Delft University of Technology
Faculty of Architecture
and the Built Environment

MSc thesis in Geomatics for the Built Environment

Testing and extension of a GIS-supported design tool for new urban development areas

Case study: Sloterdijk I, Amsterdam

"integration of 3D city models into the urban planning process"

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MSc thesis in Geomatics for the Built Environment
By

DOAN Truc Quynh

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List of abbreviations

ADE	Application Domain Extension
AHN3	Actueel Hoogtebestand Nederland
BAG	Basisregistratie Adressen en Gebouwen
BGT	Basisregistratie Grootschalige Topografie
CBS	Centraal Bureau voor de Statistiek
DSM	Digital Surface Model
DTM	Digital Terrain Model
FAR	Floor Area Ratio
FME	Feature Manipulation Engine
GIS	Geographic Information System
GML	Geography Markup Language
KPIs	Key Performance Indices
LOD	Level of Detail
MFH	Multi-Family House
nDSM	Normalized Digital Surface Model
OGC	Open Geospatial Consortium
PPGIS	Public Participation GIS
SFH	Single-Family house
SLQ	Structured Query Language
UML	Unified Modelling Language

Abstract

The emergence of spatial data, GIS-supported tools, web mapping technologies has opened up many applications for more inclusive spatial planning, and spatial decision support approaches. On the one hand, the site analysis is strongly supported by spatial data analysis in both 2D and 3D, which offers a more comprehensive understanding of urban settings. On the other hand, 3D city modeling and 3D web technologies not only help visualize design scenarios but also promote communication among the stakeholders for better decision-making. These functions correspond to the pre-design and the post-design stage of an urban development project. The intermediate stage that deals with the design solution and design evaluation, however, is still not widely supported.

Hence, the first version of a GIS-supported design tool for new urban development areas was developed in a previous study, which, for the sake of simplicity, we refer to in this master thesis as the "Buurt Generator". The tool works with the data context in the Netherlands to assist the realization of the 3D models of urban development projects in an interactive computer environment. In the "Buurt Generator", the pre-design stage was based on the semantic 3D city model at a fixed period with different spatial-related urban KPIs that are all stored in the 3D City Database. Template neighborhoods that match the development goals of the new urban development project were then selected to extract design KPIs for the project. The design KPIs, together with the development goals of the sites, form the basis and guidelines for generating different scenarios in the design stage. The scenarios are then integrated back into the 3D city model and visualized in 3D and are disseminated via web platforms.

This thesis aims to test, critically review, and propose extensions and improvements for the "Buurt Generator". It will start with a general review of the current tool and literature reviews on related concepts and technologies. Then, the thesis investigates the accuracy of the generated 3D City model in estimating buildings' volumes. Since volumetric measurements play a critical role in deriving urban KPIs and design KPIs, their accuracy is highly concerned. For that, a volumetric comparison approach with other existing 3D city models is employed. The second focus of the thesis will be on the expansion of urban KPIs and design KPIs. The work bases on a data-driven approach that considers spatial and non-spatial, volumetric, and non-volumetric urban parameters. Moreover, instead of developing design KPIs from template neighborhoods, the thesis proposes a comprehensive understanding of the city context and the project site based on available data. Then, it would be the task of the urban practitioners to reason the design KPIs for the new urban development project. The third focus of the thesis is to develop a framework to study the impacts of the design solutions on the urban tissue. The framework is developed chiefly based on integrating the design into the 3D city model to perform (spatial) analysis. One of the energy-related criteria from the framework – the solar radiation factor - is chosen for further elaboration.

The thesis, as a result, contributes to the further integration of 3D city models into the urban planning process and explores its possibilities in assisting urban practices. Firstly, it confirms the usability of the generated 3D model in estimating buildings' volumes, except for some specific cases of very tiny and very large building footprints. Secondly, it expands the list of urban KPIs and assists the information query to understand the city context and extract specific information. Thirdly, it bridges 3D City Database and Grasshopper for post-assessment of designs regarding solar radiation and opens the way for other urban simulations.

Acknowledgments

I would like to express my special thanks of gratitude to my supervisors Giorgio Agugiaro and Roberto Cavallo. They gave me the opportunities to work on their ongoing research on the topic “GIS-supported design tool for new urban development areas” and offer me consistent support and guidance during the run of my thesis.

I would like to thank Garcia González for initiating an interesting research approach in his master thesis entitled “An interactive design tool for urban planning using the size of the living space as unit of measurement ”, which later became the base for the development of the GIS-supported design tool for new urban development areas. He also provides me with theoretical and technical advice at different stages of my work. I would like to thank Victor Muñoz Sanz – the co-reader of my thesis – for the fruitful comments. I would also like to thank Ana Petrović for her advice in accessing different data resources and Camilo León Sánchez for his support in working with data in the first stage of my thesis.

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1 Introduction

1.1. Research statements

Spatial development is a complex decision-making process and regulatory procedure that involves developing strategies and spatial solutions embedding with policies, institutional and participatory mechanisms. Through planning activities, development goals are wished to be achieved (UN-Habitat, 2015). The process is assisted by various tools and techniques, ranging from conventional qualitative and artistic approaches to nowadays (geographical) data-driven and decision support system approaches. Among those, the geographic information system (GIS), both in 2D and 3D, has been continuously proving its crucial role in understanding the urban context, providing spatial solutions, visualization, and informing the stakeholders. The 2D GIS approach has been dominating the field of urban planning applications since the 1990s. Still, it has later been questioned about its effectiveness as urban itself is a 3D entity with 3D-related issues (e.g., shadow, viewshed, shape, etc.). Thus, various attempts in introducing 3D geo-visualization in urban planning applications have been made to be used in parallel with 2D GIS, as not all tasks are required to be in 3D or are feasible in 3D. There are also many attempts to expand the usability of 3D GIS from solely visualization to spatial analysis and decision making (Ahmed and Sekar, 2015; Herbert and Chen, 2015).

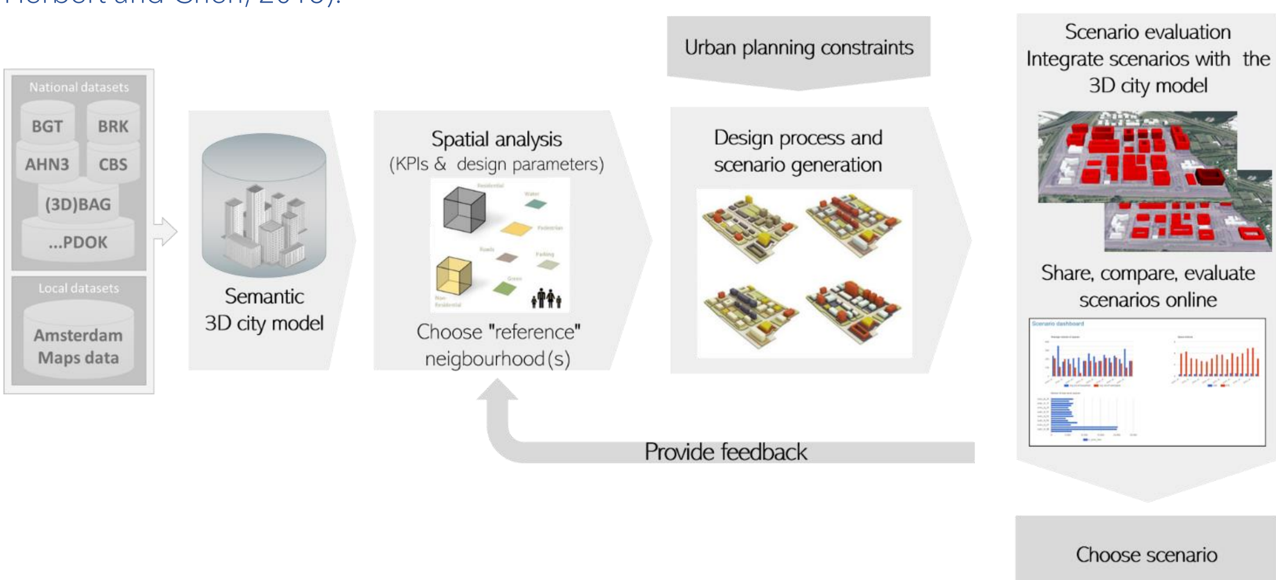


Figure 1 Overview of the GIS-supported design tool (aka the "Buurt Generator")

In a previous study by (Agugiaro et al., 2020), a GIS-supported design tool (from now on called the "Buurt Generator" for the sake of simplicity) was developed to assist the design of a new urban development project. The tool originally comprises a self-generated semantic 3D city model of today, a selection of input KPIs for the new development areas, and semi-auto generated 3D scenarios for the new development to be integrated into the 3D city model of today. All the related data and information are uniformly stored in a 3D database and could be disseminated via web platforms employing CityGML, 3D City Database (in short 3DCityDB), and CesiumJS. The first and second components of the tool correspond with the pre-design stage of an urban development project, where contextual information is gathered, generalized, and analyzed. The third component, which is the generations of scenarios, corresponds with the design stage. This component allows a fast generation of design options according to input parameters. Lastly, the dissemination via web platforms partly supports the post-design stage, where the design solution is shared among the stakeholders for evaluation and decision making. The tool adheres to the trend in integrating 3D GIS into the urban planning process, with an emphasis on the volumetric input KPIs for the design stage. The tool is developed based on the data context of the city of Amsterdam, the Netherlands. The new urban development site as a case study is located at Sloterdijk I, an industrial cluster within the Haven-stad area.

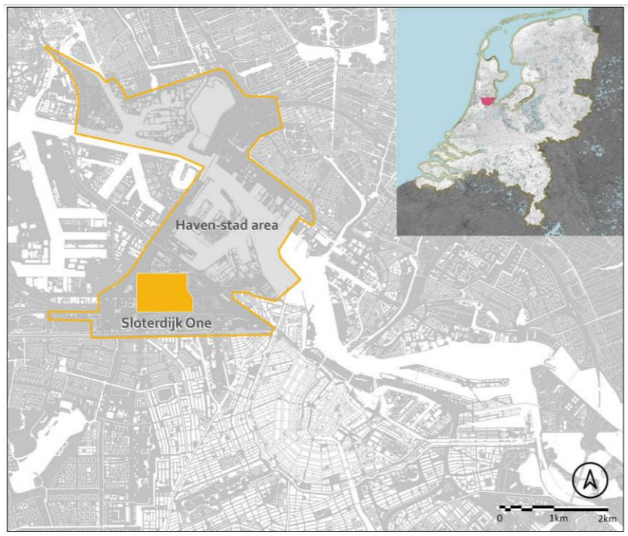


Figure 2 The case study - Sloterdijk I, Amsterdam (Agugiaro et al., 2020)

As also mentioned by (Agugiaro et al., 2020), the first version of the tool has some limitations conceptually and technically, paving the path for further development in the rather long term. This thesis, as a result, attempts to contribute to the tool development by testing and expanding some of its functionalities; the thesis employs the same case study with the previous work for continuity reasons. In terms of testing, the whole concept of the tool through the lens of urban planning is first reviewed. Then, the basic component of the tool, which is the 3D city model of today, is checked in terms of its accuracy since the model is used to analyze the urban context and generate design KPIs in the latter steps. After that, the list of input design KPIs is expanded by considering different spatial and non-spatial, volumetric, and non-volumetric urban indicators from the existing data context in the Netherlands. Lastly, the research focuses on expanding the functionalities of 3D GIS in the post-design stage.

1.2. Research questions

According to the research statement, three research questions are generated to guide the thesis as follows:

[Question 1] How accurate the 3D model is in estimating the residential and non-residential volumes within the city?

[Question 2] What key performance indices could be introduced as new inputs for the design stage of the tools? How to develop them in the pre-design stage?

[Question 3] In which aspects the developed scenarios could be evaluated in the post-design stage? How to utilize the 3D models of the scenarios, the 3D city models, and other spatial data for the evaluation?

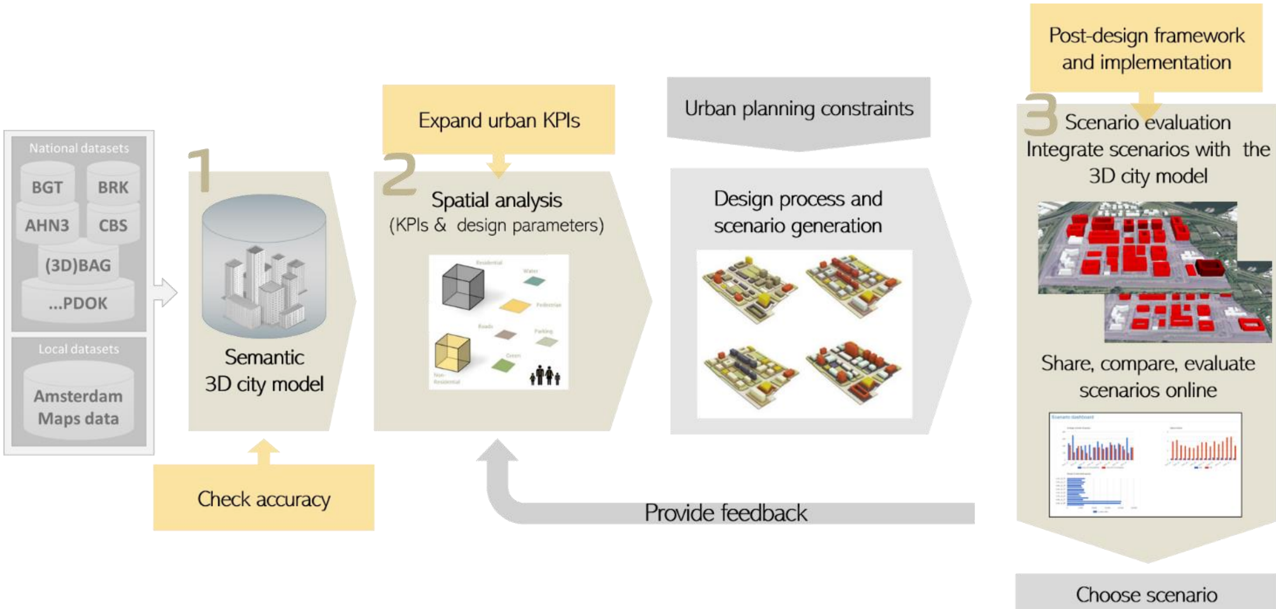


Figure 3 The research questions/objectives highlighted in yellow within the current "Buurt Generator" methodology

The research questions are highlighted in yellow in the overall framework of the "Buurt Generator" approach, in order to better visualize where this thesis places itself in terms of topics investigated and contribution to further development. Please observe that the research questions do not cover the design stage of the "Buurt Generator", where the design process takes place and different scenarios are generated. The third research question on the post-design evaluation will be based on the scenarios generated in the previous works.

1.3. Research methodologies

The research methodology is designed and elaborated according to each of the above research questions. In this part, three approaches to the three research questions are presented.

Figure 4 The research methodologies in one image

[1] The accuracy of the generated 3D model regarding volume estimation

As previously mentioned, a new 3D city model (in LOD1) was generated from scratch to derive the volume of every building in Amsterdam since the existing models show limitations in quality (Agugiaro et al., 2020). Meanwhile, a countrywide 3D model is being developed by the Dutch Kadaster in collaborating with the 3D Geoinformation research group at TU Delft. The model is delivered in several levels of details (LODs), namely LOD1.2, LOD1.3, and LOD2.2, as a refinement of the original CityGML standard LODs (Dukai et al., 2020).

Since the building's volume is one of the bases to derive the input KPIs for the design stage, it is essential to assess the accuracy of the volume used in the tool to prevent error propagation in the later steps. Hence, a comparison is carried out between the enclosed volumes of the buildings obtained from the different techniques. The statistical and spatial distribution of the volume differences between the model would reveal the comparative accuracy of the volumes among themselves. Furthermore, the visualization of some cases (in different models) would also help determine the possible conceptual or technical errors of the approaches.

[2] Key performance indices (KPIs) as inputs for the design stage

The goal is to search and generate a comprehensive structure of urban-related spatial and non-spatial data in the Netherlands in general and Amsterdam in particular. Spatial and thematic data are classified according to different urban planning fields (e.g., housing, technical infrastructure, social infrastructure, social-economic status, etc.). Then, specific domains are selected to be investigated and elaborated in terms of their spatial relationship with other data components. Moreover, in order to uniformly and comparatively assess the spatial and non-spatial datasets that are available at the neighborhood level ("buurt" in Dutch) of different size, most of the data are translated to physical density measurements (e.g., the average volume of healthcare facilities per person per neighborhood, the average volume of dwelling unit of the multi-family house per neighborhood). Different spatial tools will be employed, including FME, PostgreSQL for data manipulation, and QGIS for spatial analysis and visualization.

The spatial information derived from the datasets will be the basis to select input KPIs for the design stage of the tool. The idea of the "Buurt Generator" is to assist urban practitioners in comprehensively understand the urban development context employing data ready to be queried and visualized for further urban innovation and decision making. Hence, the tool itself would not provide a solid solution (or input KPIs) for the new urban development project but only the possibilities for different development scenarios that urban practitioners and decision-makers can choose from.

[3] Evaluation of design scenarios in the post-design stage

Evaluation of design scenarios is based on development goals from the municipalities or/and investors, who have different priorities. Theoretically, they can be evaluated based on some urban development trends (e.g., livability, sustainability, etc.). Practically, they can be assessed according to some existing evaluation tools based on the framework of sustainability or focus on some specific urban aspects.

By integrating the design scenario back to the sematic 3D city model of the City of today, the "Buurt Generator", hence, can also enable the possibility to evaluate the impacts of the design to the urban context, to store the information in the database, and to visualize it in the web platform. The assessment framework is developed based on literature and is evaluated based on technical and data availability. However, due to the time scope of the thesis, only one criterion is selected to be elaborated in detail. Different spatial analysis tools will be employed, including FME, PostgreSQL, Rhino/Grasshopper, and its extensions LadyBug. The impact assessment at this stage helps to compare the scenarios and acts as a guideline for the subsequent elaboration of urban design to cope with the negative impacts of the physical arrangement.

1.4. Structure of the report

The thesis report is structured into six chapters. The introduction chapter gives an overview of the research statements, research questions, and research methodologies. Then, the second chapter reviews the GIS-supported design tool (the "Buurt Generator") through the lens of urban planning. The chapter also studies the current concept and trend in urban planning, focusing on geospatial data and technologies. The third chapter addresses the accuracy of the generated 3D city model. Chapter 4 introduces a structure of spatial and non-spatial urban data to assist the generation of input KPIs in designing a new urban development project. After that, Chapter 5 presents a post-evaluation framework for the design solutions based on integrating the scenario in 3D back into the 3D city model of today. Then, the conclusion chapter summarizes and discusses the research results and future developments for the "Buurt Generator".

