Models and interactive tools in support of environmental decisions

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Chapter 7: Synthesis and conclusions

This study explored solutions for enhancing spatial decision support systems for environmental problems. This included optimization of different aspects of a SDSS, such as [geospatial] data integration from different domains, interactivity, model development and model integration. Different approaches and techniques have been applied in this study to enable the optimization of these aspects. The core method for optimizing the performance of the different components of a SDSS was the efficient Data-Model-Technology integration.

In line with the current limitations of SDSSs for multi-disciplinary environmental decision making processes, the following research objectives for the enhanced performance of SDSSs were defined. These objectives comprise of the development/implementation of:

- Methods 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 boosted 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 boosted speed and scale of implemented simulation models

This chapter reviews the research carried out in this study to fulfil the research objectives.

7.1. Geodesign framework for a multi-disciplinary decision making process

To provide a structure for pursuing the above research objectives, a geodesign framework was applied. Geodesign, as an iterative design and planning approach, provided a constructive outline for positioning each research objective in its proper location within the complete decision making process framework. This provided an insight on the complete picture and helped in defining the inter-relation between the different elements of the total framework, which in turn, boosted the efficiency in designing and developing the different modules of environmental SDSSs and supported the scalability of the designed modules to be reused in different sub-modules of the framework. The geodesign framework contains six models, related to the current situation as well as the alterations. Different chapters of this study addressed one or more of these models, as follows. Data-Model-Technology integration has been applied for each (sub)module of the geodesign framework.

7.1.1. Representation models

Representation models portray the spatio-temporal content of the study area (Steinitz, 2014) and are of great importance in providing a comprehensive picture of the current situation. Representation models contain different modules to include the different aspects of the illustration of the study area. Data collection and its visualization are two main components of representation models. Data collection, on its own, comprises several attributes, such as data availability, accessibility, extent, level of detail and interoperability. These features can be defined for each study, based on its problem statements and objectives. In this study, all chapters deal with these data attributes, as geospatial data is the foundation for all the research conducted. More specifically, Chapter 2 employed massive 2D and 3D open geospatial data (on city extent) and processing techniques for the estimation of UHI model parameters, namely, tree volume, sky view factor and urbanization degree. Chapters 3 and 4, incorporated tiling techniques, open standards protocols and web services for the on-the-fly serving of massive 2D/3D datasets of the whole country from different domains, untangling the data accessibility and interoperability knots. Chapter 5 applied massive 2D/3D open geospatial data on a city extent to extract different urban configuration parameters (such as roof shape model, exposed perimeter and sky view factor) for each individual building through the dedicated geospatial data processing routines to estimate the impact of spatial context on household heat demand. Chapter 6 employed open 3D geospatial data along with the BIM model, in open standard IFC information model, for the automated integration of the BIM model into the GIS environment through the developed routine. This enhanced the interoperability between BIM and GIS, which originate from different disciplines and objectives and opened up a path for increased efficiency in different analyses within a SDSS.

In addition to information content, the presentation and visualization style of spatial information is an important factor for the proper perception of the decision making team of the current situation. This study contributed to the development of an enhanced interactive 3D visualization platform where massive geospatial data on a large extent and from different domains can be served on-the-fly. Chapters 3 and 4 applied game engine for optimized scene rendering and graphical presentation, resulting in an interactive 3D visualization platform. The incorporation of geospatial information and GIS functionalities into the game engine-based system, resulted in the optimized rendering of various georeferenced data and efficient interaction with the data. Integration of tiling techniques, OGC open standards protocols and web services in the game engine environment, expanded the game engine scene capabilities on on-the-fly serving of nationwide massive geospatial data from different domains on the cloud, resolving local data storage, formatting conflictions and data update issues.

