Universidade de Aveiro
2018
Departamento de Ambiente e Ordenamento

Carole Simone Juliette BODILIS

Integração e visualisação de indicadores de *urban sprawl* e aquecimento urbano num contexto de soluções baseadas na natureza

Integration and visualisation of urban sprawl and urban heating indicators from complex data in a context of nature-based solutions

Universidade de Aveiro
2018

Departamento de Ambiente e Ordenamento

Carole Simone Juliette BODILIS

Integração e visualisação de indicadores de *urban sprawl* e aquecimento urbano num contexto de soluções baseadas na natureza

Integration and visualisation of urban sprawl and urban heating indicators from complex data in a context of nature-based solutions

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Estudos Ambientais (JEMES-CiSu), realizada sob a orientação científica do Doutor Peter Roebeling, Professor do Departamento de Ambiente e Ordenamento da Universidade de Aveiro e a co-orientação da Doutora Sandra Rafael, Investigadora em Pós-Doutoramento no Departamento de Ambiente e Ordenamento da Universidade de Aveiro e do Professor Scott Hawken da *Faculty of Built Environment - University of New South Wales (Australia).*

This thesis was developed in the context of the UNaLab project (https://www.unalab.eu/), undertaken by a consortium led by VTT and in which the UA is consortium partner as well as work package leader (Monitoring and impact assessment). The UNaLab project has received funding from the European Union Horizon 2020 research and innovation programme under Grant Agreement No. 730052, Topic: SCC-2-2016-2017: Smart Cities and Communities Nature based solutions.

o júri

Presidente	Prof. Doutor Mário Miguel Azevedo Cerqueira professor auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro
Vogal – Arguente principal	Prof. Doutor João José Lourenço Marques professor auxiliar do Departamento de Ciências Sociais, Políticas e do Território da Universidade de Aveiro
Vogal – Orientador	Prof. Doutor Peter Roebeling investigador auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

acknowledgements

I would first like to thank Prof. Peter Roebeling for his continuous fruitful support throughout the project work and this Master Thesis. I could not have had a more caring and engaged supervisor. I am particularly grateful for the trip to Eindhoven and the exciting two days at the UNaLab consortium meeting that brought added value to the Thesis and useful work experience for me. I particularly enjoyed being part of a tangible project and work with a dynamic team: thanks to Peter's "minions" and the monthly lunches that guaranteed the good working (among other) mood: Rita, David, Luiz, Catarina, Max, Marta and Isabel.

I would also like to thank my co-supervisors: Dra. Sandra Rafael for her constructive comments and her help on the urban heating model and Prof. Scott Hawken for his thoughtful comments that helped improve the flow of the Thesis. Thanks also to Bruno Augusto who ran the urban heating models for Eindhoven and whom I worked with to validate the visualisations.

Thanks also to the UNaLab Working Package nº3 with whom it was interesting to work with, both for problem solving discussions and technology knowledge exchange: Bruno again, Ricardo, Ana, Rita and Ruben.

Thanks also to the Master Thesis crew that I had the chance to meet in Aveiro, who made the time spent in the library productive, punctuated by breaks and lunches crucial for our common mental well-being: hugs to Camille, Rinke, Chloé, Suzy, Maurine, Maria and Anna.

This work would not have been possible without the support of my family to whom I dedicate this work (let's practice a bit your English!) and the amazing people from the JEMES CiSu family: I hope that wherever you choose to go after the Master, our paths will meet again someday. Muitos besos to David, Max, Marta, Majo, Nick, Biraj, Nadin, Fabri, Diego and Ana.

Last but not least, I would like to thank the tree that gave its life so that this 100-page Thesis can be printed seven times and received at the Environment and Planning department of the University of Aveiro.

palavras-chave

Ordenamento urbano, *planning support system*, Soluções Baseadas na Natureza, indicadores

resumo

A crescente urbanização global gera inúmeros desafios às cidades, especialmente devido aos cenários de crescimento populacional e alterações climáticas. O aquecimento global e o fenómeno de *urban sprawl* constituem dois dos maiores desafios, nomeadamente através de uma expansão descontrolada e fragmentada na periferia urbana e em contextos rurais assim como o aumento de temperatura nas zonas urbanas. Soluções Baseadas na Natureza (SBN) apresentam-se como alternativas inovadoras que são inspiradas ou suportadas pela natureza, sendo capazes de lidar com os desafios e mitigar consequências negativas. De facto, as SBN podem ser consideradas amenidades ambientais que atraem a população para viver perto destes espaços, para além de providenciarem espaços com potencial efeito amenizante e recreativo. No entanto, existe ainda uma necessidade de comprovar a eficiência das SBS através de abordagens integradas, nomeadamente através de indicadores. Desta forma, o objetivo deste trabalho consiste em fornecer evidências sobre indicadores de aquecimento urbano e *urban sprawl* de forma a suportar o processo de tomada de decisão relativamente à implementação, comunicação e avaliação de SBN. Com este fim, a cidade de Eindhoven, na Holanda, é utilizada como caso de estudo. Assim sendo, indicadores existentes na literatura considerados relevantes foram selecionados e dois modelos foram utilizados para avaliar fenómenos de aquecimento urbano e de *urban sprawl* (WRF-SUEWS e SULD), para posterior desenvolvimento de uma interface de utilizador destinada à visualização dos indicadores. Esta interface foi desenvolvida segundo um ciclo de *design-implementation-evaluation*, que foi testado três vezes por utilizadores piloto e partes-interessadas em Eindhoven. Os resultados mostram que o modelo utilizado reúne e fornece informação fundamental para a discussão de futuros impactos de SBN.

keywords

Urban planning, planning support system, Nature-Based Solutions, urban sprawl, urban heating

abstract

Cities are facing an increasing number of challenges as a result of rapid global urbanization, challenges that become even more critical in the face of population growth and climate change. Two major ones include urban sprawl and urban heating, namely the un-controlled low density, leapfrog and scattered development at the urban fringe and the higher temperatures in urban areas than in the rural surroundings. Nature-Based Solutions (NBS), solutions inspired or supported by nature, offer an innovative way to deal with these challenges and mitigate their harmful consequences. Indeed, NBS provide aesthetic services and attract residents while, at the same time, providing regulating and recreational services. Nevertheless, there is a need to show the effectiveness of NBS through evidence-based approaches and relevant indicators. The objective of this study is to provide policy-relevant visualisations of urban sprawl and urban heating indicators to provide information, communication and analysis support for decision-making around NBS establishment, taking the city of Eindhoven in the Netherlands as a case study. To this end, relevant indicators are selected from the literature and according to data available from the two disciplinary models used to assess urban sprawl (SULD) and urban heating (WRF-SUEWS) and, in turn, a user interface (UI) is developed to visualise these indicators in a user-friendly and understandable way. The UI is developed following a design-implementation-evaluation cycle, as it was tested and evaluated three times by pilot end-users as well as actual stakeholders in Eindhoven. Results show that complex model results rendered in a simple way at different scales (plot, neighbourhood and city) provide relevant information on the multiple impacts of NBS for stakeholders as well as the first step towards the apprehension of the interrelated impacts of NBS in cities. These results serve, in addition, as inputs for the development of the Systemic Decision Support Tool (SDST) of the UNaLab project (funded under the European Union Horizon 2020).

TABLE OF CONTENTS

Figure Index:

Table index:

Abbreviations

Abbreviation	Meaning
EU	European Union
HCI	Human-Computer Interaction
GIS	Geographical Information System
HH	Household
IoT	Internet of Things
KII	Key Impact Indicator
KNMI	Koninklijk Nederlands Meteorologisch Instituut
KPI	Key Performance Indicator
NBS(s)	Nature Based Solution(s)
PSS	Planning Support System
SDSS	Spatial Decision Support System
SDST	Systemic Decision Support Tool
SULD	Sustainable Urbanizing Landscape Development
SUEWS	Surface Urban Energy and Water Surface
UHI	Urban Heat Island
UI	User Interface
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

I. INTRODUCTION

I.1. Theoretical context

Global temperatures are rising at increasing rates since 1850 and damaging consequences are foreseen, as reported by the global scientific community (Cook *et al.*, 2013; IPCC, 2014) and acknowledged by States around the world. Indeed, 2015 was the warmest year ever recorded, and 2010 – 2015 the warmest 5 years with numerous extreme weather events (WMO, 2015). In addition, the global urban population is growing and is expected to reach 66% of the global population by 2050 (United Nations, 2014). This growth is accompanied by environmental and social threats to be considered when planning future cities and the future of present cities. For instance, demographic pressure in cities and the resulting high food, water and energy consumption is an issue in a world with limited resources – as is the general human activity that leads to air, water and noise pollution. In addition, social and economic issues, such as gentrification and spatial inequalities, need to be tackled to follow the guidelines of sustainable development (Sioen, Terada and Yokohari, 2016). Two particular challenges await growing cities in a warming world: dealing with urban sprawl and mitigating urban heating.

I.1.1. Urban sprawl

Fulfilling the need of welcoming an increasing number of inhabitants, cities have spatially expanded. From the sky, two patterns can be observed: either the development is continuous, or it is fragmented and results in urban patches in the landscape. Most cities experience both, with an extended dense urban core surrounded by low-density sparse urban patches fragmenting the landscape. This is where the phenomenon of urban sprawl can be spotted. Urban sprawl has been defined as "the physical pattern of low-density expansion of large urban area, under market conditions, mainly into the surrounding agricultural areas" (EEA & FOEN, 2016 p20) or as "an uncontrolled, scattered suburban development that increases traffic problems, depletes local resources and destroys open space" (Ji *et al.*, 2006). A recent study on the 200 biggest studies that make 70% of the world's urban population found that since the 1990's, "when population doubles, land use triples" and argues that rather we call this phenomenon "sprawl" or "de-densification", it should be tackled in its entireness to avoid or mitigate its adverse consequences (Wihbey, 2016: p 20-21). To structure the analysis of the phenomenon, one approach is to study its geographical and socio-economic ***patterns,*** the ***processes*** behind it, and its ***causes*** and ***consequences*** (Galster *et al.*, 2001).

The causes of sprawl and low-density development are numerous and comprise local economics and politics, demographics, transport improvement and personal preferences (EEA & FOEN, 2016; Mendonça, 2017). Economically, the centralization of economic activities and the competition between cities make the city centers more expensive as the demand is higher, and therefore it becomes cheaper to buy in low density areas at the urban fringe (Christiansen and Loftsgarden, 2011). This process can also be enhanced by municipalities if they provide incentives to buy land outside of the urban core. Demographically, an increase in population usually contributes to the sprawl of a city as more housing is needed in addition to already built-up residential areas (Maimaitijiang *et al.*, 2015). What's more, the increase in the number of households due to changes in societal characteristics (e.g. numerous re-composed families) also increases the number of dwellings needed. But living outside of a dense, well-connected center would not be possible without enhanced personal transportation. Consequently, automobile development was one of the major driver of sprawl in the United States during the XXth century (Glaeser and Kahn, 2003). Last but not least, personal preferences drive people outside of highly populated areas, due to the possibility of bigger living spaces in detached houses, gardens, quiet areas, better air quality and access to environmental amenities.

Nevertheless, a high percentage of urban dwellers living in comfortable detached houses and commuting principally by car leads to undesirable environmental and social consequences. First, increasing the amount of built-up impervious areas reduces the amount of green areas and associated functions such as air cooling, CO_2 absorption and runoff water infiltration (Murata and Kawai, 2018). Air quality is also impacted by the accentuated use of automobiles. Additionally, sprawl, as a scattered and leapfrog pattern of urban development, interrupts the ecological connectivity of natural habitats and can be fatal to some species (Dupras *et al.*, 2016). On the social aspect, the social interaction among neighbors was found to be smaller in sprawled areas (Farber and Li, 2013) and larger social inequalities are observed in sprawled cities in terms of education, life chances, mobility, health and access to public services (Wei and Ewing, 2018).

In Europe, the causes, patterns, processes and consequences of sprawl have been largely studied (EEA, 2006; Kasanko *et al.*, 2006; Arribas-Bel, Nijkamp and Scholten, 2011; Hennig *et al.*, 2015; Oueslati, Alvanides and Garrod, 2015). In fact, while urban sprawl was first highlighted for North American cities, European cities have been following the same process although at a slower pace and smaller scale. Indeed, European cities are usually composed by an historical compact urban centre and compact suburbs, and experience sprawl at the fringe of the compact suburbs. It has been shown that they present sprawl patterns even with stagnating or diminishing populations (EEA, 2006). Within Europe, there also exist structural and historical differences between cities. Historically, southern European cities have had a slower urbanization process than northern European cities, which has resulted in them being more compact (EEA, 2006). As in the recent years southern European cities have been developing sprawl-like at unprecedented rates, especially along the Mediterranean coast, it is likely that with insufficient planning they will reach the sprawl situation of northern European cities (EEA, 2006). One of the common characteristics of sprawl patterns throughout cities is the increase in sealed areas at the expenses of cooling green spaces, which contributes to the expansion of the Urban Heat Island (UHI) (Stone, Hess and Frumkin, 2010).

I.1.2. Urban heating

Urban heating characteristics and the phenomenon of the Urban Heat Island (UHI) have been extensively studied as the most obvious impacts of human activities on local climates. Put in a simple way, it is the fact that temperatures in urban areas are higher than in the rural surroundings. First studied by Oke (1973), the UHI phenomenon has been quantified in various ways (Rizwan, Dennis and Liu, 2008). Indeed, the UHI is occurring at different atmospheric layers (Yuan and Bauer, 2007; U.S. Environmental Protection Agency, 2008). The first layer refers to the Surface Urban Heat Island (Voogt and Oke, 2003), the second to the Canopy Layer Heat Island and the third layer to the Boundary Layer Heat Island. These latter two are characterized as atmospheric UHIs.

The factors influencing the UHI and its consequences are complex and numerous as they touch upon various elements of the urban fabric. Namely, the UHI is observed where the built environment impacts on the thermodynamic fluxes between the sky and the Earth through four aspects: reduced vegetation, properties of urban materials, urban geometry and increased anthropogenic heat (U.S. Environmental Protection Agency, 2008), categorized as “product of city design” or “controllable” factors (Rizwan, Dennis and Liu, 2008; Nakata-Osaki, Souza and Rodrigues, 2018). First, the diminished vegetation decreases the possibility of shade at the same time that the cooling effect of evapotranspiration is reduced. Second, the properties of urban materials themselves, such as the solar reflectance and the thermal emissivity, modify the surface energy balance compared to rural areas. Indeed, lower solar reflectance (known as albedo) and higher thermal emissivity that are typical of construction materials, imply that buildings absorb more solar energy than they reflect and that the absorbed heat is later released to the atmosphere (Rizwan, Dennis and Liu, 2008). Third, the urban form modifies the wind flows and the capacity of an urban area to emit longwave radiations back to space (Chen *et al.*, 2016; Ward *et al.*, 2016; Nakata-Osaki, Souza and Rodrigues, 2018). For example, a narrow street will diminish the possibility for cooling through longwave radiation (Rizwan, Dennis and Liu, 2008; Nakata-Osaki, Souza and Rodrigues, 2018), while a wide street will facilitate cooling by the wind. Finally, cities are more populated than rural areas, which results in an increase in anthropogenic heat – e.g. more energy intensive buildings and industry producing heat, notably because of air conditioning.

Additionally, “meteorological” or “uncontrollable” factors influencing urban heat exist. Indeed, the UHI effect varies temporally and spatially (Leconte *et al.*, 2017). Temporally, the intensity of the UHI is not the same in winter or summer, and is known to be accentuated under anticyclonic, low wind and low cloud cover conditions (Santamouris, 2014; Leconte *et al.*, 2017). Likewise, the UHI is more intense at night (especially in summer) when the heat absorbed by the buildings during the day is released to the atmosphere at night. Spatially, it can vary from one climate to another (e.g. arid or semi-arid regions don’t actually experience it; Schwarz, Lautenbach and Seppelt, 2011) and at the intra-urban scale. Namely, research has shown that cooler cities are more impacted than warmer cities (Ward *et al.*, 2016) and that within a city different neighborhoods experience different cooling rates (Holmer, Thorsson and Eliasson, 2007; Leconte *et al.*, 2017), in particular if the city is impacted by an ocean breeze (Santamouris *et al.*, 2017).

While the UHI can be energetically interesting during the winter as the demand for heating is reduced, most of its direct consequences are harmful to the urban socio-ecological systems. Actually, according to relevant papers synthetized by Santamouris (2014), while the heating load for specific building types for the period 1970 – 2010 diminished by 19% along with a warming of the surroundings, the total increase in energy load for heating and cooling increased by 11%, showing that that more energy was spent on cooling in the summer. Moreover, higher temperatures in cities mean that the urban population suffers from stronger heatwaves – a phenomenon that is likely to occur more often in the future (Steffen, Hughes and Perkins, 2014). During days of extreme temperatures, the human body struggles to keep its normal temperature even at night, and can suffer from heat stress and dehydration which increases mortality and morbidity (Ward *et al.*, 2016). The risk increases when the vulnerability of people does, for example due to pre-existing medical conditions, advanced age, living alone or residing in the hottest part of the city (Schinasi, Benmarhnia and De Roos, 2018). In addition, outdoor and indoor thermal comfort decrease when urban heat increases (Honjo, 2009; Martins *et al.*, 2016).

In Europe, the UHI has been the subject of a great amount of research, of which Santamouris (2007) provided a state of the art for, in particular, Mediterranean and Central European cities. It appears that the UHI happens across the continent under different climates and that the intensity depends on the European geographical region. For instance, in Italy the temperature difference was found to be between 1.4 – 2.5°C in winter and 1.6 – 4.3°C in summer with differences increasing with the size of the city. For the Netherlands, Van Hove *et al.* (2011) show that Dutch cities present a maximum UHI intensity similar to other European cities that can reach 3 to 10°C in densely built areas under clear and cloudless conditions. The reality of a UHI phenomenon in Europe induces more intense heatwaves in dense urban cores and is expected to result in higher mortality, such as the one observed in several cities during the 2003 heatwave (Le Tertre *et al.*, 2006).

I.1.3. Nature Based Solutions as mitigation measures

Several mitigations measures have been proposed in the literature to reduce urban sprawl and mitigate urban heating. For example, urban sprawl reduction measures rely on economic and political strategies, such as a change in the tax system (Altes, 2009; Eurostat, 2014) or different systems of subsidies (Perman *et al.*, 2003) that provide incentives to buy close to already built-up area and, thus, prevents inefficient scattered and low-density development. Other measures include establishing attractive blue and green spaces in the urban core to enhance the contraction of urban dwellers around the new attractive areas and hence limit spatial urban expansion (Roebeling *et al.*, 2017). Green and blue spaces can also help mitigate the UHI effect with their cooling power, as can urban design choices such as white roofs (Rizwan, Dennis and Liu, 2008). Hence, the literature shows the positive impact of green and blue spaces on urban cooling and urban sprawl with more or less replicable results.

In particular, Nature-Based Solutions (NBSs) are considered important for climate change adaptation in cities. NBS are defined as “solutions to societal challenges that are inspired and supported by nature” (EKLIPSE, 2017: p 3). At the urban scale, they gather a range of solutions that help improving health and well-being of urban dwellers and foster the adaptation of cities to climate change (Faivre *et al.*, 2017). Research on NBS can be seen as the continuity of the biodiversity research integrating science, policy and practice elements (Eggermont *et al.*, 2015), shifting the solutions to environmental challenges from a technological approach (such as the mechanical depollution of water) to a more comprehensive one that attends the complexity of the socio-ecological system (e.g. accounting for the provision of eco-systems). Indeed, NBSs can generate environmental, social and economic benefits to society (Kabisch *et al.*, 2016), in particular in urban settings where humans live close to the NBS. Regarding the actual Ecosystem Services provided by NBS, several types of NBS have been defined according to the level of engineering they require and the number of eco-systems/stakeholders they impact (see Figure 1). Urban NBSs belong to the Type 3 NBSs, namely to the “design and management of new ecosystems” category –

including new green spaces that provide new habitats, water-oriented parks with ponds, daylighting of rivers that brings back the original state of the river, or green walls and roofs that welcome new ecosystems.

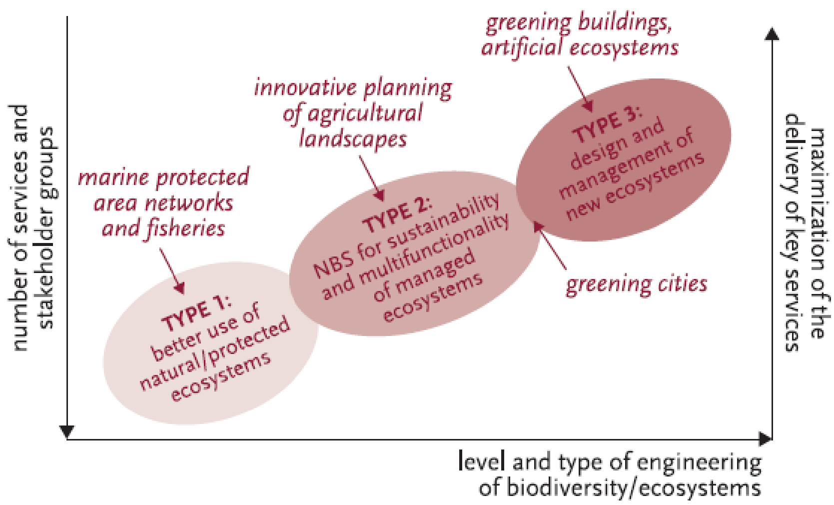


Figure 1: Schematic representation of the range of NBS approaches Eggermont *et al.* (2015)

While the positive impacts of NBSs on some urban issues, such as carbon storage in cities, diminution or buffer of high temperatures and diminished flooding have been shown (Kabisch *et al.*, 2017), there is still a need to demonstrate their real effectiveness and innovative aspects when facing population growth and climate change. To this end, the European Union has promoted several projects under the umbrella of the Horizon 2020 research cluster to make the EU the leader in “Innovating with Nature” for more sustainable and resilient cities (European Commission, 2014). In particular, this funding program wants to foster the provision of evidence-based arguments for the benefits of NBS regarding a whole range of social, natural and economical aspects. To do so, indicator-approaches are taken to provide measurable performance and impact data (Key Performance Indicators (KPI) and Key Impact Indicators (KII) ; Kabisch *et al.*, 2016), for instance to assess quantitatively the impact of NBS on urban sprawl and urban heating. Nevertheless, the sole calculation of these KPIs and KIIs is often not sufficient, as they reach their full potential if they are properly visualised and communicated to help decision-making. Therefore, KPIs and KIIs can be integrated in Planning Support Systems to be used by various stakeholders and hence provide support to the decision-making process oriented towards re-introducing the Nature in the city.

I.1.4. Planning Support Systems

Planning Support Systems (PSS) are integrated systems that aim at reconciling planners with their profession by providing powerful information that is, usually, inaccessible through simple studies (Geertman and Stillwell, 2009). PSS can be defined as a set of “software tools that use simple or complex mathematical models for analysing and forecasting development of urban or regional land use” (Russo et al., 2018: p 10). Hence, in addition to the common day-to-day and short-term planning activities, PSS help visualising the medium to long-term impacts of planning decision on various aspects – such as social, environmental and economic. Decisions related to urban planning can, thus, be taken with all the cards in hand in order to minimize the adverse effect of some decisions. For example, the establishment of a new building lot in a certain part of the city may increase the accessibility to green space for the new residents, but it will also probably disturb the transport situation as more people will commute from the developed area. Therefore, a PSS does not aim at providing one answer to a particular planning problem but rather the relevant information – usually in the form of indicators – needed to take an informed decision (Van Delden *et al.*, 2011). To achieve that, PSSs provide visualisation of complex model results made understandable with the help of indicators, and can be categorized in three main types: Informing PSS, Communicating PSS and Analysing PSS (Geertman and Stillwell, 2004). An overview of these different types can be found in Section II.1.2.

The development of a PSS requires several considerations, such as making sure that the system serves the expected purposes, that it is user friendly and that it provides reliable information (Nielsen, 1993; Russo *et al.*, 2018). As PSS have been developed in academic contexts but also for real-life planning situations, numerous examples of good and bad practices exist in the literature and can be integrated to create a working PSS. Hence, considering that the effectiveness of long-term mitigation strategies that integrate NBSs have to be proven and that working PSSs have the possibility to be implemented with the current knowledge, a PSS aiming particularly at exploring the impacts of NBS on various impact categories (including urban sprawl and urban heating) is of great interest.

I.2. Objectives

The overall objective of this Master thesis is to integrate and visualise indicators of urban sprawl and urban heating to support informed decision-making and co-creation processes in the context of urban NBS establishment. Urban sprawl and urban heating indicators are defined and calculated at various scales (grid, neighbourhood and city), and a user interface is developed that is interoperable, interactive and understandable for end-users from different backgrounds – thus contributing to reducing the gap between the academic and the professional planning field. The visualisation is applied to the city of Eindhoven (Netherlands) and the proposed framework is developed to be later transferrable to other impact categories and cities. This challenge comprises acceptability, technical feasibility and replicability challenges, as the user interface will only achieve its entire usefulness if it is broadly accepted by end-users, if it is technically feasible with the ICT framework and the data available, and if it is replicable to other impact categories and cities.

The following specific objectives are defined:

1) Build a robust list of indicators for urban sprawl and urban heating adapted to the context of NBS;
2) Calculate these indicators at various scales (grid, neighbourhood and city) for each NBS scenario; and
3) Develop a user-interface that communicates complex model results in an understandable and user-friendly way to support decision-making and co-creation processes.

I.3. UNaLab project

This Master Thesis falls within the UNaLab (Urban Nature Lab) project framework, funded by the Horizon 2020 program of the European Union, within which the University of Aveiro is project partner. The UNaLab project aims at bringing an evidence-based European framework for innovative, replicable and locally-attuned NBS solutions through a "Living Lab" approach (UNaLab, 2016). Living Labs (LLs) are defined as user-centred, open innovation ecosystems based on systematic user co-creation approach, integrating research and innovation processes in real life communities and settings (ENoLL, 2018). In particular, tangible NBS will be implemented for the UNaLab project in three front-runner cities which already have a NBS strategy (Tampere in Finland, Eindhoven in the Netherlands and Genova in Italy), while follower cities (whose NBS projects are at an earlier stage) will follow the progress and eventually engage in the same process later on. These real-life settings will allow for the actual measurement of the performance of NBS in cities on different categories and their comparison with projected impacts through model simulations. Hence, evidence-based arguments will be provided for the establishment of NBSs.

To achieve these objectives, a co-creation and evaluation framework for the establishment of NBS in cities is elaborated (see Figure 2) and applied to the front-runner cities. It includes identifying challenges cities face, proposing NBS solutions to deal with global change challenges through participatory decision-making and co-creation processes, and assessing their impacts with digital and scientific assessment frameworks through the development of a Systemic Decision Support Tool (SDST). The SDST, which belongs to the category of Planning Support Systems (PSS), will be developed to be used on a touch table/screens so that the stakeholders can gather around and discuss the impacts of NBSs on their city which will bring added value to the co-creation process. Concretely, the SDST will provide results from disciplinary models in a user-friendly way to enable stakeholders to visualise and discuss the impacts of NBSs on several impact categories (flooding, water pollution, urban heating, air pollution, ecosystem services and values, urban sprawl, real estate values, population dynamics and gentrification). Stakeholders will also have the choice to analyse the impact of NBSs for 2030 and 2050 with or without population growth and/or climate change. In the UNaLab project proposal, the SDST's goals are defined as "facilitating the assessment, visualisation and discussion of potential social, environmental and economic impacts of no-action as compared to deployment of NBS in a range of population growth and/or climate change scenarios" (UNaLab WP3, 2016: p 2). To be complete and relevant to the scale of management, different levels of details will be accessible in the SDST, depending on the end-user and purpose (e.g. some might just want a general idea of the impacts of NBS while others may want to inspect in detail the various impacts, especially the scientifically obtained ones).