2 The "Buurt Generator" review and literature review on urban planning concepts employing (3D) GIS

2.1. The "Buurt Generator"

In this part, the GIS-supported design tool (the "Buurt Generator") is reviewed in detail to understand the package and to identify gaps and opportunities to further develop the tool. Firstly, the overview on the components and the stages of the tool are presented. Secondly, the functionalities of the tool are reviewed through the lens of urban planning.

2.1.1. Overview

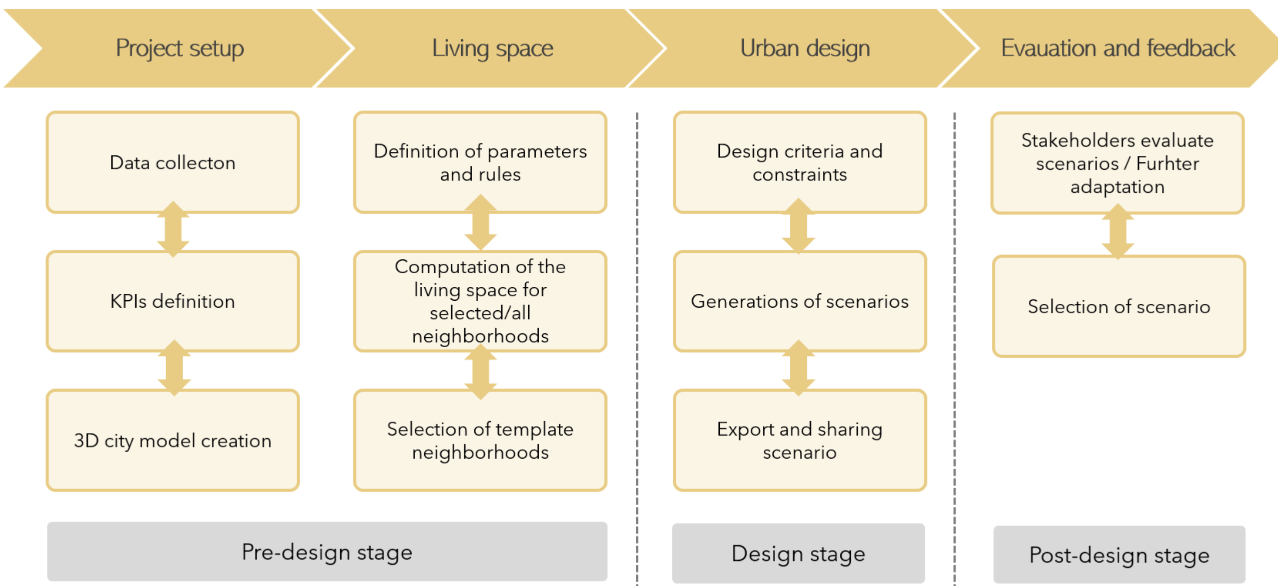


Figure 5 The "Buurt Generator" in one image – schema adapted from (Agugiaro et al., 2020)

The "Buurt Generator" is composed of three main stages, a) the pre-design stage, b) the development of design solutions (scenarios) – the design stage, and c) the visualization and dissemination of scenarios – the post-design stage. These three components are carried out in different working environments, making them the three sub-products of the GIS-supported design tool.

The pre-design stage first collects all information related to the urban context and the development site and arranges them in a (geo)database. The KPIs are then defined according to the urban fabric and the development requirements from the authorities, then are extracted from the database. Those include the Percentage of Residential Area Index, the Average Neighborhood Density Index (as the number of households per neighborhood area), the Age of Building Stock Index (as the average year of construction), the Quality-of-Life Index, and the Socio-economic Level Index (as the average price of residential construction). The value of the KPIs is set according to the development goal of the project area (for example, the average neighborhood density should be greater than 110 households/ha). Then, neighborhoods that met the KPIs are selected as templates for the new development. Eventually, some volumetric and non-volumetric parameters are extracted and are used in the design/3D generation of different scenarios for the development site.

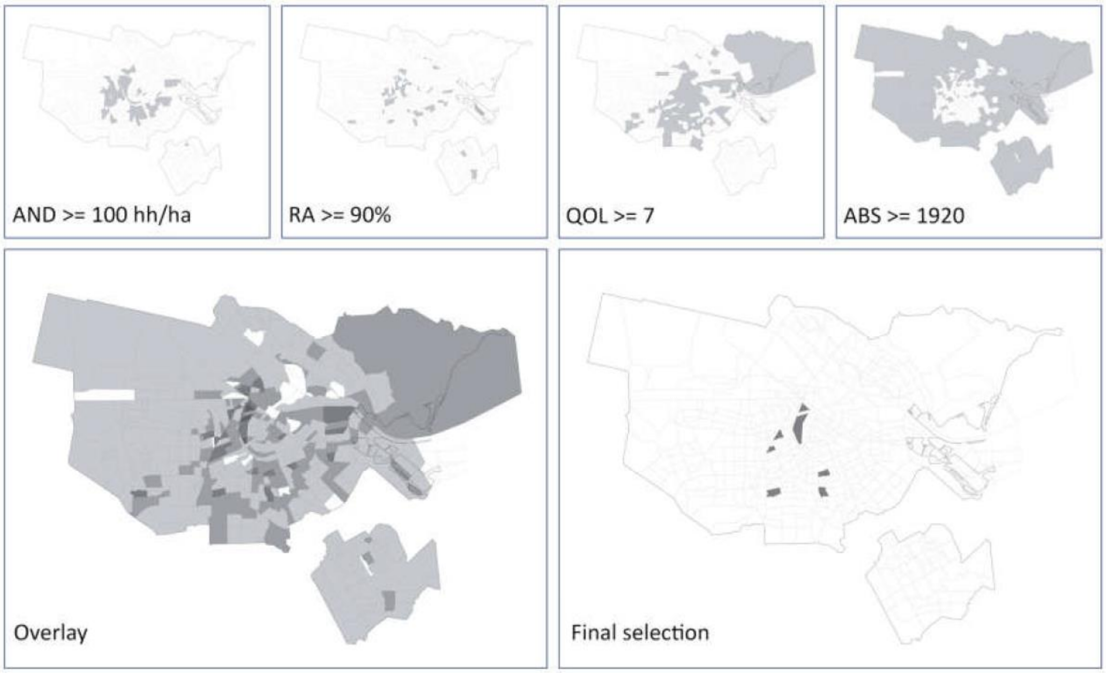


Figure 6 Selection of template neighborhoods based on the KPIs (Agugiaro et al., 2020) (AND Average neighborhood density, RA Percentage of the residential area, QLO: Quality of life, ABS: Average Building Stock)

Then, urban parameters are extracted from the template neighborhoods to be applied to the development site, particularly the average volumetric dwelling size and the average volumetric non-residential space per household, and outdoor space (in square meter) per household (green space, road, foot bath, and bike path). Volumetric parameters are derived from a 3D City model that is generated within the package of the "Buurt Generator". Most of the steps in the–design stage is carried out using FME, PostgreSQL, and 3DCityDB.

After that, in the design stage, a script is created in Rhino/Grasshopper that takes the extracted urban parameters, the pre-defined land use arrangement, and the street network as inputs to generate different 3D scenarios for the new development site. The script also considers the guidelines and constraints from the planning and building regulations applied for the area. The 3D models of the scenarios are written to the database in a different schema but still employ the 3DCityDB structure.

In the post-design stage, the 3D web map client based on Cesium JS (which is included in the 3DCityDB product package) is used to visualize and disseminate the development scenarios in a web interface. Apart from 3D visualization, output parameters from the design are also presented in the form of dashboards in the web interface. Hence, the project's stakeholders and decision-makers will be informed about the scenarios in 3D and their outcomes in an interactive environment.

2.1.2. Review the functionalities of the tool through the lens of urban planning

The tool is then reviewed according to its function, the target users, the pre-design stage, the design stage, and the post-design stage.

[1] Function: The tool is designed mainly for small-scale urban development projects in cities where specific open datasets are available, in this case, Amsterdam and potentially other Dutch cities.

[2] The users: Apart from knowledge in urban planning, the tool requires different expertise from the users that not all urban planners are qualified of but a team of different qualifications (e.g., geomatics), and with a rather complex knowledge exchange process.
Moreover, the product interface does not allow the proactive participation of stakeholders of different backgrounds throughout the planning process. It is limited to the visualization of scenarios with dashboards of output parameters in a web interface in the post-design stage.

[3] The Pre-design stage:
Since the calculation of the average volumetric size of the dwelling and non-residential volumetric space per household from template neighborhoods within the city to be used as KPIs, some concerns are raised as follows:

- As the calculated KPIs heavily depend on the generated 3D City model and its derived volumes, the accuracy of the volume estimation plays a major role.
- The demographical context and so the household structure is, in fact, continuously changing. The household sizes are more and more diverse, with the rise of single and small households. The distribution of household sizes across cities also varies. The average household density, hence, does not fully reflect the status of the template neighborhoods. There could be one neighborhood having a more significant number of households but with a relatively small average household size due to the large share of single households.
- The development patterns are different according to different development periods due to the socio-economic context and available building technologies. Hence, the threshold of 1920 for choosing template neighborhoods is questioning.
- As urban development projects should promote integration and inclusiveness, there should be a mix of different types of housing (social housing and commercial housing) and housing sizes (single housing, family housing). The tool could include inputs for these parameters (for example, as a percentage) instead of average dwelling size in general.
- Non-residential functions consist of social infrastructure buildings, commercial buildings, office buildings, or mixed-used buildings, essential or non-essential that should be treated separately.
- The pre-design step does not consider the context of the surrounding/neighboring areas and the context of the development site itself (e.g., existing buildings, landscape) but mainly relies on similar urban areas within cities. For example, the proximity to a transportation hub can affect the built-up density and the local economic arrangements of the project site. The location of the transportation station can also affect the function of its adjacent buildings. Another example is the non-residential functions of the surrounding. If they have lacked accessibilities to some functions, the new development area could consider providing more services. If not, the new area could benefit from the surroundings.
- The quality of life is a complex measurement that comprises criteria from objective to subjective measures and from different urban aspects (objective quantitative parameters in

case of the Leefbarometer used in the tool[1]). Areas that have similar quality of life indices do not necessarily share the same urban context. The quality of life and the housing price might also be the results of the surrounding context (e.g., the transportation system, accessibility to leisure activities, social infrastructure, urban parks). They might not be dealing with the physical components of the subjects themselves.
- As a result, the development context of the whole city and the project site itself should be comprehensively addressed before defining and extracting development parameters for the project.

[4] The design stage:

The built-in options and constraints within the Grasshopper script can still be further developed, for examples:
- Incorporate land use plan and other regulatory frameworks from the city;
- Setbacks at the ground floor and upper floors based on the width/type of the streets;
- Plot subdivision options with a constraint on a minimum area, number of buildings per plot with constraints based on the size of the plots, etc.
- Subdivisions of building functions;
- Building types: row house, semi-detached house, detached house, low-rise building, high-rise building, unique designs, building types for non-residential functions;
- Integration of other urban components (greenery, urban furniture).

[5] Outputs, visualizations, and disseminations:

The expansion of input KPIs can also expand the list of output parameters. Furthermore, incorporating the scenario 3D model into the 3D City model also enables the opportunities to investigate the impact (environmental, visual, etc.) of the design on the surrounding building environment. As the output is a 3D model, further visualization options could be included, such as shadows and sections.

The dissemination of design scenarios via the web interface also opens up integrating the public participation GIS (PPGIS) component into the tool package. Hence, stakeholders, including the broad public, can give opinions about the new development directly on the 3D model or through the questionnaire on the project's website.

Lastly, the tool is currently operated in different software and interfaces simultaneously and requires users with diverse expertise. To optimize the use of the tool, a unique product interface (probably web-based) could be developed that links all stages of an urban development project.

2.2. Urban planning concept and (3D) GIS

In this part, the general concept of urban planning and urban design are introduced to give an overview of how the "Buurt Generator" fits the demand from urban practices. Then, the thesis reviewed the concept of urban density and its applicability in deriving KPIs. After that, concepts and technologies relating to GIS-supported urban planning tools are introduced.

2.2.1. Urban planning / Urban design

Spatial development is a complex decision-making process and regulatory procedure that involves developing strategies and spatial solutions embedding with policies, institutional and participatory mechanisms. Through planning activities, development goals are wished to be achieved. These

[1] https://www.leefbaarometer.nl/page/indicatoren

goals vary according to the planning levels, from large scales (country, regional scales) to smaller scales – (city, local scales). Urban planning is attached to spatial planning from the city level onwards. For each country, the hierarchy, the term, and the approach might be different. However, urban planning levels can be generally classified into the city level, municipal, and neighborhood level. The focus at the neighborhood level is to improve urban quality, social cohesion and inclusion, protection of local resources, spatial integration and connectivity, human security and resilience, local democracy, and social accountability (UN-Habitat, 2015). Thus, approaches in urban planning/urban design have been continuously developed to meet the development goals, from the process/procedure to tools, notably computer/GIS-based tools.

Urban design does not have a universal process and evolves over time. From a quantitative-based approach done mainly by planners and rational decision-makers, the urban design process now also involves qualitative data from stakeholders, especially the communities, at every stage. According to (Boyko et al., 2006), although there are many varieties, the urban design process can be simplified into four stages: (1) Creating teams, appraising the situation and forming goals, (2) Designing and developing, (3) Evaluating, selecting and creating a plan, (4) Implementing, monitoring and following up; and four transition stages: (1-2) continuing to understand the context, (2-3) continuing to think about alternatives, (3-4) re-creating a plan, and (4-) continuing the process. The current tool, however, covers only the first two steps of the urban design process, with the possibility to expand towards the third step in evaluating and selecting development scenarios. The "Buurt Generator", as presented above, currently assists the first two stages of the process and one part of the third stage.

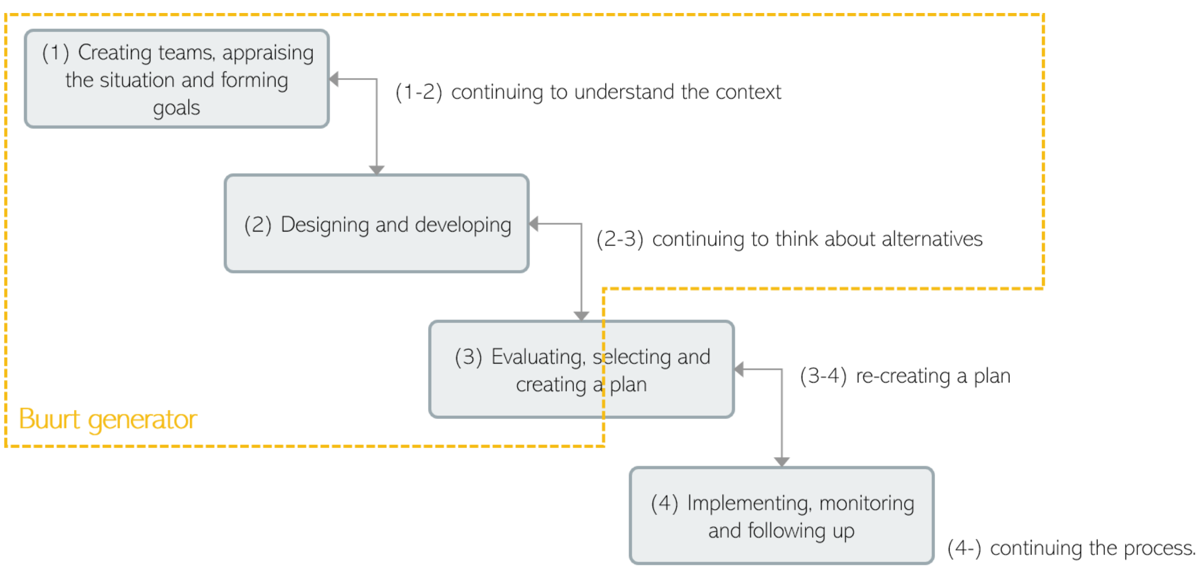


Figure 7 Urban design process according to (Boyko and Cooper, 2011)

2.2.2. Urban density

Urban density is a complex term that has been associated with urban development in all dimensions. It is differentiated into physical density and perceived density (not treated here). Physical density is a quantitative numerical measure of the concentration of people and infrastructure in a given geographical unit and is purely determined by objective spatial-related indicators. In practice, a number of people or households in a given unit or the ratio of floor area in a given land area is most renowned for representing density (Cheng, 2010). It usually serves as an instrument for urban planners, urban designers, architects, and engineers to design and access the performance of subdivision plans. The decision made on physical density is, moreover, a critical issue when dealing with the technical and financial assessment towards efficiency (Acioly Jr. and Davidson, 1996).

Regarding its role in urban development, urban density is, on the one hand, a prescription tool to guide future urban development activities. Different measurements of urban density are included in the master plan, in bulk control, and other development guidelines were attempting to ensure the housing provision, the infrastructure system capacity, the environmental and economic wellness, and the quality of life of the residents (Acioly Jr. and Davidson, 1996). On the other hand, it is a description tool to understand cities at different scales and in various aspects such as the urban form and urban morphology (Alexander, 1993; Alexander et al., 1988; Berghauser Pont and Haupt, 2009; Dovey and Pafka, 2014), the economic efficiency and the environmental impacts of urban mobilities (Boyko and Cooper, 2011; Churchman, 1999; Grazi et al., 2008; Larivière and Lafrance, 1999; Levinson and Wynn, 1963; Liddle, 2013; Marshall et al., 2005; Mindali et al., 2004; Newman and Kenworthy, 1989; Norman et al., 2006; Steemers, 2003), the effectiveness of the infrastructure and the built environment (Acioly Jr. and Davidson, 1996; Boyko and Cooper, 2011; Churchman, 1999; Coutts et al., 2007; Darabi et al., 2019; Perini and Magliocco, 2014; Skinner, 2006; Steemers, 2003; Strømann-Andersen and Sattrup, 2011), the urban vitality and creativeness (Boyko and Cooper, 2011; Carlino et al., 2007; Churchman, 1999; Couture, 2016; Glaeser and Resseger, 2009; Jacobs-Crisioni et al., 2014), and the physical and mental wellness of human being (Boyko and Cooper, 2011; Churchman, 1999). Focusing on urban form and urban morphology, urban density was assessed for its importance to planning, urban design and architecture, and the study of urban morphology. It is claimed that a set of different urban density measures helps to characterize the form of urban areas and the development pattern of cities more precisely than single measurements (Alexander, 1993; Alexander et al., 1988; Berghauser Pont and Haupt, 2009; Dovey and Pafka, 2014). The development of the concept is related to expanding physical density measurements (from built density measurements to people density measurements). As a result, to develop a framework of indicators for new urban development projects, different aspects, and levels of urban density could be considered to meet the development goals of the area.