7.1.2. Process models

Process models aim to explore the functional, structural and interaction behaviour among the elements of the study area to figure out how the study area operates (Steinitz, 2014; Reynolds, 2014). These models can indicate the operational picture of the current situation in different ways. In this study, quantitative analyses were performed for the development and application of different process models to present the interactions between different geospatial elements of the study area in different domains. Different mathematical and geometrical models have been developed/applied in the delineation procedure of the process models. While many studies mainly focus on detailed analysis on a small extent or coarse analysis on a large extent, a major objective in this study was to increase the extent of process models while maintaining a high level of detail, which was fulfilled through the efficient employment of geospatial open data and technology. This provided more detailed and comprehensive insights on the inter-relations between the elements of the study area for decision making processes on a city or national extent.

Chapter 2 developed a process model on the exploration of the impact of tree volume on the nocturnal heat island of Amsterdam. For the development of this model, tree volume from 3D models of all the individual trees in Amsterdam was calculated. While in other UHI studies, a 2D vegetation surface is applied, the employment of 3D tree volume in this study provided more accurate information on the relationship between the amount of trees and UHI. For the development of this process model, another process model, namely, sky view factor, was applied. Sky view factor, associated with heat release by urban elements, was estimated through a detailed height model for the whole of Amsterdam. Chapter 5 developed a process model exploring the impact of geospatial context on household heat demand. This research applied detailed parameters (on individual households) on the whole city of Amsterdam to investigate the relationship between the geospatial context of each household and its heat demand. These parameters were modelled through dedicated spatial data processing routines, using different mathematical algorithms and open geospatial datasets. Chapter 4 modelled the restricted areas for locating wind turbines throughout the Netherlands according to Dutch national rules based on the quantitative risk analysis of wind turbine operation on the environment. As the risk distance criteria employed depends on the wind turbine capacity, hub height and rotor diameter, different restricted areas were modelled for different wind turbine types. Upon the selection of a wind turbine type, the appropriate restricted area model is served accordingly. Furthermore, in this chapter the location and characteristics of existing wind turbines for the whole of the Netherlands were integrated in the system. This process model defines the current operation of the study area, from a wind turbine distribution point of view, which has an influence on the evaluation of the current situation as well as the positioning of new wind turbines in the area. The results of these process models are served into the system through the incorporated tiling techniques. Chapter 6 developed process models for quantitative analyses on view coverage from windows as well as roof segment shadow using a BIM model as well as 3D geospatial elements, namely, 3D building and tree models. These process models reflect the interactions between the BIM model and geospatial elements.

The development and integration of the process models, together with the employed geospatial data and visualization techniques, resulting from representation models provides an insight on the content, inter-relations and operations of the current situation. These models provide scope for the evaluation of the current situation by stakeholders through the adapted evaluation models of the planning process. Following the evaluation of the current situation, alteration scenarios are posed by stakeholders through the proposed change models.

7.1.3. Change models

Change models investigate the modality of alterations in the study area, which are determined through different scenarios. The alteration scenarios can be proposed by different stakeholders, such as designers, citizens and authorities. A multidisciplinary design platform, wherein different stakeholders from different backgrounds can interact and work collaboratively, can have a considerable impact on the competence of the alteration scenarios and the design process. The information content of the design platform is an important factor in a multidisciplinary design process, due to the presence of participants from different domains and with different insights and priorities. The interactivity of a platform can increase the stakeholders' willingness to participate in the alteration design process. The platform's responsiveness boosts the efficiency of the scenario configuration process and can lead to the conjunction in the subsequent discussion flow, regarding the proposed alterations.

In Chapters 3 and 4, interactive 3D design platforms for wind turbine site planning were developed, upon Unity game engine. The optimized 3D rendering of the game engine, as well as the interactive environment developed thereby, boosted the intuitiveness and the interactivity of the design platform. On the other hand, the incorporation of geospatial datasets and GIS functionalities enabled the rendering of existing georeferenced landscape elements and increased the extension of the platform to the whole country (as described in representation models). The feasibility of on-the-fly serving of different cloud-stored geospatial data, from different domains, through the incorporation of tiling techniques and open standard protocols, augmented the information content of the design platform, which is important for a multidisciplinary design process. Configuring alteration scenarios can be enhanced when stakeholders can design new situations on existing geospatial elements and different geospatial [thematic] information, integrated in the same design platform. The platforms' responsiveness to scenario configuration was augmented through the employment of different game engine functionalities. In addition, the systems' responsiveness to the impact assessment of the configured design is boosted through the effective integration of game engine, GIS and analytical model integration. The systems' responsiveness to these elements enabled the seamless scenario configuration and analysis in any location of the country.

