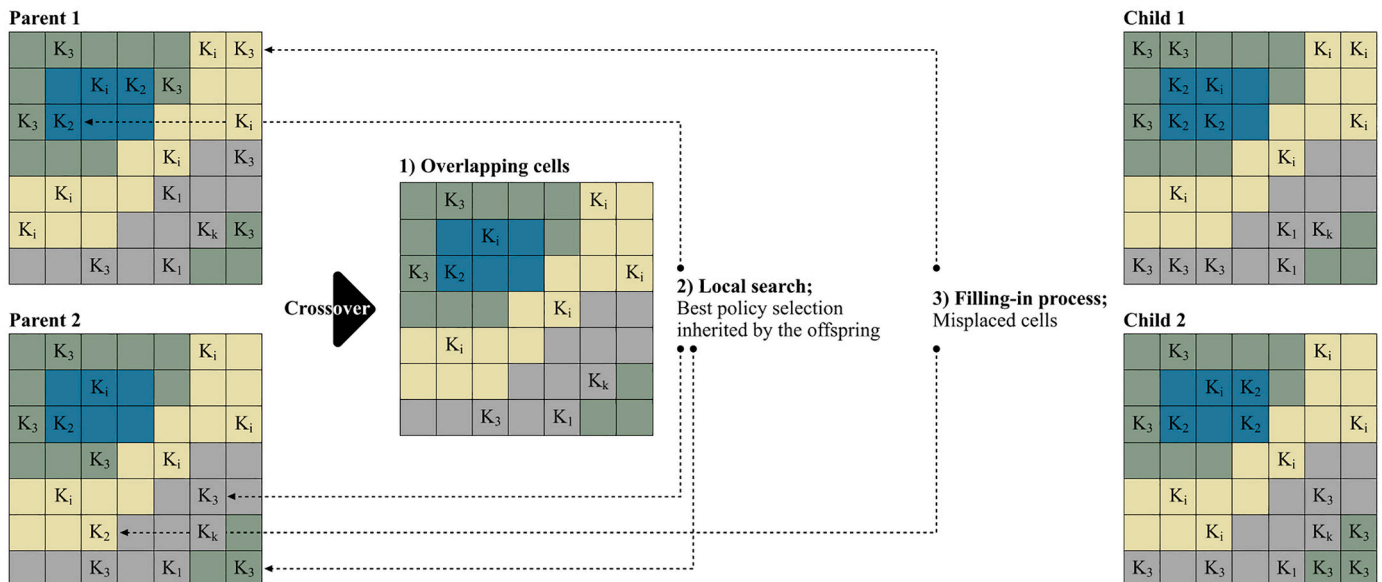

Fig. 3. Illustration of S.N.O.G. crossover operator.

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, we define an additional policy called 'empty policy' 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.

Mutation operator. This evolutionary operator evaluates whether the solutions meet the constraints; thus, some specific policies which steer the overall solution towards an improved change are chosen (see Fig. 4). 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.

B. Geometric operators

To enhance nexus policies' compactness and maintain the required land size, two geometric operators have been adopted in this study (Fig. 5). 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 our 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 neighboring 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 neighbor

remains between unbalanced policies, provided that the spatial constraints are fulfilled.

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.

4.1.5. 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.

4.1.6. 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 4, let player one (i.e., the first optimization objective) be the row and player two (i.e., the second optimization objective) the column.

Strategy S dominates a strategy $Ś$ if

- it makes higher payoffs for all players than $Ś$, i.e., $U(S) \geq U(Ś)$ for all players,
- it makes a higher payoff at least for one player than $Ś$, i.e., $U_i(S) > U_i(Ś)$ for at least one player.

1) Strategy S is the best response to the optimization objectives if no other strategy dominates it, i.e., $U(S) \geq U(Ś)$ for every strategy $S \neq Ś$ available to all players.