As for the scope of the GIS-supported design tool, physical density at the building/plot and neighborhood levels could be a good starting point to first understand the urban context, and second, to derive KPIs for new urban development projects. As stated above, a single urban measurement could not speak for the development status and the unique spatial characteristic of different urban areas, but the combination of them. On the one hand, the explanatory power of urban density can be used to understand the urban context comprehensively and comparatively. For example, the dwelling density can be accompanied by building density (number of buildings per area unit), ratio volume to area, or population density to know whether the area is crowded or physically dense or both. On the other hand, urban density can be used to prescribe inputs for the semi-auto generation of 3D models of the scenarios in the design stage (e.g., the average volume per dwelling and average non-residential volume per dwelling used in the current tool).

2.2.3. GIS-supported urban planning tools

[1] CityGML and 3DCityDB

The OGC standard CityGML is an open data model and XML-based data exchange format for virtual 3D city models. The model not only allows to describe 3D objects in different levels of details (LOD) but also their spatial and non-spatial attributes, and their (hierarchical) relations (Yao et al., 2018). For more than one decade, the issuance of CityGML has introduced many applications in urban modeling and has contributed to the development of the data-driven/computer-aided approaches in urban practices, from visualization to analysis purposes. In recent years, the development of the Application Domain Extension (ADE) (a built mechanism of CityGML to enrich the data model with new feature classes and attributes for particular use cases) has also extended the use of CityGML for many applications in the urban development field. (Akahoshi et al., 2020) presents the concept of a CityGML ADE for urban planning, which is the core of the information infrastructure "i-Urban Revitalization" of the Japanese Government as an attempt towards sustainable urban development. The concept added two new levels of detail (LOD0 and LOD-1) to manage spatial and non-spatial information at the city, regional and national levels (in the form of grid cell). Thus, the feature statistical grid is added to hold other features, such as population and accessibility indicators. The urban function feature was also added to CityObject, which introduces parameters according to the planning framework in Japan. Moreover, (Sindram and Kolbe, 2014) introduce the concept of modeling urban actions to assist the planner in comparing the outcome (impact) of different actions applied to the current city model. These extensions shorten the gap between the conceptual model and the urban planning practices in the real world.

Since a 3D city model could be extensive and complex at the city scale, database solutions for CityGML have been primarily offered to manage, analyze, and visualize large datasets. The thesis focuses only on the 3DCityDB solution, as it has been used within the "Buurt Generator". 3DCityDB is a free and open-source database solution, developed based on a relational database schema, and are currently supported the data storing procedure for two spatial relational database management systems – SRDBMS (commercial SRDBMS Oracle Spatial/Locator and open-source SRDBMS PostgreSQL). It enables the creating of citydb schema in the SRDBMS, the importing/exporting of CityGML to/from SRDBMS (with/without ADEs), the generating of generating 3D visualization models, and also the dissemination of semantic 3D models via CesiumJS based web map client. 3DCityDB has been widely used worldwide in many urban applications. It is also adapted and expanded in some products (e.g., VirtualcitySuite, novaFACTORY, etc.) (Yao et al., 2018).

The "Buurt Generator" is currently built upon CityGML and 3DCityDB. As for the pre-design stage, the semantic 3D model of Amsterdam was generated in the CityGML format and was stored in 3DCityDB along with many spatial and non-spatial attributes. Hence, queries of different urban information at different scales and levels of details are fully supported. As for the post-design stage, the designed scenarios generated in Rhino/Grasshopper were translated to CityGML format (using FME) and were stored back in the 3DCityDB for calculating output parameters and for visualization of different design options via 3D web map. The "Buurt Generator" could be developed further with the help of CityGML, its extensions and the 3DCityDB to assist the integration of design scenarios of new urban development into the existing city model to examine the impact and the benefit the scenario brings, not only at the local scale but also the city scale.

[2] Public participation GIS (PPGIS)

The term PPGIS was first introduced in the 1990s at the meeting of the National Center for Geographic Information and Analysis (NCGIA) in the US. The concept aims to promote participation from different stakeholders in the spatial decision-making process through GIS. In recent years, the emergence of geospatial web technologies, the growing numbers of people using online map services (e.g., Google Maps, Open Street Maps), and the availability of open spatial data have promoted the use of PPGIS. Internet-based PPGIS, hence, is now actively developed that enables a more significant number of participants and a wider variety of approaches to promote community involvement in knowledge production (Babelon et al., 2017; Butt and Li, 2012; Zhao and Coleman, 2006). PPGIS was defined as a "field within geographic information science that focuses on ways the public uses various forms of geospatial technologies to participate in public processes, such as mapping and decision making" (Tulloch, 2008).

There are now two approaches to online PPGIS. On the one hand, the public can voluntarily raise ideas/problems on different spatially related issues in a web map platform that provides based maps of cities (e.g., Debatomap, Community Maps). On the other hand, the public can be asked for opinions about a specific predefined project, with or without questionnaires (e.g., Maptionnaire, Bentley's OpenCities Planner). The soft local knowledge can be in the form of spatial features (point, line, polygon, 3D objects), descriptive text, or other types of interactions (like/dislike, ranking).

In brief, the evolution of PPGIS and web-based PPGIS promotes a new trend of stakeholders and broad public participation in many steps of the urban planning and design process via web-based platforms. This function can be incorporated with the GIS-supported design tool for urban development.

[3] ESRI ArcGIS Urban

One of the most notable computer-based/web-based commercial planning products is ESRI's ArcGIS Urban[2], which is first launched in 2019. The product is embedded in ArcGIS Online, a web-based solution to support urban development activities, from land use planning, zoning to the development project. The product assists (1) the creation of plans, (2) the impact assessment of plans, (3) data management, (4) the 3D visualization of plans and projects, and (5) the engagement of the public in the planning process.

Regarding the first function, the user can create multiple scenarios for zoning and land use plans with the "Plan editor" or draw buildings and create a 3D scene with the "Project Editor". The "Project Editor" has a similar approach to the GIS-supported design tool. The user can create and edit 3D geometries (e.g., buildings) and enrich the scenario with different ground types, trees, street furniture, and vehicles. The interoperability with City Engine also allows the user to enhance the scene even more with design details.

Once the plan/project is generalized, the capacity indicators can be found in the dashboard to probable the impacts by comparing the design with the existing conditions or other scenarios. The product provides a list of capacity indicators and also allows the user to customize other indicators. The indicators are differentiated to existing and target indicators to evaluate the scenarios:

First-order indicators (both existing and target indicators)	▪ Population ▪ Household ▪ Jobs ▪ Parking spots
Second-order indicators (derived from different studies based on data in the US)	▪ Required parking spots ▪ Daily trips ▪ Energy used

[2] https://www.esri.com/en-us/arcgis/products/arcgis-urban/overview

	▪ Greenhouse gas emissions ▪ Internal/external water use ▪ Wastewater / solid waste

Table 1 Output parameters - ArcGIS Urban

The data manager function, on the other hand, allows the user to import data to the urban model and configure the settings. For the last two functions, a stakeholder without a license can access the overview of the city and the project with different viewing options (e.g., with or without shadows) and provide feedback on the plans and development projects (ESRI, n.d.). The product supports two steps of the design process, which are (2) designing and developing and (3) evaluating and selecting a plan and may be used for the monitoring of the project if it is well incorporated with the municipality. It is compatible with various data types and is interoperable with other ESRI products (spatial analysis in ArcMap, or detailed design in City Engine). Moreover, it includes the PPGIS approach in the planning process. However, the product does not generate scenarios based on inputs but requires the professional user to manipulate the design directly, but it will be a source of reference regarding urban indicators (for the pre-design stage), built-in design options (for the design stage), and output parameters (for the post-design stage), and also the product's interface.

[4] Other products

While ArcGIS Urban provides a start-to-end solution for urban planning projects, many other products offer GIS-related solutions to different components of the project. Virtual City Systems[3], a 3DCityDB-based system, provides the Digital Urban Planning package that transforms design scenarios into geodata format and integrates it into the 3D City model for visualization and spatial analyses (visibility analyses, shade analyses, and height profile) in a web interface. It also offers urban simulation solutions, those include bomb simulation, wind simulation, and 3D solar potential analysis. CityCAD[4], on the other hand, is a product focusing on the generation of design scenarios and the post spatial evaluation of the designs by integrating the surrounding landscape into the working environment. The product, however, only support 2D drawing and image for the contextual information. CityScope[5] addresses the urban planning problem from a different perspective, where interactive design and participation are the core values. The product, however, also considers other spatial relationships and impact analyses throughout the design process.

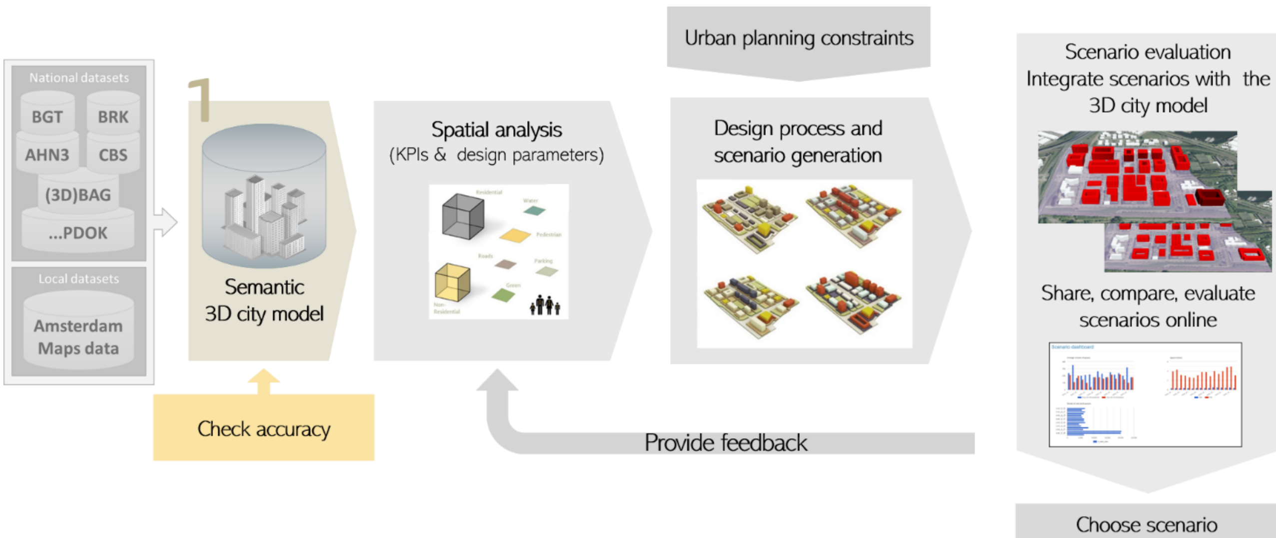
In brief, the review of the "Buurt Generator" and related urban planning and GIS-supported urban planning tools have pointed out the position of the "Buurt Generator" in the context of the current urban practices. Even though each product has its own priority, distinct concept, and technologies, they are all in the same path and contribute to the development of computer-based / data-driven / participation approaches in urban planning towards sustainability.

[3] https://vc.systems/en/solutions/digital-urban-planning/ - https://vc.systems/en/solutions/urban-simulation/

[4] https://www.holisticcity.co.uk/

[5] https://www.media.mit.edu/projects/cityscope/overview/

3 Assessing the accuracy of the generated 3D City model[6]



3.1. Chapter introduction

In the pre-design stage of the "Buurt Generator", a 3D city model of the Amsterdam city was generated from scratch to derive building volumes according to building types, those include Residential, Mixed-use, Non-residential single usage, Non-residential multi-usage, and Unknown type. These volumetric measurements then became the basis for developing volumetric design indicators for the design stage of the "Buurt Generator" (e.g., average residential volume per household, average residential volume per household, etc.). Therefore, the accuracy of the building's volumes is crucial for the quality of the design's outputs. Hence, it is in need of assessment.

The "Buurt Generator"'s 3D city model was developed based on three datasets: (1) the BAG 2D that contains the polygons of building footprint (projection of roof outlines to the ground) and corresponding building's addresses, (2) the AHN3 digital surface model (DSM) and (3) the ANH3 digital terrain model (DTM). Both (2) and (3) are raster of 0.5-meter grid resolution. As the AHN3 datasets are derived from lidar point clouds collected during the period of 2014-2016, the buildings from the BAG 2D are made sure to be dated until 2016. A normalized DSM (nDSM) was computed from the DTM and the DSM and was intersected with the BAG 2D's building footprint polygons. The polygons were then extruded by the median of the intersected value to form a LOD1 city model. The model and its associated attributes are then transformed to CityGML format and are stored in a SRDBMS using 3DCityDB (Agugiaro et al., 2020).

[6] The research results from this chapter has contributed to the content of a peer-reviewed conference paper that has been accepted for publication: ***Volume comparison of automatically reconstructed multi-LoD building models for urban planning applications,*** Truc Quynh Doan, Camilo León Sánchez, Ravi Peters, Giorgio Agugiaro, Jantien Stoter, 2021, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences)

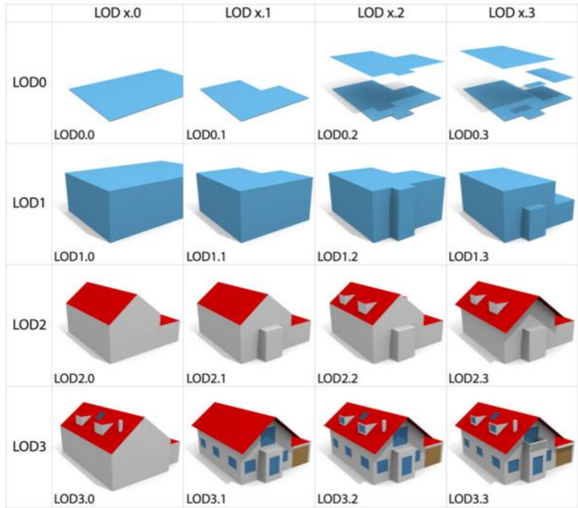


Figure 8 Examples of different level of details (LODs) of a residential building (Biljecki et al., 2016)

Meanwhile, a new countrywide 3D model (is called 3D BAG 2.0 in this thesis) has been developing by the Dutch Kadaster in collaborating with the 3D Geoinformation research group at TU Delft and is going to be soon publicly available. The model is delivered in several LODs, including LOD1.2, LOD1.3, and LOD2.2, as extensions from the original OGC's standard (Dukai et al., 2020). The LOD1.2 model follows the small details of the footprint and has a unique height, whereas the LOD1.3 model has height variations between building parts. The LOD2.2 model follows the roof shape and its details (Biljecki et al., 2016) Figure 8, which is supposed to give the best estimation of the building's volume as it is closest to the actual shape of the building. The models are also based on the AHN3 dataset collected in 2014-2016 and the BAG 2D in 2016. For that, they are compatible with the 3D model from the "Buurt Generator" for comparison purpose.

As an attempt to examine the accuracy and usability of the volume derived from "Buurt Generator"'s 3D city model, a comparison approach is carried out between the enclosed volumes of the buildings obtained from the "Buurt Generator" and the 3D BAG 2.0. For that, the building's volumes derived from the 3D BAG 2.0 are first calculated. Then, statistical and spatial analyses are carried out to compare and conclude on the measurements obtained from different models.

3.2. Volume calculation

To calculate the volume of the buildings from 3D BAG 2.0, the 3D geometries of the LODs are first stored in the database of the research. FME is then used to connect to the PostgreSQL/PostGIS database to read geometries as multi-polygons, disaggregate to polygons and transform them to FME's faces. Then, the faces are reaggregated, grouped by the "identificatie" (id) of the buildings, and are converted to FME's B-rep solid (boundary representation of solid) to calculate the building's volume Figure 9. The output volumes are then written back to the project's database.

From the result, the data from 3D BAG 2.0 are not uniform. For LOD1.3 and LOD2.2 models, the "identificatie" field cannot be used as a primary key, as in some cases, it is multi-part entries representing different parts of geometries of one building. Hence, the aggregation transformer in FME would aggregate everything as one to calculate volume, the output of volume calculation will be based on a distinct "identificatie" field. The multi-parts buildings, however, account for a tiny portion of the dataset (0.2%) Table 2.