7.1.4. Impact models

Configured alteration scenarios cannot be investigated irrespective of their mutual impacts on their environment. Impact models aim to explore the consequences of the posed alteration scenarios on the different domains involved. Quantitative assessments of the scenario design impacts can be performed through the employment of models. The existing challenges here are, among others, model complexity, performance speed, availability of input data, dependence on third-party software and the connection of the software to the design platform. These factors are obstacles to an iterative design and planning approach, as a core part of geodesign, where the immediate feedback on the impact of a proposed design into the evolution of the design process can result in a more efficient design process and more robust design solution (Lee et al., 2014). This study aimed to contribute to exploring solutions for the elimination of these obstacles through embedding different models into the design platform and the efficient integration of game engine and GIS functionalities for the performance enhancement of the incorporated models.

Chapter 3 has incorporated state-of-the-art sound models into the planning platform for wind turbine sound impact assessments on the surrounding buildings. In addition to sound models, Chapter 4 has embedded wind turbine shadow, visibility, generated power and wake area models to explore the multi-aspectual impacts of the configured wind turbines on their surroundings. These models were scripted into the game engine-based planning system through Unity game engine C# scripting API. The employment of different game engine functionalities, resulting from Unity physics and rendering engines, resulted in the real-time performance of these models. On the other hand, the incorporation of GIS functionalities, such as tiling techniques, enabled real-time impact assessments for any location in the country. In addition, the incorporation of cloud-stored open geospatial datasets and open standard protocols enabled the accessibility to and interoperability of the input data of these models, from different domains. Through the integration of these techniques, for the (re)placement of a wind turbine in the designed scene, all the embedded impact models will be (re)calculated real-time and on-the-fly and the results will be presented graphically and numerically in the scene. This immediate design-feedback loop interlocks the scenario configuration and discussion process of the design team. The models incorporated into the design platform and the integration of game engine and GIS techniques for their performance enhancement resulted in an enhanced system where alteration scenarios can be seamlessly configured in any location of the country and the impact assessment on the different aspects of these configured scenarios can be performed in real-time with no dependencies on third-party software. This provided scope for an intertwined discussion process between stakeholders from different disciplines which can enhance the efficiency and the results within a decision making flow.

Considering the impacts of the configured scenarios in all the involved disciplines and after several iterations through the geodesign steps, the decision team can converge on the final solution through the applied decision models. Based on the applied criteria, these models define the preferences among all the posed scenarios. The final decision can be inspired by the local knowledge as well as the illustrated impacts of the posed alteration scenarios.

7.2. Answers to the research questions

1. *How can [massive] 2D/3D open geospatial data, from different domains, be efficiently served in portraying the current spatial configuration in representation and change models?*

This study applies web services and open standard protocols for accessing different interoperable geospatial data from different domains. In addition, tiling techniques have been employed for on-the-fly serving of these massive 2D and 3D datasets on a large extent. These datasets are used in all the chapters of this study, for the depiction of the current situation in visualization platforms as well as inputs for the developed/implemented process and impact 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?*

The integration of technology from different domains, in this study, resulted in the performance enhancement of design platforms, regarding alteration scenario configuration as well as impact assessment of the different designs. The employment of game engine functionality, such as rendering engine and physics engine, supported the enhanced 3D scene rendering, interactivity and responsiveness of the design platform. The incorporation of GIS tiling techniques and open standards, in the game engine environment enhanced the extent of the design platform to the whole country and potentially even beyond that. This integration is addressed in Chapters 3 and 4.