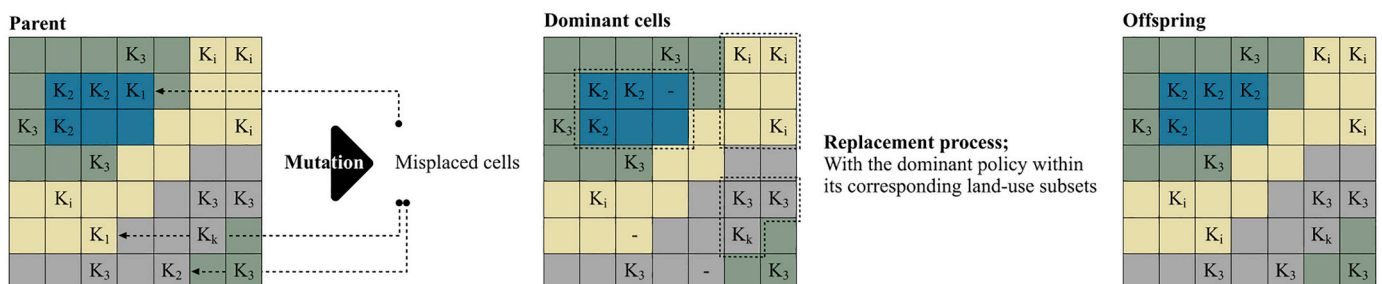Such an incentive mechanism can promote cooperation between stakeholders and positively impact the nexus process.

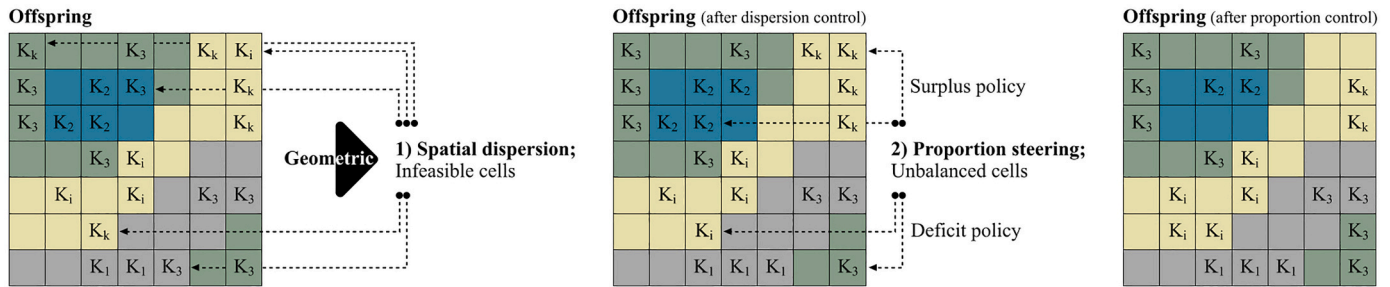**Fig. 4.** Illustration of S.N.O.G. mutation operator.

Fig. 5. Illustration of S.N.O.G. geometric operators.

Table 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 $Ś$ are considered as non-dominated strategies derived from the optimization model, and U(S) and $U(Ś$ are the payoffs each player receives from the implementation of each strategy.

| | | Player i | |
		S	$Ś$
Player j	S	U(S), U(S)	U(S), $U(Ś$
	$Ś$	$U(Ś$, U(S)	$U(Ś$, $U(Ś$

5. Application example of the S.N.O.G

5.1. 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 we study here represents an adaptive urban ambition in the Netherlands, namely BSD, to realize a sustainable, circular, and socially cohesive neighborhood that benefits from joint food production, water management, and energy generation subsystems. Fig. A.2, in supplementary material, illustrates components and interactions of the 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 socioeconomic 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 neighborhood 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.

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 (Eqs. (2)–(4)) for meeting the local FWE demand.

The S.N.O.G. design for BSD, using the Pymoo library in Python, is performed over a time period of 30 years in line with real-world nexus policies. The data used in this study is collated from available literature and BSD project reports (Centraal Bureau voor de Statistiek, 2009; Geudens & Grootveld, 2017; Geurts, van Bakel, van Rossum, de Boer, & Ocké, 2016; Leung Pah Hang, Martinez-Hernandez, Leach, & Yang, 2016; UNStudio et al., 2019; van der Bie, Hermans, Pierik, Stroucken, & Wobma, 2012; Voedingscentrum, 2019) (see Appendix: Table A.1 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. 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 m, considering the system boundary. The spatial layout optimization of BSD required approximately 4.5 h on a Lenovo laptop with an Intel(R) Core(TM) i7-8750H CPU @2.20 GHz and 16 GB RAM. The scenario development and feedback coordination required only 40 s.

Fig. 6 shows the structure of the tool performance citing the example of BSD. 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.

