Models and interactive tools in support of environmental decisions

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Chapter 1: Introduction

1.1. Geospatial information for environmental problems

Human intervention in our environment often has undesirable consequences, including major environmental problems such as global warming, threatening our environment, the life of humans and other species. Clearly, we need to make proper decisions when encountering environmental problems and find solutions for the mitigation of their effects. However, taking decisions regarding environmental issues is difficult due to the multi criteria nature of environmental problems, the involvement of stakeholders from different domains, and the uncertainty and complexity of environmental problems. The first step to address is to have reliable and updated information on the current situation. The activity of processing this information is an essential constituent of a planning procedure (Scholten and Stillwell, 1990). A major type of information in this context is geospatial information, as it provides crucial knowledge on the formation and inter-relation of different environmental phenomena, and environmental solutions often depend on the spatial context.

[Geospatial] information can be acquired from different sources, such as local people, traditional surveying methods and modern technologies, having different reliability, cost and update frequency characteristics. The data, acquired from different sources, can be stored, processed and managed in a Geographic Information System (GIS) (Longley et al., 2001). In addition to geospatial data, GIS can be enriched with different models and algorithms for the efficient and automated processing and analyzing of information from raw data.

The feasibility and efficiency (in terms of costs and computing power) of data acquisition, processing and information extraction is related to the study scale; the larger the extent (and therefore higher coverage), the less detailed the captured data and the derived information. Currently, technological advancements have led to extracting more detailed information on larger areas both due to developments in data capturing devices (e.g. advanced airborne LIDAR) as well as computer processing and optimizations in (semi) automated information extraction algorithms. Integration of these advancements in a unified platform can lead to more detailed information presentation and analysis on a larger scale, which can provide a better picture on the information and processes of the current situation. This can boost the first step of a decision process, since a proper understanding of the current situation supports its evaluation in terms of its state and functionalities, which play a crucial role in proposing the subsequent alterations.

The second step is to design the alterations meant for the mitigation of the environmental problem. In this step, an interactive platform for scenario analysis can play an important role in the designing of different alternatives. In addition, like the previous step, reliable and updated information and process models are crucial for the impact analysis of the different scenarios and the final decision. The interactivity of the platform and the optimized performance of the underlying models also help in the integrated performance of a recursive decision making framework, wherein the different components of the decision process should be visited several times.

1.2. A framework and requirements for a multi-disciplinary decision making process

Information on the current situation, as the initial step of a decision process, as well as the subsequent alteration designs, requires the access, maintenance, processing and presenting of the acquired geospatial datasets, calling for the delineation of a pertinent [geospatial] framework. In the Netherlands, different attempts were made during the last decades for the proper design of geospatial frameworks in the environmental domain. In 1989, an Environmental GIS (MILGIS) project was initiated in the National Institute of Public Health and Environmental Protection (RIVM) for the description and prediction of the quality of the environment. MILGIS contained four levels that were integrated with geographical data/results shared between them (van Beurden and Scholten, 1990). The highest level of MILGIS was mainly focused on data gathering from different institutes, data structuring and preparation for usage by different users, leading to the design of the central database. The second level contained GIS for laboratories (LABGIS) where the laboratory data of primary processes were used, selected or produced based on the particular research. The third level was analytical GIS wherein GIS software for spatial analysis (e.g. overlays, interpolation and zoning) were used in addition to models. The fourth level was the graphical level which focused on the presentation of the output, maps and graphs of the previous three levels. GIS data structure and storage were used in RIVM for serving input data to models. As the computer models often operated separately from other software, an interface between GIS and the models was required. For this purpose, Spans GIS software was used wherein models could run on its command processes and the GIS database (as inputs of the models) could be accessed through it.

Misseyer (1999) constructed a multi-dimensional framework for supporting governmental authorities to implement a proper environmental monitoring structure. This framework consists of five dimension, namely: *environmental legislation*, *environmental policy*, *information infrastructure and management*, *information needs and requirements* and *information and communication technology*. This defined model aimed at more efficient (and even maybe more effective) analysis, processing and presenting of environmental issues. Van Herwijnen (1999) developed a framework consisting of different multi-objective decision methods in combination with spatial analyses approaches to produce enhanced techniques in spatial environmental problems. Fabbri (2002) developed a framework for structuring a decision situation by coastal managers and decision makers. The integration of different methods and tools, in this study, aimed to support decision making in environmental management. These studies all emphasized the importance of appropriate frameworks for the proper integration of geospatial data (from different resources) with environmental models in the provision of a proper insight of the current situation and the support of decision making regarding environmental issues.