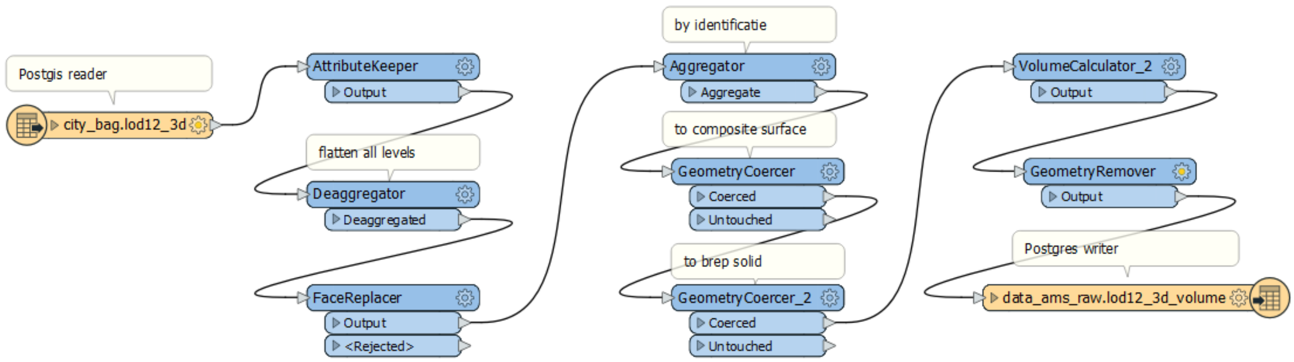


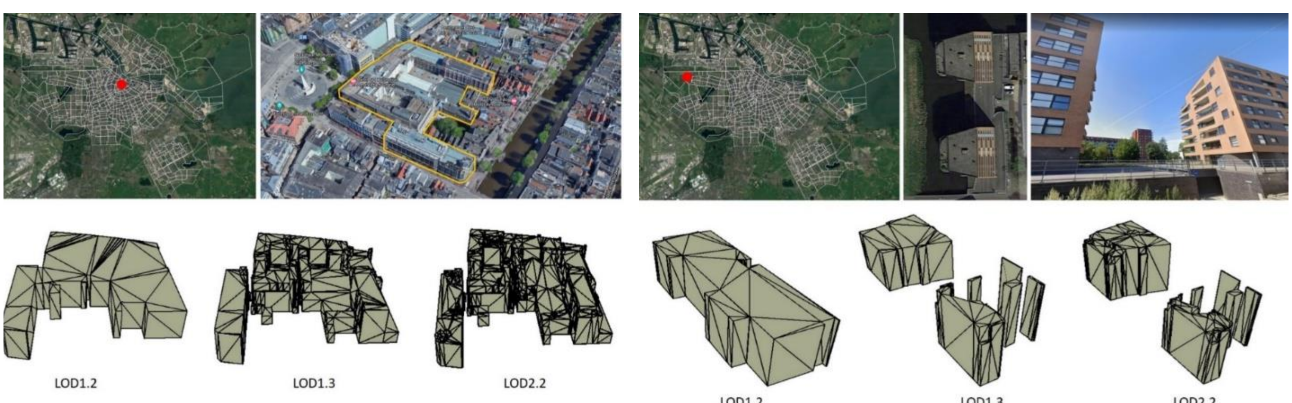
Figure 9 FME workbench to calculate the volume of different LODs

	LOD1.2	LOD1.3	LOD2.2
Count (input records)	273006	267028	267031
Count (output records)	273006	266472	266475
Difference (input vs. output records)	0 (0%)	556 (0.2%)	556 (0.2%)

Table 2 Overview on the calculated volumes from LOD1.2, LOD1.3, and LOD2.2

Moreover, there is a slight difference between the input records from the LOD1.3 and LOD2.2 models, which accounts for three building parts. A simple query was performed to find the "identificatie" that are in LOD2.2 but not in LOD1.3. Four distinct "identificatie" are returned, meaning that there are four buildings in LOD2.2 that were not reconstructed in LOD1.3.

Regarding the difference between the inputs and outputs records of the LOD1.3 and LOD2.2 models before and after volume calculation, two reasons have been identified. On the one hand, a building that has one single "identificatie" could have detached building parts that are recorded with the same "identificatie" Figure 10-a. On the other hand, errors could have occurred in the 3D reconstruction process that leads to the exploding or separating of geometries. Hence, the (exploded) separated building parts are also recorded with the same "identificatie" Figure 11-b, Figure 11.



a- Building having building parts that are detached from each other

b- Errors in the 3D reconstruction process

Figure 10 Example of multi-parts buildings

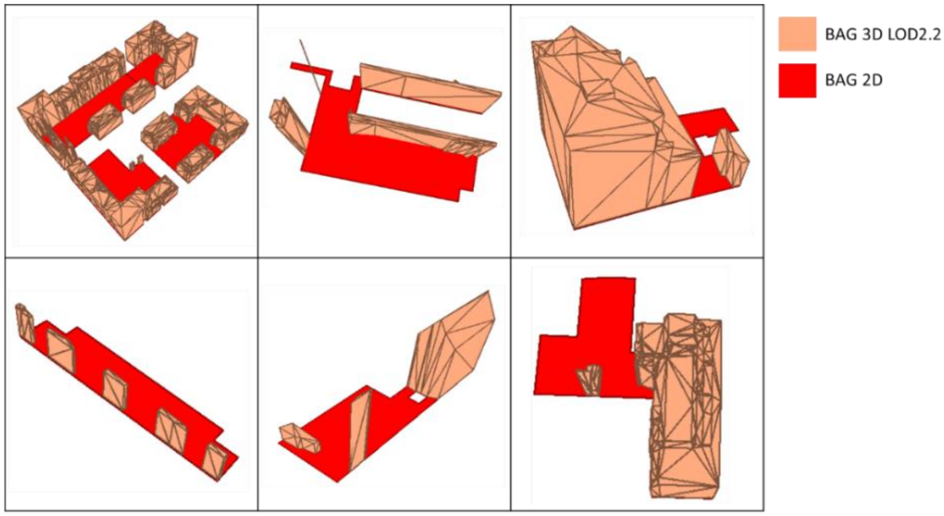


Figure 11 : Additional examples of multi-parts buildings having errors in the 3D reconstruction process – The building footprints in BAG 2D are not corresponding to the extruded properties in LOD2.2

The separated geometries do not affect the volume calculation flow in FME. The volumes derived from the second case (with errors), however, are mostly much smaller than the actual building's volume, which will eventually be specific cases while comparing the volume from different models. The density of multi-parts cases corresponds with the density of the building's footprint, meaning that they do not precisely locate in a specific area but proportional to the built density. As this phenomenon could lead to outlier cases in volume comparison, the related records are omitted and treated separately from the statistical studies in the following steps.

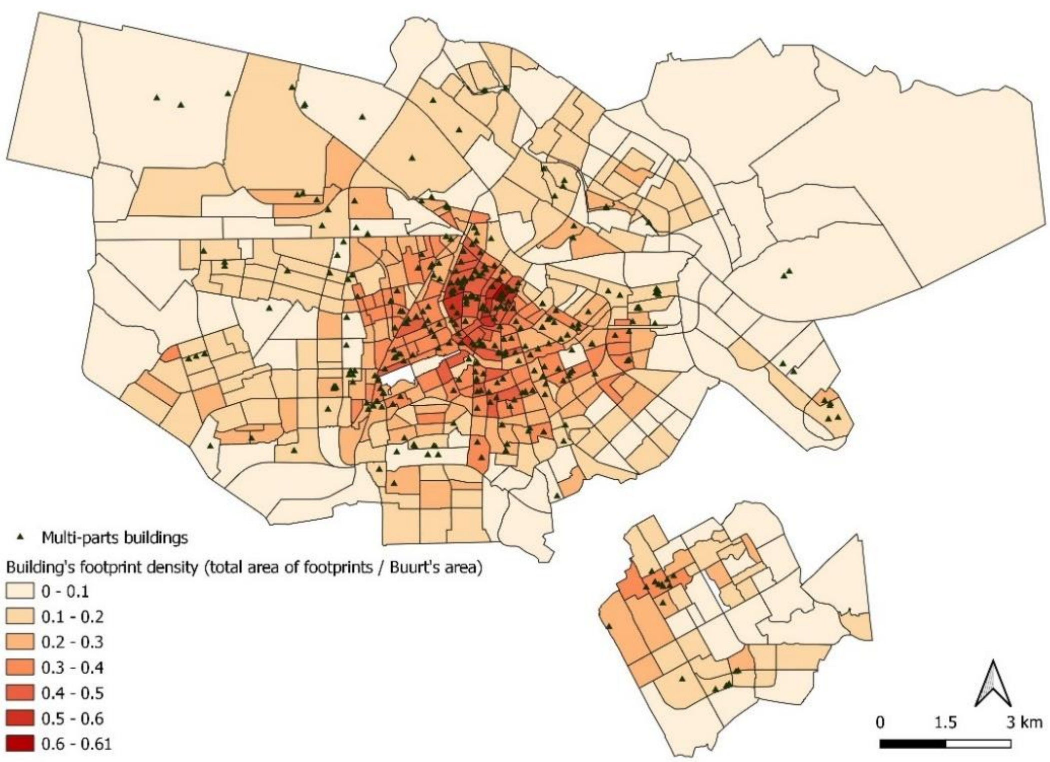


Figure 12 Distribution of the multi-parts buildings in LOD1.3 and LOD2.2 and building's footprint density

3.3. City wide volume differences

To compare the volume derived from the four approaches, the buildings' volumes from the Buurt Generator are linked to those derived from the 3D BAG 2.0 by means of the unique "identificatie" in a working table. It has resulted in 167248 matching buildings (the number of records from the "Buurt Generator" is 171515). The number of building parts of multi-parts buildings is also recorded in the working table for further classification. Although the models are generated using the same data source (AHN3 2014-2016), the approach in data pre-processing and also the data quality has led to the difference of 4267 buildings. On the one hand, the 3D reconstruction process of the 3D BAG 2.0 excludes footprints that are undergrounded or having thin point clouds. On the other hand, building footprints that are no longer exist but are still recorded in the BAG 2D might not be appropriately removed from the "Buurt Generator", as checked using queries.

Figure 13 and Table 3 give an overview of the volumes derived from the four models. Generally observed, they are pretty similar, with the values from the "Buurt Generator" model being closest with the values from the LOD2.2 model, and then LOD1.3 and LOD2.2 model, respectively. However, there are noticeable significant gaps between the extreme values (maximum values) of the four models. In the following step, the volumes derived from the "Buurt Generator" will be used as the reference for the comparison approach. The gross difference and the normalized different ratio between the approaches are derived for each record. Those include the difference between the volumes from the "Buurt Generator" and each of the LODs, and between the LODs. As the volume from the "Buurt Generator" is used as a reference for comparison, it will be the minuend and the denominator for the calculation of gross volume difference and the normalized different ratio. For example, the following formulas are used to calculate the absolute difference and the normalized different ratio between the volume from LOD2.2 and the volume from the "Buurt Generator".

Gross difference	*diff_lod22_ahn = volume LOD2.2 – volume "Buurt Generator"*
Normalized different ratio	*p_lod22_ahn = (volume LOD2.2 – volume "Buurt Generator") / volume "Buurt Generator"*

Then, a column was added to the working table to track the buildings that have significant volume differences between the models to identify extreme cases.

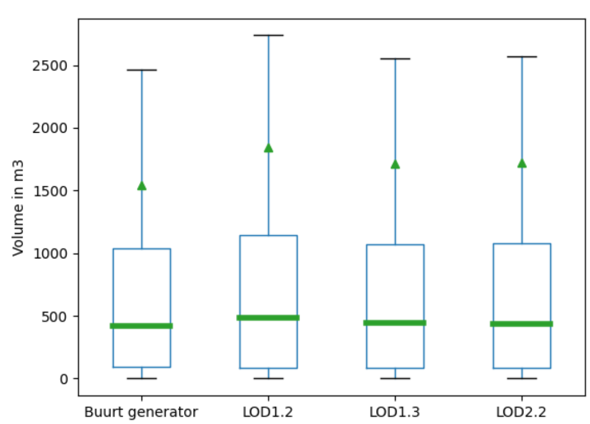


Figure 13 The distribution of the four datasets

	"Buurt Generator" (m^3)	LOD1.2 (m^3)	LOD1.3 (m^3)	LOD2.2 (m^3)
mean	1545.27	1848.58	1716.94	1724.43
std	10697.46	13554.68	17035.02	16915.04
min	0.18	2.14	1.44	0.88
25%	89.56	85.32	84.6875	82.52
50%	416.92	485.25	447.23	436.79
75%	1038.29	1146.51	1072.675	1076.15
max	1642195.57	2205115	4256801	4226450

Table 3 The distribution of the four datasets

	identificatie character varying	vol_ahn double precision	vol_lod22 double precision	vol_lod13 double precision	vol_lod12 double precision	aggregation_parts integer	diff_lod22_ahn double precision	diff_lod13_ahn double precision	diff_lod12_ahn double precision
1	0363100012139555	394.22	433.91	296.12	436.1	[null]	41.88	-98.1	39.69
2	0363100012146077	835.43	1019.16	938.77	902.41	[null]	66.98	103.34	183.73
3	0363100012183482	17.51	29.03	30.05	28.98	[null]	11.47	12.54	11.52
4	0363100012188732	32.45	36.29	36.44	36.01	[null]	3.56	3.99	3.84
5	0363100012188825	28.59	16.48	16.54	16.5	[null]	-12.09	-12.05	-12.11
6	0363100012189272	13.9	15.58	15.66	15.25	[null]	1.35	1.76	1.68
7	0363100012197570	13.79	15.89	15.82	15.39	[null]	1.6	2.03	2.1
8	0363100012211975	14.42	15.7	15.71	15.69	[null]	1.27	1.29	1.28
9	0363100012211440	13.64	14.74	14.78	14.44	[null]	0.8	1.14	1.1
10	0363100012213749	10.74	12.89	12.87	12.81	[null]	2.07	2.13	2.15
11	0363100012215126	14.38	15.87	15.83	15.4	[null]	1.02	1.45	1.49
12	0363100012215130	13.61	15.55	15.52	15.08	[null]	1.47	1.91	1.94

Table 4 Screenshot of one part of the working table for volume comparison "bag_compare"

As mentioned in the previous part, multi-parts buildings could be problematic. The thesis studies the distribution of volume differences separately for single part buildings and multi-parts buildings in the following steps.

3.3.1. Volume differences - single part buildings

The values from the "Buurt Generator"s are generally smaller than those from the LODs, as most of the records are located on the right side of the graph (see Figure 14) on the distribution of normalized volume differences. Furthermore, most of the differences (in %) are within the deviation of 20% from being equal that reveals a good correspondence between the "Buurt Generator" and the 3D BAG 2.0 in terms of enclosed volumes. Particularly, the volumes derived from the "Buurt Generator" highly resemble those derived from the LOD2.2 model, with 57.32% of cases laying in the deviation of ±5%, and 93.5% of cases are within the deviation of ±20% Figure 15. As it could be expected, the resemblance decreases for LOD1.3 and LOD1.2, respectively, since they are both derived from the simplification/generalization of the LOD2.2 model.

However, there are still outliers where huge differences between the approaches occur that highlight limitations among the models. For example, the maximum gross difference of specific cases accounts for 562,920 m^3, 227,798 m^3, 164,563 m^3 between the "Buurt Generator" and LOD1.2, LOD1.3, LOD2.2, respectively. Other figures can be found in Table 5. Ten of the extreme cases in terms of volumetric differences will be selected and investigated further in the last part of this chapter.

	Gross difference (m^3)			Difference ratio (%)		
	LOD1.2	LOD1.3	LOD2.2	LOD1.2	LOD1.3	LOD2.2
mean	303.30	171.67	179.15	12.66	5.73	4.86
std	4015.56	9235.03	9190.12	56.59	33.39	30.86
min	-99344.78	-76528.61	-45342.24	-86.73	-98.87	-98.87
25%	4.79	0.54	2.04	5.52	0.76	1.76
50%	45.52	15.42	13.08	10.47	6.57	3.89
75%	108.9	59.5	39.95	16.98	12.41	7.13
max	562919.55	2901398.13	2871046.87	15270.25	7001.61	6640.18

Table 5 Statistical figures of the volume differences between the "Buurt Generator" and the LODs

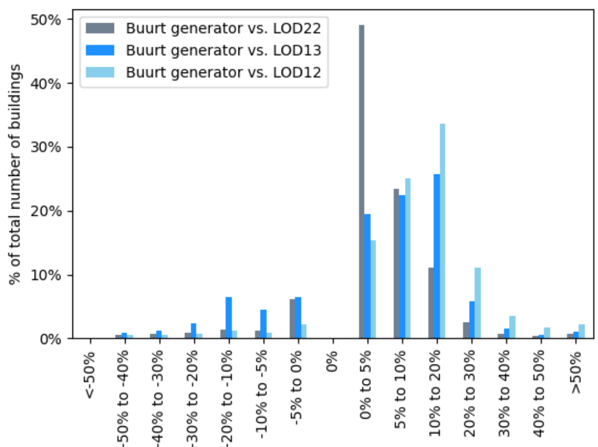


Figure 14 Distribution of normalized volume differences between the "Buurt Generator" and LODs – Single-part buildings

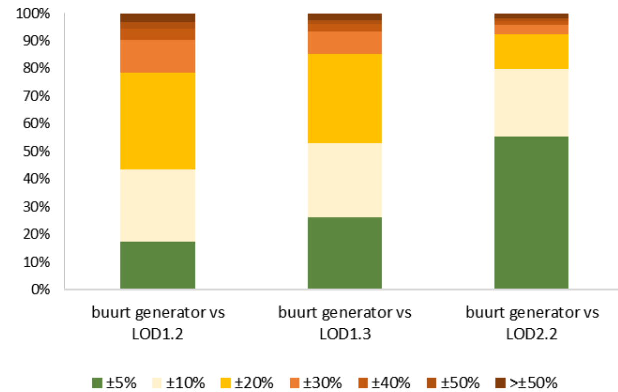


Figure 15 Distribution of normalized volume differences between the "Buurt Generator" and LODs – Single-part buildings (stacked)

Regarding the derived volumes between the BAG 3D 2.0 models, it is clearly showed that the volumes from LOD1.3 are very closed to those from LOD2.2, as the LOD1.3 model is derived from a first simplification/generalization process of the LOD2.2 model. However, there are also cases where significant differences between the models occur. Therefore, the reasons for the volume differentiation between the "Buurt Generator" and the LODs are not only from conceptual reasons (e.g., the choice of height to be extruded, height references, and building details) but possibly also from the errors in the 3D reconstruction process of the 3D BAG 2.0.

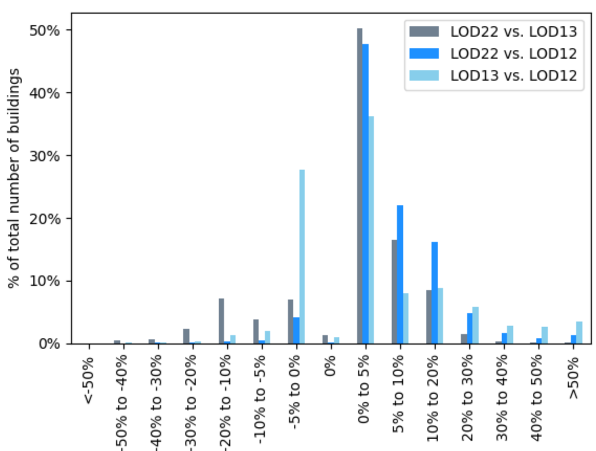


Figure 16 Distribution of volume differences between the LODs – Single-part buildings

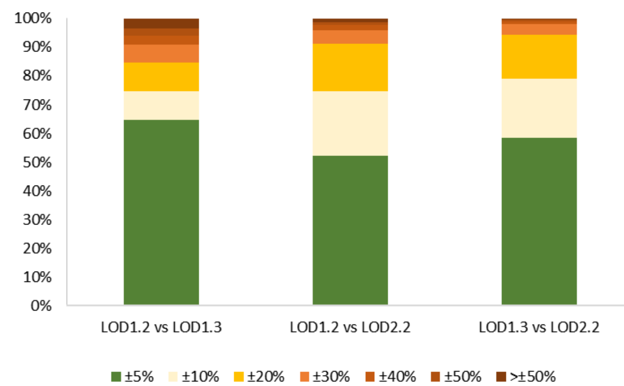


Figure 17 Distribution of volume differences between the LODs (stacked) – Single-part buildings

3.3.2. Volume differences - multi-parts buildings

Multi-parts buildings account for 319 cases out of 167248 records. According to the below figures, there is a great gap in volumes for these cases as most of the records (more than 70%) having volume differences of more than ±50% Figure 18 Figure 19. The same figures hold for the comparison between the LOD1.3 and LOD2.2 models with the LOD1.2 models Figure 20 Figure 21. As a result, multi-parts buildings are mostly wrongly reconstructed in LOD1.3 and LOD2.2, and the number of building parts of one building could be an efficient indicator for detecting problems in the 3D reconstruction process of the 3D BAG 2.0.