The multi-dimensional character of the tool 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 the contribution of a developed scenario towards CO_2 emission reduction versus the business-as-usual scenario; 2) resource management resilience characterized by system relations and physical capacities, indicating the balance between social impact on natural FWE resources and social profit from the use of the resources; and 3) social-ecological integrity, being a measure of the feasibility of a scenario to be implemented in the real world. Mathematically, calculations of these strategic measures are carried out based on the optimization model objectives, constraints, and some additional data. 'Climate stress control' is the sum of carbon footprints of all activities associated with policy choices made in the model. 'Resource management resilience' is the sum of values for the optimization model
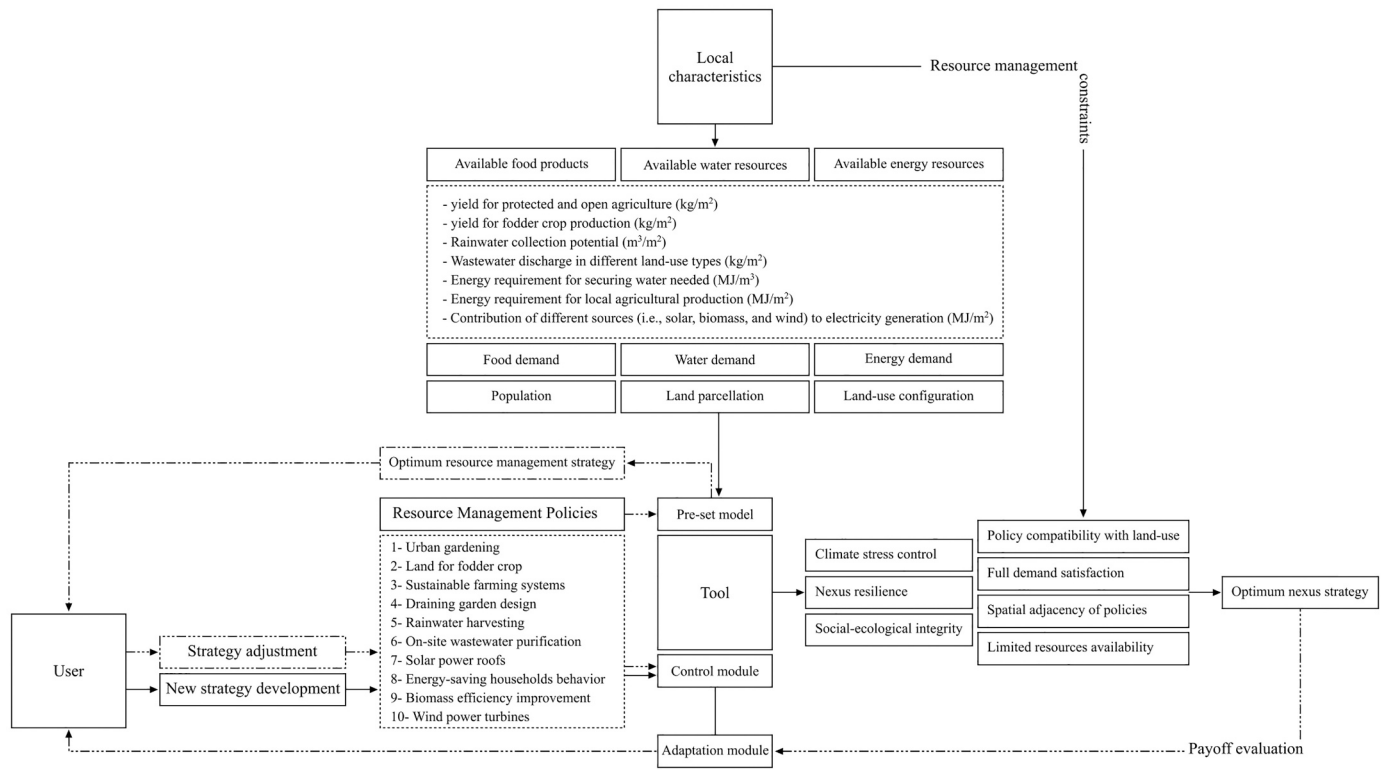
Fig. 6. Tool structure and the practical application for BSD.

objectives. And 'socio-ecological integrity' is the sum of values for the optimization model constraints. There is no maximum value for these measures to obtain. Decision-makers can define their own target for success. The calculation can also be done over all policy alternatives and per spatial region (i.e., grid cells), making clear on which policies and for each at which location to focus on in order to improve the suitability of the interventions. Thus the assessment system of interventions can advise decision-makers and explain opportunities to improve their performance in FWE nexus strategies.