Following the attempts to define geospatial frameworks for decision making regarding environmental issues, a framework of methods and techniques for an efficient and integrated design-impact for environmental decision making is investigated in this study. Geodesign, as the planning and design method which pairs design and its resulting impacts by geographic context (Flaxman, 2010), was researched for its efficiency as the framework of this study. Though rooted in the beginning of the 20th century (Manning, 1913), recent technological advancements support the implementation of this framework for direct design-impact feedbacks (Dias et al., 2013).

Geodesign, as the development and employment of design-related processes for alterations in geography, is a collection of methods and concepts derived from the geospatial domain as well as design-related disciplines (Steinitz, 2012). This iterative design and planning approach, when combined with geospatial technology, provides the scope for a simultaneous design-evaluation process, which can lead to a more robust design (Lee et al., 2014). The geodesign framework proposed by Steinitz (1990) includes six questions regarding the current situation as well as alterations in the study area, which should be reviewed iteratively and discussed by the stakeholders from different involved domains, during the planning process. This structure makes geodesign an appropriate framework for applying in multi-disciplinary environmental decision making processes.

Data incorporation and the visualization platform are the two main components of a geodesign framework. Current technological advancements have led to the availability of detailed (in terms of spatial as well as temporal resolutions) geospatial data. However, the employment of these datasets in decision processes confronts major limitations, mainly due to costs, volume and formatting issues. Emerging national and worldwide open data initiatives, e.g. UK Ordnance Survey open data (OS OpenData, 2019), and Dutch open data from the Ministry of Infrastructure and Environment (Open data van de Overheid, 2019), has broadened the opportunities for a wider application of the geospatial datasets produced. Despite these initiatives, there are substantial constraints on applying open geospatial datasets to their full extent: volume extensiveness and formatting incompatibilities with the platform used are among the main obstacles to the use of open geospatial data (Martin et al., 2013; Liu et al., 2015). In addition, the integration of data from different domains can face challenges due to inconsistencies in disciplines, scales and information models. An instance here is the integration of the Building Information Model (BIM) in the GIS environment. While BIM contains detailed semantic and geometric information on the construction level, it is often not geolocated and detached from its environment. The defined information model of BIM is focused on the building level, in line with the architecture domain. However, the focus of the GIS domain lies in the geospatial relations between [existing] objects on larger scales, with lower detail and more simplified geometry (Isikdag and Zlatanova, 2009; Mignard and Nicolle, 2014).

The visualization platform is another major component of a geodesign framework. Visualization is the main link between the quantitative substance of data and human intuition (Donalek et al., 2014). The design of a visualization environment, in terms of information content, presentation style and interactivity, can have great influence on the user perception of the environment. The information content is composed of the extent, dimension, level of detail and [domain] diversity. In addition to data availability and accessibility, these elements are limited to the computer processing and rendering capacities. Geospatial visualization platforms should mainly focus on one element and sacrifice other elements due to performance issues. This limits the provision of a comprehensive situational picture to stakeholders which can affect the subsequent steps of the decision process. Therefore, an optimized visualization platform with boosted capacity on information content can play an important role in a decision process (Jude, 2008). Here, dimension, specifically, can have significant impact on user perception. Studies mention that users perceive 3D geospatial information better than simplified 2D, due to easier association between the information and our 3D environment (Alkodmany, 2002; Dias et al., 2003). However, in the GIS domain, 2D platforms are still mainstream and 3D visualization platforms face challenges on large extents due to both performance issues as well as the scarcity of 3D geospatial information. This, in turn, is related to the burden of processing massive 3D geospatial data as well as the implementation complexity of 3D object extraction algorithms on large extents. The interactivity of a visualization platform is the other key feature for boosted perception. Different studies have shown the influence of platform-user interaction on a better perception as well as more active involvement of stakeholders in a decision process (Santhanam and Wiedenbeck, 1993; Al-Kodmany, 1999). The interactivity of a visualization platform is related to platform responsiveness as well as its [user interface] design. Agile responsiveness of a visualization platform is restricted to performance capacity. Therefore optimization on platform responsiveness can enhance its interactivity.

Subsequent to the perception and the evaluation of the current situation, involved stakeholders should pose and discuss alteration scenarios for enhancements within the defined target framework. In this stage, a common platform where all stakeholders can collaborate together on designing adaptation scenarios benefits the decision making process (Eikelboom and Janssen, 2017). The effectiveness of such a platform is reliant on several factors, among which [user interface] design, interactivity, responsiveness and ease of use play the most important roles (Shiffer, 1992; Simonovic and Bender, 1996). Furthermore, the proper incorporation and design of [geospatial] data from different domains is an influential factor for an effectual scenario design procedure in a multidisciplinary planning process, as it provides multi-aspect insight on the current situation and a foundation upon which alteration scenarios should be designed. Similar to the visualization of the current situation, in the case of the design platform the provision of 3D geospatial model can also boost the user perception. While studies have shown the importance of the mentioned factors, performance problems due to intensive data processing and rendering requirements present an important obstacle in the transition to an interactive 3D geospatial design platform.