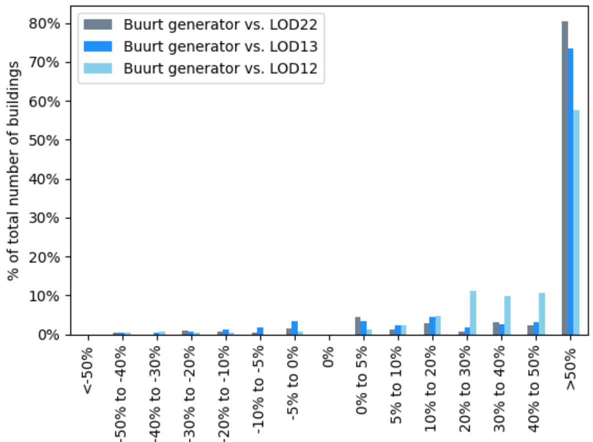


Figure 18 Distribution of volume differences between the "Buurt Generator" and LODs – Multi-parts buildings

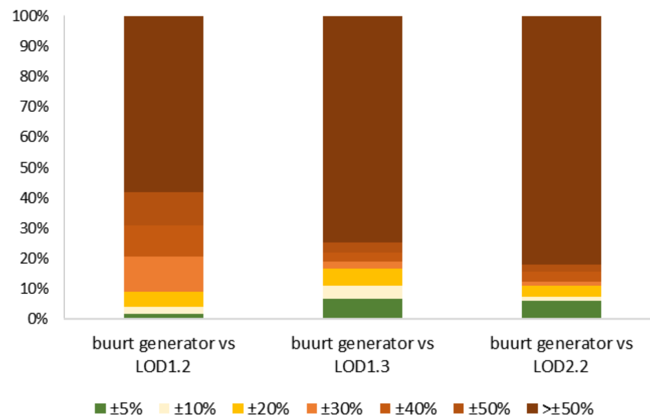


Figure 19 Distribution of volume differences between the "Buurt Generator" and LODs (stacked) – Multi-parts buildings

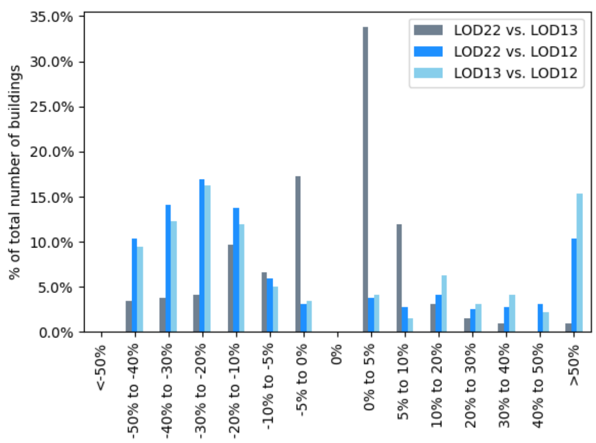


Figure 20 Distribution of volume differences between the LODs – Multi-parts buildings

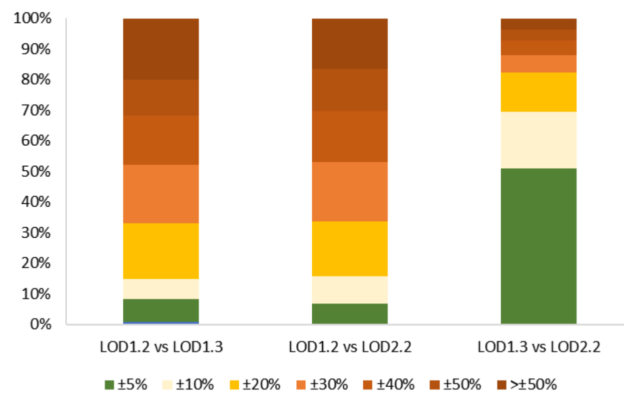


Figure 21 Distribution of volume differences between the LODs (stacked) – Multi-parts buildings

3.4. Building's characteristics and volume difference

According to the result of the previous part, the volumes derived from the "Buurt Generator" are highly matched with the volume from the LOD2.2. Therefore, the thesis focuses only on these two models for the following analyses. In this part, the relationship between building characteristics and volume differences is studied. Building characteristics involving the building footprint's area, the year of construction, and the building class were selected for further investigation.

With regards to building's footprint area (see Figure 22 and Table 6), buildings with tiny footprints (less than 20 m^2) tend to have more significant volume differences between LOD2.2 and "Buurt Generator", the same for building with a vast footprint (5000 m^2 onwards). Small footprint buildings account for a great share of buildings in the city (23.75%). However, their total volume accounts only for 0.4% of the whole building volume of the city. Hence, although they might cause an alarming figure on the number of buildings with significant volume difference, their contribution to the volume estimation for urban planning purposes is not that severe. The focus, on the other hand, must fall into the case of large footprint buildings. Buildings having a footprint larger than 5000 m^2 account only for 0.23% of the total building, but their volume account for 21% in the "Buurt Generator" and 24.6% in LOD2.2, and the gross volume difference between the two models is approximately 16,430,600 m^3. Hence, their effect on the estimation of volume in urban planning is considerably heavier.

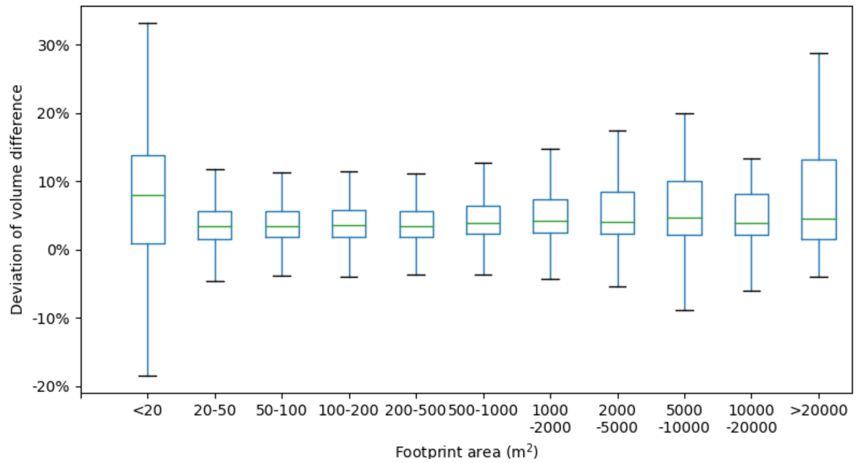


Figure 22 Distribution of volume difference ratio according to building's footprint area

Footprint area range (m2)	Volume differences in ratio				Buildings					
	Mean	Median	Max	Min	Count	%	"Buurt Generator" volume (x1000 m^3)	%	LOD2.2 volume (x1000 m^3)	%
0-20	5.12%	8.01%	3189.27%	-98.87%	39720	(23.75)	950.2	(0.4)	938.6	(0.3)
20-50	4.03%	3.39%	6640.18%	-98.14%	29131	(17.42)	8170.7	(3.2)	8456.5	(2.9)
50-100	4.55%	3.48%	4964.44%	-97.28%	64235	(38.41)	45508.7	(17.6)	47360.6	(16.4)
100-200	4.81%	3.56%	3862.77%	-98.12%	19831	(11.86)	31479.6	(12.9)	32805.7	(11.4)
200-500	5.06%	3.455%	293.87%	-96.55%	8182	(4.89)	26519.6	(10.3)	27750.9	(9.6)
500-1000	7.32%	3.935%	933.26%	-37.41%	3016	(1.80)	25768.9	(10.0)	27375.6	(9.5)
1000-2000	9.26%	4.15%	864.61%	-69.96%	1753	(1.05)	29499.2	(11.4)	31990.2	(11.1)
2000-5000	13.82%	4.1%	915.44%	-98.42%	981	(0.59)	36174.0	(14.0)	40926.1	(14.2)
5000-10000	25.77%	4.69%	497.37%	-21.6%	254	(0.15)	21288.6	(8.2)	26480.3	(9.2)
10000-20000	32.21%	3.83%	570.72%	-5.99%	107	(0.06)	17129.9	(6.6)	21948.5	(7.6)
>20000	37.82%	4.58%	405.96%	-16.31%	38	(0.02)	15953.8	(6.2)	22374.1	(7.8)

Table 6 Distribution of volume difference according to building's footprint area

With regards to building classes, residential buildings, with a very high share of 56.42%, show the highest match between the "Buurt Generator" and LOD2.2. Unknown buildings, with a share of 26.43%, show the lowest match between the models. Referring to the distribution of building class according to building footprint (see Figure 24), it is noticed that unknown buildings mostly have a small footprint of less than 20 m^2. Together with the previous finding on footprint range, it can be concluded that unknown buildings with small footprints are problematic in volume estimating. These tiny footprint buildings are often garages, sheds, storage houses that might be covered by vegetation. Thus, in the 3D modeling process, the median height of the tree above (or any other obstacles) might be used to extrude the underneath footprint. However, as shown in Table 7, their share of volume is not significant. Non-residential buildings of a single function, on the other hand, are problematic for their large percentage of volume and high gross volume difference between the "Buurt Generator" and the LOD22, which accounts for approximately 12,291,369 m^3. The mixed-use building is also as problematic with approximately 9,282,731 m^3 of gross volume difference, as also shown in Figure 25.

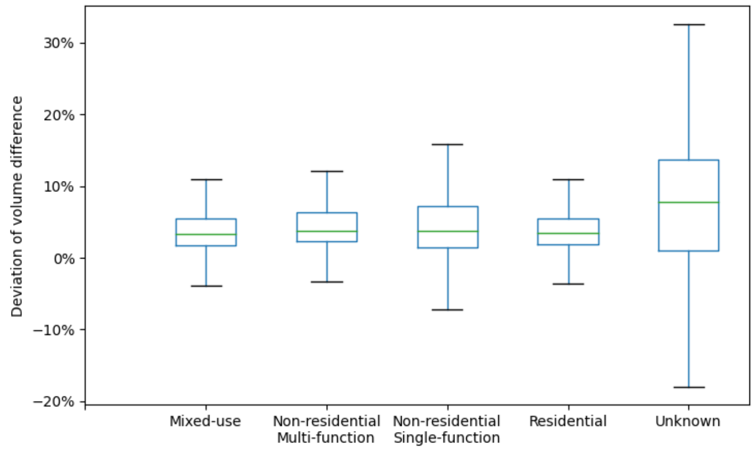


Figure 23 Distribution of volume difference according to building's class

Building class	Mean	Median	Max	Min	Count	%	"Buurt Generator" volume (x1000 m^3)	%	LOD2.2 volume (x1000 m^3)	%
	Volume differences in ratio				Buildings					
Mixed-use	5.03%	3.35%	4964.44%	-47.67%	16451	(9.84)	62633.26	(24.23)	71915.99	(24.94)
Non-residential (multi-function)	16.19%	3.78%	3862.77%	-36.16%	634	(0.38)	18228.70	(7.05)	21285.11	(7.38)
Non-residential (single function)	6.01%	3.69%	1013.46%	-97.28%	11602	(6.94)	68059.75	(26.33)	80351.12	(27.86)
Residential	4.41%	3.46%	915.44%	-98.12%	94364	(56.42)	88579.37	(34.27)	92592.73	(32.10)
Unknown	5.30%	7.74%	6640.18%	-98.87%	44197	(26.43)	20942.61	(8.10)	22262.05	(7.72)

Table 7 Distribution of volume difference according to building's class

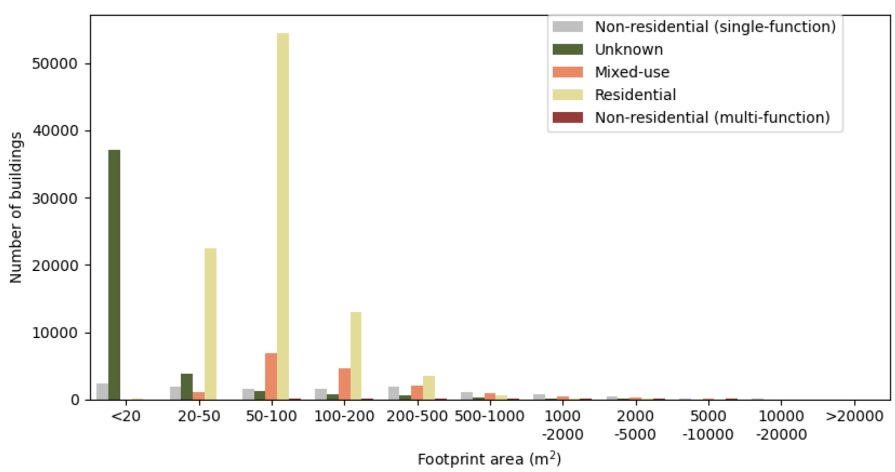


Figure 24 Distribution of building class according to building footprint area

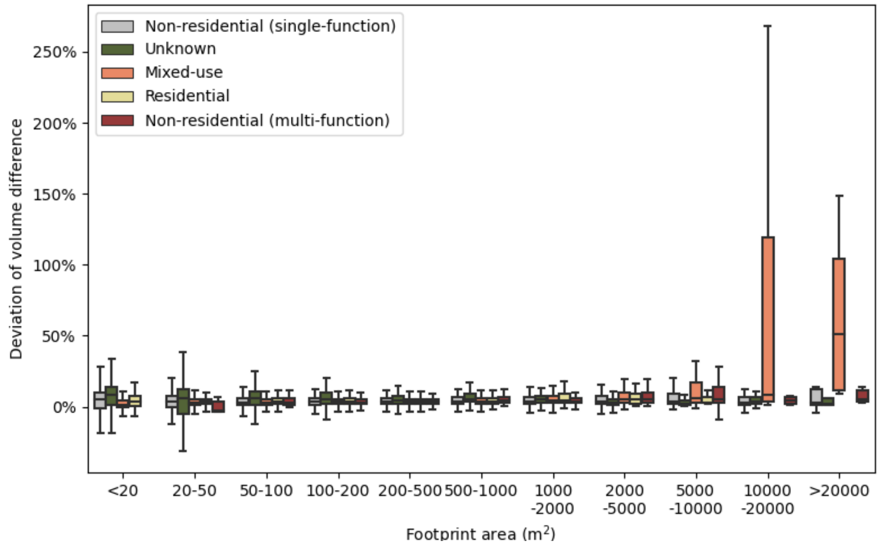


Figure 25 Distribution of volume difference according to building's class and footprint area

Regarding the year of construction, Figure 26 shows that buildings built from the 1970s onwards have a higher range of volume difference. Construction activities firmly took place in the 1900-1945 and 1970-2000 period with a larger share of residential buildings and unknown buildings (see Figure 27). However, the range of volume difference is much higher for the period of 1975-2000. One of the reasons is that there is a large portion of unknown buildings with small footprints and non-residential and mixed-use buildings with large footprint being built in the period (see Figure 29, Figure 29).

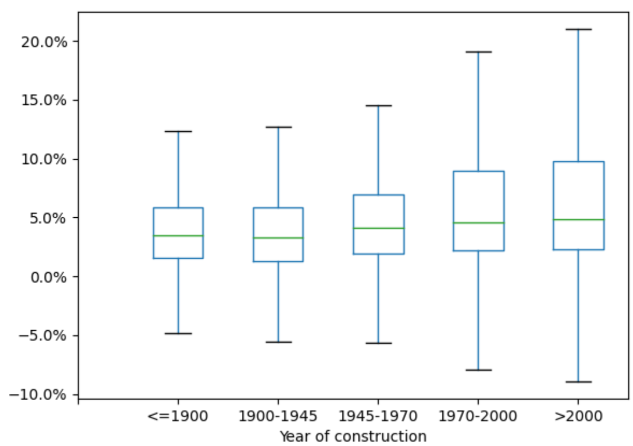


Figure 26 Distribution of volume difference according to the year of construction

	Volume differences in ratio				Buildings					
Year of construction	Mean	Median	Max	Min	Count	%	"Buurt Generator" volume (x1000 m^3)	%	LOD2.2 volume (x1000 m^3)	%
<=1900	4.284236	3.52	6640.18	-98.87	19291	(11.53)	33955.5	(13.1)	37082.2	(12.9)
1900-1945	2.278742	3.25	3189.27	-98.15	56811	(33.97)	53651.3	(20.8)	56613.1	(19.6)
1945-1970	4.284182	4.16	475.79	-98.42	27060	(16.18)	39114.6	(15.1)	42926.3	(14.9)
1970-2000	6.910253	4.59	3862.77	-96.55	46759	(27.96)	79676.3	(30.8)	92160.0	(32.0)
>2000	9.36421	4.82	962.83	-97.28	17327	(10.36)	52046.1	(20.1)	59625.4	(20.7)

Table 8 Distribution of volume difference according to year of construction

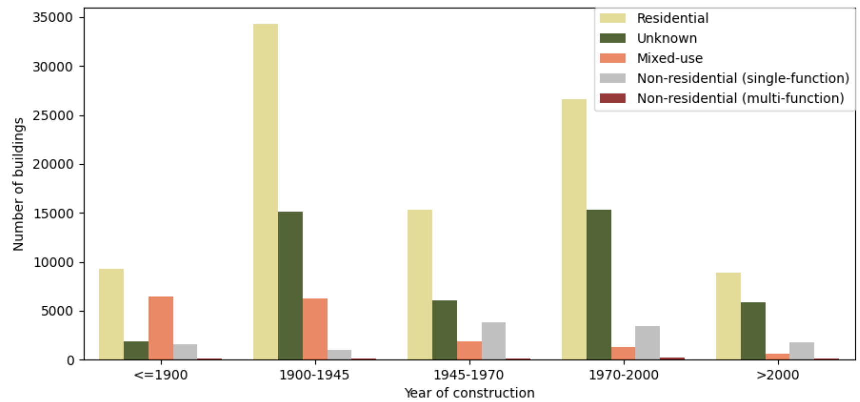


Figure 27 Distribution of building according to building class and year of construction