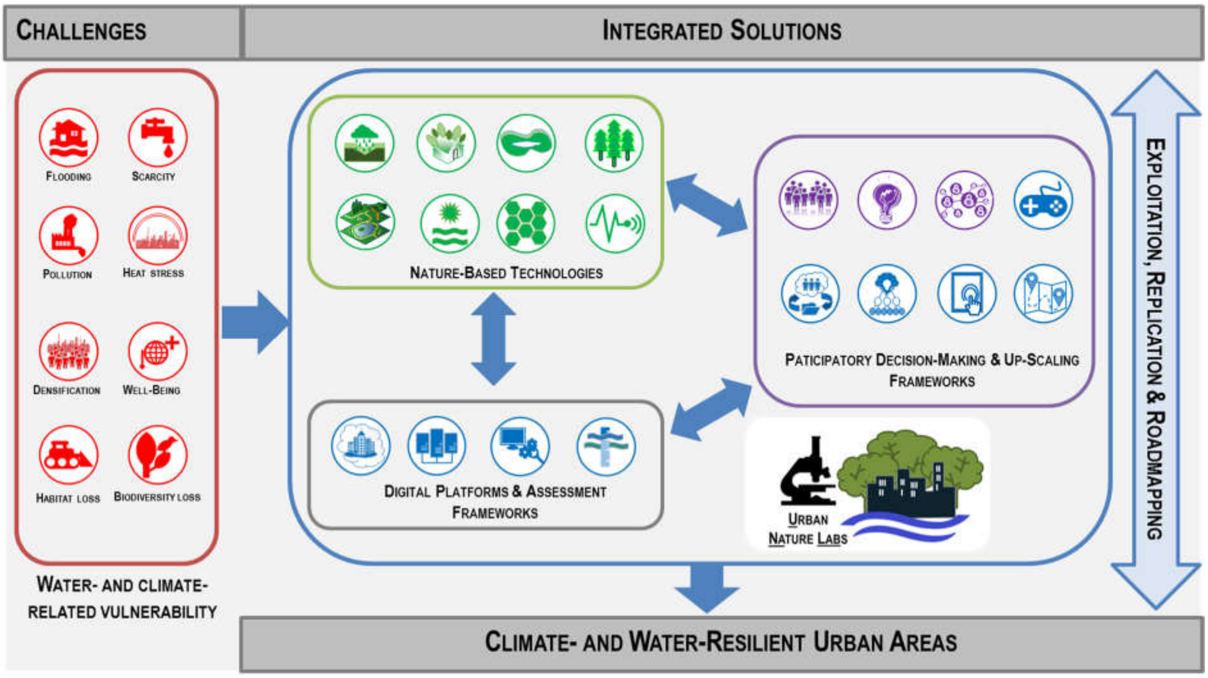


Figure 2: UNaLab co-creation framework (UNaLab, 2016)

Contributing to the SDST goals, Information and Communication Technologies (ICT) tools will be used in the form of "Digital Platforms and Assessments Frameworks" (see Figure 2) to provide interactive decision-support tools. The goal of the ICT framework is, in particular, the assessment of "the impact of NBS through a straight-forward front-end that support decision-making regarding the deployment of NBS" (UNaLab WP4, 2016: p 2). The description of the ICT tools is presented in Figure 3. Namely, after co-creating possible NBS in the area of concern, KPIs and KIIs are calculated to evaluate the NBSs measured performance (based on observed data) and expected impact (based on model simulations) and stored in the UNaLab database. Then, the NBS Impact Simulation and Monitor, that is actually the user interface for the SDST, will provide meaningful visualisations of the information stored in the database – e.g. KPIs, model results and IoT data. There will also be a possibility to create visualisation with the "Visual Data Mash Up Creator".

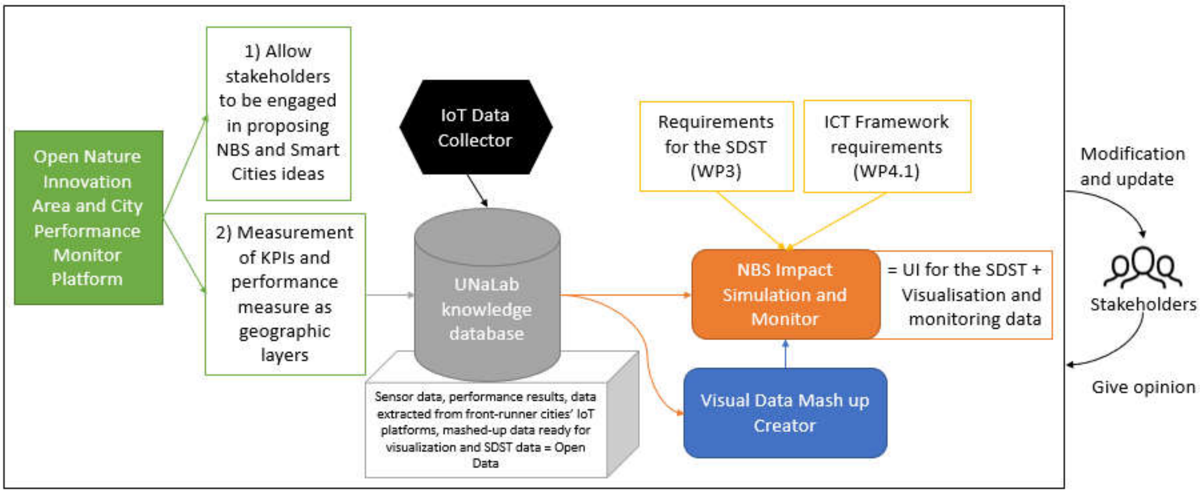


Figure 3: ICT framework of the UNaLab project ensued from the specifications of the Working Package n°4 (UNaLab, 2016)

The ICT framework insists on the constant end-users' engagement during the process resulting in an improvement of the tools according to their feedback – in particular for the NBS Impact Simulation and Monitor. Indeed, this tool will be the interface between the scientific knowledge provided by the SDST and the end-users. It will provide visualizations of the impacts of NBS with indicators in a context of population growth and climate change on a touch-table/screen style platform. The impacts comprise water, air, ecosystem services and socio-economic issues, making the UNaLab SDST a novel example of PSS that supports multiple socio-economic/environmental-oriented planning tasks, combining models that have never been presented jointly in a PSS. In this Master Thesis, the focus is on the urban sprawl and urban heating impact categories assessed in the SDST, simulated with two scientifically acknowledged models – SULD (Roebeling *et al.*, 2017) and SUEWS (Järvi *et al.*, 2014) – leaving the monitoring through Internet of Things (IoT) deviced out of the scope.

I.4. Outline

The present work is divided in seven chapters including this one. The following chapter (Chapter II) presents an overview of the literature on Planning Support Systems (PSS), including their definition, their different types, the bottlenecks that hamper their widespread use in the planning practice, and good practices in their implementation. In Chapter III, the methods are described – in particular the steps that lead to the realisation of the prototype for the SDST: i) construction of a robust list of indicators for urban sprawl and urban heating, ii) definition of the ICT framework and iii) visualisation of the indicators. Next, in Chapter IV, the Eindhoven case study is detailed, with first some background on the city and the urban issues it faces, followed by the NBS scenarios considered for the simulations. In Chapter V, results are presented – namely how the tool meets end-users' requirements of a PSS, how it works and what narratives of urban sprawl and urban heating can be drawn from it for the city of Eindhoven. These results are then discussed in Chapter VI regarding three aspects: the way they are presented, how do they communicate the impacts of different types of NBSs and how they fit in the broader goal of the SDST. Finally, conclusions and future recommendations are given in Chapter VII.

II. LITERATURE REVIEW

This chapter provides a review of the literature on Planning Support Systems and their use in the planning practice. First, they are defined, classified and the bottlenecks that hamper their mainstream use are described (Section II.1). Then, good practices for their implementation are presented (Section II.2.).

II.1. Planning support systems (PSS)

II.1.1. Definition

Cities are growing, densifying and ageing as a result of an increase of the global urban population. They are responsible for 70% of carbon emissions (C40, 2018) but also host the majority of the wealth production in Europe (up to 85% of the gross-domestic product; Mendonça, 2017). That makes them both highly valuable and vulnerable to environmental changes. To ensure that urban citizens can live in decent conditions without excessively exploiting natural resources and polluting in the near and far future, integrated and effective urban planning is needed. As Klosterman (2009) noted, the term "planning" is multiple and therefore difficult to define, but it relates in all definitions to "rational analysis, foresight, evaluation and the attempt to achieve desirable outcomes" (Klosterman, 2009, p. v). Therefore, the role of planners is to design the space they are responsible for while taking into account both short and long-term problematics. As short-term planning results in quicker and more concrete outcomes that are favourable for a political time scale, the focus of planners is nowadays more on concrete daily tasks than on prospections on the future (Geertman and Stillwell, 2009).

Planning Support System (PSS) are tools that can help to reconcile planners with their original profession by providing decision support tools that focus on planning tasks (Geertman and Stillwell, 2009). PSS can be defined as a set of "software tools that use simple or complex mathematical models for analysing and forecasting development of urban or regional land use" (Russo et al., 2018: p 10), or a "subset of computer-based geo-information instruments, each of which incorporate a unique suite of components that planners can utilise to explore and manage their particular activity" (Geertman and Stillwell, 2004: p 291). What's more, the multiplication of the amount of data available in the urban landscape and the improvement of technologies foresee great improvement in complex models that represent urban systems and their evolution over time. The integration of these models into Planning Support Systems is of great value for informed and data-based decision-making process, which is always under strong political pressures and demand for evidence to build more effective policies (Geertman and Stillwell, 2009).

In planning practice, several tools are already used to explore data and scenarios to support evidence-based policies, such as Spatial Decision Support Systems (SDSS) and Geographical Information Systems (GIS). These two tools are very similar to PSS in definition but differ to some degree in practice. While PSS support forward-looking planning actions, SDSS focus on short-term/executive actions undertaken by organisations and GIS solutions are not only planning-oriented but can serve other purposes (Geertman and Stillwell, 2004). In PSS, all technologies related to urban planning are brought together to support informed decision-making. Namely, a

PSS always gathers information (or data), models and (geo-)visualizations (Klosterman, 1999; Geertman and Stillwell, 2004). In the planning field of work, PSS are often known as "planning softwares" (Russo *et al.*, 2017) and provide the user-friendliness of paper maps together with the richness of academically developed models (Pelzer *et al.*, 2013). The variety of models existing in the literature and the disciplines that relate to urban planning opens fields of possibilities when designing a PSS, including the exploration of the impact of NBSs in cities.

II.1.2. Goals and types of PSS

Largely studied in the literature from the 1990's, PSSs attracted both researchers and planners with the possibilities they offer. Namely, PSSs aim at facilitating the participation of stakeholders, informing the public about different planning policy and topics, and supporting specific forms of planning by practitioners such as strategic planning, land use and infrastructure planning or environmental planning (Geertman and Stillwell, 2004). Regarding facilitating the participation of stakeholders, they can improve their involvement in the decision-making process by "bridging and stretching" (Xiang and Clarke, 2003) their minds. Indeed, having a common interface to visualize data and information allows people from different background to speak the same language and understand each other ("bridging") and at the same time broaden their perspectives to see beyond their professional and individual lenses ("stretching") (Pettit *et al.*, 2012; Pelzer *et al.*, 2013). Stakeholders are usually on the side of planning, development, politics and environmental *expertise*. However, a trending change in planning practice revolves around working with the stakeholders that have *experience* in the urban landscape, because they live, work and play in it (Snyder, 2003; Lieske, Mullen and Hamerlinck, 2009). Regarding informing the public, they can provide more insights on the urban planning process to a larger audience and inform the public about different planning policies and topics. Finally, regarding common planning tasks, PSS aim at supporting (and not replacing) them by providing information on the impacts of policies that are not easily accessible, either because they result from complicated calculations or need to be projected in the future with the use of models (Van Delden *et al.*, 2011). Therefore, numerous kinds of PSS exist that can be gathered into three categories: (i) Informing PSS, (ii) Communicating PSS and (iii) Analysing PSS (Geertman and Stillwell, 2004).

While noting that within each category PSS can vary in terms of functionalities, structure and area of interest (land use, transport, environment, etc..) and that a PSS can belong to two or more categories, the following paragraphs aim at describing the PSS categories succinctly and giving examples. More examples are given in Figure 4 and detailed in Annex 1.

Informing PSSs aim at simple information provision from one sender to one recipient without any analysis of the data. They can be seen as PSS showing the status quo of the urban area including small calculations, such as accessibility measures and are usually used at the beginning of the planning process. Typical Informing PSS include websites providing information on land suitability or zoning restrictions that are used mostly by promoters, officials and citizens. For example, the metropole of Nantes in the West of France provides an interactive map called the PLUM on which the user can see in detail the land use of the region as well as the buildable areas and the ones protected because of environmental or heritage reasons (Nantes Metropole, 2018). Other examples can be found in the form of online interactive maps as InViTo for the city of Turin

(SITI, 2018) that provide a good overview of the attributes of the region, such as transport and road networks, environmental amenities and cultural hotspots.

Communicating PSSs aim in particular at fostering the discussion among stakeholders and by extension, their learning process. This is mostly done by providing appealing and easily understandable scenario representation and their potential consequences. As space is the aspect of urban planning that unites all stakeholders (Pelzer *et al.*, 2013), maps are a privileged way of representation. Unlike Informing PSS, the user can play around with the data and display selected indicators. Examples include CommunityViz that allows visualisation of different development alternatives (Pelzer *et al.*, 2015), or SoftGIS that allows residents to communicate their feeling about a place, information that is then available on a map (Kahila and Kyttä, 2009). Hence, in the first example communication is fostered on which development alternative seems the best, while in the second one the discussion can be launched about the perception of the public on certain space, the reason for that and possible alternatives to improve the current situation. No in-depth analysis of the impact of changes in land occupation or policies are provided in Communicating PSS.

Analysing PSS aim at allowing in-depth analysis of various planning policies and are intended for planners and decision-makers in particular. They provide the opportunity to design new scenarios, analyse their impacts and evaluate them. Well-known and applicable ones include WhatIf? (Klosterman, 1999), Envision Tomorrow (Bunzel, 2014) and Key to Virtual Insight (K2Vi, van Maren, 2003) among others. Indeed, these PSSs aim at exploring alternative scenarios by answering to the question(s): "What if [we apply this new regulation]/[the demand in housing increase by 20%]/[we develop in this area]?" for example. As a result, the PSS provides maps but also tables and graphs to have an overview of the models output data. In some cases, models are very heavy and are run before the implementation in the PSS.

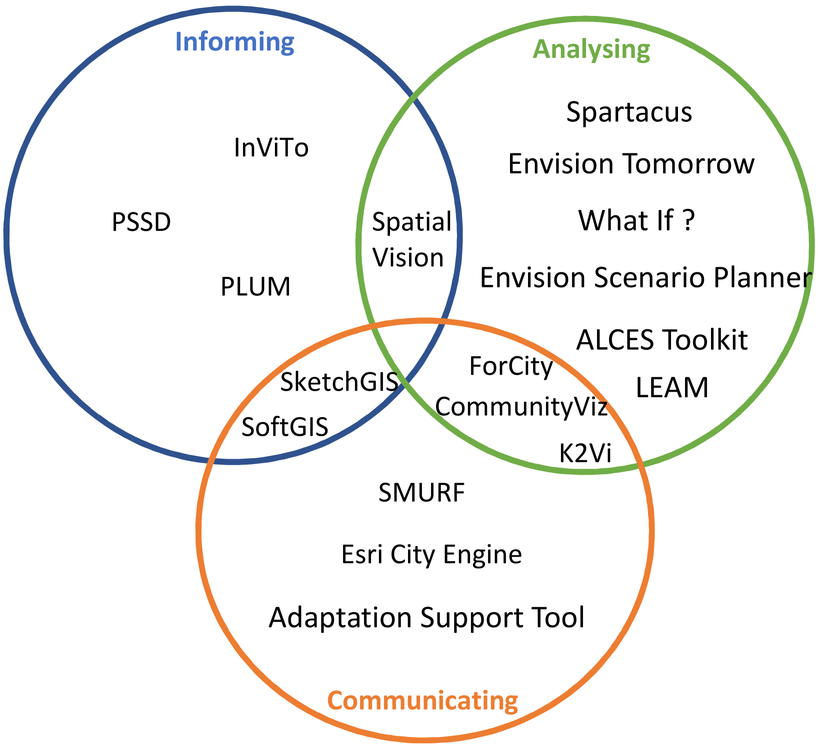


Figure 4: Overview of the types of PSS and some examples from the literature put up together by the author

The SDST of the UNaLab project will have the three components, as the same platform will be used to inform the stakeholders about the projects (Informing), foster communication around the touch table for the co-creation of NBS (Communicating) and explore scenarios in detail with the availability of multiple indicators at various scales (Analysing). To ensure a good usability of the PSS, it is important to learn from the past mistakes in terms of PSS implementation, and namely about the reasons for which it was not completely embraced by the stakeholders.

II.1.3. Bottlenecks that hamper a widespread use of PSS

While very promising as decision-helping tools, PSS are not embraced as fully as they could be by planners. The obstacles that hamper the mainstream use of PSS are called bottlenecks in the literature (Vonk, Geertman and Schot, 2005; Geertman and Stillwell, 2009), and relate to instrumental, human, institutional and organizational factors (Russo *et al.*, 2018). First, there is often a mismatch between the PSS functionalities and the actual needs or expectations of the planners and stakeholders (Vonk, Geertman and Schot, 2007; Geertman and Stillwell, 2009; Russo *et al.*, 2018), which is due to the academic focus of some PSS (Vonk, Geertman and Schot, 2005). Indeed, PSS and planning in general are very appreciated by researchers for the scientific challenge and opportunities they represent: it relates to future design or urban space and its impact on quality of life, its impact on the environment, among others. Second, the low usability as defined by Nielsen (1993) in the Human Computer Interaction (HCI) field of work is also considered as one of the major bottleneck (Russo *et al.*, 2018) and is composed of five aspects: if the PSS is i) easy to learn, ii) efficient to use, iii) easy to remember, iv) with few errors and v) subjectively pleasing as shown in Figure 5.

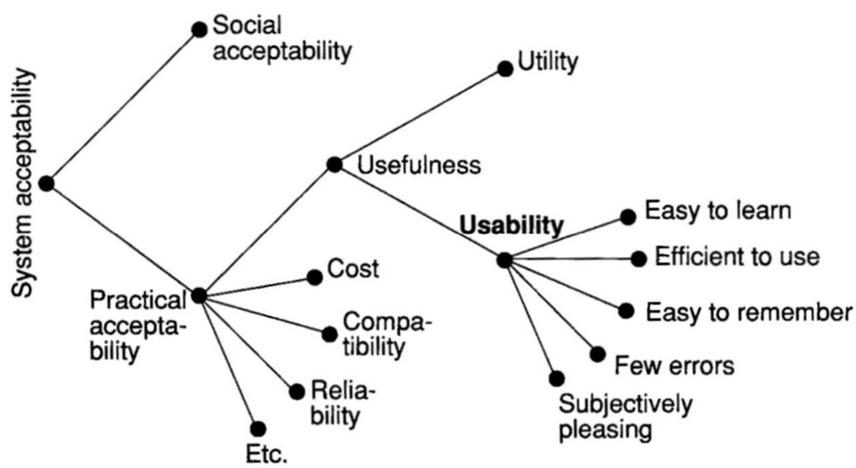


Figure 5: System acceptability framework as defined by Nielsen (1993)

Apart from these two major bottlenecks, others have been listed notably by Vonk (2006), whose doctoral work aimed at studying in depth the bottlenecks of PSS. To do so, three approaches were used: the instrument approach that relates to the tools themselves, the transfer approach that examines how PSS usage is diffused within planning practice, and the user approach that regards HCI and technology acceptance (see Figure 6)

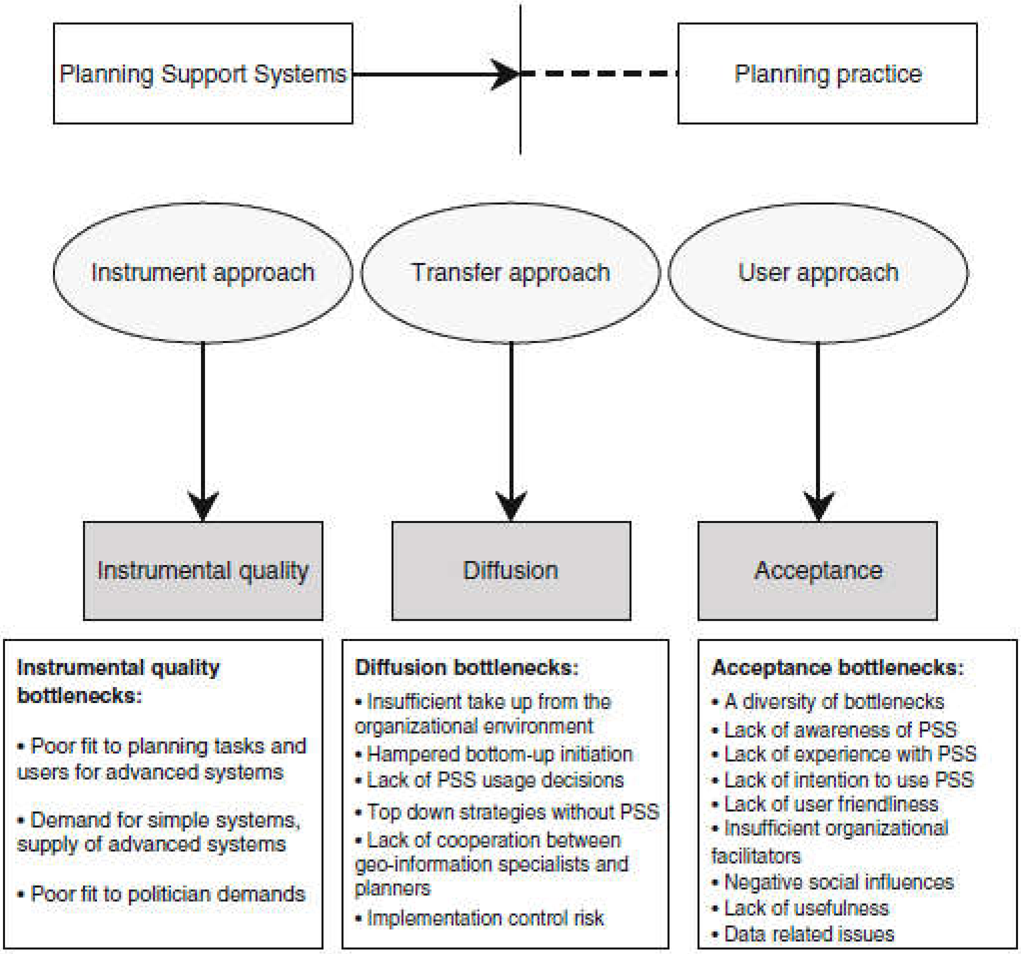


Figure 6: Bottlenecks to the widespread use of PSS following instrument, transfer and user approaches (Vonk, 2006)

The mixed environment in which decisions are taken for future urban development can be suitable for effective urban planning in which everyone is better off, but it can also be an obstacle to reach a consensus. Indeed, sometimes diverging political wills, personal goals or interests can hamper the process. This along with inevitable uncertainties are the two major challenged for long-term planning (Pensa, Masala and Lami, 2013). Therefore, work has to be done at three levels to improve the use and acceptance of PSS by planners: the tool must be integrated in a way that planners can actually use it as an easy and useful instrument, it has to be transferable throughout the planning practice and end-users should accept it in its entireness, from its original goal to its final use, including models' choice and data. Good practices have been highlighted in the literature to this goal.

II.2. Good practices in PSS implementation

Listing the good practices for PSS implementation is relevant in the scope of the present Master thesis, as implementing them in the final visualization tool will optimize the future use of the SDST. Three types of good practices will be listed in the following sections: the ones that aim at reducing the implementation gap, the ones to improve usability and the ones that optimize the communication of complicated model results.

II.2.1. Reduce the implementation gap

The numerous and various bottlenecks identified in the literature (see Section II.1.3.) also mean that there is room for improvement, for example by reducing the gap between the functionalities of the PSS and the expectations of the end-users. Concretely, the gap between expectations of planner and functions of the software can be diminished through a constant dialogue between the end-user and the developers throughout the whole process (te Bröemmelstroet, 2010; Van Delden *et al.*, 2011). This dialogue can take several shapes and happen at different moments during the PSS development. For example, all parties can meet for workshops to define the goals of the PSS at an early stage and, at fixed intervals, follow the process and provide feedback (Van Delden *et al.*, 2011; Pelzer *et al.*, 2014); alternatively, plan several workshops for the exploration phase, the problem definition phase, the solution phase and the design phase (Pelzer *et al.*, 2013). It is important during these interactions to take into account the background of each participants and their expectations to reach the most desirable outcome. For example, the vocabulary used should be understandable by all users, and if needed a glossary or a context text can be provided (Van Delden *et al.*, 2011; Russo *et al.*, 2017). Another good practices during these workshops is to discuss deficiencies of the model results or the user interface, which adds value to the discussion (Deal and Pallathucheril, 2009).

II.2.2. Improve usability

As mentioned in Section II.1.3., usability is the second major bottleneck and can be improved by working on the learnability, the efficiency, the accuracy and the aesthetic of the PSS. This is usually done by following the guidelines of the HCI field of work that proposed a design – implementation – evaluation cycle to reach a final usable software (Russo *et al.*, 2017). Namely, users give their continuous feedback in a participatory design approach to optimize the four components that make a usable software:

- Concerning the **learnability**, the PSS should be easy to use and if needed a specialist should be there to explain what is not self-explanatory,
- For good **efficiency**, the PSS should only display relevant data and be fast to use. First, it should not communicate all the model results but rather what they mean for the scale of management, for example with the use of indicators (Van Delden *et al.*, 2011). Second, it should be fast to use otherwise users get tired of it and it hampers the discussion process (Pelzer *et al.*, 2013; Maquil *et al.*, 2015). There are several solutions mentioned in the literature to keep a PSS fast while complete (e.g. with significant models): one can make an online solution and therefore the speed of it will not depend on the desktop used (Pelzer *et al.*, 2013), all the actions can be made with the back end to avoid heavy loading (Zhu *et al.*, 2013), or the scale of analysis can be changed depending on the user's needs (Van Delden *et al.*, 2011).
- For the PSS to be **accurate**, the models behind it should be trusted by users, either because they know it, because it is simple or sufficiently explained to them, or because they trust the scientists-developers that implemented it (Pelzer *et al.*, 2013). One should be very careful about black boxes by providing the most transparency possible (Pensa, Masala and

Lami, 2013) and acknowledge uncertainty (González *et al.*, 2013). Indeed, developers can be tempted to simplify at maximum the solution, but sometimes the simplicity hides the complexity of the world behind the model – complexity that is usually well-handled by stakeholders (Van Delden *et al.*, 2011). The PSS should also by flexible to change along with policy directives (Pensa, Masala and Lami, 2013),

- Last but not least, users should enjoy using the PSS (Geertman and Stillwell, 2004; Pelzer, 2017) and this is easier with an **aesthetic** interface. For touch table/screen systems in particular, it recommended that the table/screen is used at standing height and that objects can be used to interact with the table/screen, these types of interfaces being known as "tangible interfaces" (Maquil *et al.*, 2015).

Hence, it is possible to improve the usability as defined by the HCI field of work, but it is also of first importance to work on how the models' results are displayed to the user.

II.2.3. Communication of model results

The majority of PSS have an exploratory or analysing function, meaning that the user can use them to analyse future scenarios through modelling of urban systems. The representation of these models' results is an issue of extracting the relevant information from complex data by providing a "snapshot" of information that the user may find useful in the decision-making process (Deal, Pallathucheril and Heavisides, 2013). Therefore, good practices regarding user interface development and indicators' visualization should be copied to ensure a robust PSS.

II.2.3.i. User interface

First, the development of the user interface should be started early in the process and not at the end as it is usually the case in the planning practice, as "creating an interface is much like building a house: if you do not get the foundations right, no amount of decorating can fix the resulting structure" (Russo et al., 2017: p14). Namely, the interface should accomplish as much as the user wants and as much as is technically feasible, and this has to be discussed early to avoid disappointment and consequent mistrust in the tools (Vanv Delden et al. 2011). For example, different access can be granted to different people, and different information can be displayed according to the person who uses it: a specialist may want to see detailed information on air pollution, while a practitioner is concerned by the threat it represents for the public (Amann *et al.*, 2011; Van Delden *et al.*, 2011). What's more, there should be a possibility to save results or export them in Microsoft Excel to come back to them later or share them for further discussion (Amann *et al.*, 2011; Van Delden *et al.*, 2011; Zhu *et al.*, 2013).

An efficient user interface that is already on the market and used in several planning settings is the touch table/screen (Russo *et al.*, 2018). A touch-table/screen is a hardware that allows collaborative work by providing an appealing common support to engage discussions. Indeed, users can gather around the table/screen and exchange their views on what everyone can see on the screen, as well as interact with it. An example that has been used in the literature for workshops is MapTable®, for instance for learning about sustainable development (Pelzer *et al.*, 2013) or taking decisions to improve walkability in the city of Melbourne (Boulange, Pettit and Giles-Corti, 2017) as shown on Figure 7.

Figure 7: Example of a Touch Table as a support during workshops (source: https://www.mapsup.nl/maptable/)

A good practice for touch table/screen is to separate the screen in three: a parameter space where users set up the parameters (or scenarios) for simulation, a spatial component to display maps and a chart space for general indicators (Pelzer *et al.*, 2013). As for to know how to represent the indicators that fit the PSS´s goal, good practices can also be mentioned.

II.2.3.ii. Indicators' visualisation

The explorative aspect of a PSS implies that the user understands what is presented to him and makes sense of it. The separation of the interface in three mentioned in the previous section can help to do that by providing a progressive narrative answering to two questions: i) What do we want to explore? (Parameters/Scenarios space) and ii) What are the results/consequences of the scenarios? (Map and charts space). The latter is best answered by providing easily comprehensible visualisations of scale-relevant indicators derived from the complex model outputs, allowing for a comparison between alternatives provided in input. To do that, one can give a scale from 1 to 10 to all indicators, as did Pelzer et al. (2013), and use simple visualizations as graphs or tables (Amann *et al.*, 2011; Pelzer *et al.*, 2013). For example, if the indicators are gathered in categories and normalized on a scale, spider diagram are usually a good way to compare several scenarios (see Figure 8).