3. *What is the benefit of 3D geospatial information on the development of process models?*

This study demonstrates the benefit of 3D geospatial information on the development of UHI as well as on the heat demand model, in Chapter 2 and Chapter 5, respectively. In Chapter 2, the impact of tree volume and sky view factor, as local factors influencing UHI was investigated. While other studies investigated the impact of vegetation on UHI through using vegetation surface, information on the volume, which is extracted though their 3D geometry, provides additional insight on their shading and evapotranspiration cooling characteristics. This provides a more comprehensive view on the impact of urban trees on UHI. Chapter 5 investigates the impact of the spatial context on the heat demand of individual households. In this research, 3D urban configuration related elements as well as building shape parameters, such as sky view factor, tree volume, building height and roof shape, showed to have influence on housing units heat demand. 3D geospatial information, therefore, plays an important role on the impact estimation of spatial context on the heat demand of individual housing units.

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

4. *What is the influence of tree volume on nocturnal Urban Heat Island (UHI)?*

Chapter 2 investigates the impact of tree volume on the nocturnal Urban Heat Island (UHI) of Amsterdam. To explore the maximum local impact of tree volume on UHI, buffers with varying radii around each temperature observation have been defined. For each buffer, the impact of aggregated tree volumes, derived from 3D tree models, on UHI was estimated through multi-linear regression analysis. Sky view factor, as another local parameter, and urbanization degree, as a regional parameter, have also been taken into account in each buffer as additional explanatory variables, along with tree volume, in the regression model. The results of this research show that the impact of tree volume on UHI achieves its maximum on the smallest buffer radius of 40 m and that in this radius an increase of 60,000 m^3 tree volume leads to one degree UHI mitigation. Based on the geometrical characteristics of trees in the study area, this volume is approximately equal to 90 small trees or 20 medium trees or 4 large trees.

5. *How do spatial context parameters affect household heat consumption?*

Chapter 5 carried out a quantitative assessment of the relationship between household heat consumption and its spatial context on a city extent and at two different scales: housing unit and postal code level. At housing unit scale, a regression analysis was performed to explore the relation between the measured heat consumption of each individual household, for the whole city of Amsterdam, with its spatial context. A set of explanatory factors that described building shape, surroundings and basic building characteristics were applied, together with the measured heat consumption, in the regression analysis. At postal code level, heat consumption measurements and explanatory factors, also containing demographic composition of the postcode areas, were aggregated and applied in a separate regression analysis. The results of this research at both scales revealed the dominance of housing unit surface area and height on heat demand. Exposed perimeters were also found to have a high positive impact on heat demand at both scales. The number of housing units per building showed a higher impact on the housing unit level compared to postal code level. The presence of a slanted roof and urbanization degree presented a comparable impact at both levels. Tree volume presented a directional impact on heat demand. Only trees northwest of a building had a significant and negative impact on household heat demand. Demographic data at the postal code level showed the impact of occupants' age classes on heat demand.

6. *How can geospatial information be efficiently extracted from data to be used as the inputs of the predictive analytics on the whole city extent and high level of detail?*

Chapters 2 and 5 address the efficient and automated detailed 2D/3D geospatial information extraction from raw data on a large extent to be applied as the inputs of the predictive analytics. Chapter 2 discussed the automated extraction of 3D tree models as well as sky view factor from 3D LIDAR point cloud. This research also described the automated extraction of urbanization degree indicator from land use maps. Chapter 5, in addition to tree volume and sky view factor, demonstrated the automated extraction of different spatial context elements for the whole city of Amsterdam. The spatial data processing routines developed in this research integrate different mathematical algorithms into GIS where massive geospatial data can be accessed and managed efficiently. The availability/accessibility of detailed open geospatial data, in combination with the employment of GIS functionalities for the efficient management of geospatial data, serve the mathematical algorithms an optimized procedure for increasing their extent and level of detail. This integration enabled the automated extraction of detailed spatial context elements on individual building level and at the same time enabled broadening the extent of this research to the whole city and even beyond that.