5.2. Design analyses: illustration with some performance indicators

In this study, we first discovered optimal solutions to the nexus operation in BSD consistent with the two set objective functions (see Eq. 1) using NSGA-II and the concept of Pareto Front. Fig. 7 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
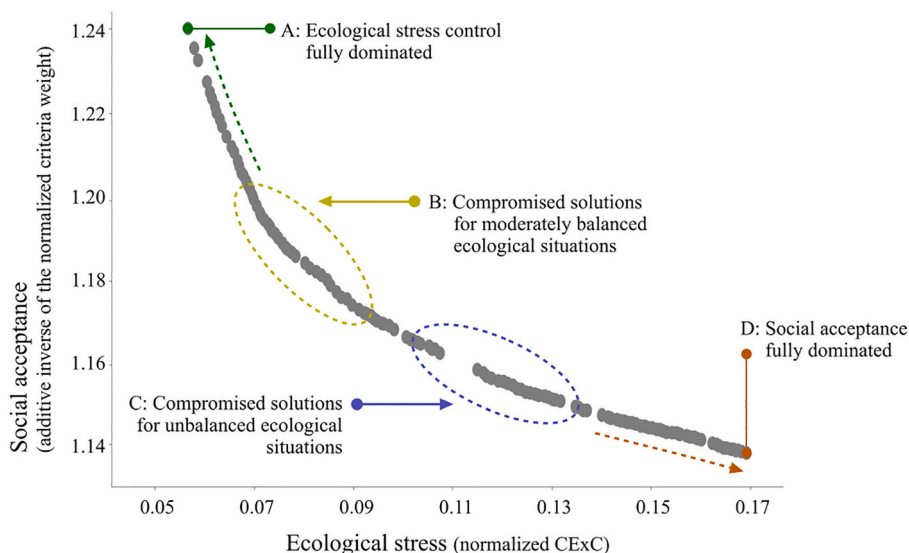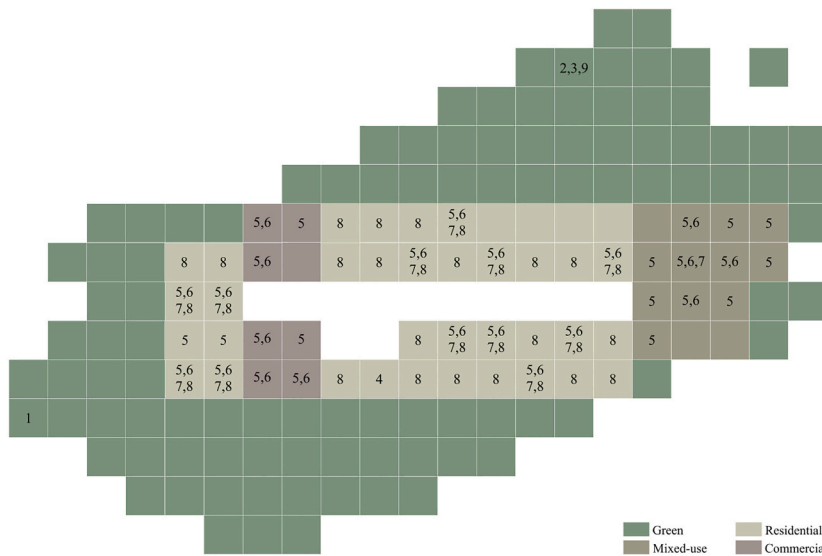

Fig. 7. Pareto Front of the S.N.O.G. optimization model for an optimum nexus process of 30 years during 2020 and 2050 in BSD.

