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The nature-based solutions planning support system: A playground for site and solution prioritization

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ABSTRACT

Cities are increasingly adopting Nature-Based Solutions (NBS) to address multiple societal challenges effectively. Successful adoption of NBS and realization of their multifunctionality requires a holistic and collaborative planning approach that incorporates stakeholders across scales and disciplines. However, such an approach is usually not aligned with the mainstream sectoral planning process in cities. Planning support systems (PSS) play an essential role in the transition to collaborative planning. Current systems used for NBS planning tend to be highly specialized, focusing on a few ecosystem services and a single scale. As a response, the NBS-PSS is introduced. This system’s novel multiscale hierarchical framework helps stakeholders to prioritize sites and solutions in an integrative manner. The NBS-PSS provides the flexibility needed for NBS planning and allows users to interact and iterate over different planning process stages. The system has been tested in the city of Eindhoven with a group of experts. Accordingly, the system appears to have a high capacity to facilitate collaboration and motivate stakeholders to engage in the planning process, given the rapid responses and easy-to-understand process and data representation. Moreover, the NBS-PSS was found to be a helpful tool for enhancing the awareness of opportunities for NBS in urban settings.

1. Introduction

Providing a vibrant, sustainable and resilient living environment is becoming a central goal for many cities across the world (Pancost, 2016). Cities are dealing with several challenges arising from rapid urbanization and climate change—such as heatwaves, flooding, air pollution, and social equity (European Environmental Agency, 2012). Nature-Based Solutions (NBS) are believed to enhance urban resilience by helping to buffer against these challenges (McPhearson, Andersson, Elmqvist & Frantzeskaki, 2015).

Therefore, NBS have increasingly been adopted by cities across the world to enhance sustainability and resilience (Laforetza, Chen, van den Bosch & Randrup, 2018). NBS refers to “actions which are inspired by, supported by or copied from nature” (European Commission, 2015) and designed to address multiple environmental, social, and economic challenges through delivering multiple ecosystem services (Cohen-Shacham, Walters, Janzen, & Maginnis, 2016). The multifunctionality is the main selling point of NBS in cities where traditional gray solutions have long been dominant (Raymond et al., 2017), and realizing the multifunctionality demands a collaborative governance and planning approach (Dorst, van der Jagt, Raven & Runhaar, 2019).

Despite the espoused emphasis on multifunctionality, trans-disciplinarity, and co-creating solutions with urban stakeholders, the NBS planning process in practice typically includes only a few experts focusing on a limited number of functions and ecosystem services. The main cause of this lack of collaboration and co-creation appears to be the silo mentality prevailing among the stakeholders involved (Kabisch et al., 2016; Sarabi et al., 2020). A lack of collaboration in the context of NBS spatial planning can have significant consequences. Many benefits arising from NBS in urban settings are local in nature, with a limited service benefit area for any particular solution (Hanssen & Pauleit, 2014). Therefore, siting NBS plays an essential role in defining who and what will be receiving these benefits (Meerow & Newell, 2019). Inappropriate spatial planning and siting of NBS does not only limit their functionality but can also lead to other issues such as ineffective resource use and environmental injustice (Wilson, Hutson & Mujahid, 2008).

Planning support systems (PSS) and related tools can play an
essential role in NBS planning. These systems can improve NBS planning by visualizing, analyzing, and combining different sources of spatial information in a format that is understandable to a wide range of stakeholders (Geertman & Stillwell, 2003). Such systems can facilitate the collaborative planning process by providing a setting in which various stakeholders can express their opinions and preferences, and test different alternatives in a fast and cost-effective way (Malczewski, 2006). However, the planning support systems that are currently available tend to be highly specialized and only a limited group of experts are capable of understanding and applying them (Kuller, Farrell, Deletic & Bach, 2018). Therefore, there is a need for models and methods that can encourage and support the collaborative spatial planning process by integrating multiple disciplines in an easy-to-understand way; models that can consider multiple social, economic, and ecological benefits provided by NBS (Ronchi, Arcidiacono & Pogliani, 2020), while taking the practicality of decisions into account.

In this paper, we introduce the so-called Nature-Based Solutions Planning Support System (NBS-PSS). This system provides a playground for collaborative NBS spatial planning process in urban areas. It integrates various functionalities of NBS in multiple scales and guides stakeholders in finding inclusive solutions that ensure the fulfillment of societal needs as well as an equitable distribution of ecosystem services (Bush & Doyon, 2019).

This paper is structured as follows. Section 2 describes the theoretical background of the NBS-PSS as well as its system architecture and development process. In Section 3, the results from testing this system in the city of Eindhoven are presented. Subsequently, the implications, strengths, and limitations of these findings are discussed in Section 4. In Section 5, a conclusion is provided.