7. *How can BIM-GIS integration support the efficiency of construction-environment impact analyses?*

In Chapter 6, a pipeline for the automated integration of BIM and GIS is introduced. Two use cases for this integration are defined in this study: view coverage and roof shadow coverage analysis, which are related to liveability and energy domains. BIM-GIS integration supports the combination of the highly detailed geometrical and semantic information of the BIM model with the large-scale geospatial data on its environment, which provides the scope for efficient construction-environment mutual impact analysis on a large extent. This is demonstrated through the applied use cases of this research. View coverage analysis can help different stakeholders, such as urban planners and architects, to perform different analyses (e.g. house pricing) on a large extent quickly and accurately. Roof shadow coverage analysis is of great benefit in, for instance, the energy sector, where the information on a building roof (horizontal orientation, steepness angle and rooftop area) from a BIM model, in combination with the shading impact of surrounding buildings and trees can be used for calculating the gain potential of rooftop solar panels.

In conclusion, as the title suggests, a major focus of this study was "Enhancing 3D spatial analysis through efficient integration of data, models and technology". To conclude, the enhancements on 3D spatial analysis include:

- Enhancing the extent of 3D analysis

The integration of web services and tiling techniques supported the accessibility to and the processing of (massive) geospatial data on a large extent, which provided the scope for performing different 3D analyses on a large extent.

- Enhancing the performance of 3D spatial operations

The integration of Unity game engine physics engine functionalities, such as 3D Linecasting and 3D Collision Detection, with existing geospatial objects, resulted in real-time performance of 3D spatial operations. Real-time performance of 3D line-of-sight analysis, through Unity 3D Linecasting, and 3D volumetric interactions, through Unity 3D Collision Detection, are the major enhancement of 3D spatial operations in this study, which augmented the performance of different spatial analyses (e.g. wind turbine noise and shadow impact analyses).

- Enhancing the detail level of 3D analysis

The integration of BIM into GIS enabled 3D analysis on a higher detail level. This integration provides complementary information to both BIM and GIS and supports carrying out more comprehensive and efficient spatial analysis on the mutual impacts of a construction project on its environment and vice versa.

- Enhancing information content of 3D analysis

The integration of open standards and web services augmented the accessibility to different (open) geospatial data from different sources and domains and the interoperability of these datasets, which enhances the information content for different 3D analyses.

The "efficiency" in the integration of data, models and technology for the enhancement of 3D spatial analysis was boosted through the development and implementation of loosely-coupled components which were reused in the different studies of this thesis. Web service/open standard/tiling for data accessibility and interoperability, the developed geospatial routines for the processing and automated spatial context information extraction, game engine rendering engine for visualization and physics engine for simulation model performance enhancement are examples of the components which were reused in the different studies.

7.3. Considerations and future perspectives

The focus of this study was to provide new insights and methods to support environmental decision making. While energy and liveability have been chosen as main cases, the developed routines and systems are scalable to other domains that make use of geospatial components. This results, on the one hand, from the cloud storage and the employment of open standards for the developed modules which support the accessibility to and interoperability of different datasets from different disciplines, making them independent from specific data providers or domains. On the other hand, the developed routines for boosting the performance of each component are made of loosely-coupled geospatial and/or game engine functionalities which are scalable and can be adapted for the development of dedicated SDSS within different domains. The representation model routines can be applied in different SDSSs as generic components, upon which the different presented routines for process, change and impact models can be adjusted based on the required functionalities depending on the SDSS scope. The basic functionalities of representation model, for its generic application in different SDSSs, include the integration of open standards and web services for the enhanced accessibility and interoperability between different datasets of different domains, which boosts the information content, required for the involvement of different stakeholders from different domains in SDSSs. Furthermore, the applied scenario designs and alterations which are performed in change models, can be recorded and published as web services so that other applications can have access to these posed scenario designs for further analyses. While the enhanced performance of the different developed components, as presented in this study, can increase the efficiency of decision making processes in different domains, their usability and user experience should be evaluated in decision making processes.