A) Optimum nexus scenario for BSD

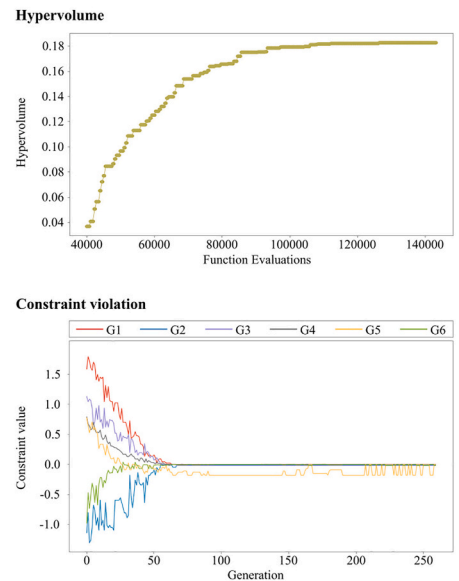**B) Model performance evaluation**

Fig. 8. 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. 6 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 Subsection 4.1. for the normalization procedure).

social acceptance. Fig. 8 illustrates the most optimal solution, compromising all the situations equally.

Based on land-use configuration and availability of resources in BSD, the optimum spatial allocation of the pre-defined nexus policies (presented in Fig. 6), either in combination or individually, was made through the simulation of long-term operation (Fig. 8). 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, we developed two other alternative scenarios (Fig. 9). 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 analyzing 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. 8). 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, allowing tool users to evaluate and discuss alternative scenarios collaboratively and reach a consensus on the most timely-appropriate solution.

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 the S.N.O.G. tool provides, to be developed in future research.

5.3. 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: Table A.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

A) Alternative nexus scenarios for BSD
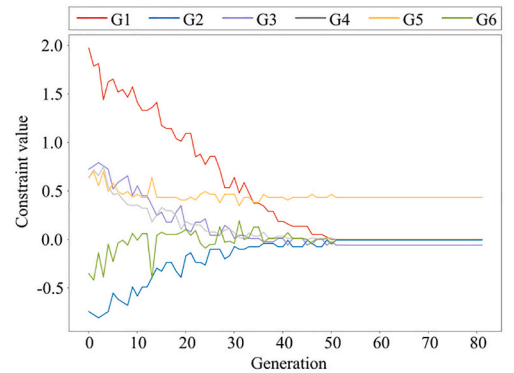
I. Self-sufficiency scenario
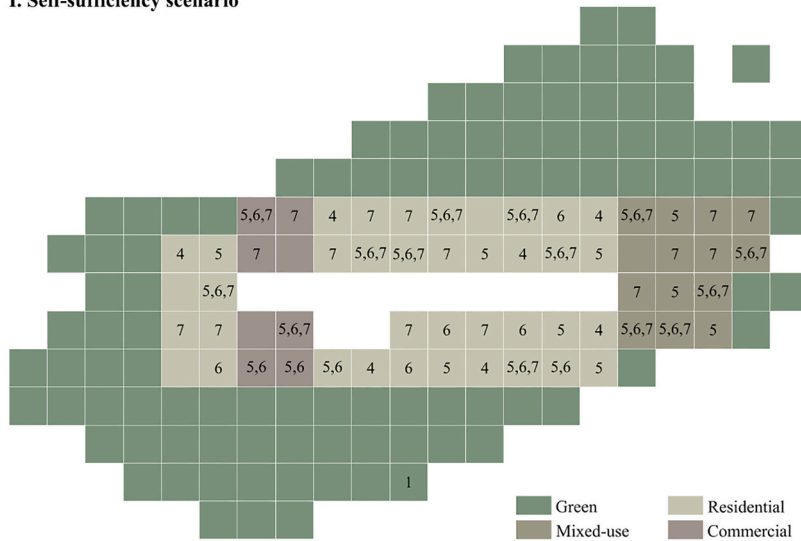
II. Eco-conscious consumerism scenario
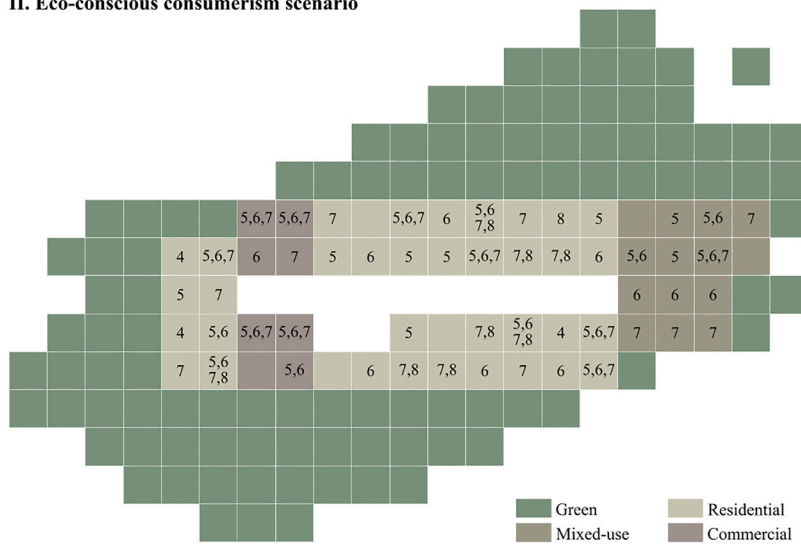
B) Scenarios evaluation