2. The NBS planning support system

2.1. Background

Several planning support systems concerning NBS development have been proposed (Voskamp, de Luca, Polo-Ballinas, Hulsman & Broksma, 2021). However, they have rarely been picked up by practitioners, mainly due to their complexity, low user-friendliness, and the extensive training and time needed to generate relevant outputs (Kuller et al., 2018). For example, the SUSTAIN model developed by the U.S. Environmental Protection Agency (EPA) helps to find the optimal location for stormwater solutions, focusing on stormwater management functionalities (Lee et al., 2012), but is a relatively complex tool that requires a trained expert to operate.

For planning multifunctional NBS, it is necessary to consider the preferences of stakeholders (Hansen & Pauleit, 2014); however, only a few of the previously proposed systems properly incorporate stakeholder-driven weighting to take different priorities and preferences of stakeholders into account. Norton et al. (2015) proposed a multiscale hierarchical framework to prioritize the placement and type of green infrastructure; however, these authors mainly focused on the cooling benefits, without using stakeholder-derived weights. Madureira & Andresen (2014) estimated the spatial priority areas for green infrastructure, based on two criteria - proximity to public green spaces and the potential to improve local temperature regulation - again without including stakeholder input to weight these criteria. More recently, several studies have integrated the multifunctionality of NBS with the preferences of local stakeholders. Meerow and Newell (2017) presented the GISP model to identify priority neighborhoods for green infrastructures, using six ecosystem services and stakeholder-derived weights. Nevertheless, their model does not provide a site suitability assessment and does not account for the various constraints of implementing green infrastructures in urban areas. Kuller, Bach, Roberts, Browne & Deletic (2019) proposed SSANTO as a tool for finding suitable sites for implementing green stormwater infrastructure, considering both ecosystem services and the feasibility of implementation; this tool is capable of weighting criteria based on the preferences of stakeholders. However, SSANTO is not able to prioritize and recommend specific green infrastructure technologies. Another proposed system that is developed as a participatory planning tool is the Adaptation Support tool (AST) (van de Ven et al., 2016). This system is capable of prioritizing and proposing specific green infrastructure technologies and estimating their performance and costs, while it is not designed to perform a site suitability analysis. Table 1 provides a summary of the features and characteristics of the systems and frameworks discussed in this section.

2.2. NBS-PSS: system’s objectives

The systems and frameworks outlined in Section 2.1 imply there is a need for planning support systems that can address questions such as ‘where to implement NBS?’ and ‘which NBS to implement?’ in an integrative manner. In this section, we introduce the NBS Planning Support System (NBS-PSS) as a multiscale collaborative planning support system that facilitates identifying suitable intervention areas and solutions, while providing the opportunity for stakeholders to express their priorities and actively participate in the planning process. NBS-PSS is designed in view of the following objectives:

(a) providing a multiscale environment to facilitate communication and collaboration across scales which is necessary for strategic NBS planning (Demuzere et al., 2014; Wyborn & Bixler, 2013);
(b) providing a flexible framework that can be adopted by cities with different goals, and with access to different types of data;
(c) providing the required flexibility and transparency for NBS planning by integrating the procedural and rule-based knowledge which is necessary for proposing effective solutions to complex problems (Leung, Fischer, & Nijkamp, 1993); This enables users to include their local knowledge in the analysis;
(d) providing an integrated framework for the prioritization of NBS measures and assessment of site suitability;
(e) maximizing the NBS benefits and co-benefits through integrating different functionalities while considering the practicality of solutions.

The main benefit of this system is that it automates and integrates the process of multi-criteria decisions that need to be made in identifying suitable NBS measures and intervention areas, which otherwise would be a highly time-consuming process. In the remainder of this section, the key process used by the system is presented.

2.3. NBS-PSS: system’s process

The proposed NBS-PSS process includes five steps: see Fig. 1 for an overview. In the first step, neighborhoods are prioritized by using a spatial multi-criteria evaluation (MCE) framework that incorporates stakeholder priorities (see also Meerow & Newell, 2017). In the second step, a set of NBS is recommended to stakeholders in response to the needs of the identified neighborhood(s). In the third step, a site suitability analysis is performed for the selected NBS in the given neighborhood. In the fourth step, users specify an intervention area for implementing the selected NBS. In the fifth step, users are provided with a comparison of various NBS regarding their suitability, and costs of implementation and maintenance in the specified intervention area.

The proposed NBS-PSS system is intended to be used in the context of collaborative planning practices. It provides the opportunity for stakeholders to test different preferences and iterate back and forth between the various steps to reach a collective solution. The multiscale hierarchical structure of the system is inspired by the framework proposed by Norton et al. (2015). In addition, an automated site and solution suitability assessment is incorporated in a collaborative framework, which accounts for the multiple benefits provided by NBS. In the following
subsections, each step is discussed in greater detail.