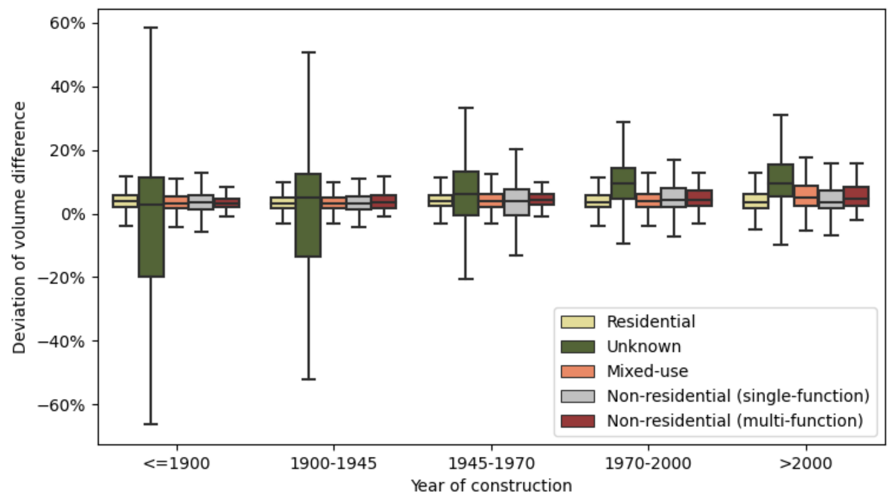


Figure 28 Distribution of volume difference according to year of construction and building class

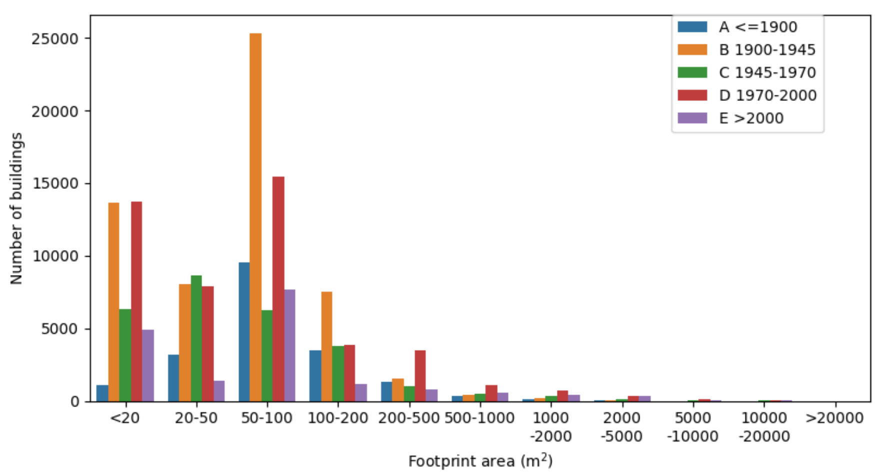


Figure 29 Distribution of building according to building footprint and year of construction

In general, in order to spot buildings having a tremendous difference in volume, some indicators could also be used as follows (besides multi-parts buildings): building with a very small footprint, building with a very large footprint, the building of unknown function (usually have small footprint), the building of non-residential, and mixed-use function (usually have large footprint).

3.5. Volume differences at the neighborhood level

In this part, the research looks further into the spatial aspect of the volume differences by comparing the building volumes aggregated at the neighborhood level. For that, another working table is created in the database to calculate and store the statistical distribution of volume differences for each neighborhood. As can be observed from the below map (see Figure 30), the resemblance level of the volumes from the "Buurt Generator" and the LOD2.2 is not evenly distributed across the city. The area within the city core and its surroundings shows a better figure, whereas the area towards the North, North-East, South, and South-West of the city shows a lower match. On the one hand, the volume matching of some neighborhoods could be not good overall, indicating a high share of buildings having a different ratio of ±10% to ±30%, notably in the North and Southwest of the city. For most of the cases, it is due to the high share of unknown buildings in these areas (see Figure 31).

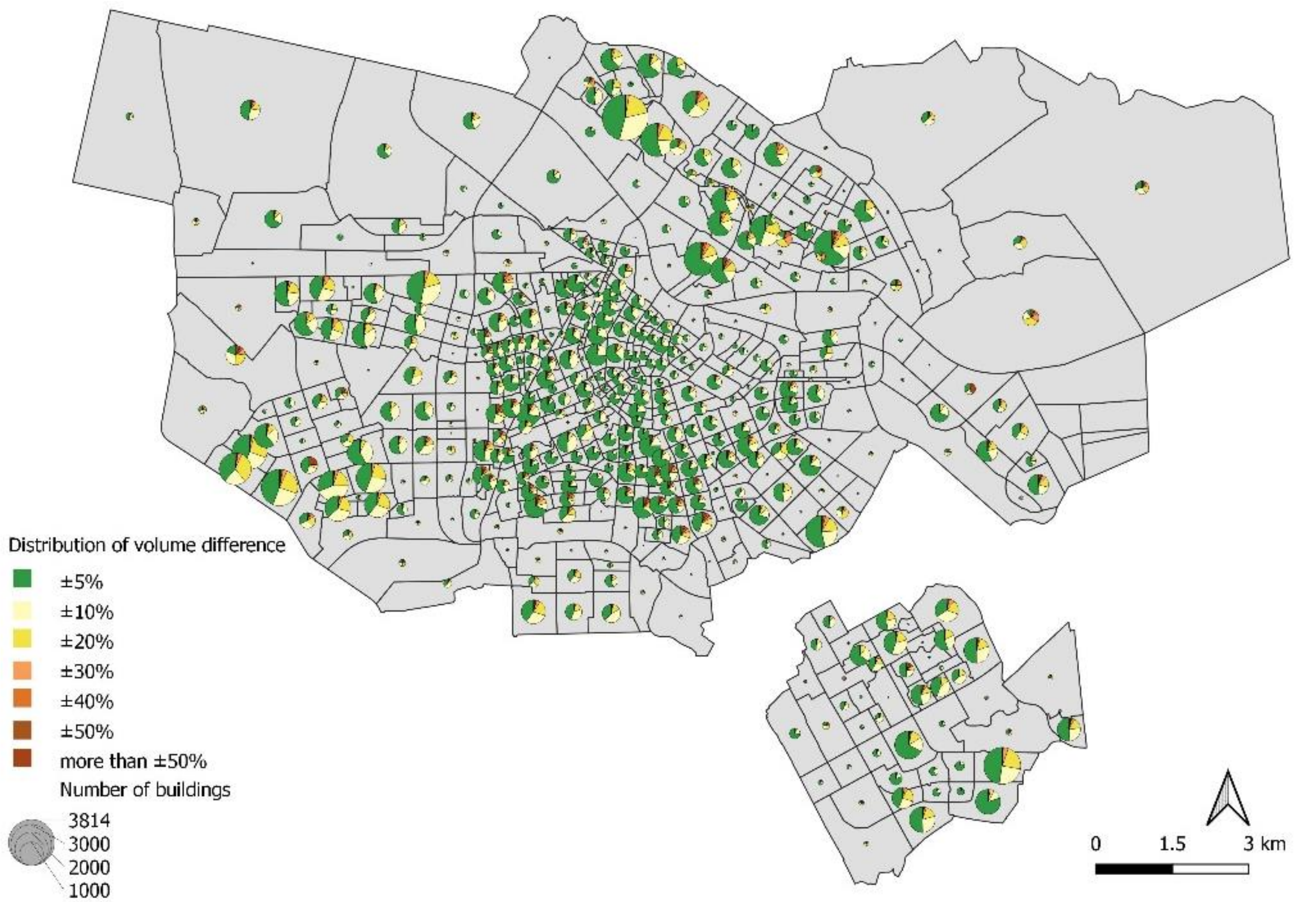


Figure 30 The spatial and statistical distribution of volume differences with a focus on the total number of buildings per neighborhood

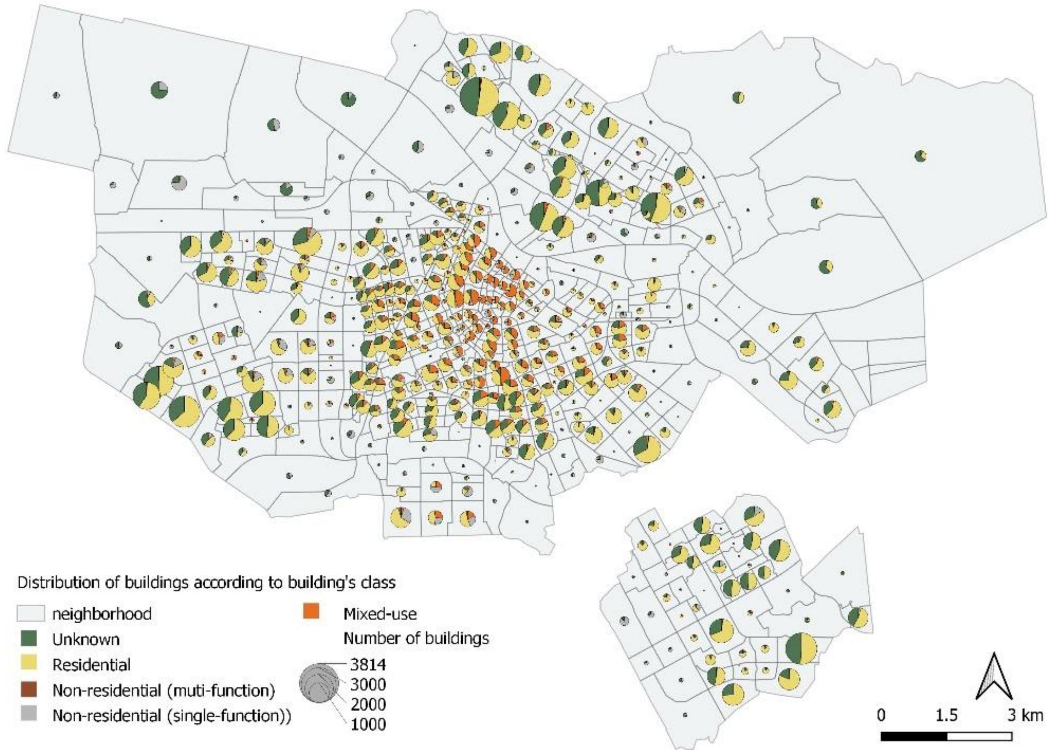


Figure 31 Spatial distribution of building class

There is, however, a specific case. The neighborhood "N73D" has a significant share of building having differences of ±10% to ±30% from being equal. By visualizing the 3D models, it can be observed that the misalignment of the building footprints is the cause for a large share of buildings having a low match in volume (see Figure 32). The error might come from the models and is not further investigated in the scope of this thesis.

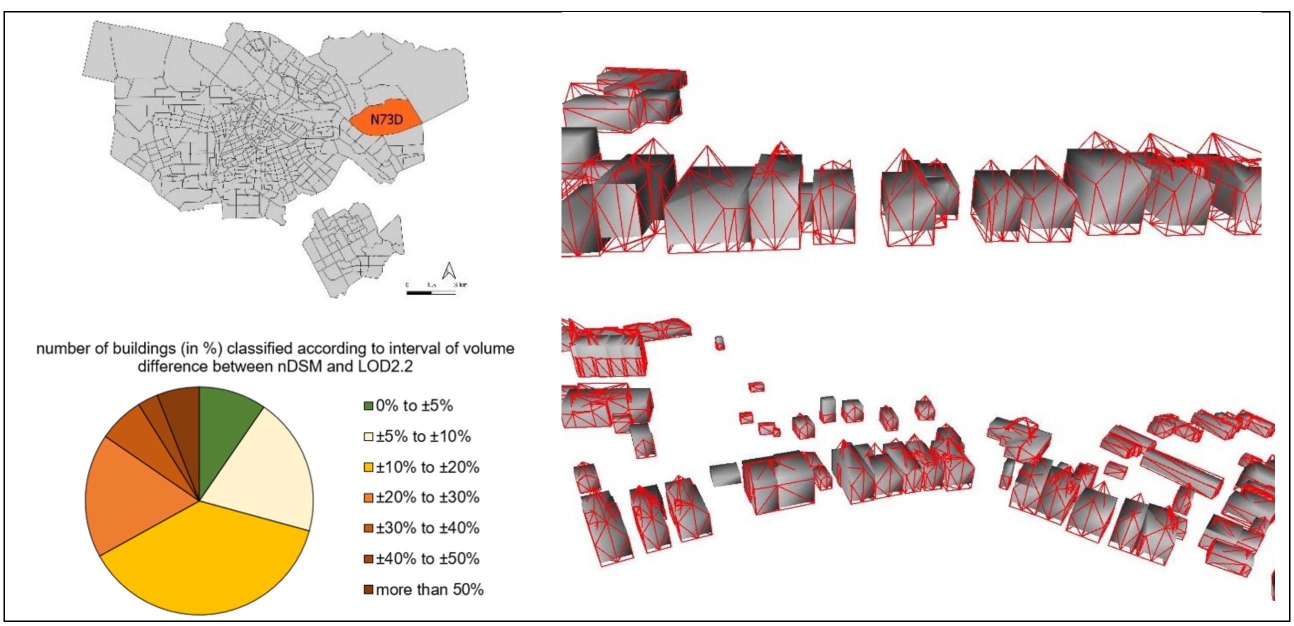


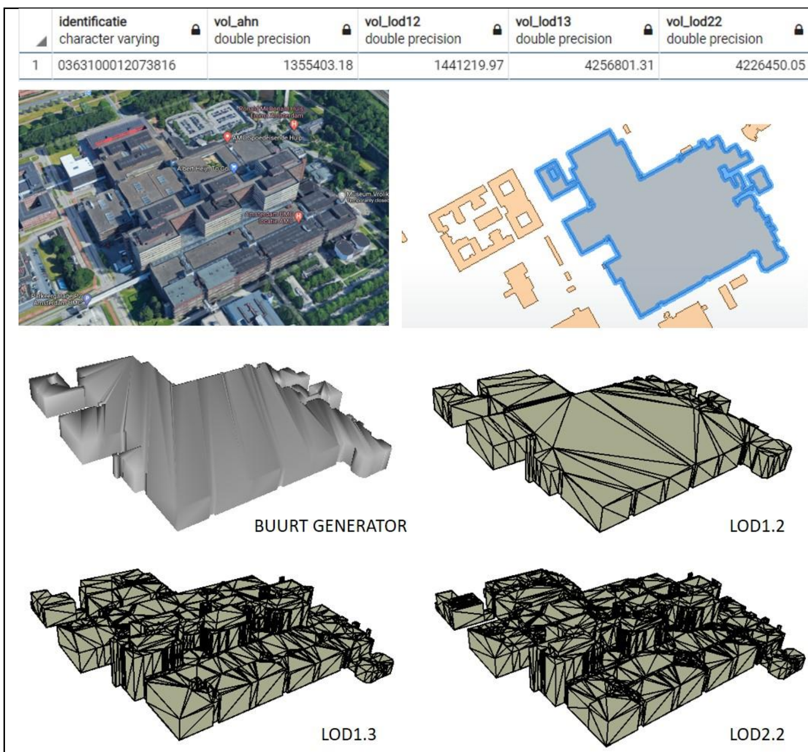
Figure 32 Buurt N73D – The LOD2.2 model is visualized in red frames and the "Buurt Generator" is visualized in grey boxes

On the other hand, the total number of buildings in some neighborhoods is simply too low for the statistical figures to make sense. As can be seen from Figure 30, some neighborhoods labeled as having low volume matching are actually having very few buildings.

3.6. Extreme cases of high volumes differences

From the above research results, (extreme) differences in volumes might be due to the "Buurt Generator", the LODs, or from both. They could have resulted from errors or misconceptions in the modeling process. In this part of the thesis, some extreme cases are shown to visualize and quantify some possible causes of the significant differences in volumes. As mentioned above, a column that notes all the cases that have large differences among the models ("Buurt Generator"s and the LODs, and between the LODs) is created in the working table. The records are then randomly selected to study the causes of volume differences. It is noted that this section focuses only on extreme cases; cases with a deviation of less than 40% that occur more frequently are not included. Furthermore, although multi-parts buildings are problematic, they are already showed in the last part and are excluded from these examples. Moreover, this part expands the comparison to the four models instead of solely "Buurt Generator" and LOD2.2.