Constraint violation
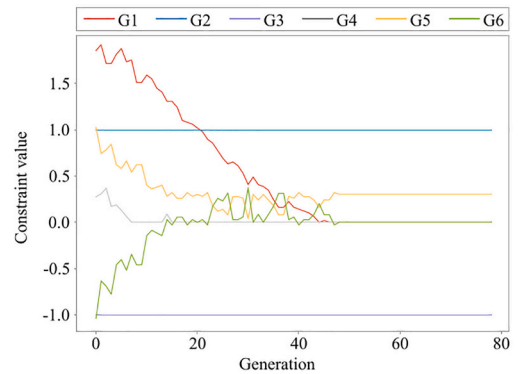

Constraint violation

Fig. 9. Illustration of alternative nexus scenarios for BSD, each employing 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.

Table 5

Payoff matrix for a coalition game model based on the sample alternative scenarios developed for BSD. In this table, player 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: Fig. A.3.

recommends the integration of the Agent-Based Modeling 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.

6. S.N.O.G. evaluation: overall tool 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. through which policymakers and communities can collaboratively formulate effective strategies 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: Fig. A.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).

In the domain of FWE nexus optimization with many objective functions, S.N.O.G. is capable to cope and perform under setting-transfer and workload-scale. Transferability is the extent to which the measured effectiveness of an applicable intervention through S.N.O.G. could be achieved in another setting. Scalability is the ability of the model to be tested by larger operational demand. These are characteristics of S.N.O.G. that highligh its effectiveness both in science and practice. On the strength of MOO, the algorithm developed and designed for S.N.O.G. can be modified easily and many other objective functions can be formulated. 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. The model can be scaled to different demands. The enhanced form of the NSGA-II algorithm in this study facilitates up or down scaling of the spatial properties of the model. As grid cells represent the spatiality of interventions in the model, calculations are simple and do not require high computation capacity, though highly depends on the complexity of optimization functions. It was assessed in the phase of grid size selection for the studied area (please see Fig. A.4 in appendix for more information on S.N.O.G. scalability). 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. Our 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 modeling (ABM). Effective nexus management requires the evaluation of the decisions derived from support tools against such modeling 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 another publication of the authors, S.N.O.G. was employed to guide a real-life nexus practice (Ghodsvali, Dane, & de Vries, 2022b). In this practical employment of the S.N.O.G. model, an online serious game by means of a web-based platform was designed, developed, and tested with real-world stakeholders. The fundaments of the game model implementation, including simulation interface, simplified visualization, simultaneous feedback, and outcome storage adds to the competence of the game's applications into integrated decision-making for FWE nexus and more importantly into sustainable development. It works like a strategic card game within

which players by deciding which is the right policy to implement within a specific region, develop different scenarios of resource management and evaluate how these policies affect the resources and the environment over time. From the multiple gameplays of volunteered stakeholders, it was evaluated that the game helped participants identify and indicate key drivers of integrated resource management, and how the game can strengthen the learning policy outcomes.

7. 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. Modeling of urban development scenarios and 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 framework for a tool that considers the need of the interconnectedness of these essential resources. Methodologically, the presented tool 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. 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 incorporate into the model as a basis for a cooperative decision-making environment. The application of the model to a synthetic nexus example problem has demonstrated that the proposed approach can produce robust decision support outcomes. The 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.

CRediT authorship contribution statement

Maryam Ghodsvali: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Gamze Dane:** Writing – review & editing, Supervision. **Bauke de Vries:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

730254.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compenvurbsys.2023.101940.