2.4. Step one: prioritize neighborhoods

Different neighborhoods in a city are usually dealing with different challenges. For example, some neighborhoods are more exposed to air pollution, whereas others are dealing more with heat stress. In this step, the neighborhoods are ranked in view of their level of exposure and/or vulnerability to a set of challenges; here, exposure refers to the presence and proximity of hazardous areas, while vulnerability refers to the characteristics of an area or community that makes it prone to the damaging effects of a hazard. Examples of challenges for which NBS can be used are heat stress, stormwater management, air quality, landscape connectivity, and spatial equity. These five challenges are among the most common objectives for developing NBS (Raymond et al., 2017; Sarabi, Han, Romme, de Vries & Wendling, 2019) and were therefore selected for testing the NBS-PSS. The challenges included here need to be tailored to the local context to which NBS-PSS is applied and the available data. The system thus provides the opportunity for users to add or remove challenges from the analysis.

2.4.1. Developing challenge maps

First, maps representing the exposure and/or vulnerability of various neighborhoods to the selected challenges should be developed. There are different indicators that can be used for each of the challenges (Raymond et al., 2017). The selection of the indicators mainly depends on the data available in the city where NBS-PSS is used. Table 1 presents examples of indicators and datasets. See appendix A for more detailed information about the challenges and the methods for developing the challenge maps. For a more comprehensive list of indicators, see Dumitru & Wendling, (2021).

2.4.2. Weighting by stakeholders

NBS are developed with the aim to address multiple societal

Table 1
Characteristics of available systems and frameworks.

| Framework | Spatial scale of analysis | Unit of analysis | Functionality | Stakeholder-derived weights | Ecosystem services and/or challenges considered |
|-----------|----------------------------|------------------|---------------|-----------------------------|------------------------------------------------|
| SUSTAIN Lee et al. (2012) | Watershed scale | Site-level | Site suitability assessment | No | Stormwater regulation, Water purification |
| Norton et al. (2015) framework | Multiscale (City-neighborhood-site) | Site-level | Site suitability assessment, Technology suitability assessment, Cost estimation | No | Local temperature regulation |
| Madureira & Andresen (2014) framework | Urban-scale | Land-use unit | Site suitability assessment | No | Local temperature regulation, Proximity to green spaces (socio-cultural functions) |
| GISP model (Meerow & Newell, 2017) | Urban-scale | Census tract | Site suitability assessment | Yes | Local temperature regulation, Stormwater regulation, Air quality, Landscape connectivity, Social vulnerability, Access to green spaces, Fresh water provision |
| SSANTO (Kuller et al., 2019) | Urban-scale | Site-level | Site suitability assessment | Yes | Local temperature regulation, Stormwater regulation, Social relations and recreation, Fresh water provisio |
| AST (van de Ven et al., 2016) | Site-scale | Site-level | Technology suitability assessment, Impact assessment, Cost estimation | No | Local temperature regulation, Stormwater regulation, Drought, Water safety |

1 Site suitability assessment considers both assessment of vulnerability and/or exposure to challenges and the feasibility of implementation.
2 Spatial priority assessment finds the hotspots for implementing NBS considering the vulnerability and/or exposure to challenges.

Fig. 1. NBS-PSS process flow (continuous black lines show the forward movement between different steps and black dashed lines refer to iterations among steps; the gray dashed lines point at opportunities for interaction between users and the NBS-PSS process).
challenges. However, not all challenges have the same level of importance across different cities and different stakeholders. Therefore, the NBS-PSS provides stakeholders with the opportunity to define specific weights for each of the challenges. That is, stakeholders give a weight, based on their perception of the importance of each challenge. To find a final weight for each challenge, a combination (of several methods such as averaging or Delphi) can be used to reach a consensus among stakeholders. To find a suitable weight for each of the challenges, we combined several methods considering the impact of each NBS on each challenge (Table 3) and the level of each challenge in the selected neighborhood (derived from the normalized challenge maps in step 1). We consider eight NBS measures, which are among the most common solutions implemented in urban areas. These eight NBS are selected in view of the different urban settings (buildings, land, water) where they can be implemented; we also acknowledge the different types and levels of benefits of these NBS, to be able to test the functionality of the system. These NBS are rain garden, bioswale, retention pond, detention basin, extensive green roof, intensive green roof, permeable pavement, and line of trees. Table 3 indicates the level of impact each NBS can potentially have on each challenge, using a scale from zero to five. These challenges are the same as the ones selected in step 1 (i.e. the five challenges presented in step 2.4.1). The values in Table 3 were collected from the literature and available knowledge repositories (Alves et al., 2018; DEFRA, 2020; NWRM, 2020). A value of five means the NBS has a relatively high potential to address the challenge, while a value of zero means the NBS cannot be helpful to address this challenge. For example, rain gardens have a high potential to address the stormwater management challenge, but have a relatively low impact on the air quality challenge; and permeable pavements have a high potential in addressing stormwater challenges, while they make a rather low contribution to landscape connectivity. For spatial equity, the potential of the NBS to provide access to nature is considered. To prioritize NBS, the relative level of each challenge in the selected neighborhood (derived from the normalized challenge maps in step 1) is first identified. Subsequently, considering the impact of each NBS on each challenge (Table 3) and the level of each challenge, the NBS are prioritized using the WLC method. The prioritized list involves a rough estimation based on the average needs of the neighborhood: that is, the NBS with the highest score can potentially best meet those needs. However, to assess the applicability of the solutions proposed, further analysis is needed, as presented in the following steps.