3.6.1. "Buurt Generator" and LODs

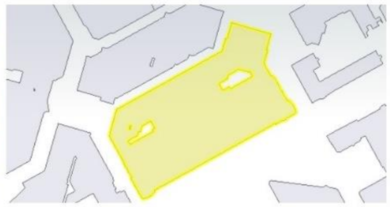


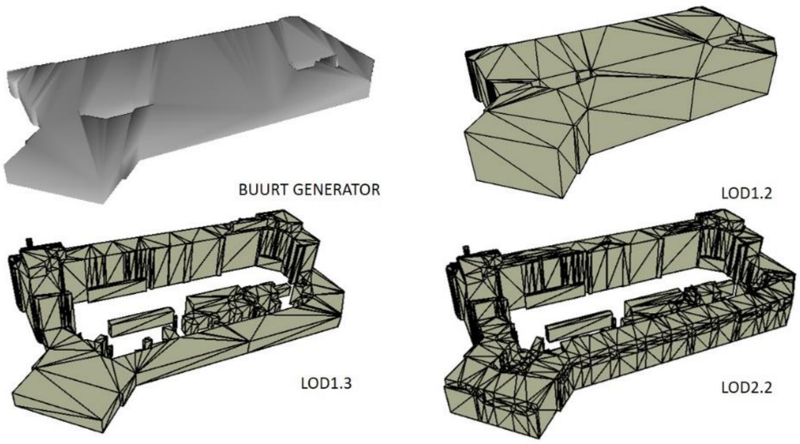
	identificatie (character varying)	vol_ahn (double precision)	vol_lod12 (double precision)	vol_lod13 (double precision)	vol_lod22 (double precision)
1	0363100012073816	1355403.18	1441219.97	4256801.31	4226450.05

Building 0363100012073816

In this case, the volumes derived from the "Buurt Generator" and LOD1.2 are similar and much smaller than those derived from LOD1.3 and LOD1.2. It is because of the large building footprint and the height variation of the building blocks. The median height used to extrude the footprint falls to the height of the largest flat surface; hence, it does not represent the actual dimensions of the building.

identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision	vol_lod22 double precision
0363100012077725	96150.16	292493.13	505578.37	644900.11

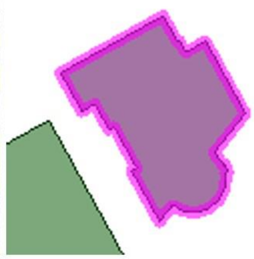


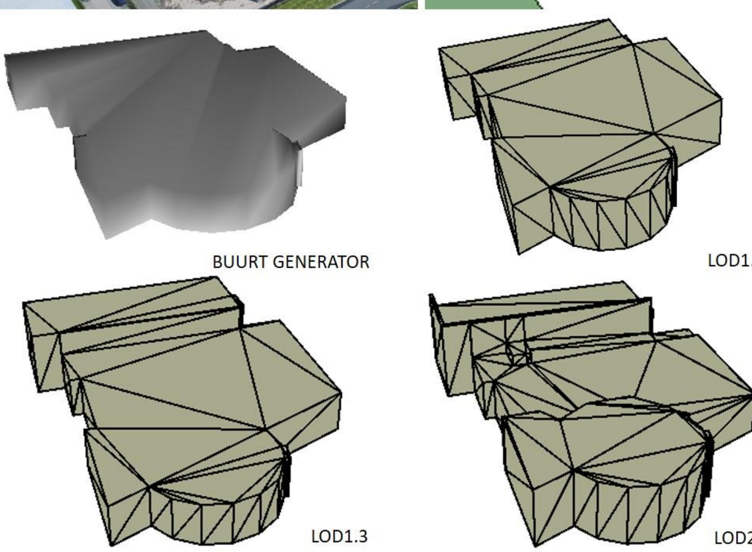


Building 0363100012077725

In this case, the building also has a large footprint and has a great variation in building height. However, the volume derived from the "Buurt Generator" in this case is underestimated. The use of median height from the normalized DSM again does not reflect the size of the building.

identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision	vol_lod22 double precision
0363100012149120	14601.73	26505	22571.02	24249.49





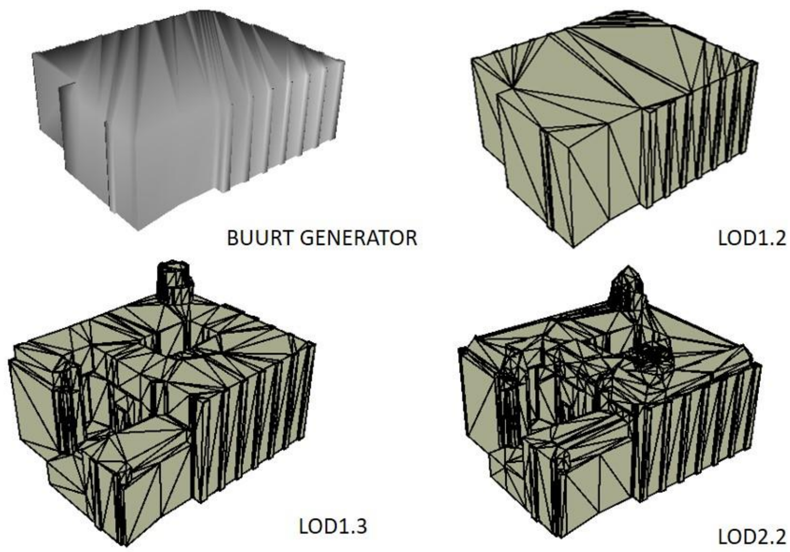
Building 0363100012149120

Another example of large footprint building with height variation.

Building 0363100012165488

Another example of large footprint building with height variation.

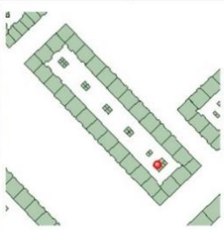
identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision	vol_lod22 double precision
0363100012165488	57391.65	75527.12	124009.11	123203.09

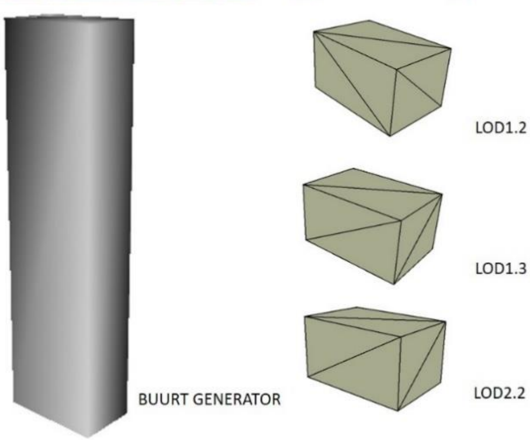


Building 0363100012184135

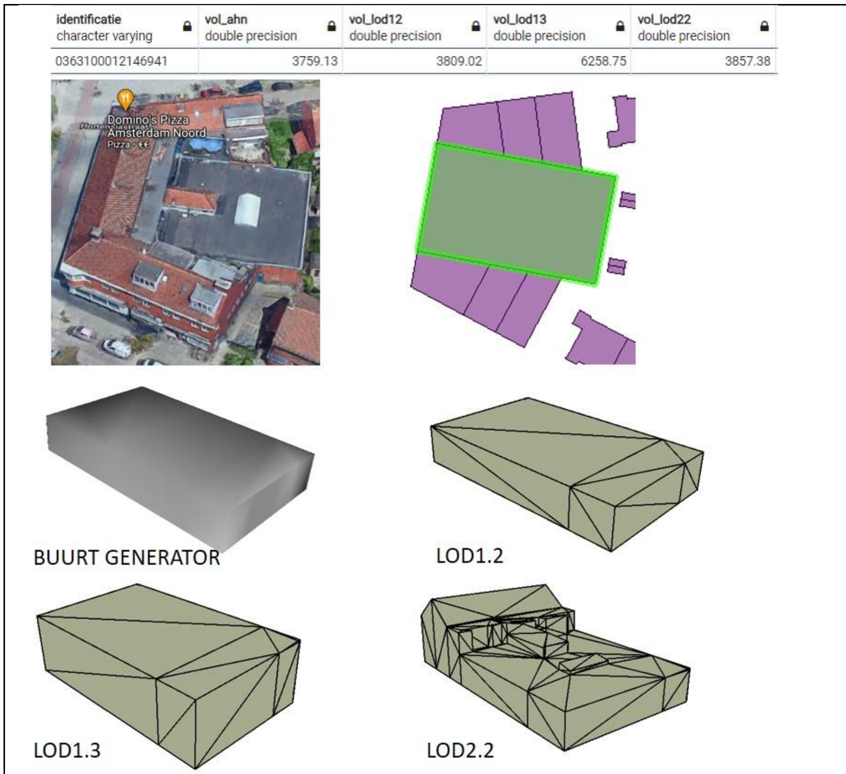
In this case, the height of the building from “Buurt Generator” is overestimated since it is located below trees. This condition affects the result of the normalized DSM, for that the median height of the tree might be chosen to represent the median height of the underneath building.

	identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision
1	0363100012184135	54.98	26.34	26.33



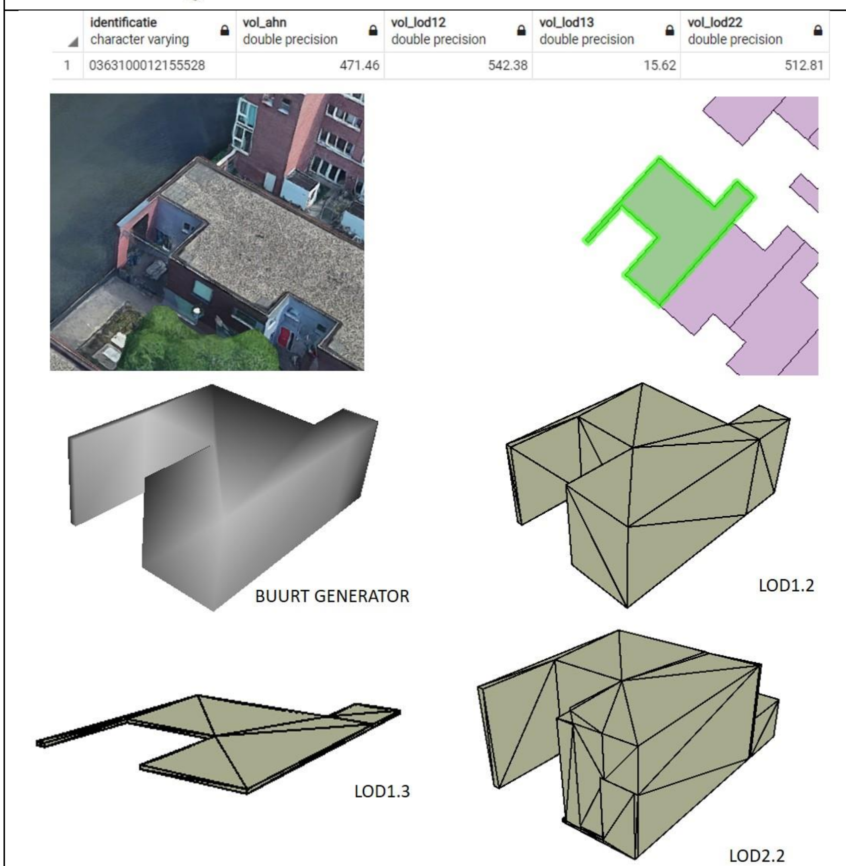


3.6.2. LOD1.3 and LOD2.2



Building 0363100012146941

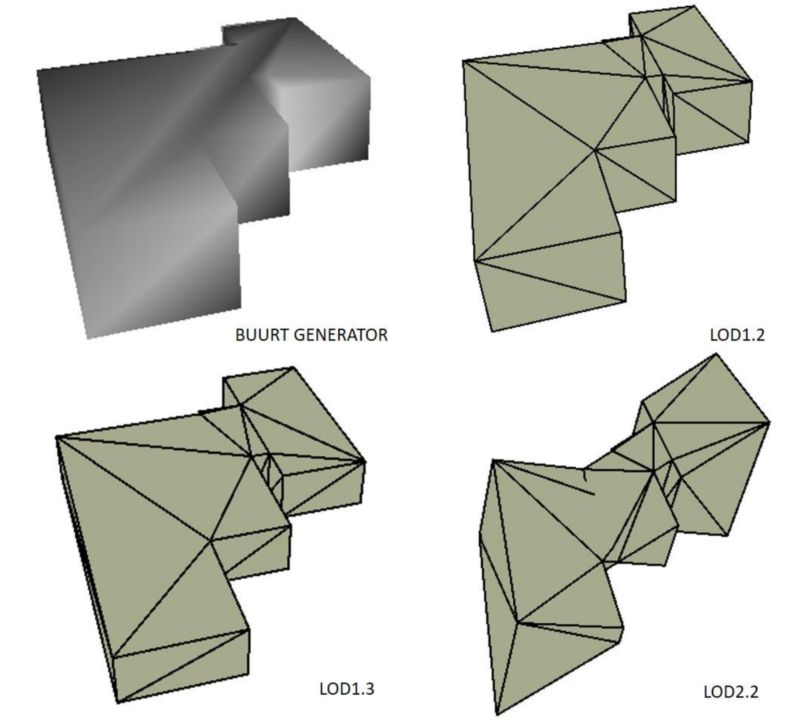
In this case, the volume derived from LOD1.3 is much larger compared to the rest. It is noticed that the LOD1.3 model is generated without considering the height variation of the building, which makes it resemble the LOD1.2 model.



Building 0363100012155528

In this case, the volume derived from the LOD1.3 model is much smaller compared to the rest. It is noticed that the model has merely been extruded from the footprint. On the other hand, the LOD2.2 shows the correct geometry of the building.

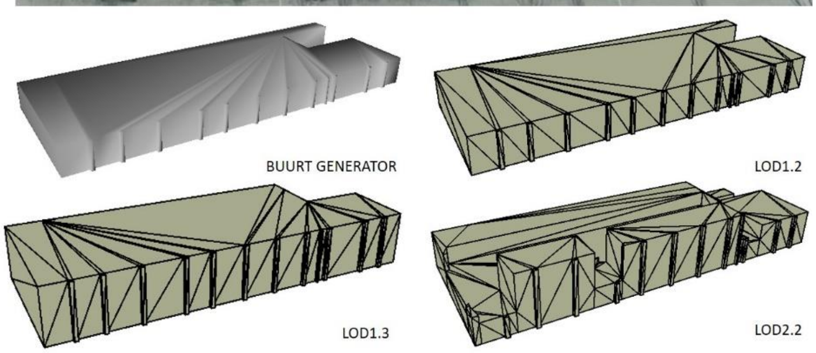
	identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision	vol_lod22 double precision
1	0363100012140483	664.53	622.66	413.44	12.51



Building 0363100012140483

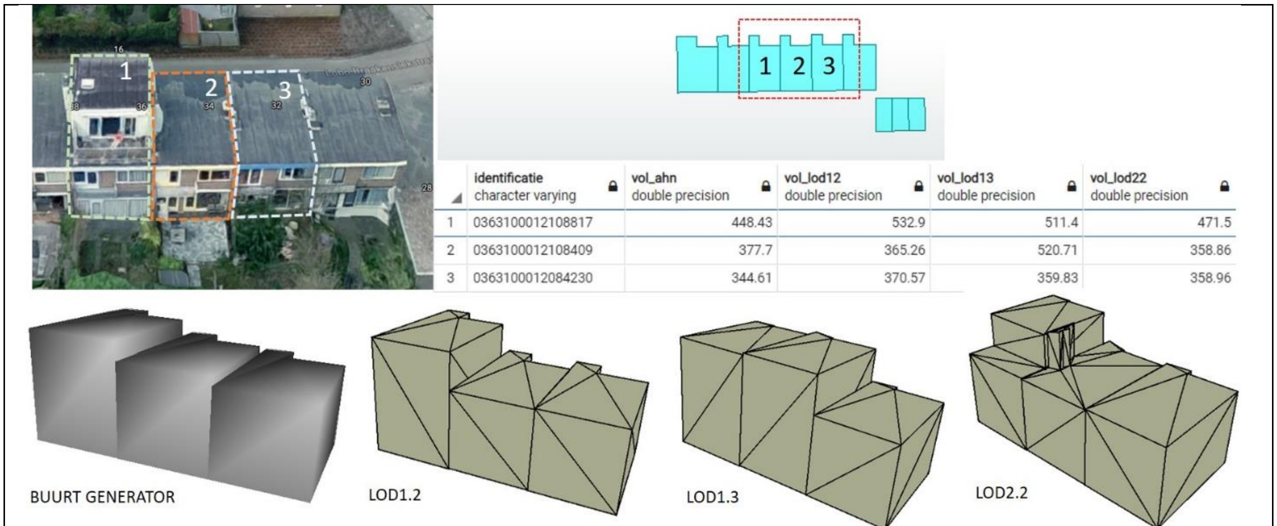
In this case, the volume derived from LOD2.2 is much smaller compared to the rest. By investigating the geometry of the building, the building form is twisted and has a weird shape. The LOD1.3, which is supposed to be close to LOD2.2, is, however having a normal shape.

identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision	vol_lod22 double precision
0363100012072115	4777.24	6311.14	9106.78	5280.79



Building 0363100012072115

This is another case where the LOD1.3 model is derived from the LOD2.2 model using the highest height, without considering the variation in heights of the building.



	identificatie character varying	vol_ahn double precision	vol_lod12 double precision	vol_lod13 double precision	vol_lod22 double precision
1	0363100012108817	448.43	532.9	511.4	471.5
2	0363100012108409	377.7	365.26	520.71	358.86
3	0363100012084230	344.61	370.57	359.83	358.96

Building 0363100012108409

In this case, the LOD1.3 model is also derived from the LOD2.2 model using the height of its neighbor.

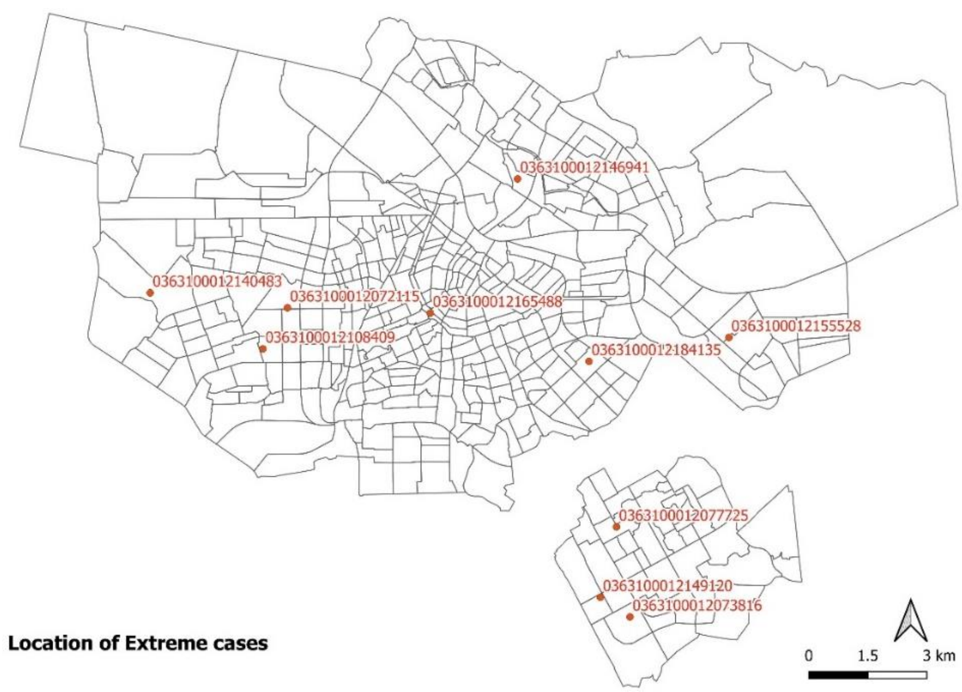


Figure 33 Locations of the ten extreme cases

In brief, volume differences happen for small building footprints and very large building footprints are due to the "Buurt Generator". On the one hand, the choosing of the median height to be extruded for large building footprint building in the "Buurt Generator" can heavily affect the building volume. On the other hand, the vegetation from the DSM might have contributed to the overestimation of the building volume. The errors from the 3D reconstruction process, however, are more random and could only be tracked rather than from multi-parts buildings indicator, the large gross volume difference, or the large volume difference ratio.