References

Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The water-energy-food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters, 13*(4), Article 043002. https://doi.org/10.1088/1748-9326/aaa9c6

Al-Saidi, M., & Elagib, N. A. (2017). Towards understanding the integrative approach of the water, energy and food nexus. *Science of the Total Environment, 574*, 1131–1139. https://doi.org/10.1016/j.scitotenv.2016.09.046

van der Bie, R., Hermans, B., Pierik, C., Stroucken, L., & Wobma, E. (2012). Food for thought, dietary and health trends in the Netherlands. *Statistics Netherlands*, 7–25 (https://www.cbs.nl/en-gb/publication/2012/49/food-for-thought).

Blank, J., & Deb, K. (2020). Pymoo: Multi-objective optimization in Python. *IEEE Access, 8*, 89497–89509. https://doi.org/10.1109/ACCESS.2020.2990567

Centraal Bureau voor de Statistiek. (2009). Livestock manure and nutrients 1990–2008. In *Statistics Netherlands*.

Daher, B., & Mohtar, R. H. (2015). Water–energy–food (WEF) Nexus Tool 2.0: Guiding integrative resource planning and decision-making. *Water International, 40*(5–6), 748–771. https://doi.org/10.1080/02508060.2015.1074148

Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation, 6*(2), 182–197. https://doi.org/10.1109/4235.996017

Endo, A., Burnett, K., Orencio, P., Kumazawa, T., Wada, C., Ishii, A., … Taniguchi, M. (2015). Methods of the water-energy-food Nexus. *Water, 7*(10), 5806–5830. https://doi.org/10.3390/w7105806

FAO. (2014a). *Evidence-based assessment of the sustainability and replicability of integrated food-energy systems*. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/i3669e/i3669e.pdf.

FAO. (2014b). The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture. http://www.fao.org/3/a-bl496e.pdf.

Garcia, D. J., & You, F. (2016). The water-energy-food nexus and process systems engineering: A new focus. *Computers & Chemical Engineering, 91*, 49–67. https://doi.org/10.1016/j.compchemeng.2016.03.003

García, G. A., Rosas, E. P., García-Ferrer, A., & Barrios, P. M. (2017). Multi-objective spatial optimization: Sustainable land use allocation at sub-regional scale. *Sustainability, 9*(6), 927. https://doi.org/10.3390/su9060927

Geudens, P. J. J., & Grootveld, J. (2017). Dutch drinking water Statistics 2017. In *Association of Dutch water companies (Vewin)*. https://www.vewin.nl/SiteCollectionDocuments/Publicaties/Cijfers/Drinkwaterstatistieken-2017-EN.pdf.

Geurts, M., van Bakel, A. M., van Rossum, C. T. M., de Boer, E., & Ocké, M. C. (2016). Food consumption in the Netherlands and its determinants. In *National Institute for Public Health and the Environment*. National Institute for Public Health and the Environment P.O. http://www.rivm.nl/en.

Ghodsvali, M. (2021). Spatial multi-objective optimization of food-water-energy Nexus in Python. https://github.com/mghodsvali/SNOG.

Ghodsvali, M., Dane, G., & de Vries, B. (2022a). The nexus social-ecological system framework (NexSESF): A conceptual and empirical examination of transdisciplinary food-water-energy nexus. *Environmental Science & Policy, 130*(July 2021), 16–24. https://doi.org/10.1016/j.envsci.2022.01.010

Ghodsvali, M., Dane, G., & de Vries, B. (2022b). An online serious game for decision-making on food-water-energy nexus policy. *Sustainable Cities and Society, 87* (September), Article 104220. https://doi.org/10.1016/j.scs.2022.104220

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

Giampietro, M., Mayumi, K., & Ramos-Martin, J. (2009). Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. *Energy, 34*(3), 313–322. https://doi.org/10.1016/j.energy.2008.07.020

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., … Ramma, I. (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change, 3*(7), 621–626. https://doi.org/10.1038/nclimate1789

Ilavendhan, A., & Saruladha, K. (2018). Comparative study of game theoretic approaches to mitigate network layer attacks in VANETs. *ICT Express, 4*(1), 46–50. https://doi.org/10.1016/j.icte.2017.12.002

IRENA. (2015). *Renewable energy in the water, energy & food nexus*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Water_Energy_Food_Nexus_2015.pdf.