2.6. Step three: site suitability assessment

The suitability of implementing each NBS differs across various locations within a neighborhood, due to the characteristics of each specific location. For example, rain gardens are not suitable for steep surfaces; and trees provide the most cooling benefits in locations with high solar exposure. Assessing these characteristics serves to identify suitable locations for placing a specific NBS. The steps taken in this part of the process are discussed in the remainder of this subsection.

2.6.1. Collecting spatial data, clipping, and developing indicator maps

Surfaces across the neighborhood are characterized based on two groups of indicators: opportunities and challenges. A similar classification of indicators is proposed by Kuller et al. (2019). Opportunities refer to indicators for assessing the feasibility regarding the planning and policy-related factors and/or physical requirements for implementing the NBS, like the slope, distance to the groundwater table, ownership, type of site (i.e. land use and/or function of the site), and so forth. For example, sites with a low distance to the groundwater table are not suitable for measures such as rain gardens or bioswales. Further information regarding each indicator and NBS can be found in Table B.1 and B.2 in the appendix. Challenges include the indicators for assessing the challenges that every location is dealing with, and the extent NBS can

| Challenges                        | Indicators          | Datasets                  |
|-----------------------------------|---------------------|---------------------------|
| Stormwater management             | Impermeability      | Satellite imagery         |
| Air quality                       | Average concentration of air pollutants (e.g. PM2.5, PM10, NOx, NO) | Air pollution concentration maps |
| Landscape connectivity            | Patch Cohesion index| Satellite imagery         |
| Heat stress                       | Land Surface Temperature (°C) | Thermal imagery |
| Spatial equity                    | Social vulnerability + green space accessibility | Census data, road networks & land use |

Table 2

Challenges, indicators, and datasets.

Table 3

Impacts of NBS on challenges.

| Challenges                  | Heat stress | Stormwater management (runoff reduction) | Air quality | Landscape connectivity | Spatial equity (access to nature) |
|-----------------------------|-------------|------------------------------------------|-------------|------------------------|-----------------------------------|
| Line of trees               | 5           | 2                                        | 5           | 4                      | 3                                 |
| Extensive green roof        | 3           | 4                                        | 3           | 3                      | 2                                 |
| Intensive green roof        | 4           | 4                                        | 5           | 4                      | 4                                 |
| Permeable pavement          | 2           | 4                                        | 0           | 1                      | 1                                 |
| Rain garden                 | 3           | 4                                        | 2           | 4                      | 1                                 |
| Detention basin             | 2           | 5                                        | 0           | 2                      | 3                                 |
| Retention pond              | 2           | 5                                        | 0           | 4                      | 3                                 |
| Bioswale                    | 2           | 4                                        | 2           | 3                      | 2                                 |
help to address them. In other words, challenge indicators represent the needs of each location which can be met by NBS. The main difference between the challenge indicators in this step and the challenge indicators used in step 1 is the spatial resolution. The indicators used in step 1 do not need to have a high spatial resolution, since the aim in that step is to make an average challenge index for the neighborhood; in the current step, a higher spatial resolution is needed to compare different sites within the selected neighborhood on a micro scale (site level). In fact, the challenges and the indicators used in this step are independent from those used in step 1; therefore, the challenges in step 3 do not necessarily have to be the same as the ones used in step 1. This is important since the high resolution data used in step 3 might not be available to every city for every challenge considered in step 1. Accordingly, the system provides users with the opportunity to employ the data available to them.

In this stage, the spatial data corresponding to the indicators from both challenge and opportunity sides are collected. The main difficulty in this step is the availability of high-resolution spatial data. The quality, type, and resolution of data available to each city are different, which defines the indicators that can be used in this step. To manage the challenge of data accessibility, in some cases, alternative indicators can be used. For example, for air quality, a buffer around the major roads can be used as an alternative indicator to high-resolution air pollution dispersion maps, which are not accessible in every city. Considering the type and the higher resolution of data used in this step, to accelerate the calculation and better account for the changes of the surface, the site suitability assessment is performed using grid cells. The size of the grid cells can be defined by the users considering the data available to them.