A proposed alteration scenario cannot be evaluated regardless of its mutual impact with its environment. This requires the development of new models or the employment of existing environmental models. On a micro-scale, these models require detailed information both for their development and their implementation. While for smaller extents, the processing of the detailed [geospatial] information is still manageable, it becomes more problematic as the study area expands. This is due to machine performance as well as data availability constraints. Therefore, in both cases of model development and implementation, studies should mainly observe the trade-off between detail level and study extent. However, this restriction can impose considerable inaccuracies when assessing the impact of a posed scenario which might cause a negative influence on the final decision. Therefore, approaches and routines for optimizing the accessibility and processing of detailed [input] data on a large extent, for model development as well as model implementation, can be of great value.

In addition to the ability to develop and/or implement environmental models on a more detailed level and in a larger extent, their implementation speed also considerably influences the decision process, as boosting the responsiveness of scenario impact analysis can support seamless scenario configurations and impact assessments. This results in an intertwined discussion process which in turn can enhance the efficiency of a decision process (Jude, 2008; Dias et al., 2013). The implementation speed of environmental models is, however, dependent on the model complexity as well as the study extent. In other words, the speed is restricted to the machine performance in the processing of input geospatial data as well as the model computations. Employing optimization techniques to boost the implementation speed of environmental models in large extent will therefore support higher responsiveness of scenario impact analysis, the overall interactivity of the scenario design platform and the conjunction of the scenario configuration/evaluation discussions.

To summarize this section, Table 1 demonstrates the elements of a spatial decision support system requiring more research for its improvement. These improvements can be carried out on a single element as well as on integrating a collection of inter-related elements.

Table 1. Limitations of current Spatial Decision Support Systems.

Limitations	**Environmental decision making process components**	**Current Situation**	**Alterations**
Accessibility	Data	✓	✓
Interoperability		✓	✓
Scale		✓	✓
Dimension (3D)	Data, Visualization	✓	✓
Interactivity	Visualization, Design platform	✓	✓
Information content		✓	✓
Experimental model development on a city scale	Process models	✓	
Responsiveness	Design platform		✓
Implementation speed of simulation models	Impact models		✓
Speed/Scale proportion			✓

1.3. Efficient Data-Model-Technology integration towards an optimized spatial decision support system

In line with the mentioned research gaps and limitations in the development of an effectual spatial decision support system, which can improve the decision making process, this thesis introduces the development of different components for supporting environmental decisions. These components comprise data processing and information extraction, interactive presentation, the development of process models (for current processes as well as for impact analysis of new scenarios) and an interactive platform for flexible scenario design and intertwined discussion processes. This thesis focuses especially on the effective integration of these components for optimizing the performance of spatial decision support systems. Different technologies, datasets and environmental models have been employed for the development of these components. Two major environmental problems, namely *energy* and *liveability*, have been chosen as the use cases for the development of the components of effective spatial decision support systems. The developed components belong to one or both domains. The scheme of this thesis, including the developed/applied components are illustrated in Figure 1.