Kaddoura, S., & El Khatib, S. (2017). Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. *Environmental Science & Policy, 77*(May), 114–121. https://doi.org/10.1016/j.envsci.2017.07.007

Leung Pah Hang, M. Y., Martinez-Hernandez, E., Leach, M., & Yang, A. (2016). Designing integrated local production systems: A study on the food-energy-water nexus. *Journal of Cleaner Production, 135*, 1065–1084. https://doi.org/10.1016/j.jclepro.2016.06.194

Namany, S., Al-Ansari, T., & Govindan, R. (2018). Integrated techno-economic optimization for the design and operations of energy, water and food nexus systems constrained as non-cooperative games. In *, Vol. 44. Computer aided chemical engineering* (pp. 1003–1008). Elsevier Masson SAS. https://doi.org/10.1016/B978-0-444-64241-7.50162-2.

Namany, S., Al-Ansari, T., & Govindan, R. (2019). Sustainable energy, water and food nexus systems: A focused review of decision-making tools for efficient resource management and governance. *Journal of Cleaner Production, 225*, 610–626. https://doi.org/10.1016/j.jclepro.2019.03.304

Rasmusen, E. (2006). *Games and information: An introduction to game theory* (4th ed.). Wiley-Blackwell.

Rosales-Asensio, E., de la Puente-Gil, Á., García-Moya, F.-J., Blanes-Peiró, J., & de Simón-Martín, M. (2020). Decision-making tools for sustainable planning and conceptual framework for the energy–water–food nexus. *Energy Reports, 6*(April), 4–15. https://doi.org/10.1016/j.egyr.2020.08.020

Salman, M. (2013). Diagnostic tools for investment in agricultural water management. *FAO*, 4–49. http://www.ipcinfo.org/fileadmin/user_upload/agwa/docs/WIF-AgWA-PPT.pdf.

Sciubba, E., & Wall, G. (2007). A brief commented history of exergy from the beginnings to 2004. *International Journal of Thermodynamics, 10*(1), 1–26.

Sohrabi, M. K., & Azgomi, H. (2020). A survey on the combined use of optimization methods and game theory. *Archives of Computational Methods in Engineering, 27*(1), 59–80. https://doi.org/10.1007/s11831-018-9300-5

Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., … Brouwer, F. (2018). Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate Nexus: The SIM4NEXUS approach. *Water, 10*(2), 139. https://doi.org/10.3390/w10020139

The World Economic Forum Water Initiative. (2011). An integrated sustainability index for effective water policy. In D. Waughray, & R. H. Mohtar (Eds.), *Water security: The water-food-energy-climate Nexus* (pp. 217–219). Island Press.

UNStudio, Felixx Landscape Architects & Planners, Metabolic, UNSense, & Habidatum. (2019). Brainport smart district stedenbouwkundige visie [Brainport smart district Urban Vision]. https://brainportsmartdistrict.nl/wp-content/uploads/2020/01/190204_A5-UNS_BSD_Executive-Summary_spreads.pdf.

Vardoulakis, S., & Kinney, P. (2019). Grand challenges in sustainable cities and health. *Frontiers in Sustainable Cities, 1*(December), 1–5. https://doi.org/10.3389/frsc.2019.00007

Voedingscentrum. (2019). Synthesis Report on Food Waste in Dutch Households in 2019. In *Healthy and Sustainable Food Systems*. https://www.taylorfrancis.com/books/9781351189026/chapters/10.4324/9781351189033-15.

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P. D., Bommel, P., … Smajgl, A. (2018). Tools and methods in participatory modeling: Selecting the right tool for the job. *Environmental Modelling & Software, 109*(August), 232–255. https://doi.org/10.1016/j.envsoft.2018.08.028

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., … Ramu, P. (2016). Modelling with stakeholders – Next generation. *Environmental Modelling & Software, 77*, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016

WBCSD. (2014). Co-optimizing solutions : Water and energy for food. In *Feed and fiber*. World Business Council for Sustainable Development. https://docs.wbcsd.org/2014/05/WBCSD_Co-op_Report.pdf.

Xiao, M., Shao, X., Gao, L., & Luo, Z. (2015). A new methodology for multi-objective multidisciplinary design optimization problems based on game theory. *Expert Systems with Applications, 42*(3), 1602–1612. https://doi.org/10.1016/j.eswa.2014.09.047

Zamarripa, M. A., Aguirre, A. M., Méndez, C. A., & Espuña, A. (2013). Mathematical programming and game theory optimization-based tool for supply chain planning in cooperative/competitive environments. *Chemical Engineering Research and Design, 91*(8), 1588–1600. https://doi.org/10.1016/j.cherd.2013.06.008