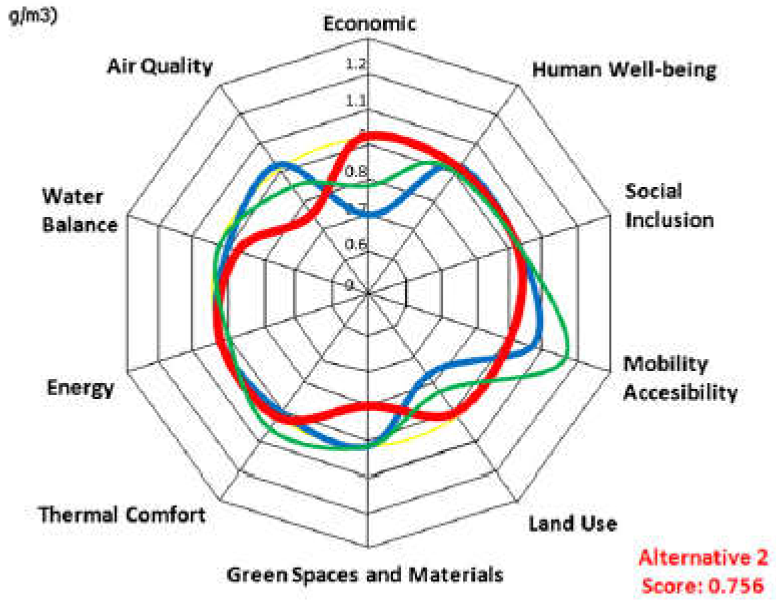


Figure 8: Spider diagram representing the performance of each alternative (Green, red and blue) from González et al. (2013).

Nevertheless, for a PSS on a touch table, a combination of maps and simple graphs to visualise the indicators are usually more powerful. Figure 9 to 12 provide example of used dashboards where indicators are presented in different ways, showing good practices in terms of information communication. In the ALCES software (Figure 9), several ways are used to explore one indicator ("Water Use"), for instance a heatmap, a table with basic information as minimum, mean and maximum, and a graph showing the evolution of the indicator through time. Maps and tables are dynamically linked so that clicking one item of the chart or table will filter the map and the other chart for the year selected. Similarly, in the Adaptation Support Tool (Figure 10), several indicators are investigated on the right-hand side panel with gauges graphs that are green or red according to their performance. Here the map represents mostly the input, as the user can draw new blue/green spaces and see their impact on the indicators. Following the same interface structure (left=inputs / centre=map / right=outputs (indicators)), the Envision tomorrow interface (Figure 11) allows the user to select a scenario and display the output indicators on the right. Here, there is the possibility to compare two scenarios, either with a table or with a bar chart. Remarkably, an important number of indicator is available if the user scrolls down the right-hand panel, and the comparison of all the indicators among all the scenarios is available with a click on the button "View Metrics". Finally, the tool developed by ForCity (Figure 12) allows the user to see the evolution on one indicator through time thanks to a short video, among other features.

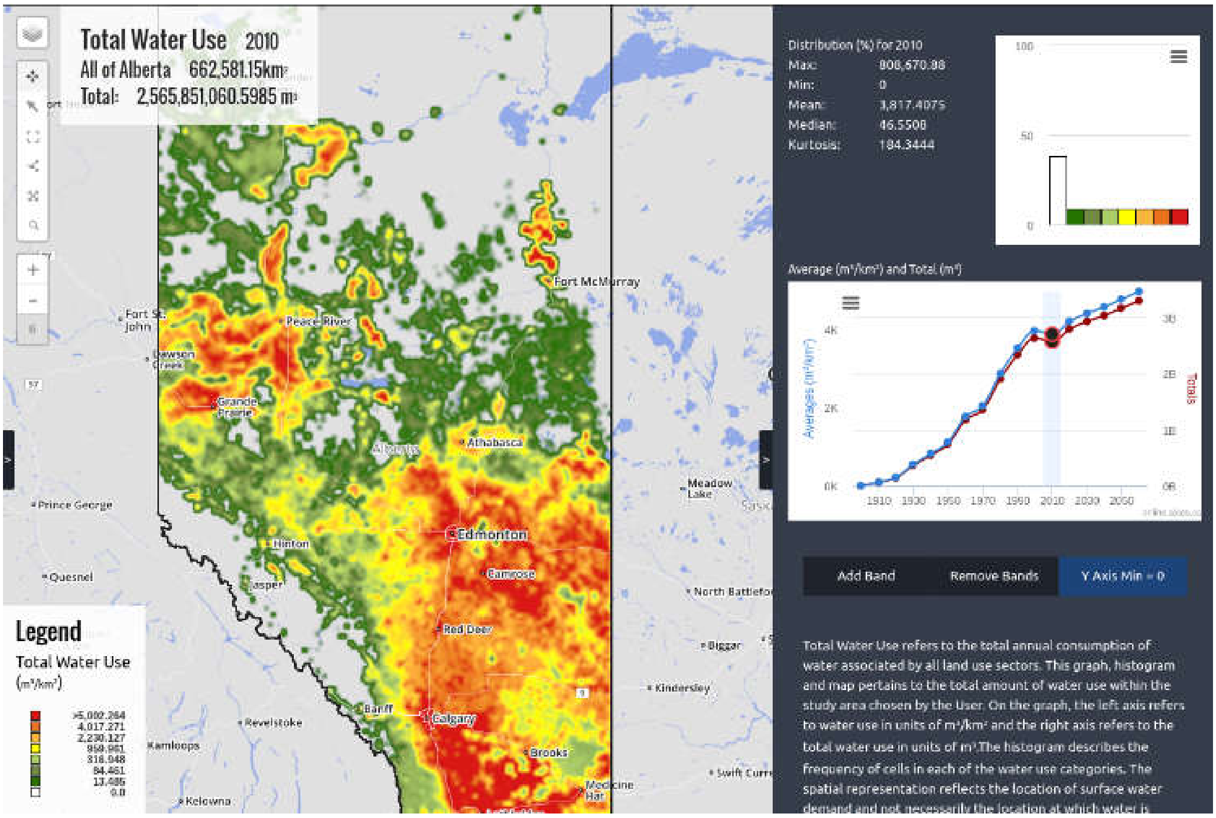


Figure 9: Screenshot of the ALCES software for the exploration or the "Water Use" indicator (source: https://alces.ca/software/)

Figure 10: Adaptation Support Tool interface (source: https://www.deltares.nl/en/software/adaptation-support-tool-ast/)

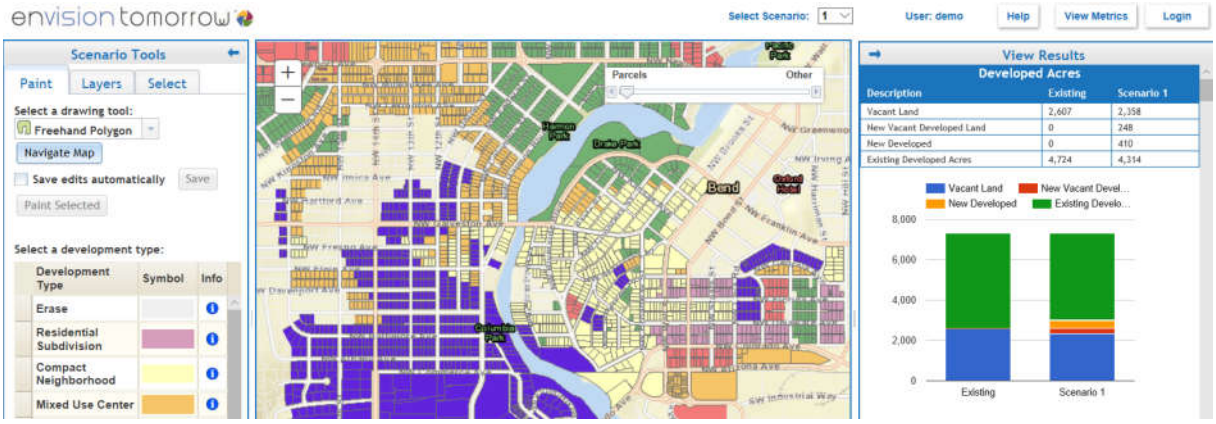


Figure 11: Envision tomorrow interface (source: http://et.tacc.utexas.edu/users/ETMap.aspx)

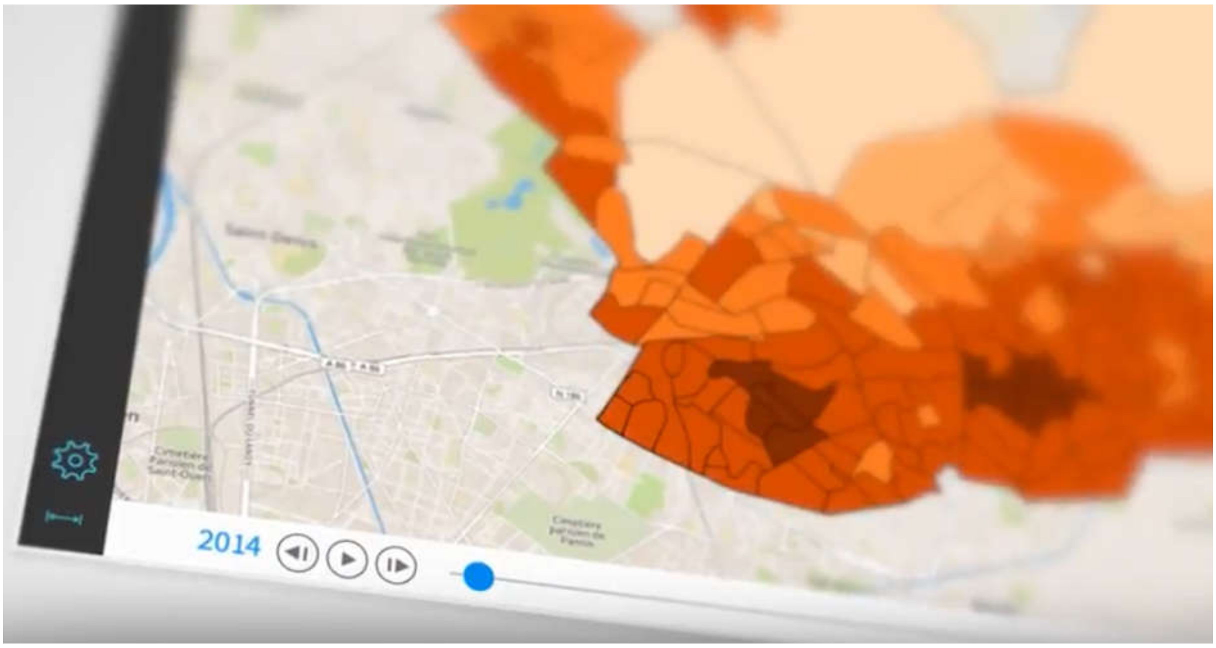


Figure 12: Tool developed by ForCity (source: https://www.forcity.com/)

Therefore, according to the intentions of the developer(s) responding to the needs of the end-users, the representation of the indicator(s) will not be the same. Namely, if the goal is to analyse one indicator in-depth, then several widgets showing several information have to be presented, as a graph to show the evolution of the indicator through time, a map to show its geographical variations, etc. (see Figure 8 above). On the contrary, if the goal is to compare several scenarios, then additional visualisations have to be provided as comparative tables or bar charts. Differential maps are also a good way to visualise changes. Last but not least, the visualisation should fit the level of meaning of the indicator. For instance, population density will be visually interesting on a heatmap per neighbourhood, while the Urban Heat Island Intensity will be better represented in a table, as it concerns the whole urban area.

Overall, several methods can be used to visualise and communicate scenario simulation results to support informed decision-making processes. In the UNaLab project, the visualisation of the SDST scenario simulation results with the NBS Impact Simulation and Visualisation tool should integrate most of these good practices to ensure high usability by the different groups of stakeholders. Namely, indicators should be displayed in an interactive and appealing way, supporting decision-making by encouraging discussions around the touch-table/screen.

III. METHODS

This chapter provides the description of the disciplinary models used to assess urban sprawl and urban heating (Section IV.1) as well as the indicators chosen to render the model results in a user-friendly way (Section IV.2.). Then, the process for the design of the ICT framework is explained (Section IV.3) as well as the process undertaken to create the final visualisation (Section IV.4).

III.1. Models of urban sprawl and urban heating

III.1.1. The SULD model

The Sustainable Urbanising Landscape Development (SULD) model is a GIS-based model based on a hedonic pricing simulation approach and has been used for various purpose, as the assessment of the impacts of urban sprawl on real estate values (Alves, 2014), the socio-economic impacts of the establishment of green/blue spaces in urban area (Roebeling *et al.*, 2017) or the impacts of different economic instruments on urban sprawl (Mendonça, 2017). Namely, SULD works with three economic components: the demand side, the supply side and the equilibrium between the two (Roebeling *et al.*, 2017).

The demand side is represented by households (hh) and their preferences for a certain set of goods, services and environmental amenities subject to a budget constraint *y*. Namely, households aim to maximise their utility *U* at a particular location *i* with a function depending on their preferences, distance to environmental amenities and their income that is split between housing expenses ($p_i^h S$), other goods and services (Z), and transportation between the living location and the closest urban centre ($p_x x$):

$$\max_{S_i, Z_i} U_i(S_i, Z_i) = S_i^h Z_i^{1-\mu} e_i^{\varepsilon}$$

$$\text{Subject to } y = p_i^h S_i + Z_i + p_x x_i$$

where p_i^h is the rental price of housing, $p_x$are commuting costs and $x_i$is the road network distance to the closest urban centre, and where μ is the elasticity of demand for residential space (S_i) and ε is the elasticity of utility with respect to environmental amenities (e_i).

The supply side is represented by developers who aim to maximise their profit at a particular location which is dependent on the rental price of housing (p_i^h), the opportunity cost of land (l_i), the constructions costs (D_i^η), the household density (n_i) and the residential space (S_i). The maximising of the profit π results in a minimum rental price that the developer is willing to accept at a particular location i:

$$\max_{D_i} \pi_i(D_i) = p_i^h D_i - \left(l_i + D_i^\eta\right)$$

$$\text{With } D_i = n_i S_i$$

Equilibrium between the demand and the supply side occurs when supply for housing equals demand for housing and hence development patterns for a certain population size and composition are determined given the location of urban centres and environmental amenities. Namely, the land rent price (r_i) is given by:

$$r_i = \left(\frac{ke_i^{\varepsilon}(y - p_x x_i)}{u}\right)^{\frac{\eta}{\mu(\eta-1)}}$$

In practice, SULD takes in input data on the current situation (geo-referenced or not) and scenarios (see Table 6 for the complete list of SULD input per cell), and provides in output data with maps, tables and graphs on different socio-economic characteristics (see Figure 13) for mid- to long-term simulation timescale. To do so, the urban economic model above described is rendered in a numerical model using a GAMS[1] script (Brooke *et al.*, 1998) and run for each scenario. In output, maps are created showing how the households are allocated throughout the area and the consequent characteristics for each cell of 22x22m: housing price (€/m^2/yr), housing quantity (m^2/hh), development density (m^2/cell), household density (hh/cell) and household type (1,2 or 3). A trade-off between land use is only possible between residential and user-defined non-residential land uses – the other land uses being fixed. In the case of Eindhoven, the residential land use is called "Urban" and the non-residential is called "Agriculture".

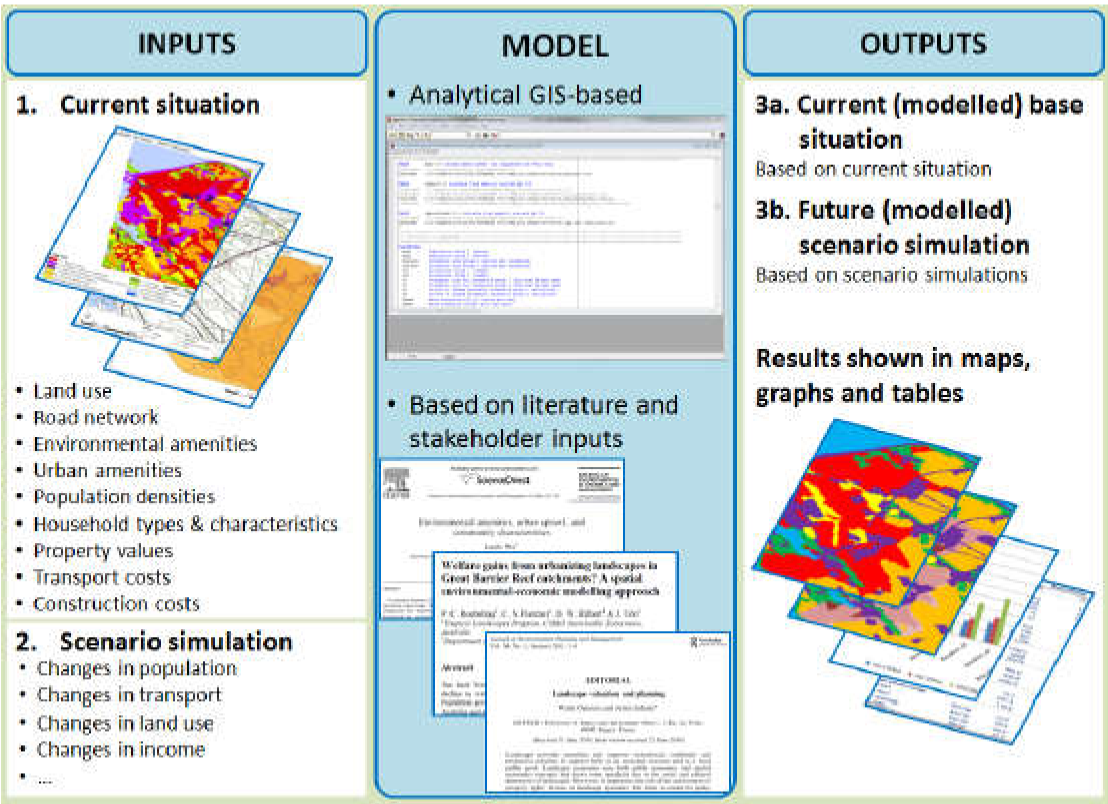


Figure 13: Structure of the SULD decision support tool (Roebeling *et al.*, 2014)

[1] GAMS (General Algebraic Modelling System) is a modelling software that uses a language very close to the traditional programming language. More info at https://www.gams.com/.

III.1.2. The WRF-SUEWS model

The Surface Urban Energy and Water Surface (SUEWS) model is used to simulate the urban energy and water balance components scale using hourly meteorological forcing data (Järvi *et al.*, 2014), obtained in this case with the Weather Research and Forecasting model (WRF) model. The SUEWS model has been used for example to assess the impact of human-induced land use changes on urban climate (Ward and Grimmond, 2017), the consequences of different urban development scenarios on neighbourhood climates (Alexander, Fealy and Mills, 2016) or the effect of urban resilience measures on urban fluxes under a climate change scenario (Rafael *et al.*, 2016). Concretely, SUEWS calculates the hourly urban energy balance (Equation 1) taking into account water components:

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S \qquad (1)$$

Where Q* is the net all-wave radiation (the net incoming and outgoing radiative fluxes), Q_F is the anthropogenic heat flux (the energy released by human activities), Q_E is the latent heat flux (the energy taken up/released with the phase change of water), Q_H is the turbulent sensible heat flux (the energy that heats the air), and ΔQ_S is the net storage heat flux (which includes soil heat flux and also the heating and cooling of the complete urban structure) (Rafael, 2017). These heat fluxes are assessed with several sub-models.

Concretely, the SUEWS model takes in input meteorological and land use data for each cell of 1x1km and returns the hourly values of heat fluxes per cell. This allows for an analysis of the impacts of NBSs solutions in urban settings, as a change in input – for instance from paved area to green space – will induce a change in urban heat fluxes. The simulations for Eindhoven were run by Augusto (2018), focused on the area of interest including the city centre and the future NBS.

Both models (SULD and WRF-SUEWS) provide complex scientific output data that has been analysed in the relevant literature. Nevertheless, to make the model results understandable and tangible by stakeholders, computing indicators from the available data is often the best solution, especially in a context of NBS establishment (Van Delden *et al.*, 2011; Kabisch *et al.*, 2016). The next section aims at describing the indicators chosen to render at best the impacts of NBSs on urban sprawl and urban heating.

III.2. Indicators of urban sprawl and urban heating

The concepts of urban sprawl and urban heating were studied in depth and defined, and a list of indicators was drawn from the literature (Bodilis, 2018). The indicators selected quantified the characteristics of the two phenomena, including their causes and consequences. For the UNaLab project, this list was modified to fit the context of NBS and to complete the work done by UNaLab project partners (Bosch *et al.*, 2017; EKLIPSE, 2017). As a result, three lists of indicators were created: one for urban sprawl, one for urban heating and one that was usable for both categories. For each urban sprawl (Table 1) and urban heating (Table 2) indicator, a short description is provided, as well as its unit, its calculation method, the data needed to calculate it, its source and its possible level of aggregation (grid/neighbourhood/city).

Urban sprawl indicators (Table 1) include indicators for the patterns and processes of low density development and its consequences. The **patterns** are described by the “Ratio of open space to built form”, the “Residential Density” (or Household Density), the “Continuity” of urban areas that states if an area is more than 80% built or not, the “Share of low/high dense areas” to qualify the housing repartition, “Land Use Mix” that quantifies how diverse is an area in terms of land use (0=monopole and 1=all land uses are present in a balanced way) and “Built up area per inhabitant” (or housing quantity). The **processes** are described by the evolution of the patterns indicators from one scenario to another, as an increase/decrease in residential density can be spotted, or the change in Land Use Mix. For the grid scale, the display of land use per cell will also be useful to observe where residential areas have appeared/disappeared. The **consequences** of urban sprawl are described with the “Accessibility to urban green spaces”, the “Loss of environmental fragile land” and the “Loss of agricultural land”. The data needed to calculate the indicators were land use data and distances to environmental amenities available with SULD input, as well as population and socio-economic data available with SULD outputs. Some adaptation of the calculation proposed in the literature had to be made to be able to use this data. For example, in the CITYkeys report (Bosch *et al.*, 2017), the accessibility to green space was defined as the number of green spaces within 500 meters. As this information is not available from the SULD output, a proxy was defined as the distance to the closest amenity (in meters). Finally, not appearing in this list are the housing price, the household types and the housing quantity that are also assessed by the SULD model but represent rather other impact categories as real-estate values and gentrification

Table 1: Indicators for urban sprawl (Bodilis, 2018)

Type	Name	Description	Unit	Calculation method	Data needed	Source	Level of aggregation
Pattern / Process	Ratio of open space to built form	Open spaces are non-built areas as agricultural land, water and green spaces	Number	Area of open space divided by area of built area	Land use data	(EKLIPSE, 2017)	Neighbour-hood or city
	Household Density	Household density in residential area	House-holds /km²	Number of households divided by their residential area	Popula-tion and land use data	EEA (2006), Kasanko (2006), Sidentop and Fina (2010)	Local, neighbour-hood or city
	Percent of built up area	Describes how much space is taken by constructed areas	%	Built up area (residential, industry/commer ce) divided by total area	Land use data	EEA (2006)	Neighbour-hood or city
	(New) built up area per inhabitant	Describe the efficiency of land use attributed to residential activities	m²/hab	(New) Built up area divided by number of (New) inhabitants (or households)	Land use data and popular-tion data	MAES framework (European Union, 2014), EEA (2006)	City

	Continuity	State if an urban area is continuous or not according to European standards	Yes/No	If there is more than 80% of buit-up area --> Yes, else No	Land use data	EEA (2006)	Neighbour-hood or city
	Land use mix	States how diverse is an urban area (0=monopole of a land use, 1=land uses equally distributed in the areas)	Number between 0 and 1	Simpson's index: $\frac{1-\sum_1^m p_i}{1-1/m}$ where pi is the proportion of the category i in the sample, and m the total quantity of classed of land use	Land use data	Arribas-Bel (2011)	Neighbour-hood or city
Consequences	Accessibility of environme-ntal amenities	Average distance to closest green or blue space. Possibility to have a differentiation of the amenity per value (see III.3.1.)	Meters	Average on all the cells in the areas of the distance to the closest environmental amenity	Distance to closest environm ental amenity	Adapted from CITYkeys (Bosch *et al.*, 2017)	Neighbour-hood or city
	Accessibility to urban centres	Average distance to closest urban centre	meters	Average on all the cells in the areas of the distance to the closest urban centre	Distance to closest urban centre	Adapted from CITYkeys (Bosch *et al.*, 2017)	Neighbour-hood or city
	Loss of agricultural land	Agricultural land lost following urban sprawl	hectares	Surface of agricultural land loss from one year to another	Land use data	MAES Frame-work (European Union, 2014), Johnson (2001)	City
	Loss of environm-ental fragile land	Environmnental land (green and blue spaces, agricultural area) lost following urban sprawl	hectares	Surface of environmental fragile land loss from one year to another	Land use data	MAES Framework (European Union, 2014), Johnson (2001)	City

Indicators for urban heating (Table 2) include causes, patterns and consequences indicators. The **causes** are quantified by the “Urban Forest Pattern” and the “Share of Blue Spaces”. Albedo was also a good indicator from the literature, but it was considered uniform among the area for the model so not relevant to observe differences between scenarios. The **patterns** of urban heating and the quantification of the UHI are described with the “Urban Heat Island Intensity (UHII)” calculated with the difference between the average temperature of the study area and the average temperature among three agricultural areas at the outskirts of the city (see Annex 2), the “UHI Magnitude” that is the difference between the highest UHII and the average one during the considered period, and the heat fluxes from the SUEWS model (“Latent Heat Flux”, “Sensible Heat

Flux" and "Anthropogenic Heat Flux"). Finally, the **consequences** of urban heating are quantified only with the "Cooling Degree Day" indicator that is a proxy for energy consumption due to cooling. Other consequences include outdoor comfort, vulnerability to heat and health issues, which are not directly calculable with the data available. Likely, the number of heatwaves defined for the Netherlands as 5 days or more where the temperature is higher than 25 including 3 higher than 30 (KNMI, 2018) was not considered as the month of July 2013 did not present this condition, but this indicator can be integrated later, especially when climate change will be considered. The land use data was extracted from SUEWS input and all the information related to temperature and heat fluxes from the SUEWS outputs.

Table 2:Indicators for urban heating (Bodilis, 2018)

	Name	Description	Unit	Calculation method	Data needed	Source	Level of aggregation
Causes	Urban forest pattern	Tree canopy (having a cooling effect through shade)	%	Tree coverage of the area	Land use data	MAES Framework (European Union, 2014)	Neighbour-hood or city
	Share of blue spaces	Percentage of urban area covered by blue spaces (ponds, rivers, lakes)	%	Area of blue spaces divided by the total urban area	Land use data	CITYkeys (Bosch *et al.*, 2017)	Neighbour-hood or city
Patterns	Urban Heat Island Intensity (UHII)	Maximum differences between temperature in the city core and the surrounding agricultural areas	°C	Maximum of the average temperature in urban areas minus average temperature in rural surroundings area (see Annex 2)	Temperature data	CITYkeys (Bosch *et al.*, 2017)	City
	Latent and sensible heat flux	Quantification of the exchanges of heat between the urban surfaces and the atmosphere	W/m²	With the SUEWS model	Heat fluxes	Rafael (2017)	Neighbour-hood or city
	UHI Magnitude	Maximum amplitude of the UHII	°C	Difference between maximum UHII and mean UHII	Temperature data	Schwarz et al (2011)	City
	Anthropogenic heat flux	Heat produced by human activity	W/m²	Different models are possible (see Sailor 2010), here SUEWS is used	Heat fluxes	Sailor (2011)	Neighbour-hood or city

Consequences	Cooling Degree Days	Used to quantify the buildings' energy demand due to cooling	°C.Day	Sum of the times (in day) when the mean outside temperature was above a threshold (here 25ºC) multiplied by the difference between the temperature and the threshold	Temperature data	Santamouris (2017)	Neighbour-hood or city

The indicators concerning both urban sprawl and urban heating comprise "Public green space" and the "Percentage of impervious surfaces". Both are consequence indicators of urban sprawl and causes indicators of urban heating. Indeed, an expansion or a contraction of the city will have an impact on the provision of green spaces, especially in a context of NBS. For example, if sprawl happens, new developments may be planned on former public green open spaces, or on the contrary if the city becomes more compact, new green spaces can be established in the congested centre to answer environmental challenges. These changes will impact the urban heating causes, as an increase of green spaces increase the provision of cooling spaces through shading and evapotranspiration, but the decrease of it can worsen the UHI effect. Likewise, urban expansion or contraction will have an impact on the surface occupied by impervious surfaces as developing land for housing and commercial activities purposes increased sealed areas at the expenses of un-sealed ones that can provide cooling through evapotranspiration.

Table 3: Indicators for urban sprawl and urban heating (Bodilis, 2018)

Name	Description	Unit	Calculation method	Data needed	Source	Level of aggregation
Public green space	Quantification of public green spaces in the city, either direct value (area), percentage of area or area per inhabitant	km^2, % or km^2/hab	Sum of the areas of public green spaces, Total area of green spaces divided by the total city area, Total area of green spaces divided by the number of inhabitants	Land use data with specification of public green spaces	Rizwan, Dennis and Liu (2008)	City or neighbourhood
Percentage of impervious surface	Surfaces that don't let water pass through them, leading to higher energy storage during the day and the release of it at night	%	Area of impervious surfaces (residential, industrial and roads) divided by the total urban area	Land use data	MAES Framework (European Union, 2014),Yuan and Bauer (2007)	City or neighbourhood

III.3. Design of the ICT framework

From the global UNaLab ICT framework described in Figure 2, a more detailed one focused on the tools needed for the indicators' visualisation is drawn (see Figure 14). Indeed, two technical elements need to be specified: (i) how to organise model results in the UNaLab knowledge database and (ii) how to use the data in the visualisation tool to fit the SDST requirements. The answers to these questions should fit the ICT Framework requirements, determined by the tools and technologies decided by the IT partner in charge of the ICT tools development (ENGINEERING).