A list of candidate indicators that can be used is presented in Table 4.

### 2.6.2. Masking & value scaling

First, the locations where the selected NBS is not applicable are masked out. These are the locations where at least one of the indicators is making the implementation of the selected NBS impossible. For example, if the selected NBS is the green roof, all non-rooftop areas are excluded from the analysis, or for a rain garden, cells with a slope higher than 15% are masked out.

To combine the challenge and opportunity indicators, they need to be standardized and transformed into a common suitability scale (similar to the approach for the neighborhood scale). The value function is used to convert indicator maps’ values into comparable units (Malczewski & Rinner, 2015). The shape of the value function is different per NBS and indicator. For example, a 7% slope has a different meaning and value for a rain garden than a line of trees. Value functions have been derived using NBS design guidelines and relevant literature (Dubovik et al., 2020; Eisenberg & Polcher, 2018; EPA, 2021; Li, Fan, & Shen, 2018). The score ranges for different NBS are presented in Appendix B. For each indicator, a value range between 0 (least suitable) to 10 (most suitable) is assigned to each cell representing the suitability of implementing a selected NBS. It should be noted that the value scale can vary in different conditions. For example, in different contexts, value scaling of the ownership might be different. In some contexts, private spaces might be considered suitable, while in another context, users might prefer to exclude them.

| Opportunities | Indicators | Datasets |
|---------------|------------|----------|
| Biophysical   | Slope      | Digital Surface Model (DSM) |
|               | Building rooftops | Building footprints |
|               | Distance to the groundwater table | Groundwater level data |
|               | Tree protection zone | Tree canopy maps (Lidar data and satellite imagery, see Appendix B) |
| Planning & policy | Ownership | Cadaster |
|                | Type of site | Land-use / Topographic maps |
|                | Width of pathways/Road sections | Topographic maps |
|                | Proximity to structures | Building footprint / Topographic maps |
|                | Lot size/Roof(flat) area | Topographic maps / Building footprints |
|                | Building age | Cadaster |

### 2.6.3. Generating the suitability map

In this step, three maps are produced: the implementation opportunity map, challenge map, and final suitability map. By combining the opportunity indicators, the opportunity map serves to identify the locations where implementation is the most practical. By combining the challenge indicators, the challenge map is generated, which helps to identify locations that may need NBS the most. Then the two maps are standardized and combined to generate the final NBS suitability map. Stakeholders can assign a weight to each of the two maps. In other words, they can express the importance of the relative effort it takes to implement a solution, compared to the impact it might have. Besides, the option is provided to indicate a weight for each indicator from both the opportunity and challenge sides. If no weight is defined by stakeholders, equal weight is assigned to all indicators. The aggregation of indicators is performed using the WLC method.

### 2.7. Step four: specify the intervention area

In this step, stakeholders need to specify a site representing the NBS intervention area, using the suitability map created in the previous step. Stakeholders should draw a shape (e.g., a polygon or circle) that shows the possible site for implementing the selected solution. The suitability map can be overlaid with an aerial image (or a topographic map) of the area to draw a more realistic shape.

### 2.8. Step five-1: compare the suitability of different NBS

Stakeholders might face another dilemma. The selected location in the previous step might be suitable for implementing the selected NBS, but the selected NBS might not be the most suitable solution at that location. To facilitate the comparison between the suitability of different NBS in the specified location, the system calculates the suitability score of each NBS in the identified intervention area. The suitability score is the sum of the opportunity and challenge score of each NBS in the intervention area. To calculate the opportunity and challenge scores, the system first identifies the characteristics of the specified intervention area using the indicator maps developed in step 3. For example, the average slope of the surface of the intervention area is assigned as its slope, or the land use covering the major part of the intervention area is assigned as its land use. Then considering the value scaling table (Appendix B), for each NBS, an opportunity and challenge score is calculated and summed up to generate the suitability score for each NBS at the intervention area, which is a value between 0 and 10.
2.9. Step five-2: estimate the implementation and maintenance costs

One of the important factors in deciding the location and type of the NBS is the cost of implementing and maintaining the solution. In this step, the system provides users with an estimation of the implementation and maintenance costs of different NBS at the selected location. The estimation is done by considering the implementation and maintenance costs of each NBS per unit area and the area of the layer drawn by stakeholders in step 4; the exception is a line of trees. In the latter case, the number of trees that can possibly be placed in the specified area is first estimated and then multiplied by the cost per tree.