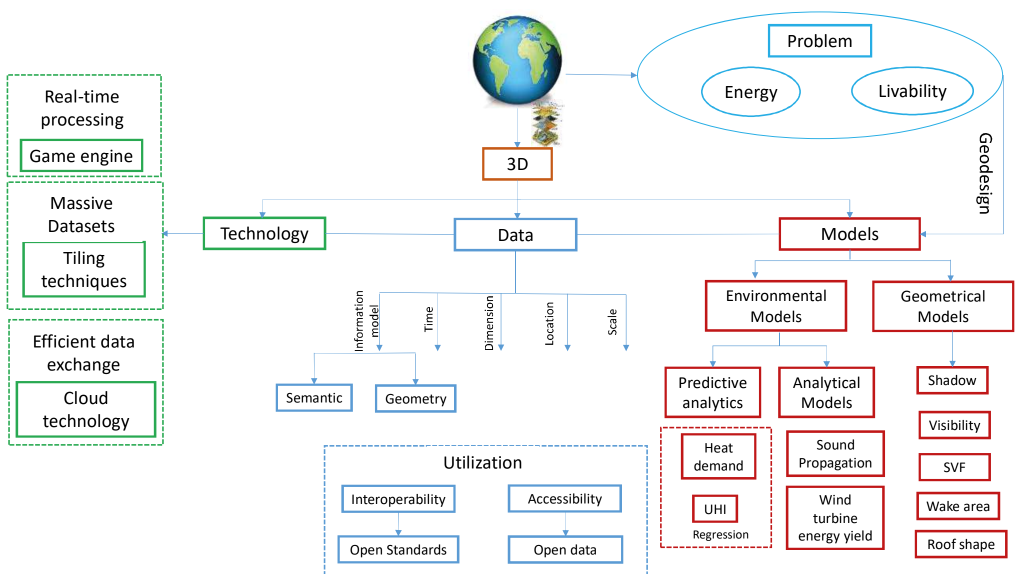

Figure 1. Thesis schema; the development of components for optimized performance of SDSS in different domains, through the efficient integration of Data-Models-Technology components.

Our environment is encountering many problems. To be able to take proper decisions regarding these problems, our environment and its interrelated processes should be described properly in each step of the decision process. The proper combination of *data*, *models* and *technology* can support us in describing and presenting our environment and its processes. Energy and liveability related environmental problems, being two major issues of concern for our era, have been chosen as the use cases of this thesis. A geodesign outline is applied for the design of the decision support components regarding these environmental problems. Each component can belong to one or more steps of geodesign framework.

Data, which is mainly comprised of geospatial data in this thesis, has different properties. In this thesis, the focus lies on scale, location, dimension and information model attributes. These parameters have different impacts on the analyses we aim to perform. The extent to which we can handle the [geospatial] data is a function of scale, dimension, time and the efficiency of the information model (which can contain geometry as well as geometry/semantic). A major focus of this thesis is the efficient employment of technology to increase the extent of the analyses while maintained high detail. The [geospatial] data dimension is 3D and the scale is at micro scale on all the analyses of this study. In addition to data characteristics, the potential utilization of data plays an important role on the scale and extent of different analyses. Data utilization is comprised of its accessibility and interoperability. Another major objective of this study is to apply nationwide open data and open standards to boost the accessibility and interoperability of geospatial data, respectively, for the different analyses involved. The former broadens the variety of data and extent of data from different domains, which can enrich the analyses and the latter avoids formatting problems between different datasets, which is a major impediment in many studies. Different open standard web services have been employed and embedded in the designed modules of this study for the accessibility of nationwide open data from different domains and their interoperability with each other. The *data* component plays an important role in the representation model as well as the process and impact models (as the input of the underlying models) of a geodesign framework.

Models are applied to depict the different processes within our environment. They can be used to describe current processes, using current environmental configurations, as well as the posed alteration scenario impacts. In this thesis, two categories of models, namely environmental models and geometrical models have been employed for the description of current/changed environmental settings, for the different studies involved. Environmental models, in turn, comprise two groups of predictive analytics and analytical models in this thesis. Predictive analytics, here, comprised mainly multi-linear regression models for the exploration of the different influential geospatial parameters on Urban Heat Island (UHI) and household heat demands in two studies. Analytical models include sound propagation models as well as a wind turbine energy yield model for the simulation of wind turbine sound impacts on the neighbouring buildings and energy yield estimations, respectively, as the two main geospatially related parameters. Geometrical models are comprised of 3D shadow, visibility, sky view factor, roof shape and wake area models. 3D shadow and visibility models are applied for the impact analysis of wind turbine shading and visibility impacts on the surrounding buildings. Furthermore these models have also been used for the shading impact of trees on the roof of a residential BIM model as well as the green/grey view coverage of its windows. The wake area model is used for each wind turbine to avoid energy yield reduction due to the proximity of wind turbines. Sky view factor is applied to estimate the urban configuration impact on UHI and household heat demand. Roof shape model is applied to estimate its impact on household heat demand.

Technology plays an important role in the efficient application and integration of *data* and *models* for the development of a decision support platform. In this thesis, different technologies have been used to optimize the performance of different components of the designed decision support systems for the environmental problems to be addressed. The core technologies applied are game engine, tiling techniques and cloud technology. Game engine is used for real-time data processing and model implementation of the wind turbine decision support system. Through applying different rendering and physics engine functionalities of the Unity game engine, different processes within the decision support system, such as 3D scene rendering and spatial operations could be optimized. This led to the real-time performance of 3D analytical and geometrical models. While game engines can have optimized performance for high details on a small scene, their performance decreases for larger areas. For this reason, geospatial tiling techniques were applied in this study to increase the extent of the study area to the whole country. Furthermore, embedding cloud technology for efficient data exchange has broadened the possibilities beyond limited (commercially) available data. Incorporating open data and open standards, in combination with the embedded tiling techniques, has increased the study extent as well as the variety of geospatial data, integrated from different domains. The integration of game engine optimized performance with GIS tiling techniques and open standards has led to the real-time performance of the underlying process/impact models as well as optimized 3D rendering for representation and change models of a geodesign framework. This performance enhancement can play a crucial role for the integrity of a decision process.