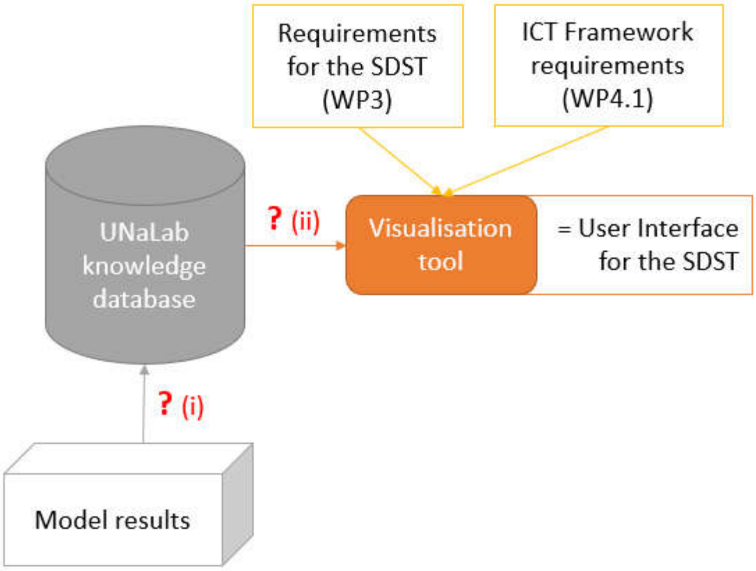


Figure 14: Challenges to be answered by the ICT tools proposal (UNaLab WP4, 2016)

For the first question (i), the challenge was to propose an integrated data structure that will allow the future representation of indicators at different scales (city/neighbourhood/grid level), will require the least-possible pre-treatment of data and will be easily adaptable to other impact categories. Namely, the steps of the process between the raw model outputs and the working indicators to visualise should be minimized to ensure the interoperability of the SDST. For the two considered models, two different ways of processing the data are needed, as the model output data do not come in the same form (Figure 15). The final step that is the visualisation of the data on Tableau Software will be detailed in IV.4.2.

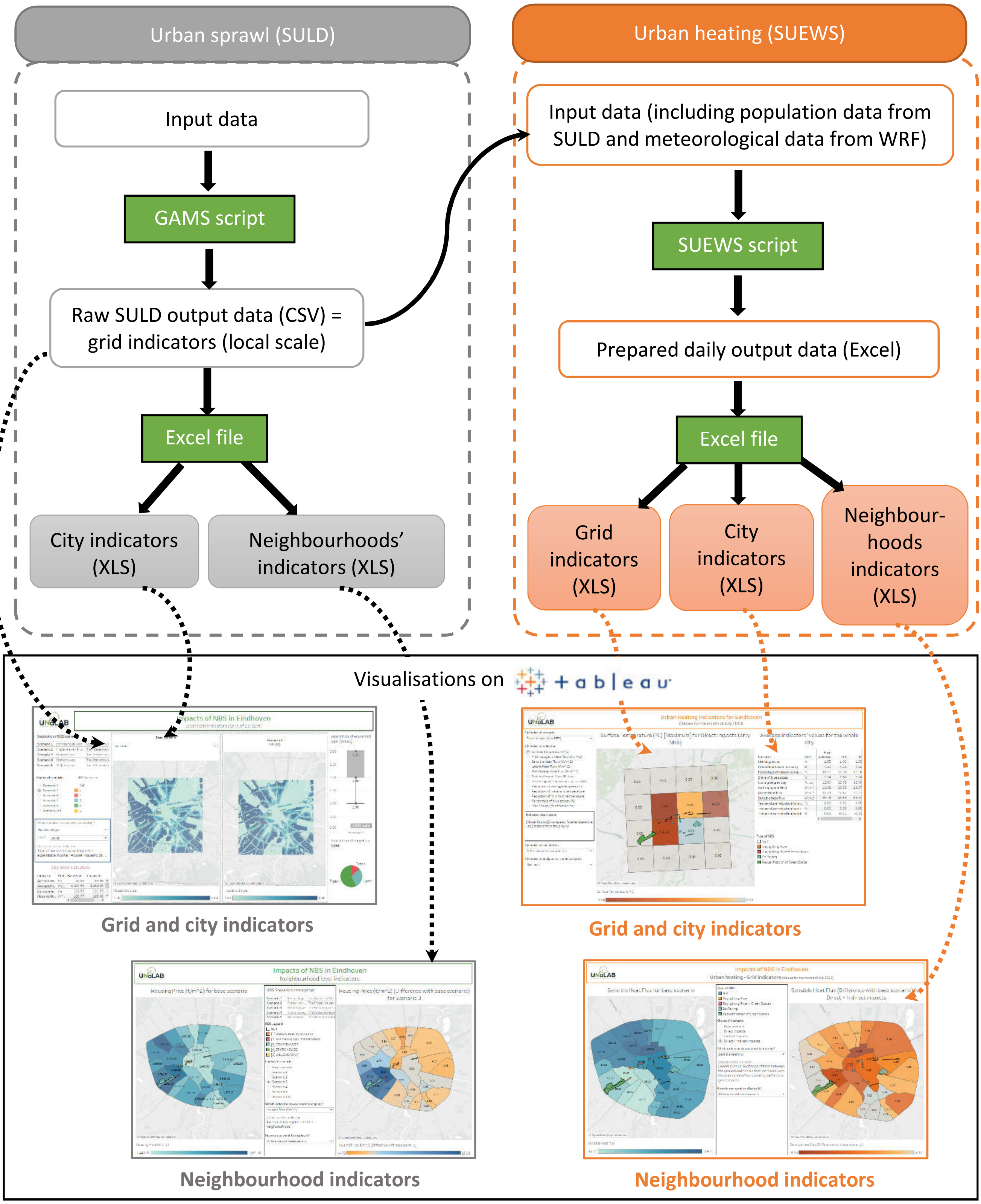
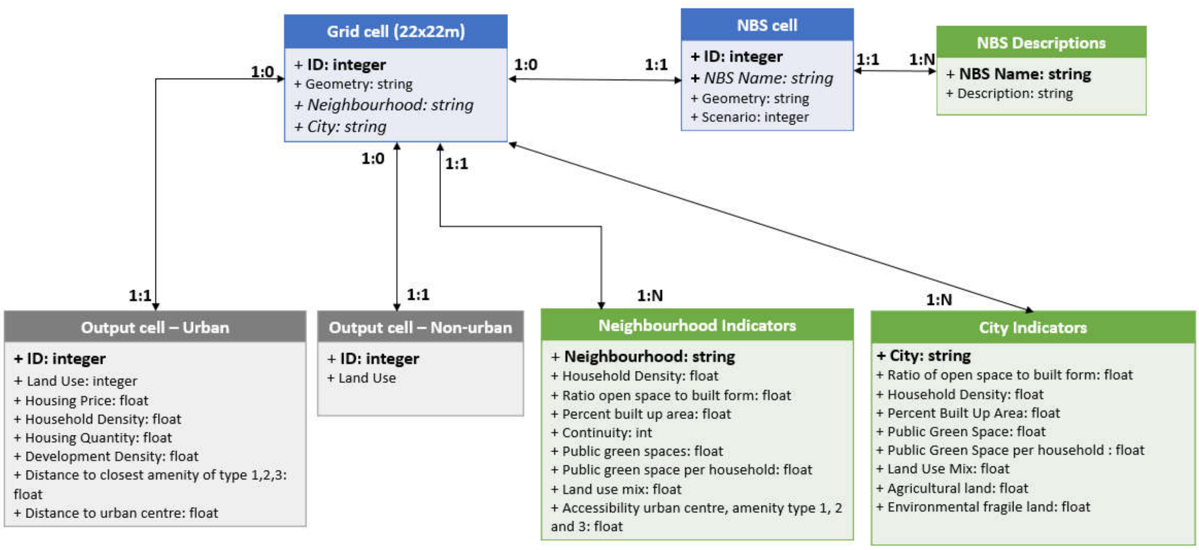


Figure 15: Process for the data preparation and the calculation and visualisation of the indicators

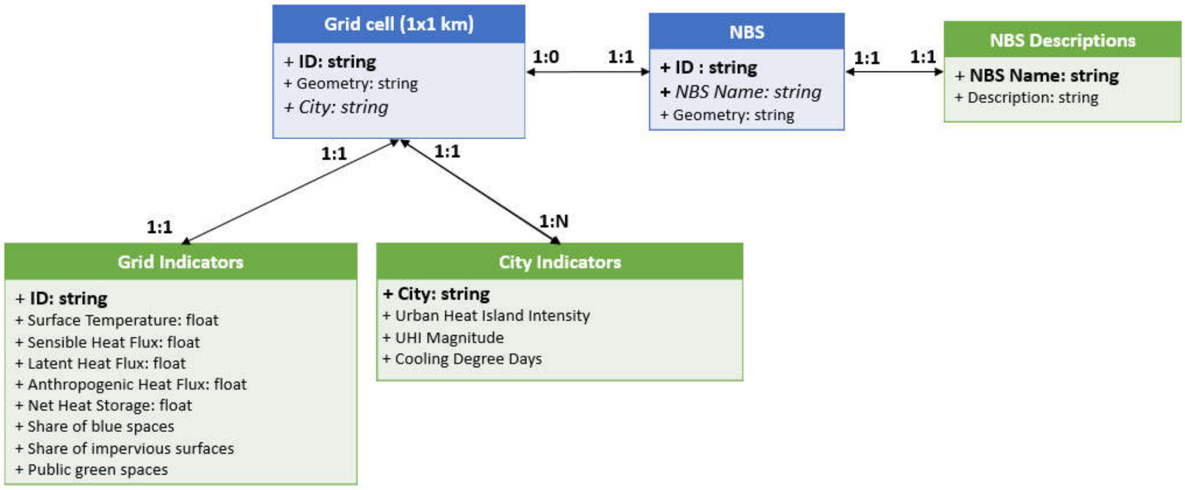
For urban sprawl and the SULD model, the raw output data from GAMS was initially imported in Excel with macros' functionalities, and then treated to obtain maps using conditional formatting for each cell (one value = one colour). To make this tedious process faster and less complicated, the GAMS code was modified to return CSV files with all the data needed – namely the information available for each cell (land use, household density, real-estate values, etc). For urban heating and the WRF-SUEWS model, minor data preparation was needed as the model returned hourly data. Simulations and data preparations were performed by Augusto (2018), who considered the output of SULD as an input for population density. Automation of this procedure is, however, crucial for the functional development of the SDST.

Then, for urban sprawl and urban heating impact categories, the data was imported in Excel and the indicators for the different scales were calculated, namely city and neighbourhood indicators as grid indicators were available directly with SULD and SUEWS output. Concretely, for urban sprawl and the SULD model, the neighbourhood indicators were either derived from the grid data by doing the average of the grid indicator for the cells in the neighbourhood, or by following the calculation methods listed in table 1 and 3. The process for urban heating neighbourhood indicators is explained in V.2.2.II. For the city indicators, the average of the grid indicators was made for both impact categories on all the cells. After the creation of Excel files with all the necessary indicators, a data structure was proposed for both impact categories in the UML language (see Figure 16 and 17). For both impact categories, the structure includes a geographical file for the NBS, a geographical file for the output grid of the model, and Excel and CSV files for the indicators. An extra Excel file was linked to the NBS geographic information to be able to describe the scenarios in detail (NBS Descriptions.xls).



Note: **Blue**= geographical file, **Green**=Excel, **Grey** = CSV

Figure 16: Data structure for the visualisation or urban sprawl indicators



Note: Blue= geographical file, **Green**=Excel

Figure 17: Data structure for the visualisation or urban heating indicators

The challenge for the second question (ii) is linked to the ICT requirements from the UNaLab project and, more precisely, to the tools chosen to answer the SDST specifications. Indeed, the tool that will be used for the SDST user interface is Knowage (UNaLab, 2016), an open source business intelligence web application developed by ENGINEERING. Unfortunately, at the time of the present project Knowage was not up and running at its full functionalities and, hence, Tableau Software was used instead (Tableau Software, 2018). This does not mean that the present work cannot be used afterwards, as it will serve as an example of good practices, improved according to stakeholders' feedback at an early stage of the project and serving as a base for the development of the final tool in terms of functionalities. The next section aims at explaining the process used for the visualisation of the indicators.

III.4. Visualization of urban sprawl and urban heating indicators

III.4.1. Process for the creation of the User Interface (UI)

The realisation of the UI for the visualisation of urban heating and urban sprawl indicators had to integrate three components mentioned in Figure 18. First, it should be feasible with the ICT framework as mentioned in the previous section, namely with the data structure and the tool chosen. Second, it should integrate good practices recommendations from the literature to ensure its acceptability and usability. Finally, it should fit the end-users needs, namely the stakeholders involved in NBS projects.

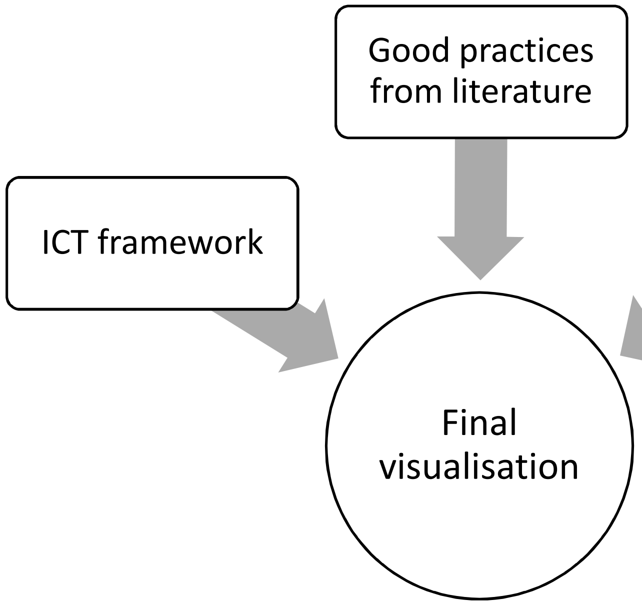


Figure 18: Considerations for the realisation of the user interface

To ensure the integration of these three components, the following process was used to achieve the final prototype for the SDST user interface (see Figure 19). First, a draft of the UI was made with the data available and the functionalities of the tool considering potential use cases. Then, the outcome was presented to pilot end-users – colleagues from the Department of Environment and Planning of the University of Aveiro – on 29-04-2018 and 22-05-2018, where they gave feedback on the general user interface, the functionalities and the indicators. Finally, the proof-of-concept version was presented to actual end-users and stakeholders during the UNaLab consortium meeting on 30-05-2018 and, in turn, the final version was elaborated.

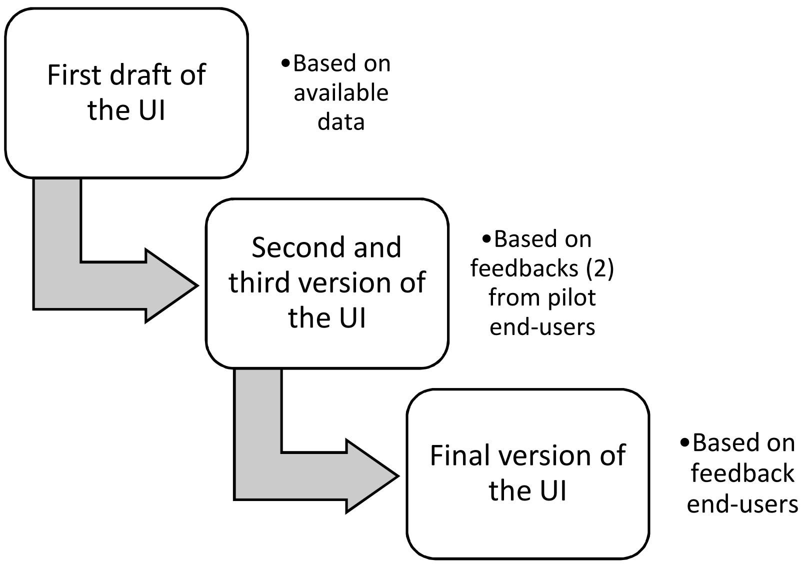


Figure 19: Process to build the final UI prototype

The realisation of an interactive and complete prototype was made possible by the use of a well-developed visualisation tool, Tableau Software.

III.4.2. Creating visualisations with Tableau Software

The visualisations were performed using Tableau (Tableau Software, 2018). Initially developed for the Business Intelligence (BI) field of work, this software is nowadays used for a broad range of data and has been recently chosen as visual analytics standards across the United Nations system. Aesthetically appealing and constantly evolving to provide features that meet user needs, Tableau has grown to be one of the leaders in the BI field. One of the strengths of the tool is the ability to handle big data sets of different natures, especially geographical data.

The process to create visualisations and dashboards in Tableau is quite straightforward (see Figure 20 for an example): after creating a data source from one or multiple sources, the user can create a *sheet* from this data source where the data is rendered visually (with maps and graphs), and then this sheet can be integrated in a *dashboard* with other sheets. On this dashboard, interactive filters can be added from one sheet to another.

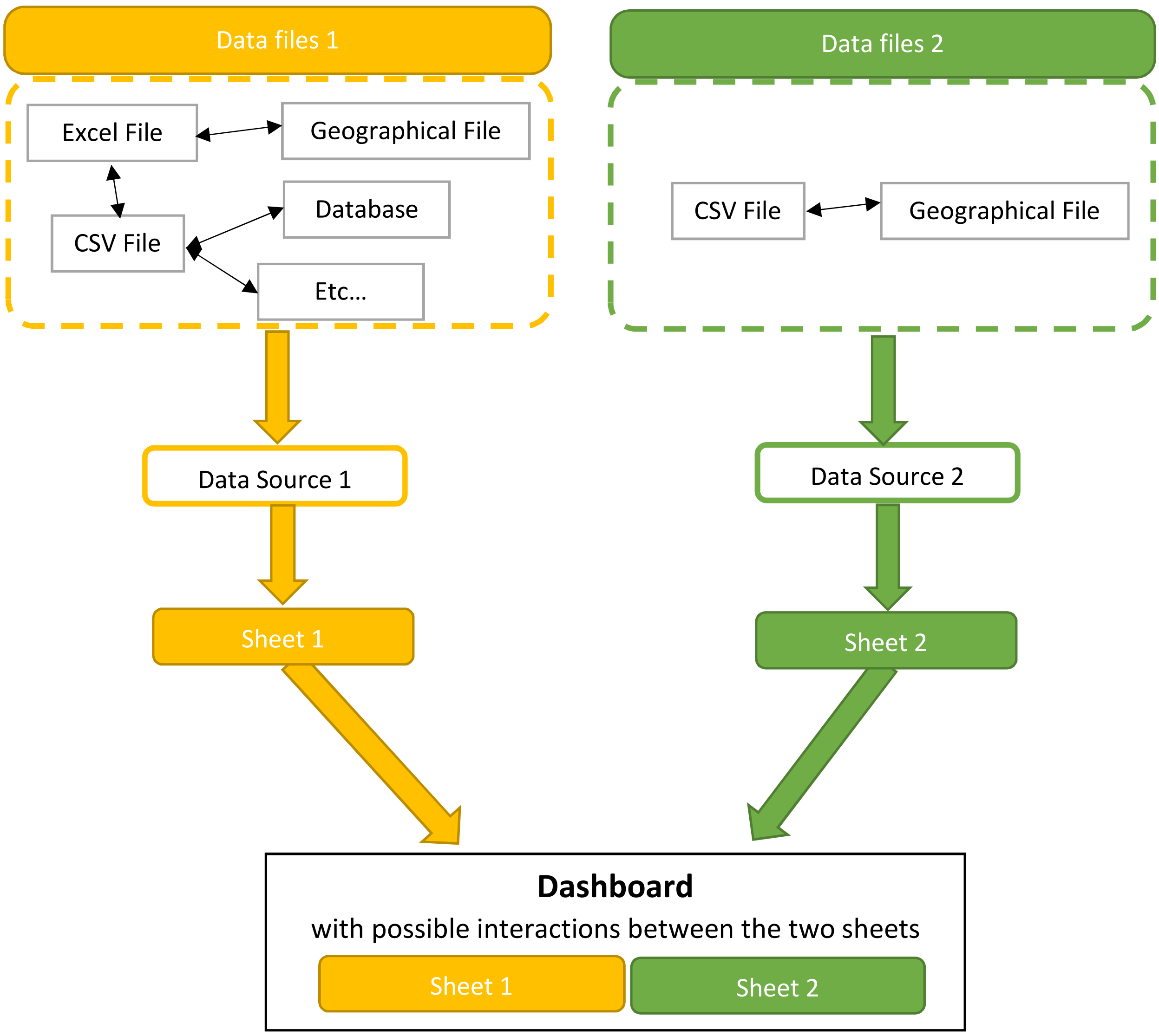


Figure 20: Process example for the construction of a dashboard composed of 2 sheets in Tableau

The dashboard format is well-adapted to the goals of the UNaLab project, as it can offer the visualisation of several information at the same time, providing insights for different NBS impacts throughout the city on the same support. What’s more, the use of a dashboard was found to be a good practice in the literature to ensure meaningful communication of model results (see Section II.2.3) and to allow informing, communicating and analysing functionalities. Indeed, it helps providing a snapshot of one phenomenon at a given time, here the impact of NBSs on urban sprawl and urban heating, while allowing the possibility of exploring scenarios at different scales.

IV. CASE STUDY DESCRIPTION

In this study, a partial prototype for the visualisation of the SDST model results is presented for Eindhoven, one of the front-runner cities of the UNaLab project with good data availability and established NBS plans. The prototype will be an example of decision-support tool for the establishment of NBS considering urban sprawl and urban heating, and will be tested with stakeholders. Using one city as a case study allows an in-depth development of the tool and a better familiarisation with the results while keeping open the option to extend to other cities.

IV.1. Eindhoven

Eindhoven is the fifth largest city of the Netherland, and the largest of the Noord Brabant region, with a population of 229,319 inhabitants in 2018 (CBS, 2018). Well connected with Germany and Belgium (see Figure 21), the city experienced a growth of 19,000 inhabitants between 2000 and 2014 (Nabielek, Hamers and Evers, 2016) and is expected to host up to 300,000 urban dwellers by 2030. As a result, the city is facing challenges due to rapid population growth.

Figure 21: Location of the city of Eindhoven in the Netherlands

As a city that went successfully from an industrial town in decline to a thriving technology and design-oriented city, Eindhoven has been attracting talents and qualified workforce to work in the booming technology hub (Fernandez Maldonado and Romein, 2009). Yet, the city centre can only welcome 3% of the entire housing stock (Fernandez Maldonado and Romein, 2009), which means that solutions had to be found to fulfil housing demand. The recommendations from a public consultation (called “Eindhoven SUPERvillage”) were that the development should stay close to the historical regional landscape, namely a mix of rural areas and a network of medium-sized towns and villages. This coincides with the preference of knowledge workers for spacious and green living environment, while living relatively close to their workplace. Hence, the Eindhoven region is nowadays fragmented, with rural village and modern cities, which opens up the challenge of developing the city of Eindhoven while limiting the conversion of agricultural land and limiting urban sprawl.

Another challenge that awaits the municipality of Eindhoven is the heating of some parts of the city and the increase of the urban heat island effect. Indeed, an increase of the latter can lead to an increase in the frequency and the duration of heatwaves in the urban core, resulting in an increase in hospital admissions – up to +12% at the national scale during a heatwave (Gerard, 2015). For example, a heat stress map for the 26th of July 2013 at 3 pm is presented in Figure 22, showing the parts of the city cooler (blue) or hotter (red) than an open field in the outskirts for the same day. Large cooler areas are located where big green spaces provide shading, as the Stratumse Heide area on the South East part of the city or the Strijp area at the North West part of the city. Hottest parts are located in big industrial areas. The Urban Heat Island Intensity has been measured for Eindhoven and was found to be, on average, 4.4ºC during the day and 3.8ºC at night (Klok *et al.*, 2012).

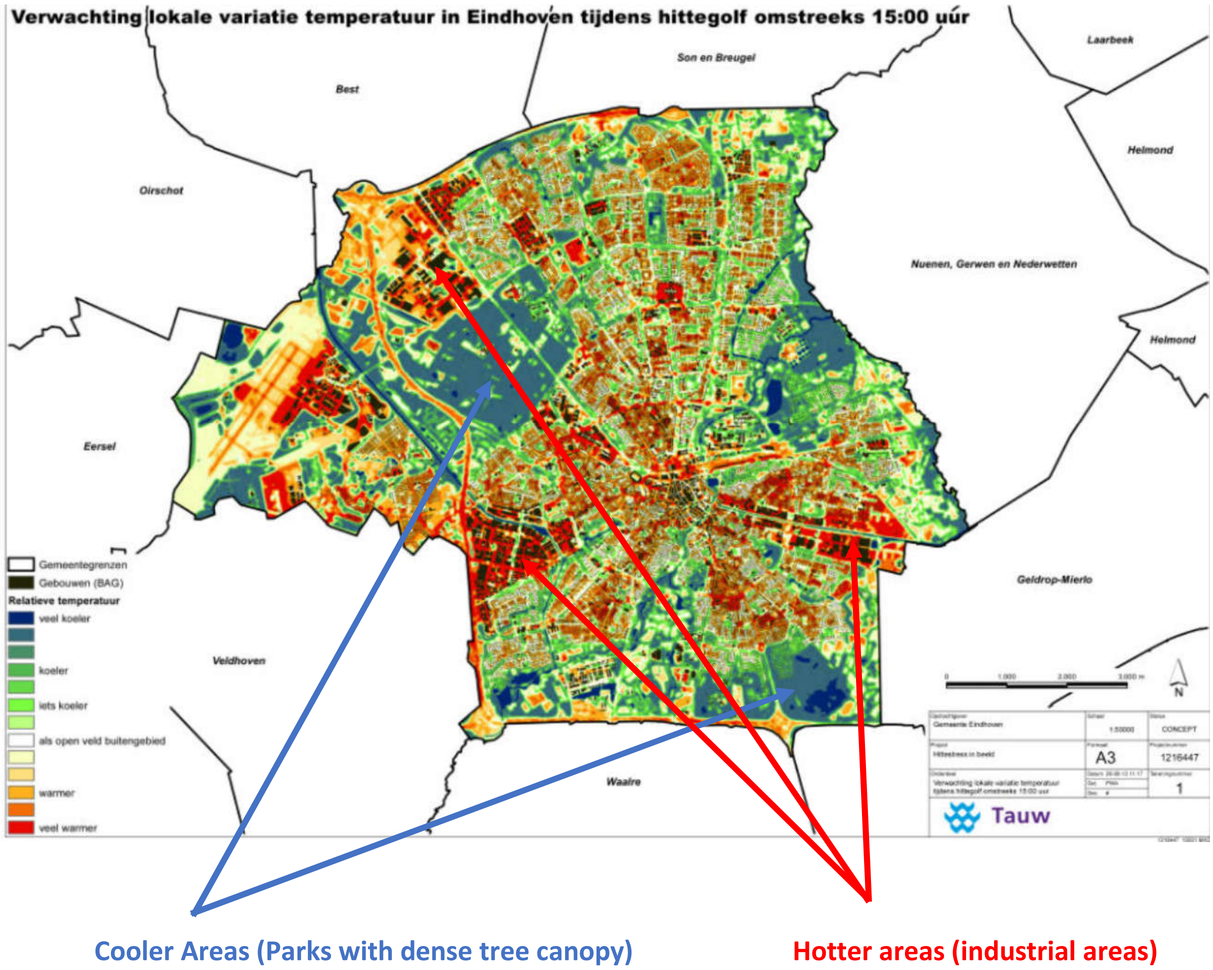


Figure 22: Heat Stress map for Eindhoven on the 26th of June 2013, around 3 pm (source: https://www.bjmgerard.nl/?p=1818)

Other critical problems faced by the municipality of Eindhoven include flooding, air pollution and water pollution in a context of population growth and climate change (UNaLab, 2016). Therefore, Eindhoven is a front-runner city of choice for the UNaLab project, as the city is openly interested in the issues that the project strives to address and can provide a consistent living lab. The UNaLab project will complement municipal strategies dealing with the city's sustainable development, as "*Eindhoven op weg*" focusing on mobility, "*Binnenstadsvisie*" focusing on the inner-city development and "*Klimaatplan*" focusing on climate adaptation. One of the elements missing in this range of strategies was to achieve a climate resilient, nature-based city centre. Investigating the impacts of Nature Based Solutions on a broad range of urban issues will help providing evidence-based arguments for the re-introduction of natural elements in the city and achieve this goal in the medium to long term.

IV.2. NBS scenarios

The city of Eindhoven has invested a total of 6.7 million Euros in the regeneration of the city centre, including 3.8 million for the establishment of NBS themselves (UNaLab, 2016). During the preparation of the UNaLab project proposal, various NBS were proposed (Roebeling *et al.*, 2014;

Postmes, 2017) and will be assessed in this study. The 15 NBS simulated are presented in Figure 23 and described in Table 4. Namely, three locations of daylighting the river Gender (of which one combined with the creation of a green space), ten locations of de-paving and one location of green space requalification (*Gendervijver*, the largest one).