The average costs for the Netherlands, where the system was developed, are considered as the default costs per unit area in the system (see Table 5). The costs presented in Table 5 were obtained by reviewing the relevant literature and reports (Deltares, 2020; Dubovik et al., 2020; Eisenberg & Polcher, 2018). These costs can vary significantly across municipalities and in different conditions; therefore, the users have the opportunity to modify these values. However, the main intention is to provide the opportunity for making a rough comparison between the costs of different solutions, not to give a highly accurate estimation of the costs. Since here the costs are calculated only based on the size of the intervention area and unit area costs of NBS without taking the local conditions into account.

3. Testing the NBS-PSS

3.1. Case study

3.1.1. Context

Eindhoven is the fifth-largest city in the Netherlands; it has a temperate oceanic climate and is located in the basin of the river Dommel. It has an all-time temperature record of 40.3 °C on 25 July 2019 and –21.7 °C on 13 January 1968 and an average temperature of 11.96 °C in 2020 (KNMI, 2021). Eindhoven is a city with a population density of 2674 persons per square kilometer and a total population of 234.401 (Statistics Netherlands, 2020), where the gray elements are dominant in its central areas. Eindhoven includes 116 neighborhoods, each dealing with different challenges. In recent years, the municipal administration of Eindhoven has been actively looking for and adopting different innovative approaches to build up the city’s resilience towards climate change, including NBS (Ascenso et al., 2021; Augusto et al., 2020).

Despite agreeing on the importance and effectiveness of NBS to address multiple societal challenges in Eindhoven, the adoption of these solutions has thus far been limited in this city, due to several barriers (Sarabi et al., 2020): two critical barriers to NBS adoption are that municipal departments are suffering from sectoral and informational silos and many staff members are lacking knowledge and experience in NBS. These barriers make Eindhoven an ideal case for testing the NBS-PSS.

3.1.2. Workshop

This test can be conceived as an alpha test. Alpha testing is typically performed with an active engagement of the designers, to validate the functionality of the system and the generated results as quickly as possible (Craig & Jaskiel, 2002). For this purpose, an online workshop was conducted with eight expert stakeholders from different departments of the municipality and external agencies with diverse backgrounds, including water management experts, climate adaptation strategists, urban ecologists, urban planners, and health and well-being specialists. The online format of this workshop was a direct implication of the COVID-19 lockdown situation in the Netherlands at the time. Experts were selected based on the relevance of their expertise and role to NBS planning and their experience with planning practices at the city of Eindhoven. In this workshop, every step in the system was tested, and the participants’ feedbacks were recorded.

3.1.3. Data collection

To facilitate the system’s adoption, we mainly used data that are easily accessible for cities. Most data were obtained from European, national, or municipal databases that are publicly accessible. The datasets for the challenge maps used in step 1 and the indicator maps used in step 3 were collected before the workshop. A further description of the data used for the test is provided in Appendices A and B.

3.2. Results

3.2.1. Step one: prioritize neighborhoods

Prior to the workshop, the challenge maps were prepared. The methods used for generating the maps are discussed in Appendix A. The first task for the participants was to assign a weight to the challenges. In this step, the Delphi method was used to reach a consensus on the weights of the challenges. Participants were asked to give a weight based on their perception of the importance of each challenge in the city of Eindhoven. This task was done in two rounds. After the first round of rating, participants shared their perspectives and the reasons for their ratings, and then they were asked to rate the challenges again. The average of the weights provided by the participants at the end of the second round was assigned as the final weights for the challenges. Table 6 presents the identified weights.

The challenge maps were combined, considering the identified weights, to generate the final neighborhood priority map (see Fig. 2). After a discussion concerning the seven various neighborhoods identified as having a high priority, participants decided to select Strijp-S as the target neighborhood for further analysis (highlighted in Fig. 2). Strijp-S is a former industrial park that has gone through a rezoning process during the last decade. The neighborhood has become a destination for the creative sector. Residential buildings have also been introduced in this neighborhood during the last years. The most significant challenges in this neighborhood are stormwater management and air quality.

3.2.2. Step two: prioritize NBS

The level of challenges in Strijp-S was derived from the normalized challenge maps (see Appendix A). Based on the level of challenges and the impacts of NBS presented in Table 3, a total score is calculated for each NBS (see Table 7). Accordingly, intensive green roof and line of

| Challenges                  | Heat stress | Stormwater management | Air quality | Landscape connectivity | Spatial equity |
|-----------------------------|-------------|-----------------------|-------------|------------------------|---------------|
| Stakeholder defined Weights | 6.4         | 8.8                   | 7.1         | 8.1                    | 5.6           |

Table 5

| NBS Type               | Average Implementation Cost in €/m² | Maintenance Cost in €/m²/year |
|------------------------|-------------------------------------|-------------------------------|
| Extensive green roof   | 120                                 | 6                             |
| Intensive green roof   | 220                                 | 10                            |
| Raingarden             | 60                                  | 0.5                           |
| Permeable pavement     | 100                                 | 0.4                           |
| Retention pond         | 40                                  | 0.2                           |
| Detention basin        | 25                                  | 0.2                           |
| Bioswale               | 70                                  | 0.7                           |
| Line of trees          | 570 (per piece)                     | 17 (per piece)                |

Table 6

Stakeholder identified weights.
trees are identified as the top two NBS with the highest scores.