1.4. Thesis outline: Research objectives and applied methodologies

This thesis is composed of seven chapters that cover the main goal of this thesis, namely, efficient [geospatial] Data-Model-Technology integration for the development of different components of optimized decision support systems in energy and liveability domains. The following research objectives are defined to fulfil the main goal of this study. They comprise the development/implementation of:

- Methodologies for efficient accessibility to massive 2D/3D open geospatial data from different resources and different domains on a large extent

- Methodologies for efficient integration and interoperability between the geospatial datasets from different domains and disciplines

- Approaches for boosting visualization from both information content as well as interactivity and scene rendering perspectives

- Experimental environmental model development on an extended (city) scale and the third dimension

- Techniques for the development of interactive and responsive 3D design platforms with augmented information content and rendering capabilities

- Methods for boosting the speed and scale of implemented simulation models

Each study of this thesis follows certain objectives, which are sub-classes of the overall research objectives. Data-Model-Technology integration is used to achieve these research objectives. Each of the Data, Model and Technology groups contains sub-categorical elements, as depicted in the thesis schema (Figure 1). Each study employs a set of these elements to fulfil its objectives.

Following the research objectives, subsequent research questions have been posed which are answered in this thesis:

1. How can [massive] 2D/3D open geospatial data, from different domains, be efficiently served in portraying current spatial configuration in representation and change models?
2. How can the interactivity, extent and responsiveness of a 3D spatial design platform be enhanced through the employment and integration of technology from different domains?
3. What is the benefit of 3D geospatial information on the development of process models?

More specifically on process models, based on the defined use cases of this study, the following research questions have been posed:

4. What is the influence of tree volume on nocturnal Urban Heat Island (UHI)?
5. How do spatial context parameters affect household heat consumption?
6. How can geospatial information be efficiently extracted from data to be used as inputs of predictive analytics on the whole city extent and high level of detail?
7. How can BIM-GIS integration support the efficiency of construction-environment impact analyses?

A more detailed overview on the research performed within the depicted thesis framework follows:

1.4.1. Local impact of tree volume on nocturnal urban heat island: A case study in Amsterdam

One of the environmental problems of the current era is Urban Heat Island. Urban Heat Island (UHI) is the temperature increase in urban areas compared to rural areas due to human activities. UHI can cause health problems to citizens, moreover, it increases the energy demand related to air-conditioning. The growth in urbanization leads to higher construction in urban areas, which in turn, leads to higher urban heat island. As the urban configuration has a high influence on the heat released, proper urban design is of great importance for UHI mitigation. The first step for a proper design is information on the parameters influencing UHI. Studies show the effects of different parameters, among which urban compactness and vegetation cover have considerable impacts on UHI (See Chapter 2 for more details). In this study, Chapter 2 focuses on the quantification of the local impact of tree volumes on nocturnal urban heat island intensity. This research area is in the liveability domain. An empirical model, through a multi-linear regression model, was developed to explain the contribution of local tree volume to UHI.

The urbanization degree, as a regional factor, and the sky view factor, as a local factor, were also taken into account. While the impact of vegetation cover on UHI has been investigated in different studies, it is mainly restricted to 2D vegetation surface estimation and/or on a limited extent. In our study, we have employed 3D tree models of the whole of Amsterdam for the estimation of their impact on its nocturnal UHI. Scale was taken into account by testing different radii to explore the radius wherein the aggregated tree volume has the highest impact on UHI. An additional contribution of this research is the demonstration of a scalable methodology for the automated extraction of geospatial information, to be employed in the analysis, at a city scale using geospatial data and GIS techniques, which can be employed in similar studies. This research covers the following research objectives:

- The improvement in process models: Exploring the impact of tree volume (rather than vegetation surface) on urban heat island
- Information extraction from massive point cloud data: Calculating sky view factor and tree volumes for the whole city, using airborne LiDAR technology and efficient 3D data processing

1.4.2. Developing a wind turbine planning platform: Integration of "sound propagation model–GIS-game engine" triplet

CO2 increase and global warming resulting from the excessive use of fossil fuel is another environmental problem of our current era. This has prompted the growth of renewable energy as an alternative clean energy source. Wind energy is an important source of renewable energy which is being employed in many countries. The Netherlands has a long history in using wind energy due to its climatic conditions, and is aiming to expand it in accordance with European renewable energy targets. In spite of the benefits of wind energy as a clean source, wind turbine development projects are hindered by citizens' opposition due to wind turbine externalities. Therefore, planning the proper location of wind turbines for the minimum environmental externalities and maximum energy yield are of great importance. In addition, citizens' involvement, from the beginning phase of the project, in the decision making process for wind turbine allocations can increase their trust and support.