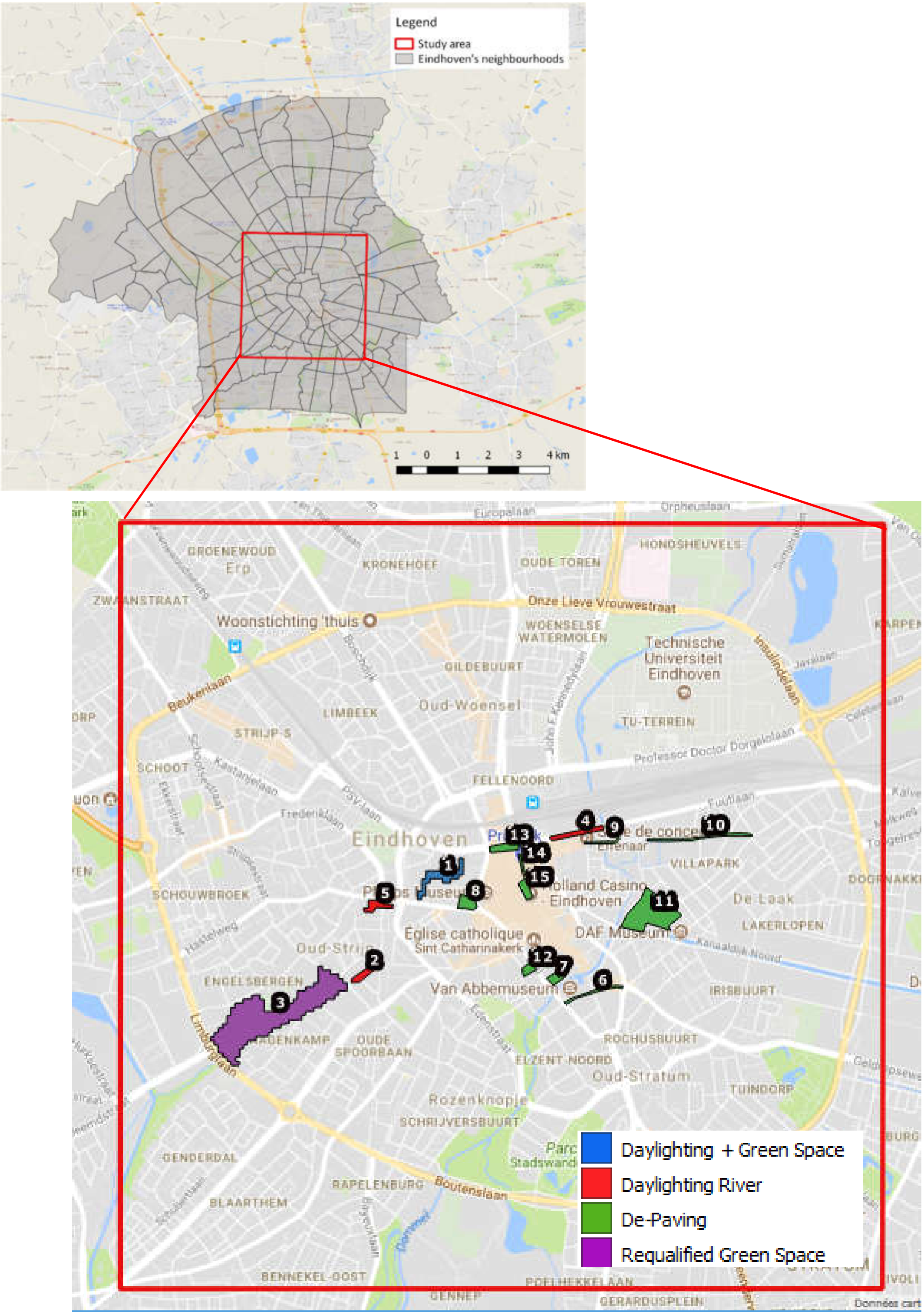


Figure 23: Nature Based Solutions scenarios planned for Eindhoven (Source: http://suld.web.ua.pt/ and Postmes (2017))

Table 4: Description of the NBS scenarios for Eindhoven (source: http://suld.web.ua.pt/ and Postmes (2017))

NBS	Name	Description	Picture	Source	Type of NBS
1	Emmasingel-kwadrant	Located in the Witte Dame neighbourhood, this project entails the creation of a new park in the city centre of Eindhoven. This area consists of offices and a car park, which is privately owned. The picture provides a visualisation of the project area where the car park is replaced by 'the Gender'. The idea inspires people to create more blue and green space in Eindhoven.		Aqua-Add project	River daylighting
2	Frederika van Pruisenweg	The Frederika van Pruisenweg is a very wide street with houses on both sides and a very wide green area in the middle in the Eliasterrein, Vonderkartier neighbourhood. The municipality has the intention to transform this street by having the Gender flowing through the green area in the street, providing storm water control and recreation areas. The picture shows one of the presented possible layouts of the Gender in the Frederika van Pruisenweg.		Aqua-Add project	River daylighting
3	Gendervijver	The Gendervijver at the border of the neighbourhoods of Engelsbergen and Hegenkamp is already a nice pond. Still the soil under the pond is polluted and needs cleaning. This gives the municipality a good opportunity to make the Gendervijver even nicer as shown, for example, in the picture. With this design the ecological value and the water quality will both improve. In addition,		Aqua-Add project	Requalification of green space

		after the reconstruction the Gendervijver will have a more natural look.			
4	Stationsweg	The Stationsweg in the Binnenstad neighbourhood is the last part of the Gender before it flows into the river Dommel. This part of the Gender is a challenge because the width of the public space is limited. The street combines numerous functions – for example, it's a main street for cars as well as bicycles. The traffic department wants to reduce the amount of cars in the street, which will leave some space to create a visible Gender combined with green slopes as shown in the picture.		Aqua-Add project	River daylighting
5	Willemstraat	The Willemstraat in the Eliasterrein (Vonderkwartier neighbourhood) is a part of the Gender alongside a very busy road with only little space left to make the Gender visible (see picture). The water level of the Gender will be hardly visible from the street and only few people walk along this area – hence, keeping the Gender underground is more appropriate. A little further along the Willemstraat more space is available – in this area the municipality will build several houses and, thus, will be a better location to create an open water course.		Aqua-Add project	River daylighting

6	Bilderdijklaan	The long street along the Dommel river is under renovation and will host more bicycle lanes in the future, separated from the street with a green line. This will make the major bicycle road of the city more pleasant (picture taken during the UNaLab consortium meeting).		Postmes (2017)	De-paving
7	Stadhuisplein	The city hall building is being renovated and with it the entrance will be made greener. Currently, the surface is an un-attractive paved area and it will be vegetated (grass and trees) in the near future.	 	Postmes (2017)	De-paving
8	Clausplein	The Clausplein is a paved square in the city centre, constructed in a design trendy in the 1980's. A discussion is on the way to de-pave the area and make it a more convivial place for the citizens of Eindhoven.		Postmes (2017)	De-paving
9-15	Miscellanous	Other de-paving projects are planned throughout the city, including a big re-qualification of an old gas factory (number 10).		Postmes (2017)	De-paving

IV.3. Data available

The impact of NBS on urban sprawl and urban heating will be assessed with two scientifically recognized models:

- The Sustainable Urbanizing Landscape Development (SULD) decision support tool for the assessment of urban sprawl, real-estate valuation and gentrification (Roebeling et al., 2017; see Chapter III); and
- The Surface Urban Energy and Water Surface (SUEWS) model forced by Weather Research and Forecasting model (WRF) for the assessment of the Urban Heat Island effect (Järvi et al., 2014; Rafael et al., 2017; see Chapter III).

The data used to calculate the indicators for Eindhoven was extracted from the input and output data for these two models, either already available from previous projects (see Section IV.3.1) or produced in an integrated way for the UNaLab project (see Section IV.3.2). An overview of the characteristics of the model simulations is given in Table 5 before describing in detail the data available from the models.

Table 5: Model simulations characteristics

	SULD	WRF-SUEWS
Base year	2010 – 2011	2013
Projected year	Mid- to long-term	Short-, mid- and long-term
Study area	4x4 km	4x4 km
Cell size and number	34,225 cells of 22x22 m	16 cells of 1x1 km
Number of scenarios	6	4

IV.3.1. From the SULD model

The impacts of NBS on urban sprawl were assessed with the SULD model for 6 scenarios from a previous project (Roebeling et al., 2014, see also Table 4):

- **Scenario 1** corresponds to the new park surrounding a daylighted section of the Gender river (*Emmasingelkwadrant*),
- **Scenario 2** corresponds to the gender river daylighting on the *Frederika van Pruisenweg* street,
- **Scenario 3** corresponds to the requalification around the *Gendervijver* pond,
- **Scenario 4** corresponds to a daylighting of the Gender river near the train station (*Stationsweg*),
- **Scenario 5** corresponds to a daylighting of the Gender river on *Willemstraat*,
- **Scenario 1-5** corresponds to all the previous scenarios combined.

For each scenario, input data is gathered and formatted, the script from the SULD model is executed with the formatted files in input, and output files are created. The study area of 4x4 km comprises the inner-city and is divided in 34,225 cells of 22x22 m. The content of the input and output files are listed in Table 6. The information that SULD provides for the whole city was not used directly as the goal was to use the less intermediary steps to calculate the indicators, e.g. all the indicators were derived from the most detailed level of aggregation (grid scale).

Table 6: Inputs and outputs of the SULD model. In black the one used later on for the indicators, in grey the one not used but that can be used

Input
Land use per cell (ha): 1 = Forest 2 = Water 3 = Agriculture (non-residential areas) 4 = Industry/Commerce 5 = Urban parks 6 = Urban (residential areas) 7 = Roads
Road distance to closest urban centre per cell (m)
Euclidian distance to closest urban park per cell (m)
Euclidian distance to closest neighbourhood park per cell (m)
Euclidian distance to closest local park per cell (m)
Location of urban centres (points)
Location of urban parks (polygons)
Location of neighbourhood parks (polygons)
Location of local parks (polygons)
Other input data: - Household type differentiated by number of households, expendable income, shares of housing expenditures and levels of utility, - Annual commuting costs, - Opportunity costs of land, - Construction costs

Output
Land use per cell (type)
Household type per cell (type)
Real estate value per cell (€/m²/yr)
Household Density per cell (hh/cell)
Development Density (m²/cell)
Housing Quantity per cell (m²/hh)
Totals for the whole city: - Population (#) - Real estate value (€/m²/year; m€/year) - Real estate value (€/m²/year; m€/year) - Household Density per cell (hh/cell) - Development density (m^/cell) - Housing quantity (m²/hh)

In the model, the parks and the blues spaces (rivers, ponds, lakes) are gathered in the category "environmental amenities" and classified according to their quality: lower value amenities such as local parks are amenities of Type 1, neighbourhoods parks are amenities of Type 2 and urban park are amenities of Type 3.

IV.3.2. From the WRF-SUEWS model

The impacts of NBS on urban heating were assessed for 4 scenarios for the month of July 2013:

- The **Base Scenario** representing the status quo in July 2013,
- The **Direct Impacts** scenario considering just the establishment of all the NBS (NBS 1-15 from Table 4) and the consequent change in land use (short-term simulation),

- The **Indirect Impacts** scenario considering only the change in population density found after running the SULD model for the Scenarios 1-5 combined (long-term simulation),
- The **Direct + Indirect Impacts** considering both input type (establishment of all NBSs and change in population density – short and long-term simulations).

For each scenario, the WRF model is used to force the SUEWS model with the corresponding input data. The study area is also a square of 4x4 km comprising the inner-city, divided in 16 cells of 1x1 km. The inputs/outputs of the WRF-SUEWS available from the simulation for each cell and each scenario are presented in Table 7. The inputs are divided in two: meteorological data and land use characteristics. The outputs are available hourly, daily and by deduction monthly.

Table 7: Inputs and outputs available from the WRF-SUEWS model

	Inputs
Land use characteristics	Building area (% of grid cell area)
	Paved area (% of grid cell area)
	Bare soil area (% of grid cell area)
	Evergreen trees area (% of grid cell area)
	Deciduous trees area (% of grid cell area)
	Unirrigated grass area (% of grid cell area)
	Irrigated grass area (% of grid cell area)
	Water (% of grid cell area)
	Tree height (m)
	Building height (m)
	Average albedo
	Population density (hab/ha) **(from SULD)**
Meteorological data	Measured solar radiation (W. m^{-2})
	Air temperature (K)
	Relative humidity (#)
	Surface air pressure (Pa)
	Wind speed ($m.s^{-1}$)
	Precipitation ($kg.m^{-2}.s^{-1}$)

Outputs
Surface Temperature (ºC)
Sensible Heat Flux ($W.m^{-2}$)
Latent Heat Flux ($W.m^{-2}$)
Anthropogenic Heat Flux ($W.m^{-2}$)
Net Storage Heat Flux ($W.m^{-2}$)

V. RESULTS

This chapter presents the final user interface (UI) and its functionalities, notably in terms of providing visual support for urban sprawl and urban heating exploratory narratives. Section V.1. justifies how the UI responds to usefulness requirements, while Section V.2. presents the UI itself for the city of Eindhoven and how it can have informing, communicating and analysing capacities.

V.1. User Interface

The final UI is composed of four dashboards: two for urban sprawl and two for urban heating. Three of them were tested three times with (pilot) end-users to maximise their usefulness, namely their utility and their usability, while the last one (neighbourhood indicator for urban heating) was added for the final version of the UI.

V.1.1. Utility

Utility as defined by Nielsen (1993) refers to the extent to which the system can accomplish its tasks, namely if it is useful in terms of functionalities for the end-users. To maximise the utility of the UI, a first set of questions relevant to the future impacts of NBSs on the issues of urban sprawl and urban heating was put up together (see Table 8) prior to its realisation. The user interface was developed keeping in mind these questions and trying to answer them at best.

Table 8: Questions used to guide the development and design of the user interface

Urban sprawl
Where will the residential area mostly develop? Where will it shrink?
How much agricultural land will be lost/gain?
How will impervious surfaces evolve?
How will the accessibility to environmental amenities affected?
Will real estate values increase/decrease on the outskirts or next to the NBS?
How will the residential density evolve?
Average journey to work time?
Hours spent in the car?
Number of individual VS collective housing?
Social interaction?
Impact of population growth?
More energy consumption?

Urban Heating
What will be the impact of NBS on temperature reduction?
Will the Urban Heat Island effect decrease?
How will the number of heatwaves evolve?
Will there be more energy spent for cooling?
Will the magnitude of the UHI decrease?
Will the average temperature increase with climate change?
Will the average temperature increase with population growth?
Mortality/Morbidity increase?
More heatwaves in the city?

Ideally, all of these questions will be answered by the UI, while in practice some of them (in grey) could not be answered with the data available at the time of the present study. For example, there is no data on the type of housing unit available, nor a way to calculate the average journey to work time. What's more, the questions related to climate change and population growth will be answered later in the project, once the projections are integrated in the model inputs. It was also considered that some of these questions can be answered at different scales (e.g. how did the residential density evolve locally, but also per neighbourhood or at the city scale?) which provides even more insight in the data.

Additional questions not directly relevant for end-users without scientific backgrounds were also answered, as the models return a wide range of data. For instance, the urban heating model computes the surface temperature thanks to heat exchange equations and, thus, the values of these exchanges are also available (latent/sensible heat fluxes, anthropogenic heat fluxes and net storage heat fluxes). This coincides with the requirements of the SDST, as different levels of complexity will be available depending on the end-user. Namely, the UI should have informing, communicating and analysing functions to be usable by various stakeholders. Indeed, citizens may just want to observe the overall impact of NBS (Informing), while planners or politicians want to discuss several scenarios with indicators they can understand (Communicating) and engineers want to see the impacts of NBS on scientific variables and understand the models behind it (Analysing).

V.1.2. Usability

The usability of the UI and its underlying components (learnability, efficiency, accuracy and aesthetics, see Figure 5) were ensured by a design – implementation – evaluation cycle (Russo *et al.*, 2017) as shown in Figure 19. Pilot end-users first gave feedback on the first two versions of the UI, emphasizing the general presentation, the information displayed and the interaction end-user/interface. The first session allowed for a profound improvement of the *learnability* and *aesthetics*, as feedback was given on missing information necessary for the comprehension of the data displayed (e.g. the description of the indicators and scenarios, and position of the NBSs), general outlook (colour scales, position of the elements) and possible additional information to display. The second session was more useful for the efficiency and accuracy, as the discussions focussed on the model results and the indicators displayed. *Efficiency* was guaranteed by keeping the UI fast and complete and at the same time simple enough for the scale of management. Namely, three scales were possible to analyse: grid (local for SULD), neighbourhood and city, and relevant indicators were displayed for each one. *Accuracy* is dependent on the model results and on the trust in indicators' calculation methods, which are the base for the visualisation but are not available directly on the user interface. In this case, the usefulness of the tool depends on the end-users, as the ones with scientific background will want to assess the methods used, while the ones relying on those models because they know them / know the person who use them can work sufficiently with the proposed visualisations.

Finally, the improved version of the UI was presented to the actual end-users, namely the stakeholders involved in NBSs co-creation in Eindhoven on the 30/05/2018 during the UNaLab consortium meeting (Figure 24). The session was divided in three parts corresponding to the preliminary results of the UNaLab Working Package 3 "Monitoring and Impact assessment", namely the baseline scenario, climate change and population growth scenarios, and finally the visualisations of the first output of the models for the SDST. A time for feedback was allocated the end of each part and the participants could give their opinions on what they just saw, helped by a moderator (see Figure 24). The session was very constructive to improve the learnability and the accuracy of the UI as it was the first time the model outputs and the indicators were presented to end-users with different backgrounds.

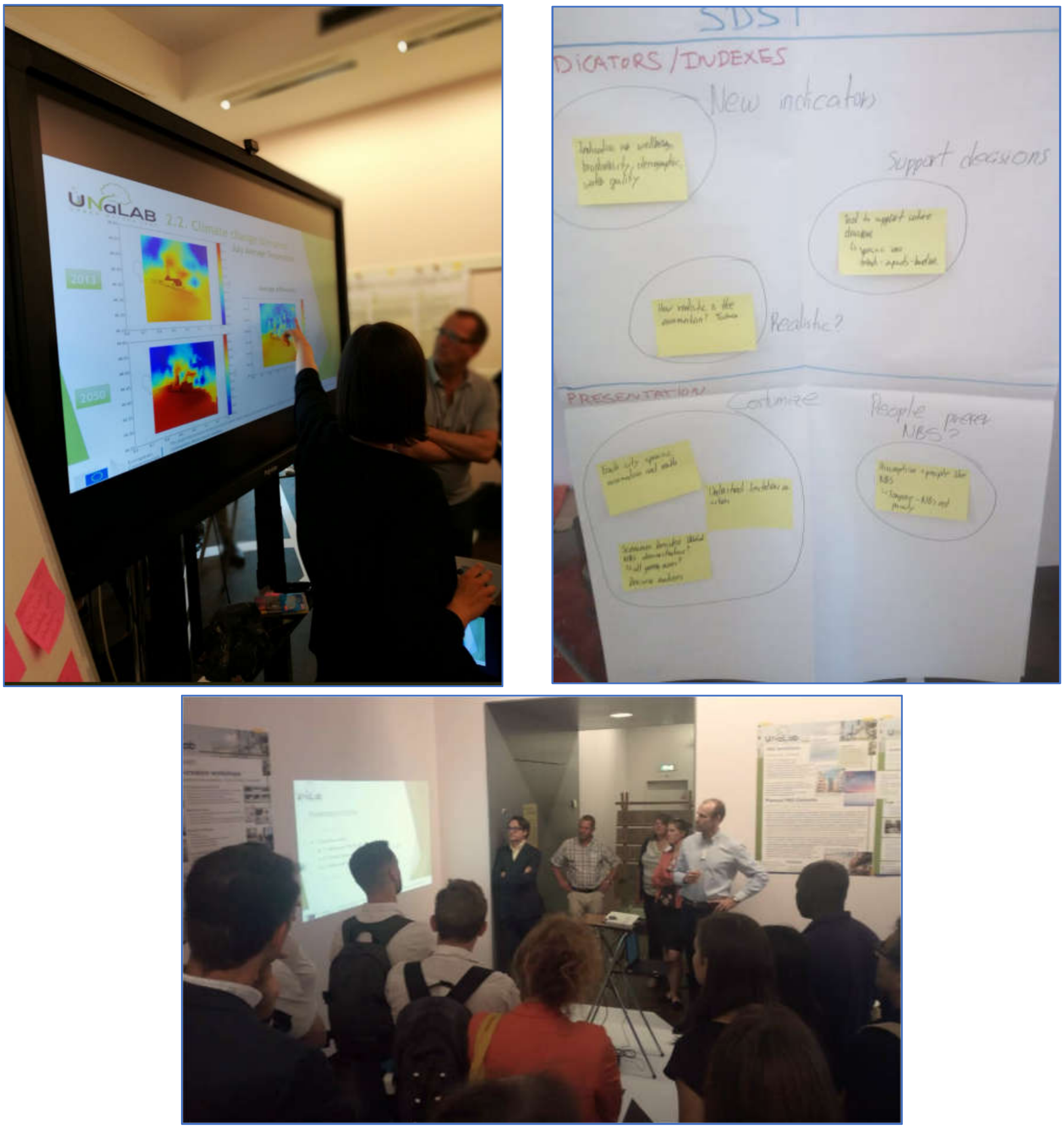


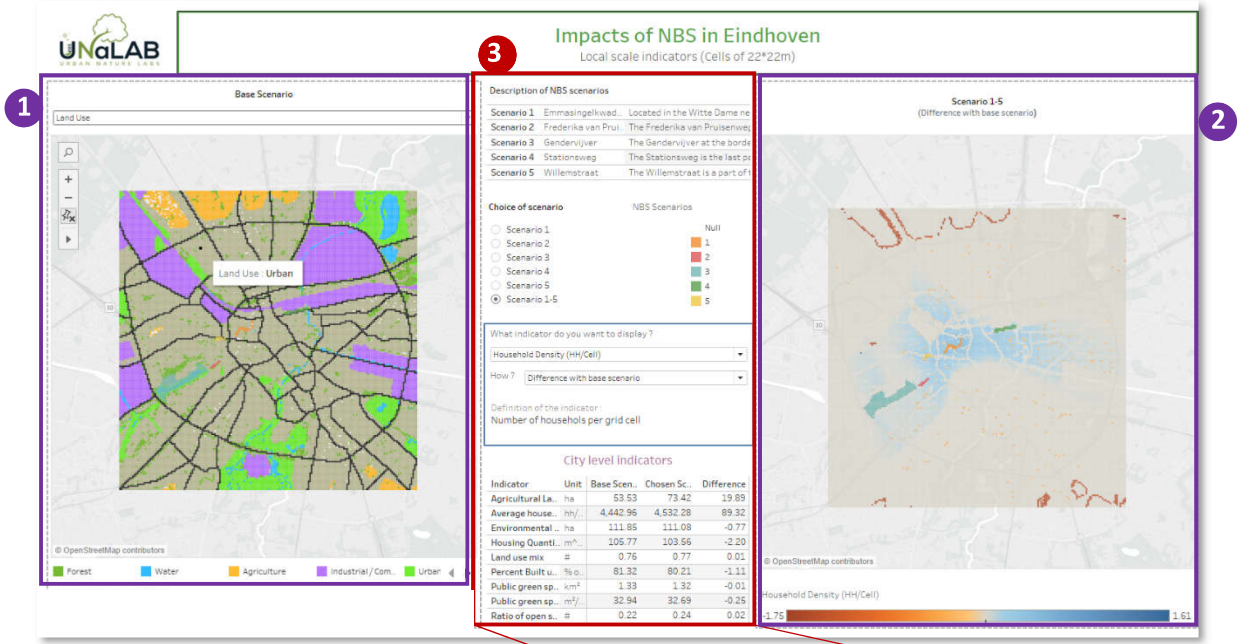
Figure 24: Presentation of the UI at the UNaLab consortium meeting on 30/05/2018 (credits: Piersaverio Spinatto on Twitter, Max Alberto Lopez)

The comments on the UI for the visualisation of indicators of urban sprawl and urban heating were guided along two particular aspects: the indicators (relevance, missing ones, etc..) and their representation. First, it was raised that indicators related to well-being, biodiversity, water quality and air pollution were missing. Indeed, apart from well-being these aspects are other impact categories that will be assessed in the UNaLab project. Well-being as a part of urban heat indicators related to health were listed in the first list of indicators (e.g. the outdoor comfort) but were found difficult to estimate as impact indicators. Rather, they can be monitored and considered as performance indicators. Regarding the representation of the indicators and the overall look of the UI, several comments were made that are useful to improve the learnability of the tool. Namely, for urban heating in the presented version, it was not possible for someone who knew the city to locate the NBS and the indicators because the grid indicators were presented without transparency on the underlying map. Adding some landmarks or roads will help to locate the NBS in the city and improve the understandability of the displayed model results. What can also help to better understand the NBS projects and their impacts is to give more information on the project area: when clicking on an NBS the user will not only have the description of the project but also more technical details as what will be concretely implemented with a small map for example, or data on the change in land use (+300 m^2 of grass, +5 evergreen tree, etc..). This way, the transparency of the model inputs is also enhanced, which is an aspect that was highlighted during the discussion. Another aspect missing to grasp the complex impact of NBS on urban heating was the differentiation summer/winter. This will be done later in the project, once the simulations are done for the entire year.

Overall, interest was shown for the UI from the end-users, namely from the municipalities of the front-runner cities (Eindhoven, Tampere and Genova) and the follower ones. Indeed, for Eindhoven's municipality it was a way to visualise the impacts of NBS on their city and to discuss indirect ones as gentrification. For the others, it was a way to envision what results they could have for their city, and therefore they were eager to ask about the process to do the same for their city. Interestingly, the prototype UI allowed the start of a conversation on the impact of NBS in the city. For example, if the NBS chosen are not efficient to decrease the UHI, maybe we should consider other types of NBS, or if real estate values increase so much around the NBS areas, we have to be careful of the gentrification effect, etc…

V.1.3. Overview of the functionalities

The functionalities of the final UI are described in Figure 25. Two dashboards are developed, one for 'Grid and city indicators' and one for 'Neighbourhood indicators', and within these the user can make three choices: what scenario he/she wants to analyse, which indicator he/she wants to display and how he/she wants to display it ("Values" or "Difference with Base scenario"). The UI itself is divided in three panels: one panel for the base scenario, one panel for the parameters settings and one panel for the selected scenario. For the base scenario of the urban sprawl indicators dashboard it is possible to choose two views: the "Land Use" view (Figure 25) or the "Indicators" view (Figure 26) to display the value of the indicator selected for the base scenario. For the urban heating dashboards, the same functionalities are available with the choice between the Base, Direct (short term), Indirect (long-term) and Direct + Indirect (short and long-term) Scenarios, as well as a precision on the type of NBS considered (de-paving, river daylighting or green space requalification) as this information is necessary to understand the results. All dashboards were made available online.