As mentioned before, a major focus of this study was the employment of the techniques for accessibility to and integration of different open geospatial datasets from different domains which play an important role in multi-disciplinary decision making processes. While the employment of these techniques is of great importance in broadening the decision-making scope and boosting the efficiency of the data collection/presentation procedures, the differences in accuracy, scale, update and level of detail between these datasets are further challenges and should be considered in their integration. Incorporating harmonization methods for the integration of heterogeneous geospatial data, as described in different studies (von Goesseln, 2005; Butenuth et al., 2007) can contribute to overcoming this challenge.

Furthermore, integration of data from different disciplines, for instance BIM and GIS, with different objectives, information models and levels of detail, contain different geometrical and topological inconsistencies (Ohori et al., 2017). This can lead to different errors and mismatches in their conversion process. Understanding the nature and sources of these errors is an important step for their repair, aiming at improving integration. Biljecki and Tauscher (2019) constructed a framework for quality assessments of BIM and GIS interoperability. They have employed different methods and tools for error detections, such as val3dity (Ledoux, 2018) and custom

Extract-Transform-Load process. In addition to error detection, Donkers et al. (2016) presented an algorithm for automated error repair, resulting in a BIM conversion to a geometrically and semantically correct 3D GIS object. Incorporation of this error detection and repair algorithm in the framework of this study can reduce errors and mismatches between the datasets of different disciplines (BIM and GIS in this study) and enhance the multidisciplinary data integration and the subsequent analyses.

The focus of this study on the use of simulation models is their efficient integration with geospatial data and techniques for their optimized performance. These simulation models have been obtained from validated literature. However, the employment of the simulation and the developed process/impact models in actual applications should be carefully done and the applied assumptions and validations under certain circumstances should be cautiously investigated. The decision making team should be aware of the validity and applicability of these models in their case studies, considering the spatial settings and scale of their study as well as the availability and detail level of model input data.

The developed wind turbine planning system is a multidisciplinary tool which contains models for wind turbine impact analysis in different domains. While the energy yield module of this tool is a crucial factor in cost-benefit analysis, the integration of a more comprehensive cost and benefit model, including among others, investment, financing, land rent, grid power delivery, maintenance and insurance, taxes, electricity sale and subsidies (Consult, 2009) will provide a broader insight on wind turbine site planning.

Cloud computing was applied for the storage and serving geospatial data into the visualization/design platform and additionally as inputs of process and impact models. While the underlying analytical models of process and impact models employ cloud-stored data as their input, the computations are performed in the client. Implementing these models in the cloud can enhance the performance and reusability of the simulation models of SDSS.

The employed game engine in this study, Unity, has demonstrated its benefits in different studies. Multi-platform support, light rendering of 3D objects and providing variety of functions are among the outstanding features of Unity game engine, mentioned in different studies (Buyuksalih et al., 2017; Bae and Kim, 2014). In our study, Unity supported agile 3D scene rendering, and in addition, its physical simulations boosted the performance of spatial interactions. Despite the benefits of Unity game engine, there are some limitations regarding its employment in geospatial context, such as lack of explicit tools/libraries for coordinate transformations as well as format interoperability problems, as it supports limited input formats (also verified by Buyuksalih et al., 2017). In our study, the incorporation of open standards in Unity game engine environment was a solution to the latter limitation. On the comparison of Unity with other game engine, Bourhim and Cherkaoui (2018) compared the functionalities of Unity, Unreal Engine and CryEngine for fire safety training goals using a Multi-Criteria Decision Making (MCDM) method. They have applied six comparison criteria (based on Petridis et al., 2010), namely Audio Visual Fidelity, Functional Fidelity, Composability, Accessibility, Networking and Heterogeneity. Fidelity is the matching degree between the virtual and real world environment. Composability describes the reusability of created content in a game engine as well as its efficiency in importing and employing data from other sources. Accessibility refers to the support, documentation, costs and license. Networking refers to the support for large-scale communities and heterogeneity refers to the deployment support across a broad range of hardware and software platforms. Based on their results Unity acquired the highest score, indicating that it should be chosen as the optimal game engine. Šmíd (2017) compared Unity and Unreal and concluded that both Unity and Unreal are powerful game engines. Nonetheless, he mentioned some differences on the performance of these two game engines, among which is the more target platforms as well as import formats in Unity, more powerful shade generation in Unreal and better solution for foliage and terrain in Unreal. However, the latter can be added to Unity using plugins. More detailed comparison can be find in his study.