The first step for the efficient involvement of citizens is a properly designed information system to provide a common picture to citizens and other involved stakeholders. In this study, we developed an interactive 3D wind turbine planning platform aimed at the effective involvement of stakeholders from different backgrounds. The platform focuses on wind turbine visual and sound externalities. The designed/implemented framework for this integrated environmental information system [for the support of wind turbine planning processes] is described in detail in this study. This system integrates game engine, GIS and analytical sound propagation models. This integration supported the optimized performance of the different components of the system and led to real-time wind turbine sound calculation in any location of the whole country. The interactive 3D virtual environment, provided through Unity game engine, can support an immersive experience for the users. Massive 3D models were derived through LIDAR point cloud and generated on-the-fly for both visualization in the virtual 3D environment as well as employment in the sound propagation models. The GIS component of the system supported the serving of massive geospatial data through tiling techniques as well as accessibility and interoperability to different datasets from different sources through the employment of cloud-based architecture and the incorporation of open geospatial standard protocols. The integration of state-of-the-art sound propagation models (through Unity game engine C# scripting API) supports the provision of more accurate information on the sound impact of a wind turbine on the surrounding buildings. This can attract stakeholders from different domains such as noise experts and legislation authorities, along with citizens. Different sound propagation modules were optimized through the employment of different game engine and GIS functionalities. This led to the real-time performance of sound propagation modules which normally take a long time in a conventional sound/GIS software. The real-time performance of wind turbine sound propagation models supports an intertwined discussion process where no interruptions for the (re)calculations are required.

This system can be used for the presentation of data and processes on a current situation (such as 3D building and terrain model) through an interactive 3D visualization platform. The incorporation of open standard protocols as well as tiling techniques in this system enables the flexible incorporation of other open geospatial data and [process] model results through the web. Being able to effectively present the current situation is an important aspect for proper evaluation of the situation, serving as a bridge for subsequent alteration designs. In the next step, this system can be applied as an interactive design platform for posing different alteration scenarios by interactively placing different 3D wind turbine models from different suppliers in the game engine scene. This step is followed by an immediate impact analysis of each design scenario, including aesthetic and wind turbine sound impacts on the surrounding buildings, which will be evaluated by the stakeholders. This study covers the following research objectives of this thesis:

- Development of an interactive 3D design platform
- Connection to analytical (wind turbine sound) models
- Incorporation of open geospatial standards and employment of open geospatial data for visualization as well as input for the sound models as impact analysis models
- Scalability to the whole country and even beyond
- Real-time performance of sound models

1.4.3. Interactive 3D geodesign tool for multidisciplinary wind turbine planning

Wind turbine site planning is a multidisciplinary task involving many stakeholders from different domains. The final location of a wind turbine should be discussed among the stakeholders involved who will have different, and sometimes conflicting, interests and priorities. This makes the siting of a wind turbine a multi-criteria decision making process. An information system which is capable of integrating knowledge on the different aspects of a wind turbine can play an important role in providing a more comprehensive picture to the stakeholders involved of the different domains and backgrounds. Such information system should act as the interface between the different components of a participatory plan process from providing information on the current situation and the subsequent evaluation to the design of the new situation, the evaluation of its impacts and the convergence to a final decision. This makes geodesign a proper framework for the design of a wind turbine multidisciplinary tool. In Chapter 4, we have developed an interactive 3D information system for planning wind turbine locations in any location in the Netherlands. The architecture developed for wind turbine planning through the game engine-GIS-sound model integration of the previous chapter, can be an appropriate basis for further development of the tool to include other aspects in wind turbine planning.

This system supports iterative design loops and has been designed based on the geodesign framework proposed by Steinitz (1990) aiming to support an interactive multidisciplinary plan process. Each of the geodesign models, namely *representation models, process models, evaluation models, change models, impact models* and *decision models* has been implemented in Falcon and together they form a multi-criteria decision support system for wind turbine siting in the Netherlands. Different game engine, GIS functionalities and analytical models have been employed in the design and efficient implementation of these geodesign models.