Number	Element
1	Base scenario panel
2	Selected scenario panel
3	Menu
4	Table with the description of the scenario (details when hovering a scenario)
5	Button to choose a scenario to display
6	NBS scenarios legend on the map
7	Panel relative to the indicator to display : 1) Button for the choice of indicator 2) Button for the choice of display way (« Values » or « Difference with base scenario ») 3) Description of the indicator
8	Table with city scale indicators

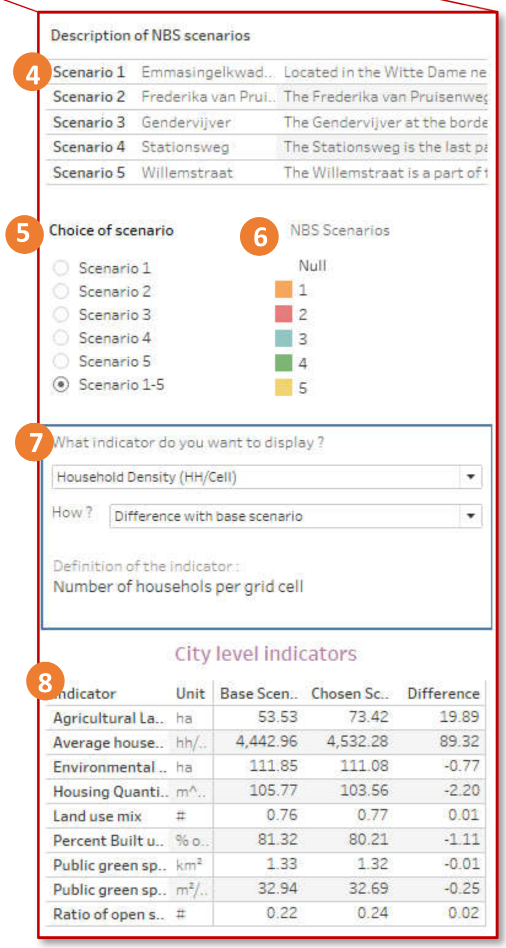


Figure 25: Grid indicators – Land Use view. Description of the components of the user interface

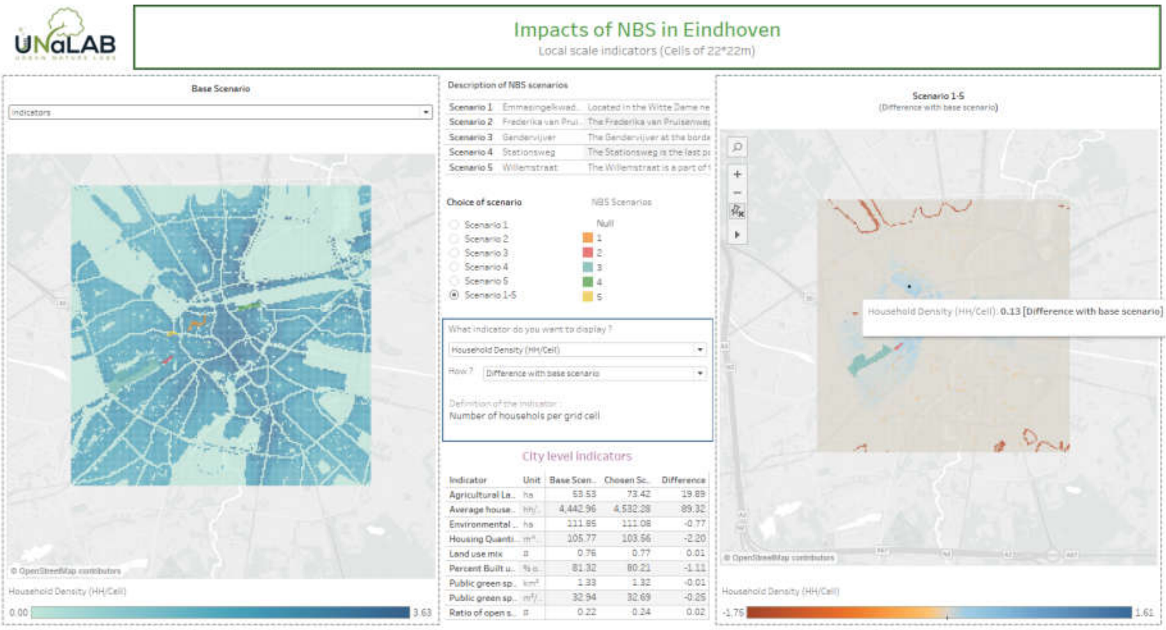


Figure 26: Grid indicators - Indicators view

V.2. Empirical example for Eindhoven

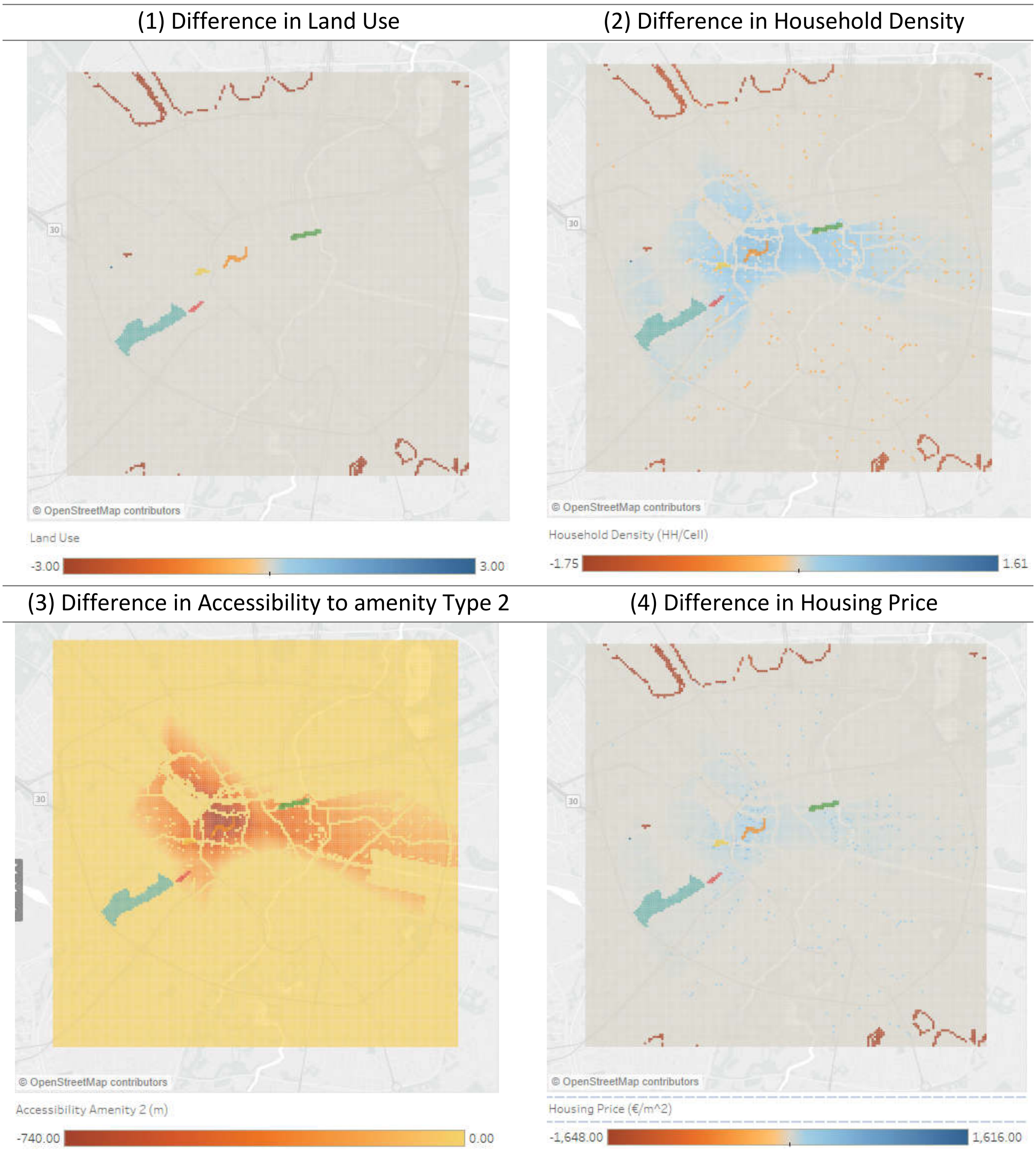
A UI prototype was designed and implemented for Eindhoven. It presents the model results for urban sprawl and urban heating and the corresponding indicators at different scales. Different narratives drawn from the visualisations are detailed in the following section, showing the informing, communicating and analysing functionalities of the designed UI.

V.2.1. Impacts of NBSs on urban sprawl

V.2.1.i. Grid indicators

The online version of the urban sprawl 'Grid indicators' dashboard is available here. Urban sprawl is characterized by a low density, leapfrog and scattered development at the urban fringe, resulting in the conversion of agricultural and natural areas. NBSs are seen as a mitigating measure as they can attract more people in the city centre and limit the low density urban expansion. The urban sprawl grid indicator visualisation tool allows the user to visualise this effect (see Figure 27). Indeed, when the difference in Land Use between the Scenario 1-5 (all NBS projects at the same time) and the Base Scenario is displayed (1), the user can see the change from residential areas to non-residential areas close to the outer border of the study area (in red). The display of the difference in Household Density (2) allows a deeper understanding of this phenomenon: a higher Household Density (in blue) is observed around the area where the NBSs will be established, consistent with the fact that NBSs are attractive. What's more, daylighting rivers and creating more parks bring the urban citizens closer to environmental amenities (3), especially to those of Type 2 (neighbourhood parks). Indeed, Scenarios 1, 2, 4 and 5 are considered as mediumly attractive environmental amenities (Type 2), as opposed to Scenario 3 and its highly attractive requalified park (Type 1). Both the increase in Household Density (2) and Accessibility to environmental amenities (3) lead to an increase In Housing Prices (4) around the NBS area.

Figure 27: Grid indicators for urban sprawl: comparison between Scenario 1-5 and Base Scenario for Land Use, Household Density, Accessibility to amenity 2 and Housing Price



This UI for local indicators has mostly an analysing and communicating function. Indeed, it allows the end-user to dive into the data at a very fine scale and analyse the impacts of different NBS projects. The display of this detailed information also helps to launch the discussion on the proposed NBS and fosters the co-creation process, as users are able to discuss the positive and negative impacts of each scenario. This was witnessed during the workshops, where discussions around “What If?” questions, as “What if you establish this other NBS in this other area?” occurred between the pilot and end-users. The interactive aspect of the UI will be enhanced with the use of a touch table/screen around which stakeholders can gather and interact with the data.

Considering the effectiveness of specific NBSs, results show that the establishment of areas where a new park is built around a daylighted section of the river Gender impact the Housing Quantity (or “Living Space”) proportionally to the size of the NBS project area considered (r^2=0.93): the biggest NBSs of Scenarios 1 and 4 reduce the Housing Quantity at the city scale by 0.91 and 0.87 m^2/hh respectively, while the smallest ones in Scenario 2 and 3 reduce it by 0.34 and 0.17 m^2/hh. The same analysis is valid for the Housing Density, except for Scenario 5 where the increase in Housing Density is close to the one in Scenario 4, while the size of the NBS project area of the latter is more than twice the one of Scenario 5. Hence, areas where new parks are created around newly open river sections make the surroundings areas more attractive to live in, and the bigger the project area is, the more attractive it is. The impact of size is also visible through the Housing Price that increase by 3-4 €/m^2 for the biggest scenario and between -0.55 and 1.8 €/m^2 for the smallest one. After weighting these three indicators according to the size of the NBSs, it was found that daylighting increases more the housing density and housing price and decreases more housing quantity than requalification of green spaces: +32 versus +21 hh/km^2 for Household Density, +2.7 versus +0.58 €/m^2 for Housing Price and -0.7 versus -0.66 m^2/hh for Housing Quantity.

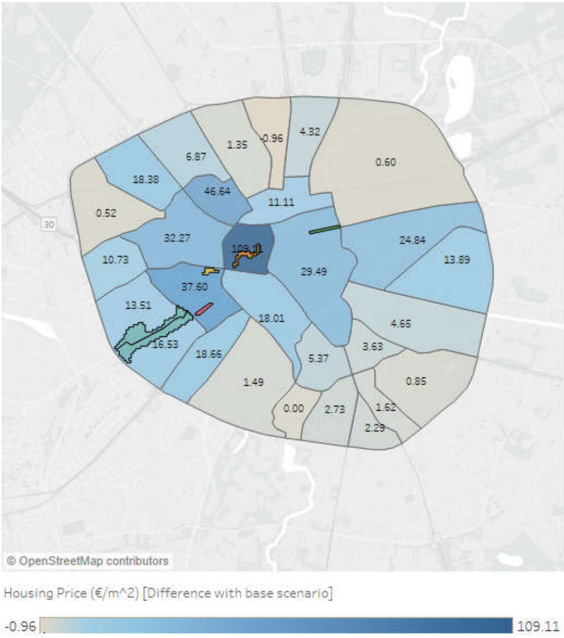
V.2.1.ii. Neighbourhood scale

The online version of the urban sprawl ‘Neighbourhood indicators’ dashboard is available here. At the neighbourhood scale, the dashboard has more an informing function, as the information is displayed at a larger scale. Indeed, the intrinsic reasons for the changes in indicators values cannot be analysed and, thus, the goal is more to provide operational and reporting information. This dashboard is useful for the municipality to discuss and create future plans, having access to the gains and losses for each neighbourhood after the establishment of different types of NBSs.

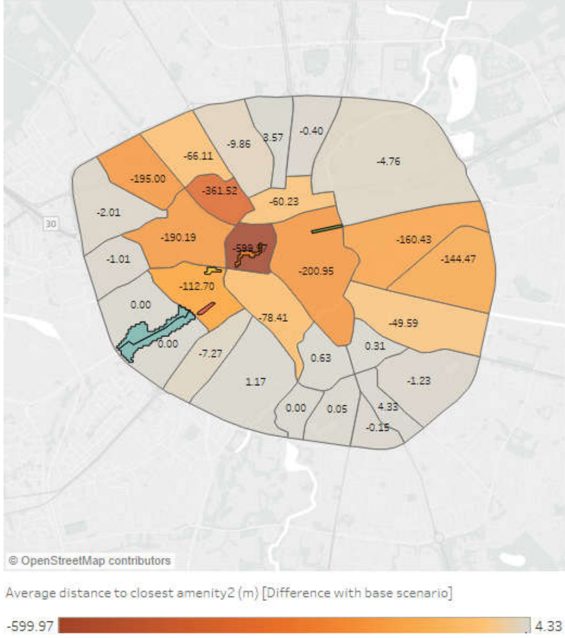
Here too, narratives can be derived from the UI. The urban sprawl neighbourhood indicator visualisation tool (see Figure 28) shows the neighbourhoods where housing prices increase most (1), and the user can observe that the pattern is opposed to the one of the Accessibility to amenity Type 2 (the Housing Price increases with the decrease in the distance to the closest environmental amenity) and similar to the one of Household Density (3). The highest increase in Household Density and Housing Price is around the NBS “Emmasingelkwadrant” in the Witte Dame neighbourhood of type “Daylighting + Green spaces”, trend that is also observable for the grid indicators. This is likely because this NBS area is located in-between all other NBS areas and, therefore, benefits from the sum of the impact of all NBS areas.

Figure 28: Neighbourhood indicators - Difference between scenario 1-5 and base scenario for Housing Price, Accessibility to amenity 2 and Household Density

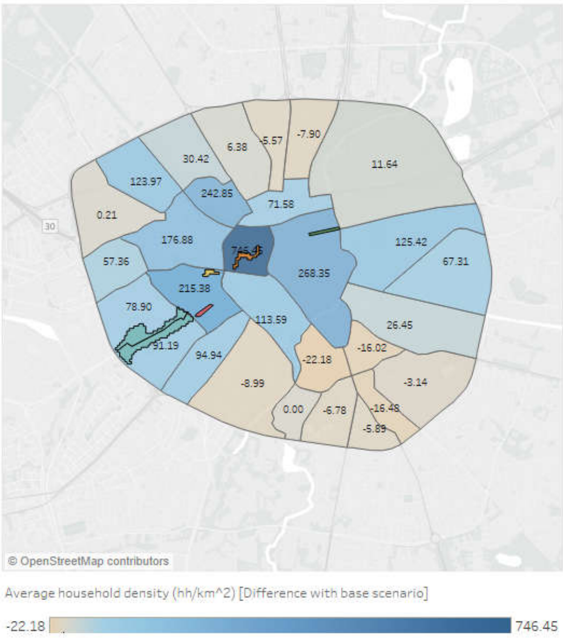
(1) Difference of Housing Price



(2) Difference of Accessibility to amenity 2



(3) Difference of household density



V.2.1.iii. City scale

At the city scale, the goal is mostly to inform the stakeholders on the impacts of NBS at the highest scale of management. For example, it can be seen that the establishment of NBS increases the amount of agricultural (or non-residential) areas by almost 20 hectares and, thus, leading to a decrease in the Percent built up area by 1.1 percent points. City contraction is accompanied by a decrease in housing quantity (- 2.2 m^2/hh) and an increase in household density (+89.3 hh/km^2).

Table 9: City scale indicators for urban sprawl for Scenario 1-5

	Indicator	Unit	Base Scenario	Chosen Scenario	Difference
	Agricultural Land	ha	53.53	73.42	19.89
	Average household density	hh/sqkm	4,442.96	4,532.28	89.32
	Environmental fragile land	ha	111.85	111.08	-0.77
	Housing Quantity	m^2/hh	105.77	103.56	-2.20
	Land use mix	#	0.76	0.77	0.01
	Percent Built up area	% of city area	81.32	80.21	-1.11
To be improved	Public green space	km^2	1.33	1.32	-0.01
	Public green space per household	m^2/hh	32.94	32.69	-0.25
	Ratio of open space to built form	#	0.22	0.24	0.02

The indicators related to Public Green Space have to be improved in the future, as the current SULD land use input does not take into account the conversion of residential areas into green spaces. Once this data is integrated, the indicators will be accurate.

V.2.2. Impacts of NBSs on urban heating

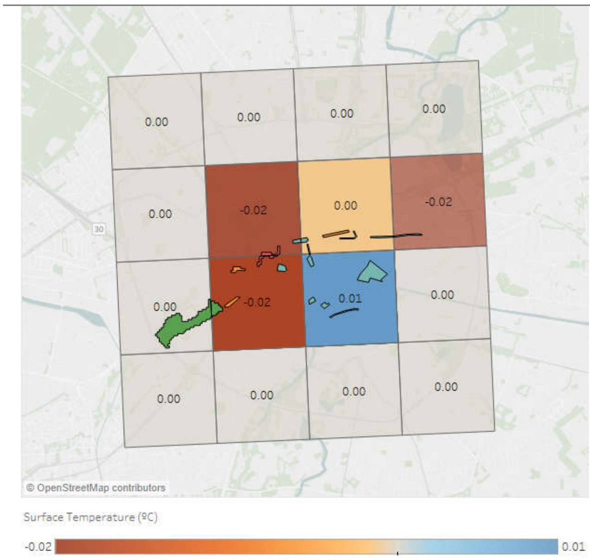
V.2.2.i. Grid indicators

The online version of the urban heating 'Grid indicators' dashboard is available here. The narrative that can be derived from the grid indicators revolves around the impact of humans on local urban climate and the disturbance of urban heat fluxes following the establishment of green and blue spaces (Figure 29). Indeed, the difference in temperature, which is the most relevant information when assessing urban heating, is very small (up to -0.02ºC, (1)) as the assessed NBSs are small (from 0.01 to 0.1 km^2) as compared to their scale of impact assessment (1 km^2). The indirect impact of NBS on anthropogenic heat fluxes are more visible, as NBS attract households from other (peripheral) areas – leading to densification and an increase in anthropogenic heat (2) by up to 2.3 W.m^{-2} for the cell comprising the daylighted NBS "Emmasingelkwadrant". Now regarding the direct impact of NBS and more precisely the physical impacts of river daylighting, de-paving and establishment of green space, the variation of the latent and sensible heat flux can be explained and commented. Indeed, the latent heat flux increases around the NBS (3) as a result of de-paving and river daylighting, as more heat is stored in vegetation and the humidity that comes with it. On the contrary, the sensible heat flux that is the heat that heats up the air decreases (4) around the NBS. If we want to see the connection between the changes in indicators and the parametrization of the different scenarios, the display of the input is also possible, as the difference in percentage of impervious surfaces (5) or the difference in percentage of blue spaces (6): the percentage of impervious surfaces decreases with NBS as sealed surfaces are replaced with un-sealed ones, and the percentage of blue spaces increases as some parts of the Gender river are daylighted.

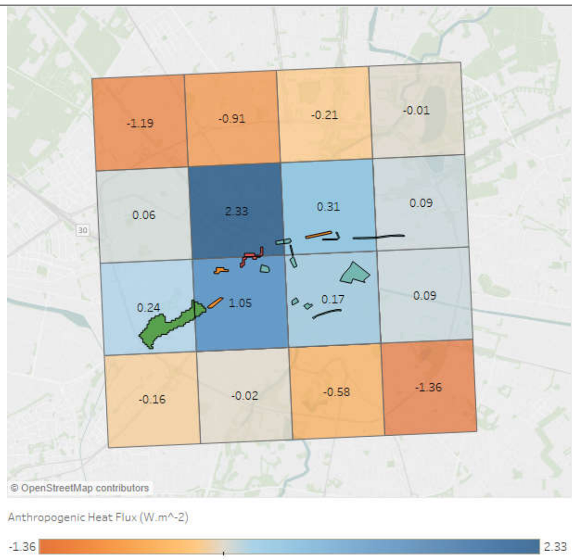
Figure 29: Grid indicators for urban heating.

Note: NBS types: **orange** = river daylighting, **pink** = daylighting river + green space, **blue** = de-paving, **green** = requalification of green spaces

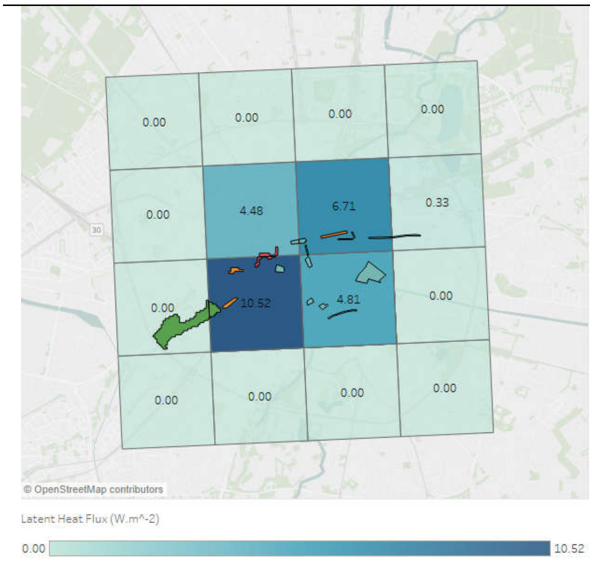
(1) Temperature difference for Direct Impact scenario



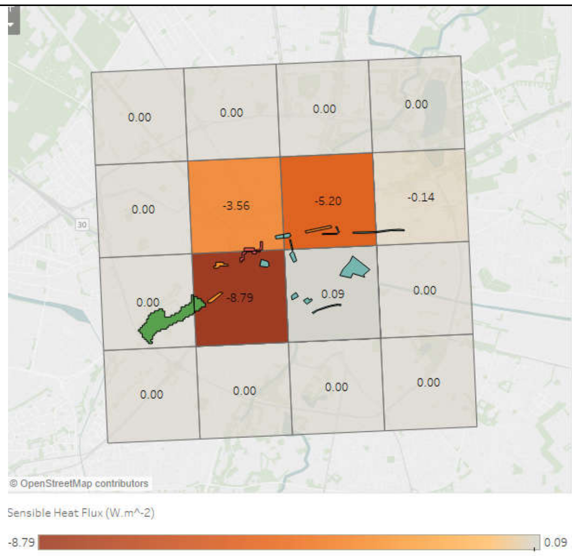
(2) Anthropogenic Heat Flux difference for Indirect Impact scenario

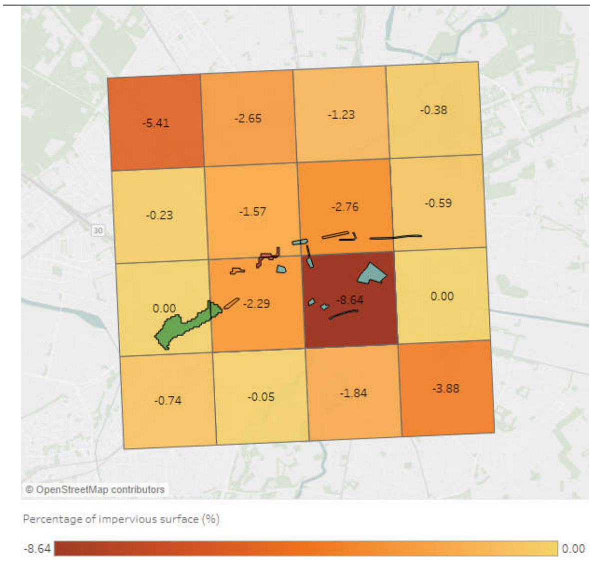
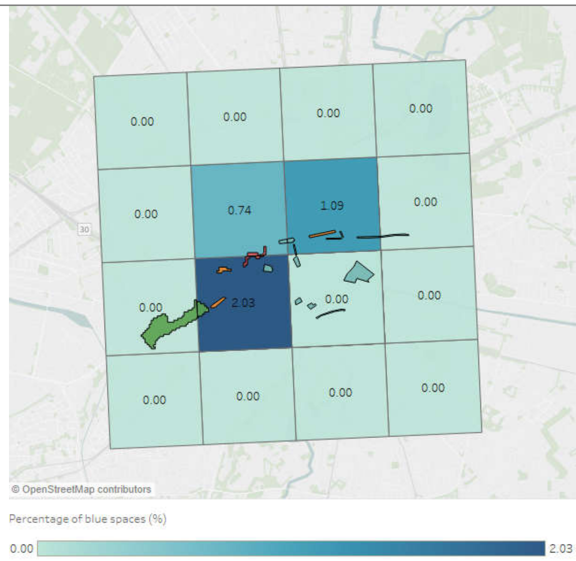


(3) Latent Heat Flux differences for Direct Impact scenario



(4) Sensible Heat Flux differences for Direct Impact scenario



(3) Percentage of impervious surface for Direct + Indirect Impacts scenario	(4) Percentage of blue spaces for Direct + Indirect Impacts scenario
	

As for urban sprawl, this UI presenting the grid indicators has a communicating and analysing function. Indeed, the communicating aspect was witnessed concretely when testing the UI with pilot end-users, when while showing first the decrease in air temperature and the increase in anthropogenic heat, a participant asked the question of the relevance of NBS if it brings more people to live in the city centre, especially if the centre is already congested. There the power of an integrated UI is demonstrated, as a discussion is launched on complex issues that cannot be answered by a simple response. Indeed, just with two impact categories some advantages and disadvantages of NBS are shown and can feed the discussion leading to decision-making or supporting the co-creation processes.

Considering the impacts of specific types of NBS, results show that the requalification of green spaces does not have an impact on temperature and heat fluxes but does on Anthropogenic Heat fluxes. Indeed, the land use of the project area does not change but its quality does: from a mediumly attractive park it becomes a highly attractive one, namely after soil de-polluting and improvement of the ecological ecosystem, and hence more heat due to human activities is forecasted. River daylighting, on the other hand, has a consequent impact on heat fluxes: the Latent Heat fluxes increase (up to +10.5 W.m^{-2}) and the Sensible Heat Fluxes decrease (up to -9.8 W.m^{-2}) in the grid cell with most river daylighting projects. For de-paving, the interpretation is a bit more difficult. Indeed, while the Latent Heat fluxes increase (by 4.81 W.m^{-2}) in the area with the biggest de-paving project, the Sensible Heat fluxes also increase slightly which is a bit counter-intuitive. Hence, the most robust description of the impacts of different types of NBSs on urban heating is that requalification of green spaces and other attractive NBSs, such as river daylighting, increase Anthropogenic Heat fluxes in their surroundings, while river daylighting in particular also decreases Sensible Heat fluxes and increases Latent Heat fluxes, which may result in mitigation of the increased anthropogenic heat. To quantify completely the mitigating power of river daylighting and see its effectiveness, the scenarios comprising this type of NBS should be run separately.

V.2.2.ii. Neighbourhood scale

To be consistent with the urban sprawl indicators and to answer some questions raised during the final workshop, a prototype for the neighbourhood indicators for urban heating was compiled for the final version but not tested on stakeholders. This was done by cutting the neighbourhoods in sub-sections according to the grid cells and calculating the percentage of grid cell per neighbourhood (see Annex 3). Then, the indicator value per neighbourhood was derived with Equation (2):

$$\text{Indicator}_{\text{Neighbourhood}} = \sum_{1}^{n} x_i * \text{Value (i)} \qquad (2)$$

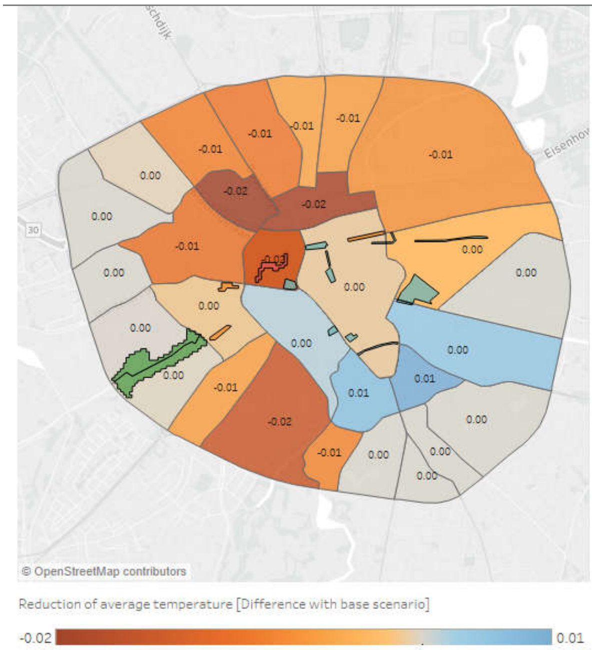
With:

- n the number of sub-sections in the neighbourhood following the grid cells (if the neighbourhood overlaps 3 grid cells, n=3),
- x_i the portion of the sub-section in the entire neighbourhood (if the sub-section represents 10% of the area of the neighbourhood, x=0.10),
- Value (i) the value of the indicator for the grid cell i.

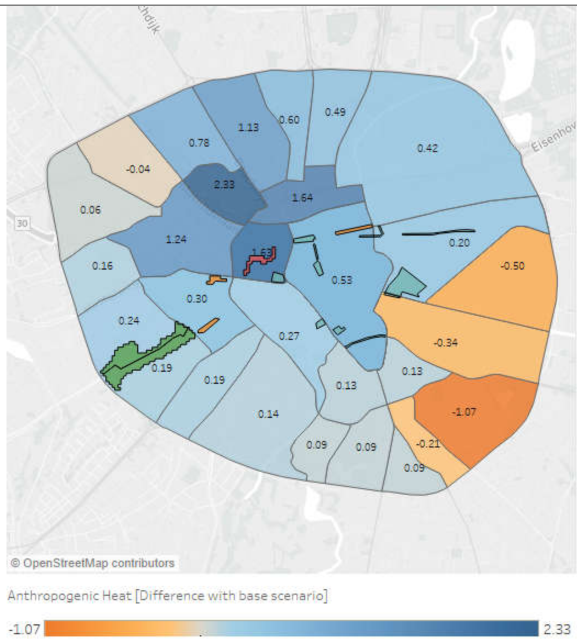
The online version of the urban heating 'Neighbourhood indicators' dashboard is available here. The urban heating neighbourhood indicator visualisation tool (see Figure 30) shows that: i) all neighbourhood do not show a consequent change in Temperature (maximum -0.02°C) (1); ii) the neighbourhoods the most impacted in the short term are the ones around the NBSs (3 and 4), iii) all neighbourhoods are impacted (either positively or negatively) in the long term (2). These observations follow the ones from the grid indicators, namely that NBSs disturb the Latent and Sensible Heat fluxes in their close surroundings and impact the Anthropogenic Heat allocation, as it increases next to the NBSs where the population density increases, and decreases near the city boundaries where the density decreases, here in the South-East of the city (Lakerlopen, Irisbuurt, Tuindorp and Jorikwartier) and in the North-West (Strijp S) (2). The neighbourhood the most impacted in the long term by an increase of heat due to an increase in population density is Limbeek-Zuid with +2.3 $W.m^{-2}$ in Anthropogenic Heat Fluxes (2), while the neighbourhood the most impacted in the short term is Fellenoord (+7.7 $W.m^{-2}$ of Latent Heat Flux (3) and -5.4 $W.m^{-2}$ in Sensible Heat Flux (4)). However, it was found with the urban sprawl 'Neighbourhood Indicators' visualisation tool that the neighbourhood with the highest increase in Household Density was Witte Dame and not Limbeek-Zuid. This has to do with the method of calculation of the urban heating neighbourhood indicators, as the breakdown of the grid cells following the neighbourhood does not reproduce the original input data: the data from SULD is integrated in WRF-SUEWS in the form of an increase in Household density per cell and becomes obsolete when the cells are re-divided to calculate the neighbourhood indicators. Hence, the Anthropogenic Heat Flux and the other heat flux will gain meaning when the study area will be divided with 400 cells of 200*200 m, as the new neighbourhood indicators will be closer to the original data.