During the work on the different projects and modules, I have learned important points which can also be applicable in other studies. A major point was the significance of 3D data in the different modules of this study. 3D data was especially crucial for the extraction of spatial context, implementation of simulation models and for an enhanced perception of the environment in scenario designs. The availability of height data for the whole Netherlands (AHN) as open data provided the scope for the development and implementation of these modules on a large extent. While the availability of 3D data is of great importance, extraction of targeted information from this data enabled its applicability in the different modules. Extraction of information from massive 3D data was a complex and challenging task which required the development/implementation of different algorithms. The development of routines for efficient data processing and automated information extraction was a crucial part of this study. The proper design of these routines has a significant impact on the efficiency of the study implementation. In addition, the reusability of data in different models showed to have great impact on the efficiency of study implementation. While the same data can be the input for different models, the formatting requirement of each model can be an impediment to the efficient integration of the data in the models. Incorporation of simulation models and open standards into the study platform helped in the efficient integration of a single dataset into all the corresponding models. In addition, this opens up the scope for the inclusion of different models regardless of their formatting requirements.

The developed components and routines in this study can be applied in different developing platforms and processes. Digital transformation is an important on-going process wherein integration of technologies from different domains plays a crucial role. European Commission has defined different traits for Europe's digital future in European Digital Strategy, namely, the benefits for all people, creation of fair and competitive digital economy and an open and sustainable digital society. Europe's horizon for smart cities is an instance where innovative technologies and digitalization plays an important role on a city's prosperity and sustainability enhancement (European Commission, 2020). Digital twin of, which is a virtual representation of its physical reality, can be considered as the first step of digital transformation (Emerson, 2019) and has recently gained popularity in different domains. Amsterdam Smart City[37] is one of the platforms where digital twin plays an important role in providing the spatial and functional picture to the involved stakeholders (such as citizens, knowledge institutes and public authorities) for designing the future city. Two major components of a digital twin

[37] https://amsterdamsmartcity.com/network/amsterdam-smart-city

comprise of data and process models. The Smart City Operating System collect massive [geospatial] data from different resources and should in real-time extract information from them to depict the situational picture to the stakeholders. From 2017, Municipality of Rotterdam works on Digital City program wherein researches have been carried out to explore the form of the future city. In the framework of this program an Open Urban Platform is being developed through which data from different sources and domains can be shared among different stakeholders and new applications and services can be developed. The core of this platform is formed through the digital twin of the city, which depicts the current picture upon which new applications and services can be developed. Sharing data among different stakeholders via open standards, enables the better handling of more complex questions and decisions makings (Gemeente Rotterdam, 2020). These platforms emphasize on the incorporation of open standards for the integration of geospatial data from different sources. Furthermore, efficient serving of massive geospatial data in these platforms is of great importance for the digital twin of a dynamic urban environment. In addition, the integration of process and impact models into these platforms enables them to depict the functional picture of the urban area to the different stakeholders, which helps in different decision makings in the city. Regarding these attributes, the developed modules of this study can be applicable in different segments of these platforms, from techniques for massive geospatial data integration based on open standards, to enhanced visualization platforms to the large scale developed process models and efficient implementation of impact models. The scalability of the developed modules in this study enables their supple employment in such platforms.