The criteria applied in this system are: wind turbine sound, shadow, visibility from buildings, energy yield, wake effects and regulations. Game engine-GIS-analytical model integration, as introduced in the previous chapter, supported the real-time performance of the different analytical models applied (e.g. sound, energy) in this system in any location in the country. This has been achieved through optimizing the performance of these models by employing different game engine as well as GIS functionalities in the model implementations. The interactivity and the real-time feedbacks as well as the applicability of the system for any location in the country, support the seamless exploration of various scenarios and their real-time environmental impacts in different locations which can help an intertwined discussion process. The multi-aspectual feature of this system supports the provision of a more comprehensive depiction of the environmental impacts of wind turbines in their site planning which can broaden its applications and lead to the involvement and collaboration of stakeholders from different backgrounds. This study covers the following research objectives:

- Development of a multidisciplinary interactive 3D design platform
- Connection to analytical and geometrical (wind turbine sound, shadow, visibility and wake area) models as impact analysis models
- Incorporation of open geospatial standards and employment of open geospatial data for visualization as well as input for the sound models
- Scalability to the whole country and even beyond
- Real-time performance of wind turbine sound, shadow, visibility and wake area models

1.4.4. Analyzing the impact of spatial context on the heat consumption of individual households

Heating demand, especially in countries with colder climates, when combined with the use of fossil fuels increases global warming and environmental problems. The heating of houses accounts for a considerable share of total energy consumption. Therefore, a reduction in the heating demand of residential buildings leads to significant energy demand mitigation. The first step for such a mitigation is to have information on the factors affecting the heat demand of the residential sector. When these factors and their behaviour are known, proper policies can be taken in order to achieve the heat demand reduction target.

Four major groups of factors have an impact on household heat demand: occupants' behaviour, (interior) building design, the system's efficiency and the spatial context. While the first three factors depend mostly on individual choices that are difficult to influence through urban planning, the last factor (spatial context) can be influenced by planners. Yet the impact of spatial context on household heat demand has had limited attention. This may be due to the lack of geospatial data and massive computer processing requirements. The aim of this study is to explore the combined impact of building shape and its surroundings on household heat consumption, both at individual household level and postal code level. Highly detailed geospatial data has been used to capture the characteristics of all individual buildings in Amsterdam and their spatial context. The 2D/3D spatial context of all the buildings is characterized using the spatial data processing routines that characterized buildings' shapes and their surroundings. The applied routines employed massive geospatial data and mathematical algorithms for the automated extraction of building shape characteristics, height, area, roof shape, exposed perimeter, as well as their spatial context variables, sky view factor, urbanization degree and tree volume. These variables, together with other building characteristics (year of construction) and the measured gas consumption per household have been applied in a multi-linear regression analysis to explore the relation between the heat consumption of individual buildings and their spatial context. In addition to the individual level, a separate regression analysis was performed at postal code level to study the impact of urban configuration variables on heat consumption at a different scale. At this scale, we are able to include demographic variables in the regression model, which enables us to investigate the relative contribution of these variables compared to that of spatial context variables on heat consumption. This study covers the following research objectives of this thesis:

- Improving process models (through exploring the impact of the geospatial context (2D and 3D) on household heat demand).
- Increasing the detail level of process models to individual household level
- Expanding the research area to the whole city rather than specific parts
- Applying detailed 2D/3D open geospatial data as the explanatory variables

1.4.5. From BIM to geo-analysis: view coverage and shadow analysis by BIM/GIS integration

Environmental analyses in urban areas, play an important role in different decision making processes. This includes analyses regarding current processes as well as those of new designs. An important aspect in such analyses is a consideration of the multiple processes which play a role in an urban area. This expresses the necessity of data integration from different domains and sources. These data might be from different disciplines, levels of detail and information models, which makes integration challenging. A well-known instance of such an integration challenge is BIM-GIS integration. BIM (Building Information Model), an important information source for different urban area analyses (such as urban planning), contains detailed geometrical and semantic information of a construction. This rich information source is often, however, not integrated with large-scale geospatial data due to the different level of detail in the BIM information model compared to geospatial datasets in a GIS system, caused by different scales. GIS, on the other hand, contains a physical and functional representation of the environment. The integration of BIM and GIS enriches both BIM and GIS environments and provides the opportunity for different automated detailed analyses on a large extent and will broaden analysis possibilities on the mutual impact of a building (including detailed semantic/geometric information) and its environment. [From a BIM perspective] This integration can be beneficial in different phases of BIM, from initial planning to maintenance, due to the impact of the environment on the construction and the corresponding decisions and actions which should be taken. [From a GIS perspective] This integration provides the opportunity for detailed analyses on the impact of BIM (building and infrastructure) on the environment.