Figure 30: Neighbourhood indicators for urban heating

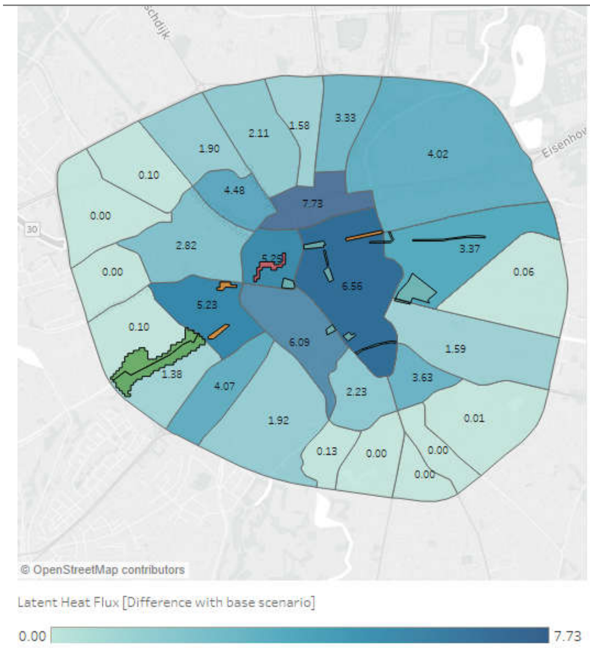
(1) Temperature difference for Direct impact scenario



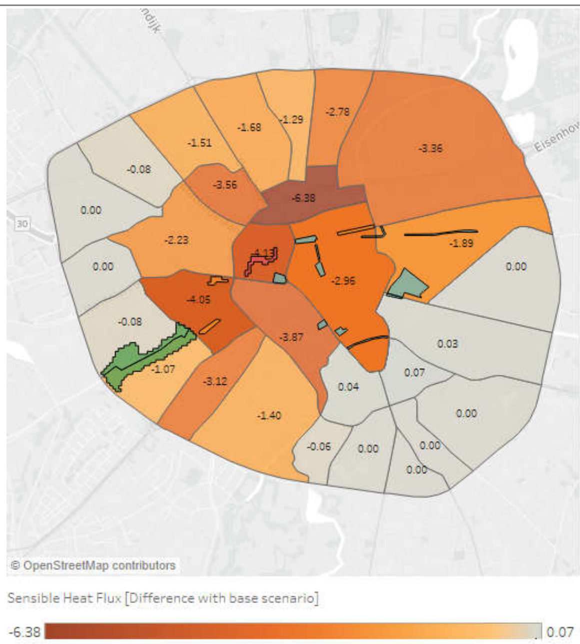
(2) Anthropogenic Heat Flux difference for Indirect Impact scenario



(3) Latent Heat Flux differences for Direct Impact scenario



(4) Sensible Heat Flux differences for Direct Impact scenario



V.2.2.iii. City scale

At the city scale, the urban heating indicators have the same function as the urban sprawl ones: informing by giving the general impacts of NBS on the whole city. Here for example, the urban heat island intensity is calculated and presents no variation[2] among the scenarios at the level of detail chosen (2 decimals). Likewise, the UHI magnitude does not vary from one scenario to another. These two indicators will be very informative and serve good base for evidence-based arguments for the establishment of NBS, once climate change considerations are added in input. Additionally to these two relevant indicators, an overview of the grid indicators aggregated at the city scale is available, showing the same trend as mentioned before: overall decrease in percentage of impervious surfaces, sensible heat flux and temperature, and overall increase in latent heat flux and blue spaces.

Table 10: City indicators for urban heating

Indicator	Unit	Base scenario	DIS	IIS	DIS+IIS
UHI Magnitude	ªC	1.65	1.66	1.65	1.65
Urban Heat Island Intensity	ºC	4.12	4.12	4.12	4.12
Percentage of impervious surface	%	43.17	42.18	42.15	41.16
Share of blue spaces	%	2.74	2.98	2.74	2.98
Cooling Degree Day	ªC.day	12.00	12.00	12.00	12.00
Anthropogenic Heat	W.m-2	15.58	15.58	15.57	15.57
Latent Heat Flux	W.m-2	41.14	42.82	41.77	43.45
Sensible Heat Flux	W.m-2	89.79	88.69	89.03	87.93
Temperature reduction for average values	ºC	0.00	0.00	0.00	-0.01
Temperature reduction for maximum values	ºC	0.00	0.00	0.00	0.00
Temperature reduction for minimum values	ºC	0.00	-0.01	-0.01	-0.02

[2] The variation of the UHII is actually -0.007ºC for the Direct + Indirect impact scenario which is negligible with the precision of the data of the city-scale indicators

VI. DISCUSSION

This chapter presents a discussion of the previous results divided in three sections: Section VI.1. discusses the way the results are communicated and the issues regarding partiality, transparency and accuracy; Section VI.2. discusses the implications of the results in terms of the effectiveness of particular types of NBSs; finally Section VI.3. broadens the scope of the presented user interface by explaining how to extend the work done to other impact categories to create a complete integrated SDST.

VI.1. Communication of the results

The different dashboards available with the designed UI presented in this study provide to the end-users a visual support for the narratives of urban sprawl and urban heating, following the establishment of NBS in urban settings. Indeed, they present the evolution of selected urban sprawl and urban heating indicators for medium and long-term scenarios, offering the possibility to assess the effectiveness of different NBS projects in an interactive setting. Nevertheless, these indicators were selected and calculated from the input and output data of disciplinary models and, therefore, partiality and accuracy issues have to be thought through.

Impartiality can happen at the indicators' selection stage and when the visualisation methods are chosen. Indeed, the selection depends on the literature but also on the data available and the choice of the researchers. Here, the first list of indicators was extracted from the literature and skimmed according to the data available, but their calculation methods found in the literature were sometimes adapted or arbitrarily defined (such as the 25ºC threshold for the Cooling Degree Days). For the choice of visualisation, one should be very careful to stay un-biased as it is very easy to distort reality with indicators (Geertman and Stillwell, 2004). For instance, it was not possible to customize the colour scale with Tableau® and, hence, the visualisation is sometimes accurate (see Figure 31) and sometimes over-assessed or counter intuitive (see Figure 32). Indeed, in Figure 31 the difference in household density goes from -1.75 hh/cell to +1.61 hh/cell and is therefore well-balanced on the scale and make the differences visible. In Figure 32, the temperature difference goes from -0.02ºC to +0.01ºC which is negligible at the scale of the overall temperature but yet very visible on the map: it looks like the increase/decrease was really important. Furthermore, if someone looks very briefly at the results in Figure 32 he/she might think that the cell in blue got colder and the ones in red cooler, while it is the opposite (in Tableau, red always means "decrease" and blue "increase"). In a future version on the final ICT tool Knowage, this could be improved by adapting the colour scale to the indicator, or by providing different perspectives of the same phenomenon, for example with different layers (Maquil *et al.*, 2015), as the tool will be customizable.

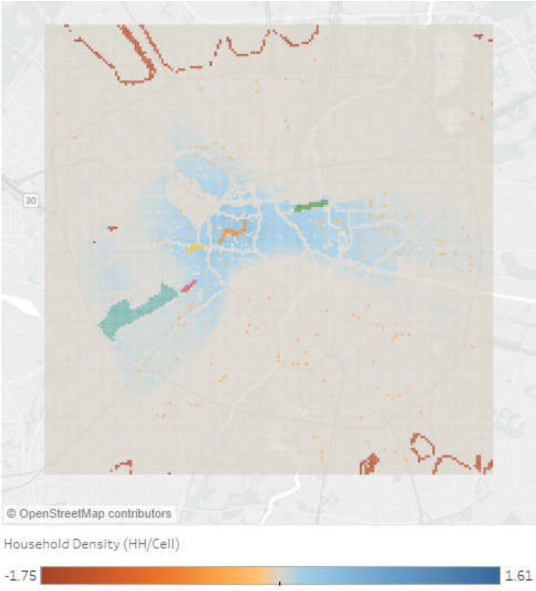


Figure 31: Difference of Household Density for Scenario 1-5

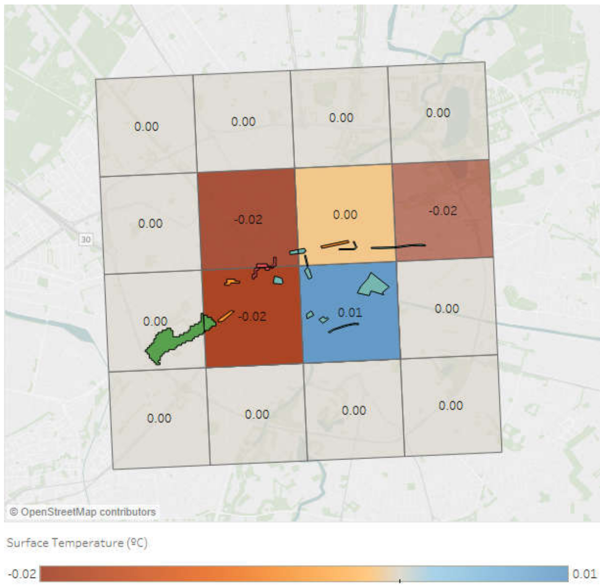


Figure 32: Difference of Surface Temperature for Direct Impacts scenario

Furthermore, providing the transparency of the methods chosen to calculate the indicators is a pre-requisite for the trust of end-users in the tool and should be therefore ensured. The trust in the tool comes also with the trust in the models, which in the case of the UNaLab project were not known by the end-users. This was witnessed during the workshops, where the question of the accuracy of the models popped up in the discussion, as it is important for stakeholders to understand on what ground the model works and how trustworthy it is. To ensure the trust in the models, a brief or long description of them could be made available on the UI or in the data management system according to the need of the user, with the related scientific references and the percentage or error if applicable.

Regarding the accuracy of the information displayed for the urban sprawl issue, some adjustments can be made to grasp the entire scale of the phenomenon, regarding both the data used and the model parametrization. Indeed, the current study area is the one from a previous project, Aqua-Add (Roebeling *et al.*, 2014), and comprises only the inner-city area. Sprawl being by definition the transformation of agricultural land for residential area, the study area should at least go until the closest agricultural area. In the case of Eindhoven, extending the area to the city boundary would be enough as it already comprises agricultural land and would allow the calculation of additional indicators, such as the linearity index (maximum distance of new residential area to closest road) and the leapfrog index (maximum distance of new residential area to closest residential area). What's more, some update of the input data is needed. Indeed, the base scenario of the Aqua-Add project was 2010 – 2011 while the baseline scenario chosen for the UNaLab project is around the year 2013, and the current data does not include climate change and population growth considerations which is important to get as close as possible to the foreseeable future and to answer the goals of the UNaLab project. In terms of the model parametrization, interesting comments from the workshops can be discussed. Indeed, the SULD model relies on a supply/demand equilibrium of the housing market, considering that households want to live as close as possible to environmental amenities, including green spaces. The municipality of Tampere mentioned the fact that citizens of Tampere do not necessarily feel the need to move closer to green spaces but rather to blue ones. Therefore, the parametrization of the SULD model should be adapted to the case study and, in particular, with respect to the characterization of environmental amenities (Type 1, 2 and 3).

For the urban heating dashboards, the accuracy relies on the scale of the data and on the local particularities of the cities. Indeed, the current 1x1km scale was considered not very meaningful for the users who tested the tool. A finer scale that will allow the assessment of the local impact of NBS is planned for the UNaLab project (cells of 200x200m) and will help to better apprehend NBS scenario simulation results. This will also improve the accuracy of the neighbourhood indicators that are currently assessed from the geographic breakdown of the 16 cells or 1x1km according to the neighbourhoods and will be derived later from 400 cells of 200x200m. What's more, the input data behind the model should be better communicated so that users understand what lies behind the model: the information of the detailed land use (evergreen/deciduous tree, unpaved area, etc..) and the change compared to the base scenario should be available for each cell. To not overload the visualisation, it could be provided when clicking on a button "Additional information" for example. Finally, the choice of indicator could be adapted to each city. Indeed, in cooler climates as the ones experienced in Eindhoven or Tampere, the proxy of the energy consumption due to cooling with the Cooling Degree Days assessment is maybe not a good indicator, as air conditioning is not widely used in Finland and the Netherlands. More accurate would be the assessment of the Heating Degree Days, proxy for the energy demand for heating during the winter, which may decrease with climate change. The importance of separating the summer and the winter indicators, which was mentioned during the final workshop, is thus shown as well as the need to customize the indicators according to the city.

Studies by Te Brommelströet (2010), Pelzer *et al.* (2015) and Russo *et al.* (2018) show similar issues, such as lack of transparency, difficulties to communicate the data without distortions, lack of different interfaces for different users and limitations in terms of choice of the input parameters. Other studies, such as Craft and Cairns (2005), González *et al.* (2013), Pensa, Masala and Lami (2013) and Zhu *et al.* (2013) answered these issues by proposing: i) the use of simple models or easily understandable ones accompanied by the reporting of their inputs and outputs and a user-friendly guide to tackle the transparency issue; ii) to provide the three acknowledged components of a working UI in the HCI field – Overview, Zoom and Filter, Details on Demand – or by proposing different types of visualisations for the same phenomenon to improve the communication of the data; iii) to create user profiles that can access the information worthy for their level of utility, by adding a data management system that can store a lot of different information (models results, indicators useful for decision-making, model documentation, etc..), iv) to simplify all the indicators on a 1-10 scale so that people with different backgrounds can still communicate on the same UI. Regarding the possibility to change the input data and namely the NBSs in the present study, studies show that end-users are eager to be able to create their own scenarios, which is not possible with the current SDST as the models are complex, heavy and can take hours to run.

VI.2. Impacts of different types of NBS

Considering the effectiveness of specific NBSs, results show that daylighting impacts both urban sprawl and urban heating in a consequent way, as the newly daylighted areas become more attractive and therefore more subject to Anthropogenic Heat, but also more beneficial for urban temperatures as they have a cooling power observable through the increase in Latent Heat fluxes and decrease in Sensible Heat fluxes they induce. Green space requalification does not impact urban heating directly but does rather through the increase in household density due to the change in attractiveness of the area and the subsequent increase in Anthropogenic Heat fluxes. Finally, de-paving does not impact urban sprawl as the de-paved areas are not significantly more attractive than before, but it impacts urban heating through the increase of latent heat fluxes. To give an overview of the overall impacts, Table 11 gathers impacts of NBS on urban compaction and urban cooling with their intensity ("0": no impact; "+": small positive impact; "++": high positive impact).

Table 11: Overview of the impacts of different types of NBS on urban sprawl and urban heating

NBS type	Urban compaction	Urban cooling
Daylighting	++	++
Requalification	+	0
De-paving	0	0/+

Note: "0": no impact; "+": small positive impact; "++": high positive impact

These results are in line with Roebeling *et al.* (2017), Wu (2001) and Crompton (2005), that show that the establishment of parks attracts more people in the surroundings as well as increase real-estate prices and decrease living spaces, as middle and high class households are willing to pay more for smaller living spaces next to green and blue areas. This is especially the case for more attractive green and blue spaces like requalified parks or a daylighted rivers, as they both bring additional well-being benefits in the form of recreational areas with enhanced biodiversity. As a consequence, the city witnesses the opposite of urban sprawl: urban compaction. Regarding de-paved areas, no impact has been shown in the literature in terms of socio-economic impacts as the newly de-paved area do not present a higher attractivity, but they impact slightly the local climate.

Indeed, evidence of the cooling effect of daylighting and de-paving has been provided in the literature. For daylighting of water bodies or water courses (also referred as blue spaces), Theeuwes, Solcerová and Steeneveld (2013), Cai, Han and Chen (2018) and Gunawardena, Wells and Kershaw (2017) showed that blue spaces have a cooling capacity, capacity that depends on their intrinsic characteristics and their surrounding environment. For example, it was measured that blue spaces can have a cooling effect up to a 1-km radius with an intensity diminishing with the distance, and that this effect can provide on average 2.5 °C of temperature reduction. The type of blue space greatly impacts its cooling power, as it may be more effective to establish several small shallow ponds that utilise all their available thermal capacity equally spread out through the city, rather than establishing a big deep one (Gunawardena, Wells and Kershaw, 2017). Dynamic water courses as rivers have a smaller capacity of energy exchange at the atmosphere-water interface as there are in constant movement, but they present a cooling power under favourable local climate conditions as high solar exposure, high wind velocity and low humidity. For de-paving of paved surfaces, it has been shown in the literature that establishing un-natural permeable or porous surfaces diminishes the surface and air temperature as compared to sealed soil (Maleki and Mahdavi, 2016). Indeed, permeable or water-holding soils allow for a higher evaporating capacity and can decrease the soil temperature up to 4-5 ºC the soil at 20 cm depth (Fini *et al.*, 2017) and consequently the surrounding air (Santamouris, 2013). For natural de-paving, such as the establishment of grass or parks, Gunawardena, Wells and Kershaw (2017) showed that they have a greater potential to mitigate the UHI than blue spaces, especially at the end of the summer when the water has heated up. Nevertheless, both NBS types can be established throughout the city at strategic locations in the shape of small water courses/bodies and green areas, to reach their full cooling potential (Gunawardena, Wells and Kershaw, 2017).

Hence, studies have shown the impact of NBS on urban compaction and urban cooling, but none of them considered the simultaneous effects of NBSs on urban sprawl and urban heating –

namely the impact of compaction on urban heat and its compensation – or not – by the cooling effect of green and blue spaces. Indeed, Chapman *et al.* (2017) found that in the literature on the impacts of urbanization on urban temperatures, anthropogenic heat was usually entered as a default parameter or based on future energy demand or urban growth, and excluded in half of the papers selected for the meta-study. No paper was found in the urban heat mitigation literature on the adverse effect of the attractivity of new blue and green spaces in dense areas that induce an increase in anthropogenic heat, and the possible mitigation measures. This is probably due to the fact that both phenomena happen at different time scales, as the impact of a green or blue space can be quite quick as compared to population movements that will take several years. This Master Thesis has started to answer this question by integrating the SULD and WRF-SUEWS models to visualise the impact of NBS on urban heat with or without considering the consequences of compaction. The results showed that overall the anthropogenic heat did not increase but was rather re-distributed within the study area, with higher values around the NBS where the population increased and lower on the outskirts of the city.

VI.3. Systemic Decision Support Tool

The final SDST that will be developed for the UNaLab project is designed to provide to stakeholders an overview of the different impacts of NBS. Hence, the same work as the one made here for urban sprawl and urban heating will be done for flooding, water pollution, air pollution, ecosystem services and values, real estate values, population dynamics and gentrification. This answers the “replicability” issue mentioned in the objectives of the present work. Namely, to achieve the same type of results as the present study, the following steps will have to be realised for each impact category. First, after the selection of the relevant indicators from the literature, the study of the model used to assess the impact category is needed. This includes the list of available input and output data as well as the model assumptions. Then, the transfer of the model output data to the UNaLab knowledge database has to be made as easy as possible, step that has to be done jointly with the company in charge of the ICT tools development. Finally, an interactive visualisation is proposed and validated with pilot end-users and ultimately with final end-users. Some facilitation between the input and the output of some models have to be considered. For example, household density output data from SULD have to be integrated as input data for SUEWS, or the urban heating output data from WRF should be considered as input data for the model assessing air quality. Finally, to make the aggregation at different levels easier, a geo-referenced table could be used for each model as proposed by Zhu *et al.* (2013).

To get back to the ultimate goal of the SDST, i.e. is to provide informing, communicating and analysing support for stakeholders through a user-friendly interface, the first question to answer is “What is, overall, the effectiveness of a certain NBS?”. To give a simple overview of the impact of different NBS, a table as the one presented in Table 12 could be presented as a welcome page to the SDST web application for a selected NBS, and the possibility to explore the results at the grid, neighbourhood or city scale – with access to the corresponding dashboards when clicking “more info”. To give more meaning to the indicators, a colour code could be adopted as **green**=positive impact, **red**=negative impact, **grey**=neutral impact. The same information could also be represented with a spider diagram by giving a score from 1 to 10 to each impact category.

Table 12: Example table for the overview of the impact of NBS for one scenario

Impact	Major indicators	Unit	Difference with Base scenario	More info?
Flooding	Water depth	Meter	**-0.03**	Click here
	Flooded area	Square meter	**+0.6**	
Urban heating	Number of heatwaves	#	**-1**	Click here
	Urban heat island intensity	ºC	**-0.5**	
Urban sprawl	Constructed area	Km^2	**-0.3**	Click here
	Agricultural land	Km^2	**+5**	
	Living space per household	m^2 per household	**-1**	
Gentrification	Percentage of people with a higher education around the NBS area	%	+5	Click here
	Percentage of households of type 1 around the NBS area	%	**+2**	
Real estate values	Housing price	€/m^2	**+20**	Click here
…	…	…	…	

The possibility to explore different impact categories can be found in the Spatial Vision tool for peri-urban Melbourne and the comparison of different scenarios in the form of a spider graph in González *et al.* (2013). The table and the SDST in general should be adapted and focused on the major challenges that the city faces, as some cities may be more focused on water issues and others on air quality problems. This customizability was mentioned during the workshops by the stakeholders who wish to have the possibility to modify the information displayed on the SDST.

VII. Conclusions and future recommendations

The objective of this Master Thesis was to integrate and visualise indicators of urban sprawl and urban heating to support informed decision-making and co-creation processes in the context of urban NBS establishment. Hence, a prototype of an interactive user interface for the visualisation of indicators of urban sprawl and urban heating in a context of Nature-Based Solutions was developed and applied to the city of Eindhoven. It contributes to the goal of the European Union funded project UNaLab that aims at creating a European framework for the co-creation and implementation of NBs in cities, following an evidence – and indicators-based approach that builds, amongst others, on the development and application of a Planning Support System (PSS) called the Systemic Decision Support Tool (SDST). To do so, a theoretical background on the urban sprawl and urban heating phenomena was given, as well as the state-of-the-art on Planning Support Systems in the literature and in particular the good practices for their implementation. Then, the methods used to go from the complex disciplinary model output data available to the final user-friendly visualisations were described, namely the listing of the data available, the selection of the indicators, the design of the ICT framework and the design-implementation-evaluation cycle used to create the final UI prototype. The tool was tested first on pilot end-users and then on actual end-users to ensure its future usefulness. The process for creating the interactive user interface was designed to be replicable to other impact categories that will have to be assessed to grasp the full impact of NBS in cities, including flooding, air and water quality, real-estate values and gentrification. Finally, the tool itself was presented through three components: its utility, its usability and its functionalities. Narratives that can be drawn from the visualisations were presented, and the results were discussed notably in terms of accuracy of the transmitted information and further elaboration of the SDST.

The prototype of the UI presented in this study provides a good first example of how the SDST will provide information to support co-creation processes and decision-making ones. Namely, it shows how a PSS can be developed in an integrated way with interconnected disciplinary models (here the outputs of the SULD model serve as input for the SUEWS model) and provide insights in the multiple impacts of NBS. Indeed, the tool does not focus on one impact category but, rather, on several ones and analyse how each of them evolves following the establishment of NBS – for example, de-paving may be beneficial in terms of biodiversity but not necessarily impacting the urban heat island (UHI) effect, while the creation of a big new pond in the city may improve the UHI effect but worsen flooding problems. This way, the tool is not providing one answer focussed on one problem but, instead, provides a common interface for stakeholders to discuss the multiple positive and negative impacts of NBS. This is a very important part of the co-creation process: being able to analyse different possibilities and propose others. To the best of our knowledge, the models used in this study (SULD and SUEWS) and the other models considered to be included in the SDST have never been jointly used and, hence, this work contributes to the knowledge creation on the multiple impacts of the establishment of NBS in urban areas.

Future improvements for the tool are mainly the integration of more impact categories and a better transparency of the results. This was mentioned as a good practice but not well implemented in the prototype presented to the stakeholders. Indeed, none of the stakeholder knew the chosen disciplinary model and therefore additional information has to be made available on the platform, notably about the input data, the sources of the data and the reliability of the model (e.g. percentage of error). This will increase the robustness of the tool on which stakeholders from different background can “bridge” their vision by speaking the same language and “stretch” them as they can have better insight in areas they don’t master (e.g. more details on the flooding model can help better understand the flooding simulations and their consequences) and therefore hold a discussion that goes beyond their competences.

BIBLIOGRAPHY

Alexander, P. J., Fealy, R. and Mills, G. M. (2016) 'Simulating the impact of urban development pathways on the local climate: A scenario-based analysis in the greater Dublin region, Ireland', *Landscape and Urban Planning*. Elsevier, 152, pp. 72–89. doi: 10.1016/j.landurbplan.2016.02.006.

Altes, W. K. K. (2009) 'Taxing land for urban containment: Reflections on a Dutch debate', *Land Use Policy*. Pergamon, 26(2), pp. 233–241. doi: 10.1016/J.LANDUSEPOL.2008.01.006.

Alves, H. M. T. C. (2014) *Modelação da Expansão Urbana Residencial na Região da Ria de Aveiro*. Universidade do Porto, Faculdade de Letra. Available at: https://repositorio-aberto.up.pt/handle/10216/76613 (Accessed: 26 April 2018).

Amann, M. *et al.* (2011) 'Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications', *Environmental Modelling and Software*. Elsevier Ltd, 26(12), pp. 1489–1501. doi: 10.1016/j.envsoft.2011.07.012.

Arribas-Bel, D., Nijkamp, P. and Scholten, H. (2011) 'Multidimensional urban sprawl in Europe: A self-organizing map approach', *Computers, Environment and Urban Systems*. Elsevier Ltd, 35(4), pp. 263–275. doi: 10.1016/j.compenvurbsys.2010.10.002.

Augusto, B. (2018) *Direct and indirect impacts of Nature-Based Solutions on urban heat*. University of Aveiro.

Bodilis, C. (2018) *Collection and classification of indicators relative to urban sprawl and urban heating in the context of Nature Based Solutions*.

Bosch, P. *et al.* (2017) *CITYkeys indicators for smart city projects and smart cities*.

Boulange, C., Pettit, C. and Giles-Corti, B. (2017) 'The Walkability Planning Support System: An Evidence-Based Tool to Design Healthy Communities', in Geertman, S. et al. (eds) *Planning Support Systems for Smarter Urban Futures*. Springer, Cham, pp. 153–165. doi: 10.1007/978-3-319-57819-4_9.

te Bröemmelstroet, M. C. (2010) 'Making planning support systems matter: improving the use of planning support systems for integrated land use and transport strategy-making'.

te Brommelstroet, M. (2010) 'Equip the warrior instead of manning the equipment: Land use and transport planning support in the Netherlands', *Journal of Transport and Land Use*, 3(1). doi: 10.5198/jtlu.v3i1.99.

Brooke, A. D. *et al.* (1998) *GAMS Release 2.5: A User's Guide*.

Bunzel, K. (2014) 'Web-based Envision Tomorrow 1.0 Technical Documentation'. Fregonese Associates. Available at: http://envisiontomorrow.org.

C40 (2018) *Why Cities?* Available at: http://www.c40.org/why_cities (Accessed: 14 March 2018).

Cai, Z., Han, G. and Chen, M. (2018) 'Do water bodies play an important role in the relationship between urban form and land surface temperature?', *Sustainable Cities and Society*. Elsevier, 39, pp. 487–498. doi: 10.1016/J.SCS.2018.02.033.

CBS (2018) *CBS StatLine - Bevolkingsontwikkeling; regio per maand*. Available at: http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=37230NED&D1=17-18&D2=101-650&D3=l&LA=EN&HDR=T&STB=G1,G2&VW=T (Accessed: 24 April 2018).

Chapman, S. *et al.* (2017) 'The impact of urbanization and climate change on urban temperatures: a systematic review', *Landscape Ecology*. Springer Netherlands, 32(10), pp. 1921–1935. doi:

10.1007/s10980-017-0561-4.

Chen, A. *et al.* (2016) 'Application of a new integrated landscape index to predict potential urban heat islands', *Ecological Indicators*. Elsevier Ltd, 69, pp. 828–835. doi: 10.1016/j.ecolind.2016.05.045.

Christiansen, P. and Loftsgarden, T. (2011) *Drivers behind Urban Sprawl in Europe*. Oslo. Available at: https://www.toi.no/getfile.php/Publikasjoner/TØI rapporter/2011/1136-2011/1136-2011-el.pdf.

Cook, J. *et al.* (2013) 'Quantifying the consensus on anthropogenic global warming in the scientific literature', *Environ. Res. Lett*, 8, pp. 24024–7. doi: 10.1088/1748-9326/8/2/024024.

Craft, B. and Cairns, P. (2005) 'Beyond guidelines: What can we learn from the visual information seeking mantra?', in *Proceedings of the International Conference on Information Visualisation*. IEEE, pp. 110–118. doi: 10.1109/IV.2005.28.

Crompton, J. L. (2005) 'The impact of parks on property values: Empirical evidence from the past two decades in the United States', *Managing Leisure*. Routledge, 10(4), pp. 203–218. doi: 10.1080/13606710500348060.