3.2.3. Steps three and four: site suitability assessment and intervention area specification

Intensive green roof and line of trees were selected as the target NBS to assess site suitability. The opportunity and challenge indicator maps were generated prior to the workshop. More detailed information regarding the indicators used in this step is presented in Appendix B. The site suitability analysis was performed on 1-meter grid cells considering the spatial resolution of the utilized datasets. By performing the site suitability assessment, opportunity and challenge maps were produced for each NBS (Appendix C), and the final suitability maps were generated (Fig. 3a and b). Using the generated maps, participants selected a target location for each NBS and drew the shapes representing the intervention areas (Fig. 3c and d). The intervention areas were drawn by overlapping the prioritization map with the aerial image of the sites. The selected intervention area for tree plantation is a parking area along a road, and the selected rooftop for implementing an intensive green roof belongs to a mixed-use building. A part of this rooftop was specified as the intervention area.

3.2.4. Step five: compare the suitability of NBS and estimate the costs

In this step, users were provided with a comparison between the suitability of implementing different NBS in the selected intervention area and an estimation of the implementation and maintenance costs for different NBS.

In the selected area for the line of trees, the chosen solution had the highest suitability score. The implementation cost was relatively lower, and the maintenance cost was only slightly higher than for other solutions; therefore, planting a line of trees was recognized as a suitable solution for the selected location. In the intervention area for the intensive green roof, the other applicable solution was the extensive green roof. The suitability score of the intensive green roof was higher considering the higher impact and services it can provide; however, there is a relatively big gap between the implementation and maintenance costs of the two solutions, which can be an essential factor in deciding on the solution to implement (Teotónio, Silva & Cruz, 2021) (see Fig. 4).

3.2.5. Iteration

In the selected site for planting a line of trees, rain garden was identified as the second suitable solution; in the result of step 2, it also
had the third-highest score, which made participants explore the suitable sites for implementation of rain gardens across the neighborhood. Therefore, steps 3, 4, and 5 were repeated to identify the intervention area for implementing rain gardens. Appendix D presents these results.
3.3. Participants’ feedbacks

The stakeholders participating in the workshop provided feedback afterward regarding the functionality and adoptability of the system and various improvement points. In general, these stakeholders found the results to be relevant and the whole process of the system to be rather straightforward. They agreed that the system has a high capability to engage different people in the planning process, especially those who are less represented in mainstream NBS planning practices, like experts from the social and health departments in the municipality. As one participant observed: “This system can help us to motivate our other colleagues, who are not usually involved in this kind of planning sessions, to play a more active role because it allows them to express their needs and see how their choices can affect the plans.”

Several participants signaled that, without a tool like NBS-PSS, performing an adequate NBS analysis takes an enormous amount of time; they acknowledged that this system is very useful for collaborative planning, considering the fast responses in providing valuable results and insights. The participants also emphasized that this tool enhances awareness regarding the adoption of NBS in urban areas.

Moreover, the participants found the process flow to be understandable; operating it could be handled by anyone with a basic knowledge of the GIS software who is usually present in every municipality. However, the usability of the tool for stakeholders outside the municipality, who do not have access to the GIS software, may be limited. In this respect, the participants observed that the main difficulty in operating the tool is moving back and forth between the various steps, since each step needs to be conducted separately. This finding obviously calls for an integrated platform, in which going back and forth in the process requires lesser effort; such an integrated platform is likely to make the system easier to adopt and use.

4. Discussion

NBS are widely recognized as effective solutions to catalyze the transition to more sustainable and resilient cities, considering the multiple ecosystem services they provide. NBS is an inter-and transdisciplinary concept that entails a systemic and holistic perspective on major societal challenges. In this paper, we explored how this holistic approach can be adopted in the spatial planning process by developing a planning support system that serves to mainstream this approach.

As such, we introduced NBS-PSS as a planning support system that facilitates a more strategic and integrated planning process by connecting different stages of the NBS planning process—from defining challenges and selecting solutions to identifying intervention areas and estimating costs—while taking the multifunctionality of NBS as well as the preferences of stakeholders into account.

In this system, we have tried to balance the validity and usability aspects. Multiple criteria in two different scales provide a valid and relevant result, while the system’s logic and functions remain understandable for different stakeholders. One of the main challenges for a system that is designed to facilitate decision-making on complex issues is to validate the results; validation is particularly challenging because of the inherent uncertainties associated with NBS and the lack of available data to assess (van Asselt & Rotmans, 2002). We evaluated the validity and usability of NBS-PSS by testing it in the city of Eindhoven with experienced stakeholders and experts with local knowledge. The main benefit of this system appears to be its potential in facilitating and developing a shared understanding among different groups and supporting the co-creation of strategic roadmaps for NBS.