While BIM can be modelled through different proprietary formats, the employment of open standards can reduce its interoperability obstacles and support its broader applications in different domains. Industry Foundation Classes (IFC) is the most common open standard for BIM data exchange. It is an object-based data model for the exchange of detailed geometric and semantic information on a construction. In this study, we have developed and implemented a routine for the automated integration of an IFC BIM model in a 3D GIS environment. We have applied BIM-GIS integration in two studies, namely, view coverage and shadow analysis. In the view coverage analysis, detailed information on windows have been extracted automatically from a BIM model, which was integrated in the 3D GIS environment. Based on the location and geometry of each window, the view quality for each window has been determined through an indicator, defined from existing 3D geospatial elements (3D building and 3D tree models). In the second study, roof segments derived from the BIM model were used with the generated 3D shadow models of surrounding buildings and trees (using 3D buildings and tree models) to estimate the rooftop portions lying in the shadow (for a specific time and date). The routines developed lead to the automation of the whole process from BIM-GIS integration to the different analyses, which is beneficial for fast and accurate analyses on a large scale. This study covers the following research objectives:

- Integration of data from different domains
- Applying open standards for the incorporation of geospatial data

- Connection to process/impact models for view coverage and shadow analysis
- Applying 3D geospatial data for these analyses

The position of the chapters within the framework of this thesis is depicted in Figure 2.

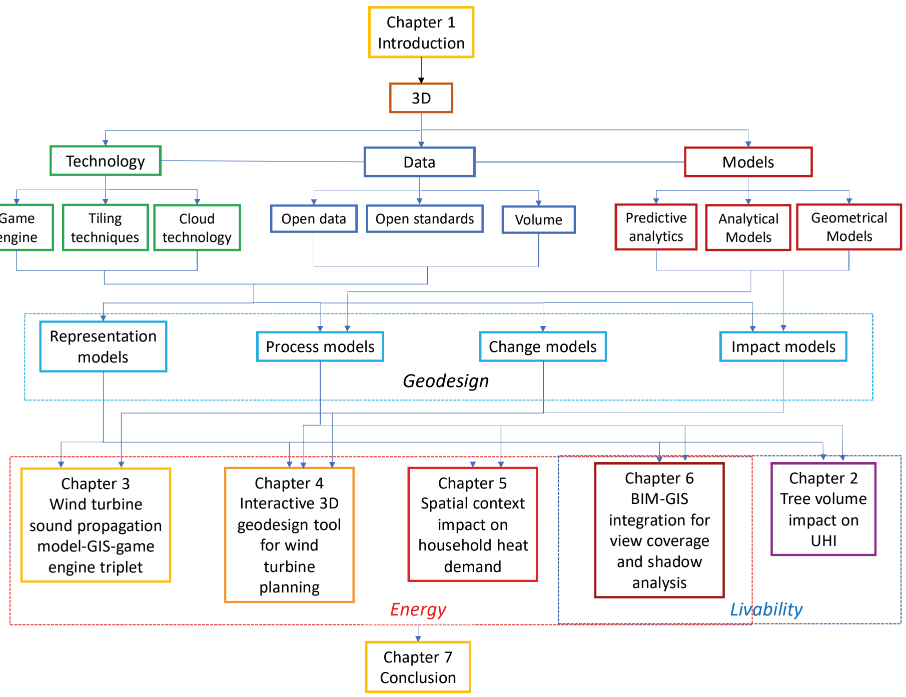

Figure 2. Thesis outline: the position of research papers in the thesis framework.

Table 2 presents the publications associated with the chapters of this thesis.

Table 2. Overview of the publications associated with the chapters of this thesis.

Chapter	Publication
2	Rafiee, A., Dias, E., & Koomen, E. (2016). Local impact of tree volume on nocturnal urban heat island: A case study in Amsterdam. Urban forestry & urban greening, 16, 50-61.
3	Rafiee, A., Van der Male, P., Dias, E., & Scholten, H. (2017). Developing a wind turbine planning platform: Integration of "sound propagation model–GIS-game engine" triplet. Environmental Modelling & Software, 95, 326-343.
4	Rafiee, A., Van der Male, P., Dias, E., & Scholten, H. (2018). Interactive 3D geodesign tool for multidisciplinary wind turbine planning. Journal of environmental management, 205, 107-124.
5	Rafiee, A., Dias, E., & Koomen, E. (2019). Analysing the impact of spatial context on the heat consumption of individual households. Renewable & Sustainable Energy Reviews, 112, 461-470.
6	Rafiee, A., Dias, E., Fruijtier, S., & Scholten, H. (2014). From BIM to geo-analysis: view coverage and shadow analysis by BIM/GIS integration. Procedia Environmental Sciences, 22, 397-402.