Deal, B. and Pallathucheril, V. (2009) 'A Use-Driven Approach to Large-Scale Urban Modelling and Planning Support', in Geertman, S. and Stillwell, J. (eds) *Planning Support System Best Practices and New Methods*, pp. 29–51. doi: 10.1007/978-1-4020-8952-7_2.

Deal, B., Pallathucheril, V. and Heavisides, T. (2013) 'Ecosystem Services, Green Infrastructure and the Role of Planning Support Systems', in Geertman, S., Toppen, F., and Stillwell, J. (eds) *Planning Support System for Sustainable Urban Development*, pp. 187–207. doi: 10.1007/978-3-642-37533-0_11.

Van Delden, H. *et al.* (2011) 'A methodology for the design and development of integrated models for policy support', *Environmental Modelling and Software*. Elsevier Ltd, 26(3), pp. 266–279. doi: 10.1016/j.envsoft.2010.03.021.

Dupras, J. *et al.* (2016) 'The impacts of urban sprawl on ecological connectivity in the Montreal Metropolitan Region', *Environmental Science and Policy*. Elsevier Ltd, 58, pp. 61–73. doi: 10.1016/j.envsci.2016.01.005.

EEA (2006) *Urban sprawl in Europe - The ignored challenge*, *EEA report*. doi: 10.1080/02697451003740312.

EEA & FOEN (2016) *Urban sprawl in Europe - joint EEA-FOEN report*. doi: 10.2800/143470.

Eggermont, H. *et al.* (2015) 'Nature-based Solutions: New Influence for Environmental Management and Research in Europe', *GAIA - Ecological Perspectives for Science and Society*, 24(4), pp. 243–248. doi: 10.14512/gaia.24.4.9.

EKLIPSE (2017) *An impact evaluation framework to support planning and evaluation of nature-based solutions projects*.

ENoLL (2018) *About us | European Network of Living Labs*. Available at: http://enoll.org/about-us/ (Accessed: 25 April 2018).

European Commission (2014) *Nature-Based Solutions*. Available at: https://ec.europa.eu/research/environment/index.cfm?pg=nbs (Accessed: 28 May 2018).

European Union (2014) *Mapping and Assessment of Ecosystems and their Services: Indicators for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020 - 2nd report - Final*. doi: 10.2779/75203.

Eurostat (2014) *Taxation trends in the European Union*. Edited by EU Law and Publications. doi: 10.2785/751842.

Faivre, N. *et al.* (2017) 'Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges', *Environmental Research*, 159(August), pp. 509–518. doi: 10.1016/j.envres.2017.08.032.

Farber, S. and Li, X. (2013) 'Urban sprawl and social interaction potential: An empirical analysis of large metropolitan regions in the United States', *Journal of Transport Geography*. Elsevier Ltd, 31, pp. 267–277. doi: 10.1016/j.jtrangeo.2013.03.002.

Fernandez Maldonado, A. M. and Romein, A. (2009) 'The reinvention of Eindhoven: from industrial town in decline To capital city of a technology and design region.', in *City Futures Congress*, pp. 1–23. Available at: http://www.cityfutures2009.com/PDF/18_AM_Fernandez_Maldonado_A_Romein.pdf.

Fini, A. *et al.* (2017) 'Nature based solutions to mitigate soil sealing in urban areas: Results from a 4-year study comparing permeable, porous, and impermeable pavements', *Environmental Research*. Academic Press, 156, pp. 443–454. doi: 10.1016/J.ENVRES.2017.03.032.

Galster, G. *et al.* (2001) 'Wrestling Sprawl to the Ground: Defining and measuring an elusive concept', *Housing Policy Debate*, 12(4), pp. 681–717. doi: 10.1080/10511482.2001.9521426.

Geertman, S. and Stillwell, J. (2004) 'Planning support systems: An inventory of current practice', *Computers, Environment and Urban Systems*, 28(4), pp. 291–310. doi: 10.1016/S0198-9715(03)00024-3.

Geertman, S. and Stillwell, J. (2009) 'Planning Support Systems: Content, Issues and Trends', in Geertman, S. and Stillwell, J. (eds) *Planning Support System Best Practices and New Methods*, pp. 1–26. doi: 10.1007/978-1-4020-8952-7_1.

Gerard, B. (2015) *Klimaateffecten in Brabant – 3: de Brabantse steden als hitte-eiland – Weblog Bernard Gerard*. Available at: https://www.bjmgerard.nl/?p=1818 (Accessed: 14 May 2018).

Glaeser, E. L. and Kahn, M. E. (2003) *Sprawl and Urban growth*. 9733. Cambridge, Massachussets. doi: 10.3386/w9733.

González, A. *et al.* (2013) 'A decision-support system for sustainable urban metabolism in Europe', *Environmental Impact Assessment Review*. Elsevier Inc., 38, pp. 109–119. doi: 10.1016/j.eiar.2012.06.007.

Gunawardena, K. R., Wells, M. J. and Kershaw, T. (2017) 'Utilising green and bluespace to mitigate urban heat island intensity', *Science of the Total Environment*. The Author(s), 584–585, pp. 1040–1055. doi: 10.1016/j.scitotenv.2017.01.158.

Hennig, E. I. *et al.* (2015) 'Multi-scale analysis of urban sprawl in Europe: Towards a European de-sprawling strategy', *Land Use Policy*, 49, pp. 483–498. doi: 10.1016/j.landusepol.2015.08.001.

Holmer, B., Thorsson, S. and Eliasson, I. (2007) 'Cooling rates, sky view factors and the development of intra-urban air temperature difference', *Geografiska Annaler, Series A: Physical Geography*, 89 A(4), pp. 237–248. doi: 10.1111/j.1468-0459.2007.00323.x.

Honjo, T. (2009) 'Thermal Comfort in Outdoor Environment', *Global Environmental Research*, 13(1), pp. 43–47.

Hove, L. W. A. van *et al.* (2011) *Exploring the urban heat island intensity of Dutch cities : assessment based on a literature review, recent meteorological observation and datasets provide by hobby meteorologists - Alterra report*. Wageningen. Available at: https://www.wur.nl/en/Publication-details.htm?publicationId=publication-way-343036383139 (Accessed: 28 May 2018).

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the*

Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva.

Järvi, L. *et al.* (2014) 'Development of the Surface Urban Energy and Water Balance Scheme (SUEWS) for cold climate cities', *Geoscientific Model Development*, 7(4), pp. 1691–1711. doi: 10.5194/gmd-7-1691-2014.

Ji, W. *et al.* (2006) 'Characterizing urban sprawl using multi-stage remote sensing images and landscape metrics', *Computers, Environment and Urban Systems*, 30(6), pp. 861–879. doi: 10.1016/j.compenvurbsys.2005.09.002.

Johnson, M. P. (2001) 'Environmental impacts of urban sprawl: A survey of the literature and proposed research agenda', *Environment and Planning A*, 33(4), pp. 717–735. doi: 10.1068/a3327.

Kabisch, N. *et al.* (2016) 'Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action', *Ecology and Society*, 21(2):39(June). doi: 10.5751/ES-08373-210239.

Kabisch, N. *et al.* (2017) 'Nature-Based Solutions for Societal Goals Under Climate Change in Urban Areas – Synthesis and Ways Forward', in Bonn, N. et al. (eds) *Nature-Based Solutions to Climate Change Adaptation in Urban Areas*, pp. 323–336. doi: 10.1007/978-3-319-56091-5_19.

Kahila, M. and Kyttä, M. (2009) 'SoftGIS as a Bridge-Builder in Collaborative Urban Planning', in Geertman, S. and Stillwell, J. (eds) *Planning Support System Best Practices and New Methods*. Springer, Dordrecht, pp. 389–411. doi: 10.1007/978-1-4020-8952-7_19.

Kasanko, M. *et al.* (2006) 'Are European cities becoming dispersed?. A comparative analysis of 15 European urban areas', *Landscape and Urban Planning*, 77(1–2), pp. 111–130. doi: 10.1016/j.landurbplan.2005.02.003.

Klok, E. J. *et al.* (2012) 'De stedelijke hitte-eilanden van Nederland in kaart gebracht met satellietbeelden Samenvatting', *TNO Rapport*. doi: TNO-060-UT-2012-01117.

Klosterman, R. E. (1999) 'The What if? collaborative planning support system', *Environment and Planning B: Planning and Design*, 26(3), pp. 393–408. doi: 10.1068/b260393.

Klosterman, R. E. (2009) 'Planning Support Systems: Retrospect and Prospect', in Geertman, S. and Stillwell, J. (eds) *Planning Support System Best Practices and New Methods*, pp. v–vii.

KNMI (2018) *Hittegolven*. Available at: https://www.knmi.nl/nederland-nu/klimatologie/lijsten/hittegolven (Accessed: 29 June 2018).

Leconte, F. *et al.* (2017) 'Analysis of nocturnal air temperature in districts using mobile measurements and a cooling indicator', *Theoretical and Applied Climatology*, 130(1–2), pp. 365–376. doi: 10.1007/s00704-016-1886-7.

Lieske, S. N., Mullen, S. and Hamerlinck, J. D. (2009) 'Enhancing Comprehensive Planning with Public Engagement and Planning Support Integration', in, pp. 295–315. doi: 10.1007/978-1-4020-8952-7_15.

Maimaitijiang, M. *et al.* (2015) 'Drivers of land cover and land use changes in St. Louis metropolitan area over the past 40 years characterized by remote sensing and census population data', *International Journal of Applied Earth Observation and Geoinformation*. Elsevier B.V., 35(PB), pp. 161–174. doi: 10.1016/j.jag.2014.08.020.

Maleki, A. and Mahdavi, A. (2016) 'Evaluation of Urban Heat Islands Mitigation Strategies Using 3Dimentional Urban Micro- Climate Model Envi-Met', *Asian Journal of Civil Engineering*. ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING), 17(3), pp. 357–371. Available at: http://www.sid.ir/En/Journal/ViewPaper.aspx?ID=484742 (Accessed: 3 July 2018).

Maquil, V. *et al.* (2015) 'A geospatial tangible user interface to support stakeholder participation in urban planning', *GISTAM 2015 - 1st International Conference on Geographical Information Systems Theory, Applications and Management, Proceedings*, pp. 113–120. doi: 10.5220/0005370801130120.

van Maren, G. (2003) 'Key to Virtual Insight: A 3D GIS and Virtual Reality System', in. Springer, Berlin, Heidelberg, pp. 193–204. doi: 10.1007/978-3-540-24795-1_11.

Martins, T. A. L. *et al.* (2016) 'Impact of Urban Cool Island measures on outdoor climate and pedestrian comfort: Simulations for a new district of Toulouse, France', *Sustainable Cities and Society*. Elsevier B.V., 26, pp. 9–26. doi: 10.1016/j.scs.2016.05.003.

Mendonça, R. M. (2017) *Assessing the effectiveness of economic instruments to steer urban sprawl: a hedonic pricing simulation modelling approach*. Universidade de Aveiro.

Murata, T. and Kawai, N. (2018) 'Degradation of the urban ecosystem function due to soil sealing: involvement in the heat island phenomenon and hydrologic cycle in the Tokyo metropolitan area', *Soil Science and Plant Nutrition*. Taylor and Francis Ltd., 64(2), pp. 145–155. doi: 10.1080/00380768.2018.1439342.

Nabielek, K., Hamers, D. and Evers, D. (2016) *Cities in the Netherlands: Facts and figures on cities and urban areas*. Available at: http://www.pbl.nl/en.

Nakata-Osaki, C. M., Souza, L. C. L. and Rodrigues, D. S. (2018) 'THIS – Tool for Heat Island Simulation: A GIS extension model to calculate urban heat island intensity based on urban geometry', *Computers, Environment and Urban Systems*. Elsevier, 67(September 2017), pp. 157–168. doi: 10.1016/j.compenvurbsys.2017.09.007.

Nantes Metropole (2018) *Plan Local d'Urbanisme Métropolitain (PLUM) - Cartographie Interactive*. Available at: https://nantesmetropole.maps.arcgis.com/apps/webappviewer/index.html?id=05e51947a91f43a384be16c81c25d649 (Accessed: 14 May 2018).

Nielsen, J. (1993) *Usability engineering*. Academic Press.

Oke, T. R. (1973) 'City size and the urban heat island', *Atmospheric Environment (1967)*, 7(8), pp. 769–779. doi: 10.1016/0004-6981(73)90140-6.

Oueslati, W., Alvanides, S. and Garrod, G. (2015) 'Determinants of urban sprawl in European cities', *Urban Studies*, 52(9), pp. 1594–1614. doi: 10.1177/0042098015577773.

Pelzer, P. *et al.* (2013) 'Using MapTable® to Learn About Sustainable Urban Development', in Geertman, S., Toppen, F., and Stillwell, J. (eds) *Planning Support System for Sustainable Urban Development*, pp. 167–186. doi: 10.1007/978-3-642-37533-0_10.

Pelzer, P. *et al.* (2014) 'The added value of Planning Support Systems: A practitioner's perspective', *Computers, Environment and Urban Systems*. Elsevier Ltd, 48, pp. 16–27. doi: 10.1016/j.compenvurbsys.2014.05.002.

Pelzer, P. *et al.* (2015) 'Planning Support Systems and Task-Technology Fit: a Comparative Case Study', *Applied Spatial Analysis and Policy*, 8(2), pp. 155–175. doi: 10.1007/s12061-015-9135-5.

Pelzer, P. (2017) 'Usefulness of planning support systems: A conceptual framework and an empirical illustration', *Transportation Research Part A: Policy and Practice*, 104, pp. 84–95. doi: 10.1016/j.tra.2016.06.019.

Pensa, S., Masala, E. and Lami, I. M. (2013) 'Supporting Planning Processes by the Use of Dynamic Visualisation', in Geertman, S., Toppen, F., and Stillwell, J. (eds) *Planning Support System for*

Sustainable Urban Development, pp. 451–467. doi: 10.1007/978-3-642-37533-0_26.

Perman, R. *et al.* (2003) *Natural Resource and Environmental Economics - Third Edition*. Edited by P. E. Limited. Harlow, UK.

Pettit, C. *et al.* (2012) 'Visualisation Support for Exploring Urban Space and Place', *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, I-2(April), pp. 153–158. doi: 10.5194/isprsannals-I-2-153-2012.

Postmes, L. (2017) *UNaLab (NBS) in Eindhoven - UNaLab internal report*.

Rafael, S. *et al.* (2016) 'Influence of urban resilience measures in the magnitude and behaviour of energy fluxes in the city of Porto (Portugal) under a climate change scenario', *Science of the Total Environment*, 566–567, pp. 1500–1510. doi: 10.1016/j.scitotenv.2016.06.037.

Rafael, S. *et al.* (2017) 'Quantification and mapping of urban fluxes under climate change: Application of WRF-SUEWS model to Greater Porto area (Portugal)', *Environmental Research*, 155(March), pp. 321–334. doi: 10.1016/j.envres.2017.02.033.

Rafael, S. (2017) *Urban air quality and climate change: vulnerability, resilience and adaptation*. Universidade de Aveiro.

Rizwan, A. M., Dennis, L. Y. C. and Liu, C. (2008) 'A review on the generation, determination and mitigation of Urban Heat Island', *Journal of Environmental Sciences*, 20(1), pp. 120–128. doi: 10.1016/S1001-0742(08)60019-4.

Roebeling, P. *et al.* (2017) 'Assessing the socio-economic impacts of green/blue space, urban residential and road infrastructure projects in the Confluence (Lyon): a hedonic pricing simulation approach', *Journal of Environmental Planning and Management*. Taylor & Francis, 60(3), pp. 482–499. doi: 10.1080/09640568.2016.1162138.

Roebeling, P. C. *et al.* (2014) *Sustainable Urbanizing Landscape Development (SULD) decision support tool: report on frontrunner Aqua Cases*.

Russo, P. *et al.* (2017) 'Adoption and Use of Software in Land Use Planning Practice: A Multiple-Country Study', *International Journal of Human–Computer Interaction*. Taylor & Francis, 00(00), pp. 1–16. doi: 10.1080/10447318.2017.1327213.

Russo, P. *et al.* (2018) 'Towards satisfying practitioners in using Planning Support Systems', *Computers, Environment and Urban Systems*. Elsevier Ltd, 67, pp. 9–20. doi: 10.1016/j.compenvurbsys.2017.08.009.

Sailor, D. J. (2011) 'A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment', *International Journal of Climatology*. John Wiley and Sons Ltd, 31(2), pp. 189–199. doi: 10.1002/joc.2106.

Santamouris, M. (2007) 'Heat island research in Europe: The state of the art', *Advances in Building Energy Research*, 1(1), pp. 123–150. doi: 10.1080/17512549.2007.9687272.

Santamouris, M. (2013) 'Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments', *Renewable and Sustainable Energy Reviews*. Elsevier, 26, pp. 224–240. doi: 10.1016/j.rser.2013.05.047.

Santamouris, M. (2014) 'On the energy impact of urban heat island and global warming on buildings', *Energy and Buildings*. Elsevier B.V., 82, pp. 100–113. doi: 10.1016/j.enbuild.2014.07.022.

Santamouris, M. *et al.* (2017) 'Urban heat island and overheating characteristics in Sydney, Australia. An analysis of multiyear measurements', *Sustainability (Switzerland)*, 9(5). doi: 10.3390/su9050712.

Schinasi, L. H., Benmarhnia, T. and De Roos, A. J. (2018) 'Modification of the association between high ambient temperature and health by urban microclimate indicators: A systematic review and meta-analysis', *Environmental Research*. Elsevier Inc., 161(November 2017), pp. 168–180. doi: 10.1016/j.envres.2017.11.004.

Schwarz, N., Lautenbach, S. and Seppelt, R. (2011) 'Exploring indicators for quantifying surface urban heat islands of European cities with MODIS land surface temperatures', *Remote Sensing of Environment*. Elsevier Inc., 115(12), pp. 3175–3186. doi: 10.1016/j.rse.2011.07.003.

Sioen, G. B., Terada, T. and Yokohari, M. (2016) 'Sustainability Science as the Next Step in Urban Planning and Design', in *Sustainability Science: Field Methods and Exercises*. Cham: Springer International Publishing, pp. 117–135. doi: 10.1007/978-3-319-32930-7_6.

SITI (2018) *LUMAT - IT | InViTo, Interactive Visualization Tool*. Available at: http://www.urbantoolbox.it/project/lumat-z-o-11/ (Accessed: 14 May 2018).

Snyder, K. (2003) 'Tools for Community Design and Decision-making', in Geertman, S. and Stillwell, J. (eds) *Planning Support Systems in Practice*. Springer, Berlin, Heidelberg, pp. 99–120. doi: 10.1007/978-3-540-24795-1_6.

Steffen, W., Hughes, L. and Perkins, S. (2014) *Heatwaves : Hotter, Longer, More Often.* Available at: http://www.climatecouncil.org.au/uploads/9901f6614a2cac7b2b888f55b4dff9cc.pdf.

Stone, B., Hess, J. J. and Frumkin, H. (2010) 'Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities?', *Environmental health perspectives*. National Institute of Environmental Health Science, 118(10), pp. 1425–8. doi: 10.1289/ehp.0901879.

Tableau Software (2018) *Tableau & the United Nations*. Available at: https://www.tableau.com/account/united-nations (Accessed: 27 May 2018).

Le Tertre, A. *et al.* (2006) 'Impact of the 2003 Heatwave on All-Cause Mortality in 9 French Cities', *Epidemiology*, 17(1), pp. 75–79. doi: 10.1097/01.ede.0000187650.36636.1f.

Theeuwes, N. E., Solcerová, A. and Steeneveld, G. J. (2013) 'Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city', *Journal of Geophysical Research Atmospheres*, 118(16), pp. 8881–8896. doi: 10.1002/jgrd.50704.

U.S. Environmental Protection Agency (2008) *Reducing Urban Heat Islands: Compendium of Strategies. Draft.* Available at: https://www.epa.gov/heat-islands/heat-island-compendium.

UNaLab (2016) *Urban Nature Labs (UNaLab). Project proposal submitted to H2020-SCC-2016-2017 (Smart and Sustainable Cities) on 06-09-2016 and funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 730052 Topic: SCC-2-2016*.

United Nations, D. of E. and S. A. (2014) *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER/A/352)*. Available at: https://esa.un.org/unpd/wup/publications/files/wup2014-highlights.pdf (Accessed: 13 March 2018).

Vonk, G. A. (2006) *Improving planning support : the use of planning support systems for spatial planning*. Koninklijk Nederlands Aardrijkskundig Genootschap, Faculteit Geowetenschappen Universiteit Utrecht. Available at: https://dspace.library.uu.nl/handle/1874/8576 (Accessed: 28 February 2018).

Vonk, G., Geertman, S. and Schot, P. (2005) 'Bottlenecks blocking widespread usage of planning support systems', *Environment and Planning A*, 37(5), pp. 909–924. doi: 10.1068/a3712.

Vonk, G., Geertman, S. and Schot, P. (2007) 'A SWOT Analysis of Planning Support Systems', *Environment and Planning A*, 39(7), pp. 1699–1714. doi: 10.1068/a38262.

Voogt, J. A. and Oke, T. R. (2003) 'Thermal remote sensing of urban climates', *Remote Sensing of Environment*, 86(3), pp. 370–384. doi: 10.1016/S0034-4257(03)00079-8.

Ward, H. C. and Grimmond, C. S. B. (2017) 'Assessing the impact of changes in surface cover, human behaviour and climate on energy partitioning across Greater London', *Landscape and Urban Planning*. Elsevier B.V., 165, pp. 142–161. doi: 10.1016/j.landurbplan.2017.04.001.

Ward, K. *et al.* (2016) 'Heat waves and urban heat islands in Europe: A review of relevant drivers', *Science of the Total Environment*. Elsevier B.V., 569–570, pp. 527–539. doi: 10.1016/j.scitotenv.2016.06.119.

Wei, Y. D. and Ewing, R. (2018) 'Urban expansion, sprawl and inequality', *Landscape and Urban Planning*. doi: 10.1016/j.landurbplan.2018.05.021.

Wihbey, J. (2016) 'Boundary Issues: The 2016 Atlas of Urban Expansion Indicates Global Dedensification', *Land Lines*, October, pp. 19–25. Available at: https://www.lincolninst.edu/publications/articles/boundary-issues (Accessed: 2 July 2018).

World Meteorological Organization (2015) *WMO: 2015 likely to be Warmest on Record, 2011-2015 Warmest Five Year Period*. Available at: https://public.wmo.int/en/media/press-release/wmo-2015-likely-be-warmest-record-2011-2015-warmest-five-year-period (Accessed: 10 January 2018).

Wu, J. J. (2001) 'Environmental amenities and the spatial pattern of urban sprawl', *American Journal of Agricultural Economics*. Oxford University PressAgricultural & Applied Economics Association, 83(3), pp. 691–697. doi: 10.1111/0002-9092.00192.

Xiang, W.-N. and Clarke, K. C. (2003) 'The Use of Scenarios in Land-Use Planning', *Environment and Planning B: Planning and Design*. SAGE PublicationsSage UK: London, England, 30(6), pp. 885–909. doi: 10.1068/b2945.

Yuan, F. and Bauer, M. E. (2007) 'Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery', *Remote Sensing of Environment*, 106(3), pp. 375–386. doi: 10.1016/j.rse.2006.09.003.

Zhu, Y. *et al.* (2013) 'Flexible Geospatial Platform for Distributed and Collaborative Urban Modelling', in Geertman, S., Toppen, F., and Stillwell, J. (eds) *Planning Support System for Sustainable Urban Development*, pp. 375–394. doi: 10.1007/978-3-642-37533-0_22.

ANNEXES

Annex 1: Details on the Planning Support Systems

PSS	Type	Pre-run simula-tions ?	Description	3D/ 2D	Input data (examples)	Output data	Model-ling scale	Applied in a specific area ?	Open Source ?	Deve-loper	Website
Adaptation Support Tool	Commun-icating	No	Assess the impact of adaptation measure (green/blue infrastructure) on urban heat, water systems and cost/benefit information	2D	Land use data, perimeter of the adaptation measure and its characteristics	Indicators (no map)	Building	Utrecht (NL)	No	Deltares®	https://www.deltares.nl/en/software/adaptation-support-tool-ast/
ALCES toolkit	Analysing	N/A	Provides a holistic planning perspective by assessing cumulative effects of overlapping land uses and ecological processes. From simple to complex models.	2D/ 3D	Land use data, landscape composition	2D/3D visuali-sations	City/ Region	Mostly Canada, but also Australia, India, Kenya and Paraguay	No	Alces®	https://alces.ca/software/
Community-Viz	Analysing / Commun-icating	N/A	On demand scenario creation and simulation	2D/ 3D	Depends on the project	Maps	City/Reg-ion	Mostly in the US	No	City Explained, Inc. ®	http://communityviz.city-explained.com/index.html
Envision Scenario Planner	Analysing	No	At the lot scale, allow to design new buildings and their characteristics (water system, energy, etc), for example for development of unused areas	3D	Land use, new building characteristics (water treatment system, energy	Indica-tors (no map)	Building	Yes	Yes	AURIN	https://aurin.org.au/projects/lens-sub-projects/esp/

					efficiency, type of building, etc)						
Envision Tomorrow	Analysing	No	Scenario planning package that allows to explore the current situation and the impacts of different scenarios in terms of land use, housing, demographics, economic growth, development feasibility, fiscal impacts, transportation, environmental factors and quality of life	2D	Land use	Indica-tors (tables and graphs)	Parcels	N/A	Yes	Envision Tomorrow	http://envisiontomorrow.org
Esri City Engine	Commun--icating	Yes	Allows visualisation of before / after urban projects in detailed 3D (with swipe map for example), and is very powerful for traffic flow simulations	3D	3D buildings and their characteristics	New visualisation	Building	Philadephia (USA), Singapore	No	Esri®	http://www.esri.com/software/cityengine
ForCity	Analysing	Yes	Collection of tool to help decision-making, destined in particular to public entities and firms in the energy, planning, environment and real-estate sectors	3D	3D city and scenarios	Videos ("4D") showing the impact of the scenarios through time	Building	Paris (FR)	No	ForCity®	https://www.forcity.com/
InViTo	Informing	Yes	Interactive visualisation tool where users can select what to display on the map, as accessibility	2D	Landscape detail (land use, elevation, cultural spots,etc..)	Maps	City/Region	Southern Europe (IT, SP, PT)	Yes	InViTo	http://www.urbantoolbox.it/case-studies/
K2Vi	Commun-icating / Analysing		Visualise the environment in VR and provide simulations as traffic flow, flooding and assess scenarios	3D	Complete 3D models (including hydrological aspects)	3D maps	Building	Used in New Zealand and in other countries, also military actions	No	AAM®	http://www.aamgroup.com/services-and-

											technology /3d-gis
LEAM	Analysing but static (no interaction with the tool)	Yes	Land use Evolution and impact Assessment Model, support regional planning pratices, spatial dynamic model, understand interactions between complex systems, focused on land use change.	2D	Land use, policies, ecological models	Change in land use and consequent water quality, air quality, traffic patterns, air quality	Regional	Chicago (USA), Stockholm (SW)	N/A	LEAM	http://www.leam.uiuc.edu/
PLUM	Informing	No	Show the zoning regulation of the Nantes Metropole region, including the protected areas and the transport network	2D	Land use	Land use	Metropole	Nantes (FR)	Online	Nantes Metro-pole	https://nantesmetropole.maps.arcgis.com/apps/webappviewer/index.html?id=05e51947a91f43a384be16c81c25d649
PSSD	Informing	Yes	Planning Support System for Sustainable Development, allows to navigate through different aspects of sustainable development, with all the knowledge at hand	2D	Land use, theoretical concepts explained, good examples,…	best practices, sustaina-bility indicators,	City/Regional/National	Baltic region	N/A	Geertman and Stillwell, (2004)	N/A
SketchGIS	Informing / Commun-icating	No	Standalone Toolbox to support the first phase of a participatory plan making process	2D/ 3D	New development design	3D models	Local / Regional (disaggregated)	Randmeren (NL)	N/A	Geert-mann and stillwell (2003)	N/A
SMURF	Commun-icating	Yes	"System for Monitoring Urban Functionalities" developed for	2D	Landscape information	Indicators	City/Region	Western Africa	N/A	Soutter (2003)	

			the support of urban management in Africa. It consists of a data exchange platform, simple and accessible for developing countries								
SoftGIS	Informing /Commu-nicating	No	Support the design of user friendly design settings by providing information on the perception of urban citizens on their environment	2D	Opinions on certain routes, certain places	Maps	City/neighborhood	Helsinki (FN)	Yes	Kahila and Kyttä (2009)	
Spartacus	Analysing	No	Analyse the interactions between land use, transport, economy, environment and social factors and forecast in the future, evaluate policy measures	2D	Landscape information					Geertman and Stillwell, (2004)	
Spatial Vision for Peri Urban Melbourne	Informing / Analysing	Yes	Several web-apps dealing each one with a particular problematic: population projection, supply and demand, impact analysis, offsets/mitigations, township analysis	2D			City	Melbourne (AU)	N/A	Spatial Vision ®	https://spatialvision.com.au/html/IA/
UrbanSim	Analysing	No	Comprehensive, integrates land-use, transportation, economic, demographic and environment variables	3D	Open Data		Census	The US (40 metropolitan areas)	No	UrbanSim ®	http://www.urbansim.com/home/
What if?	Analysing / Commun-icating	No	Off-the-shelf land suitability DSS, land use (suitability), project population, housing and employment	2D	Land use		Census block	15 countries, 48 users	No	Pettit	http://www.what-if-pss.com/

Annex 2: Positions of the agricultural areas taken for the measurement of the UHII