This system is not intended to replace human judgment and prescribe solutions in an independent manner but to facilitate a more holistic and robust planning process. The NBS-PSS thus enables stakeholders to express their preferences and integrate their local knowledge with the information provided by the system. However, to enhance the system’s validity, connecting it to other planning and engineering tools can be highly beneficial. For example, combining the NBS-PSS approach with hydrological simulation tools for identifying flow paths can help to more effectively choose and place NBS.

One of the main issues limiting the adoption of multicriteria spatial decision support systems is the availability of data (Ferretti & Montibeller, 2016). The NBS-PSS was tested using the data available for cities in the Netherlands, where high resolution and detailed datasets are openly accessible to cities. In other countries and cities, such datasets might not be accessible. The multiscale structure of the system and the ability to modify the sets of criteria and indicators used in the analysis, allow cities with access to different types of data to adopt the framework. For example, in cities with limited access to data with high spatial resolution, the first two steps of the NBS-PSS process will not be much affected; in other steps, since the users are focusing on specific neighborhood(s), they can better and easier integrate local expert knowledge with the system’s results and still get valuable insights.

There are also limitations in the NBS-PSS presented in this paper. Currently, there are only eight NBS included, while several other solutions can be incorporated for a more robust analysis (Eisenberg & Polcher, 2018). Moreover, to provide more accurate results, other criteria such as soil type and position of underground infrastructure can be included in the site suitability analysis. Another important improvement of the current version of the NBS-PSS can be to account for the synergies and trade-offs between the various ecosystem services. Different ecosystem services affect each other, but not always in a positive way (Haase, Schwarz, Strohbach, Kroll & Seppelt, 2012). In this respect, understanding the synergies and trade-offs is essential for developing realistic and effective plans. Finally, future work can provide an estimation of the impact of the chosen NBS at the selected location; this can further help stakeholders to compare different solutions and prioritize actions.

Furthermore, the NBS-PSS needs to be tested with a larger and more diverse group of stakeholders, also without the designers being present. The alpha test conducted and reported in this paper only involved various experts. In future work, beta tests of the proposed NBS-PSS need to include citizens, company representatives, and other stakeholders living in the local settings to which the system is applied.

5. Conclusion

NBS are being promoted by scholars and other advocates as well as increasingly adopted by cities worldwide as strategies to enhance sustainability and resilience. The multifunctionality of NBS is their main characteristic, which makes them suitable interventions in urban areas where space is limited. However, this multifunctionality is not yet properly integrated into mainstream planning practices, which can significantly limit the ability of NBS to deliver multiple ecosystem services.

This paper introduces a planning support system that integrates different stages of the planning process to find suitable intervention areas and solutions, while taking the multifunctionality of NBS into account. The NBS-PSS has a multiscale hierarchical structure, moving from the city level to the neighborhood, and subsequently to specific sites, streets, and buildings. In different stages of the process, NBS-PSS allows stakeholders to interact with the system, express their priorities and use local knowledge to influence the results. This structure can help stakeholders from different disciplines to interact and develop more integrated and effective NBS strategies.

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.
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information based tools for co-creation of resilient, ecosystem-based urban plans with urban designers, decision-makers and stakeholders. *Environmental Science & Policy, 66*, 427–436. https://doi.org/10.1016/j.envsci.2016.06.010

Voskamp, I. M., de Luca, C., Polo-Ballinas, M. B., Hulsman, H., & Brolsma, R. (2021). Nature-based solutions tools for planning urban climate adaptation: state of the art. *Sustainability, 13*(11). https://doi.org/10.3390/su13116381

Wilson, S., Hutson, M., & Mujahid, M. (2008). How planning and zoning contribute to inequitable development, neighborhood health, and environmental injustice. *Environmental Justice, 1*(4), 211–216. https://doi.org/10.1089/env.2008.0506

Wyborn, C., & Bixler, R. P. (2013). Collaboration and nested environmental governance: Scale dependency, scale framing, and cross-scale interactions in collaborative conservation. *Journal of Environmental Management, 123*, 58–67. https://doi.org/10.1016/j.jenvman.2013.03.014

Nature4Cities, (2021). NBS catalogue explorer. Retrieved February 10, (2021), from https://nbs-explorer.nature4cities-platform.eu/.

NWRM, (2021). Rain gardens. Retrieved November 2, (2021), from http://nwrm.eu/measure/rain-gardens.

NWRM, (2020). Catalogue of NWRM. Retrieved November 15, (2020), from http://nwrm.eu/measures-catalogue.