3.7. Chapter conclusion

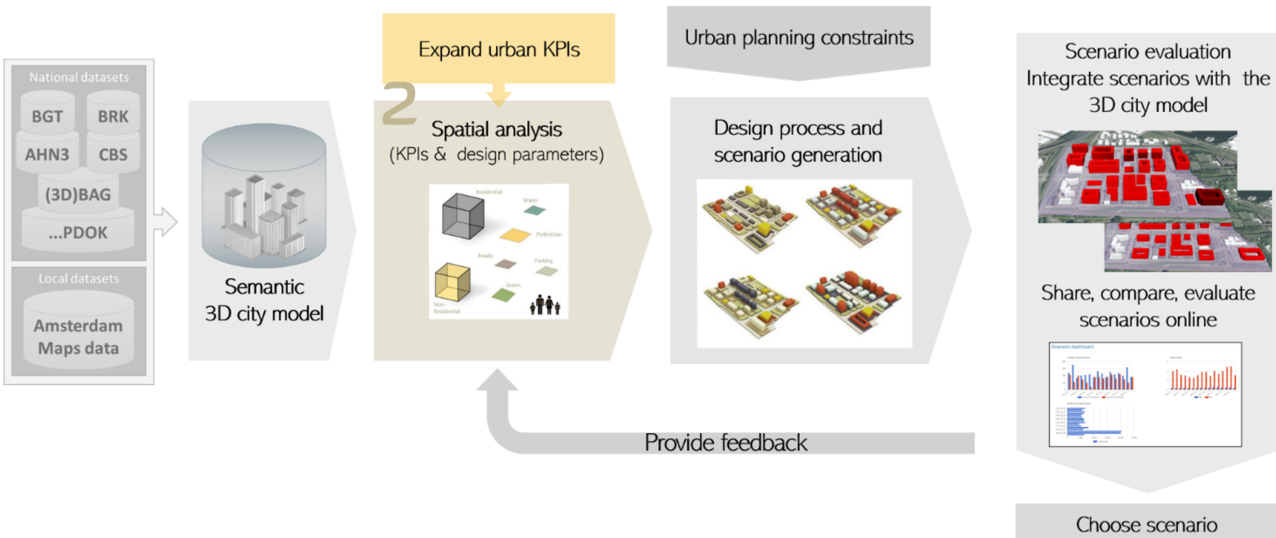
Overall, the current approach to the 3D city modeling of the "Buurt Generator" shows high similarity with the LOD2.2 regarding building's volume. Therefore, in practice, in case the LOD2.2 model is not available, the "Buurt Generator" approach could be used as a replacement for urban planning activities as it is pretty fast and straightforward to be generated. Moreover, DSM and DTM rasters are considerably widely available. However, there are also cases where the volume gaps between the models are high due to errors from one of the models or both.

On the one hand, buildings might be incorrectly reconstructed, which are typical errors from the 3D BAG 2.0. The above investigation has pointed out that multi-parts buildings in LOD1.3 and LOD2.2 are problematics and might underestimate the building volume. There are some other cases where the buildings are wrongly generated that do not represent the shapes and sizes of the buildings in reality. On the other hand, the model from the "Buurt Generator" might overestimate the buildings' volumes in the case of buildings with tiny footprints or might underestimate the buildings' volumes in the case of buildings with very large footprints. By querying buildings with extreme volume differences (more than 40% in ratio), buildings with errors could be rapidly screened out.

Hence, there are some concerns in using the 3D model of the "Buurt Generator" for the volume estimation and deriving urban KPIs. Residential buildings, that are usually average in size, show the lowest gap in volumes between the models. Hence, volumetric urban KPIs relating to residential aspects from the "Buurt Generator" are rather reliable. Buildings with tiny footprints are problematic but they are mostly of unknown function which are not addressed in deriving urban KPIs, thus, they are not a great concern at this development stage of the "Buurt Generator". However, for mixed-use and non-residential buildings of large footprint, the gap of millions of cubic meters is problematic. It is due to the chosen height value to extrude the building footprint. Hence, further investigation is needed for a better choice of height value. It could have resulted in a higher percentile value than the median value, that is currently used in the "Buurt Generator".

The assessment of volume derive from the 3D city model in the "Buurt Generator" clarifies the reliability in using volumetric urban KPIs in the latter steps of the tool. Furthermore, it also points out some limitations regarding tiny building footprint and very large building footprint. It is important to note that the volumes derived from the model do not represent the true volumes of the buildings but their relative values, as the model is in LOD1. However, for the purpose of extracting urban KPIs at the city and neighborhood level, the volumes derived from LOD1 model are sufficient and also efficient regarding the effort it takes to generate the model.

4 Urban KPIs for the pre-design stage



4.1. Chapter introduction

In the pre-design stage, the fundamental principle of the "Buurt Generator" is to learn from the current context – the City of today – by extracting urban KPIs at the neighborhood scale. Some urban KPIs are used to identify template neighborhoods for the new development site, whereas some other urban KPIs are extracted from the template neighborhoods to be used as inputs for the design of the new project. The very first version of the tool – which was developed by (Garcia González, 2019) – selected the template neighborhoods based on personal experiences towards the city context, then KPIs are extracted from these neighborhoods. These include the average volumetric size of a dwelling unit, the average volumetric size of non-residential space per dwelling unit, and the average area of open spaces (bike lanes, footpaths, parking, greeneries, and roads). The current version of the tool (Agugiaro et al., 2020) queries template neighborhoods based on a set of urban KPIs stored in a database Figure 6. The KPIs of the template neighborhoods should meet the development requirement of the new project site (see Table 9). Then, the same volumetric KPIs are extracted from the templates to be applied in the design stage.

Requirements from the development site (Sloterdijk One)
80 % residential – 20 % non-residential
Density: 192 households/ha
Respect existing mobility infrastructure
23 m. Max height commercial
30 m. Max height residence
40 m. Max height offices
FSI = 2.2 / 3.5 (or FAR – floor area ratio)
Car index = 0.9
Super high quality of life

Table 9 Development requirements of the new development site (Garcia González, 2019)

The current approach limits the contextual information at the neighborhood scale and limits the choice of design KPIs by template neighborhoods. However, the selection of a perfect neighborhood that fits the development goal of the new site is not convincing enough. The neighborhoods that were developed in different periods of time and contexts (location, available construction technologies, and materials, architectural trends) have their own trademark, pros, and cons. Furthermore, the KPIs shortlist to select template neighborhoods is also oversimplified.

Therefore, this thesis attempts to approach the pre-design stage differently by first reading the city in terms of its available spatial/social-economical information. It also attempts to step out of the neighborhood's boundary to include other contextual information and to break down the information as much as possible to avoid oversimplification. The approach is destined to give a comprehensive overview of the current status of the city and the development site from different perspectives and to generate a ready database of urban KPIs to be used in the design stage. After that, it will be the task of the urban practitioners to interpret the development context and to reason the selection of KPIs for any new urban development sites within the city. This chapter is therefore structured into two main parts. The first part introduces the development of urban KPIs and interprets the city context. The second part focuses on the extracting of urban KPIs for the new development sites.

4.2. Urban KPIs and Interpretation of City Context

A list of different urban aspects and criteria is first developed (based on the literature on physical density and urban development – Chapter 1) to guide the computations of urban KPIs in the subsequent steps. Accordingly, urban data are collected, and urban KPIs are computed for the whole city.

Urban aspects	Criteria
Demographic	Distribution of population according to size and age classes Distribution of household according to size and types
Built environment	Distribution of volumetric density Distribution of footprint density Distribution of buildings according to functions
Housing	Distribution of dwelling types and dwelling sizes
Indoor amenities	Distribution of built infrastructure/amenities according to types and total volume
Outdoor amenities	Distribution of road types (regional and local street, pedestrian, bicycle lanes) Distribution of natural amenities (greeneries, watershed)
Development period	Distribution of building according to the development period
Quality of life	Overall indicator and categorical indicators (housing, amenities, safety, and security)

Table 10 Urban aspects and criteria

4.2.1. Data preparation and calculation

[1] Volumetric KPIs

In the previous work, the average volume of dwelling and the average volume of non-residential function per dwelling was derived from the total residential/non-residential volume of a neighborhood divided by the corresponding total number of households. Based on the BAG dataset and the FUNCTIEKAART dataset, the buildings that have non-residential functions were identified, and the non-residential volumes were calculated based on the data on the net floor area of each function from the FUNCTIEKAART. In the case of mixed-use buildings, the total residential volumes were then derived from the difference between the total building volume (from the "Buurt Generator" as discussed in Chapter 2) and the calculated non-residential volume.

There are some concerns about the current approach in deriving volumetric urban parameters. Firstly, the denominator of the calculations is the number of households per neighborhood obtained from CBS. However, it is noted that the number of households is not necessarily corresponded with the number of dwelling units, as one dwelling can possibly contain more than one household. Secondly, there was no differentiation between types of housing (Multi-family house, Single-family house, Mixed-use house) as the living space might be different among those. Thirdly, the FUNCTIEKAART dataset is available only for Amsterdam City that potentially limits the reusability of the "Buurt Generator" tool in the case that data equivalent to the FUNCTIEKAART are unavailable for other cities.

The thesis, hence, attempts to differentiate housing types, derive the number of dwelling units per housing type, and the average dwelling size of each housing unit. Regarding the indoor amenities, the current product grouped them into only one single type to derive the non-residential volume. However, as discussed in Chapter 1, urban amenities could be classified into different groups according to the need of the inhabitants and the function of the new development site. Therefore, the thesis attempts to differentiate indoor urban amenities, arrange them into groups, and derive the total volume per group per neighborhood. Only a national dataset (BAG) is used for reproducibility purposes.

Data	Sources	Description
BAG PAND	ftp.data.amsterdam.nl	The dataset contains the 2D geometries of building roof outlines with attributes on the year of construction, building types, etc. Each building has a unique id stored in the field "identificatie"
BAG VERBLIJFSOBJECT		The dataset contains the smallest unit of use located within one **or more buildings** and suitable for residential, commercial, or recreational purposes. It has its own lockable access from the public road, a yard, or a shared traffic area, may be subject to property law, legal acts, and is functionally independent. (https://www.amsterdam.nl/stelselpedia/bag-index/catalogus-bag/objectklasse-vbo/)

Table 11 BAG datasets used in the tool

Data manipulation in FME – see Figure 34

In FME, the buildings are classified in terms of Single-family house (SFH), multi-family house (MFH), non-residential (single function), non-residential (multi-functions), mixed-use, and Unknown function. In addition, the building functions and the respective net floor areas are also recorded for each building. For the "BAG PAND" dataset, only building footprints used in Chapter 1 are kept for data consistency reasons.

After that, spatial relation was performed that for each building footprint, there will be a list of related functions (with function names and net areas) attached to it. Building footprints that have no spatial relation are classified as "Unknown building". A simple query was performed to check on these buildings, highlighting that they mostly have a very small building footprint (less than 20 m^2) – therefore, it is reasonable to classify them as Unknown, as the floor space is indeed too small to be considered for residential function. Then, the remaining buildings were classified in terms of single function (having one spatial relation) or multi-functions (having more than one spatial relation). Those that are single function are classified into SFH and Non-residential (single function) based on the "woonfunctie" (residential function) keyword in the list of functions. Those that are multi-functions are divided into two groups: with "woonfunctie" (multi-family houses and mixed-use buildings) and without "woonfunctie" (Non-residential (multi-functions) building). For the buildings that are mixed-use or non-residential, their function lists are exploded, classified into groups of urban amenities, aggregated in terms of the number of functions and net area of functions. This information is later merged back to the building footprint id, then, are written directly to PostgreSQL database, table "Building_info" after removing geometry.

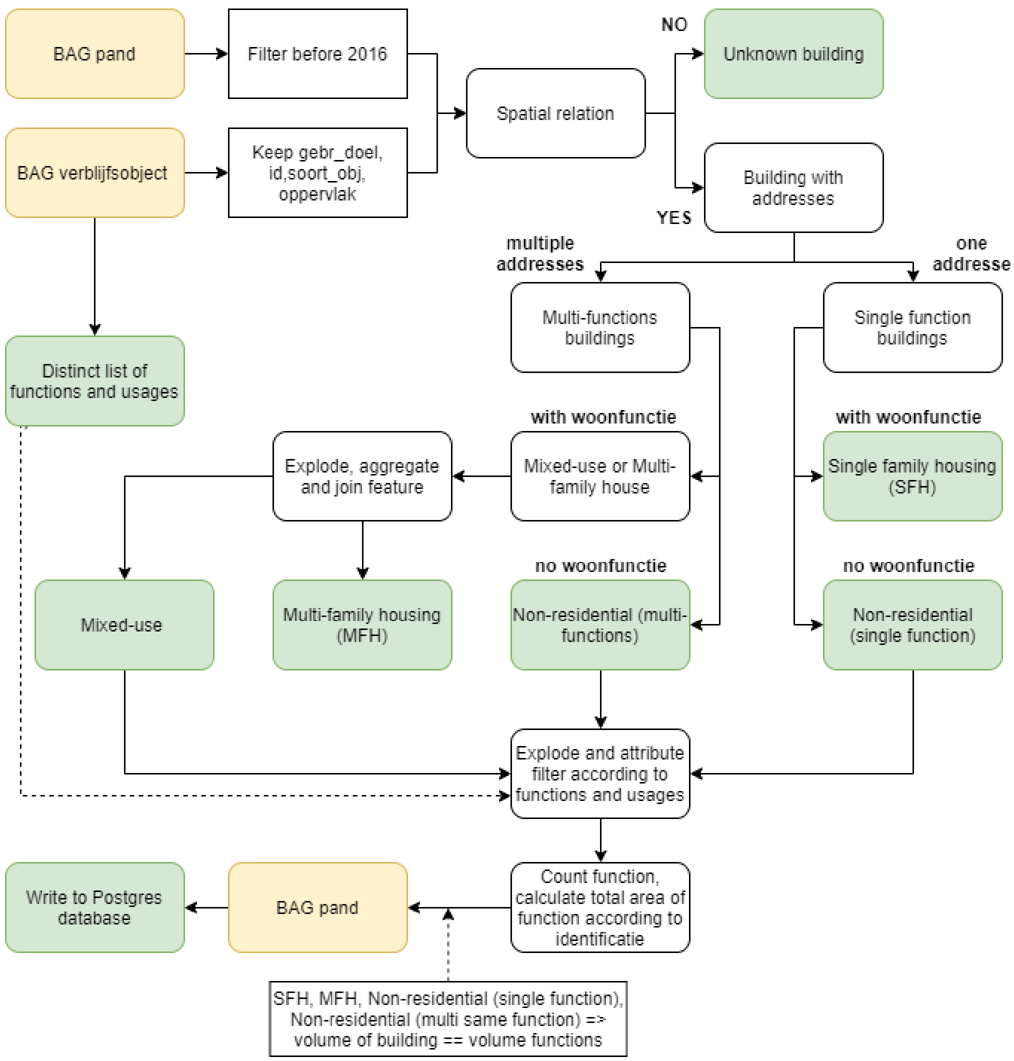


Figure 34 Building classification workflow in FME

The same procedure was applied for the "BAG PAND" and the "FUNCTIEKAART" datasets (that are used in the current "Buurt Generator" tool) to find out which approach gives more information. It was later found out the computed functional areas from both datasets are quite similar. However, "BAG VERBLIJFSOBJECT" has more records. Furthermore, "BAG VERBLIJFSOBJECT" can also be used for other urban areas in the Netherlands, while the "FUNCTIEKAART" is available only in Amsterdam.

Data manipulation in PostgreSQL

In the PostgreSQL database, additional information was added and calculated, that includes:

- The total building volume from the "Buurt Generator" 3D models is added to table "Building_info". For buildings that have significant differences in terms of computed volume between the "Buurt Generator" and the 3D BAG 2.0 LOD2.2 (the volume from "Buurt Generator" is much smaller), the volume from LOD2.2 is used instead (refer to Chapter 2 for more details).
- For buildings that are SFH, MFH, Non-residential (single function), Non-residential (multi-functions) with one type of function, the total building volume is assigned to the function volume.
- For buildings that are Mixed-use and Non-residential (multi-functions) that have more than one type of function, the net area information is used to calculate the volume of the function. A conversion factor from net area to gross area of 1.2 and an average height of 3.5 meters are used. In the current "Buurt Generator", the used factors are 1.3 and 3.5 accordingly, they are, however, results in a large number of buildings having a total functional volume greater than the volume derived from the 3D model. Hence, smaller factors are selected that still fit the thresholds from the literature review. The residential volume in Mixed-use buildings is calculated by subtracting the total building volume from the calculated volume of non-residential functions.
- The average dwelling volume per residential building is calculated by dividing the residential volume by the number of dwelling units of the building.
- All building-related information is stored in the table "Building_info"

Although errors are minimized from the total building volume (by use LOD2.2 for building with large volume gap) and the conversion factors from net area to gross volume, some problems still occur as follows:

- Very small average dwelling volumes occur that do not align with the city's policy on minimum dwelling size (i.e., minimum net floor area of 25 m^2).
- For Non-residential (multi-functions) buildings, in some cases, the total building volume is still smaller than the sum of the volumes of all the functions (calculated from net floor area) within the building.
- For Mixed-use buildings, in some cases, there are no volumes left or negative volume after subtracting the sum of the volumes of all the non-residential functions from the building volume, that there is no volume left for residential functions.
  (This phenomenon also happens if the "FUNCTIEKAART" is used instead)

From visual inspection, there are cases where the records of net floor area are not reliable (e.g., 1 m^2, 9999 m^2) and there are cases where the total volume of non-residential functions – when converted into the corresponding building height - would lead to very high building, which is not likely in the case of Amsterdam. On the one hand, they could be errors or simply a lack of information. On the other hand, the case where one non-residential function that is attached for one building but actually belongs to more than one building is also the case (see Table 11). As a result, buildings that do not meet the following constraints are filtered out:

- Minimum average dwelling volume of 90 m^3.
- Minimum net floor area of 10 m^2 for store, catering, indoor infrastructure, parking garage, and 30 m^2 for the other non-residential function.

- Difference between the total volume of non-residential functions and the total volume of non-residential (multi-functions) building larger than 100 m^3.

Lastly, the information of volumetric parameters at the building level is aggregated to the neighborhood level. Four sets of data are created as follows:
- Information on building at the neighborhood level,
- Information on housing at the neighborhood level,
- Information on indoor urban amenities at the neighborhood level,
- Information on indoor urban amenities at the neighborhood level with a buffer zone.

The first three datasets are derived directly in PostgreSQL. For the fourth dataset, the purpose is to include the urban facilities within a distance from each neighborhood, as the neighborhoods are not self-sustaining.

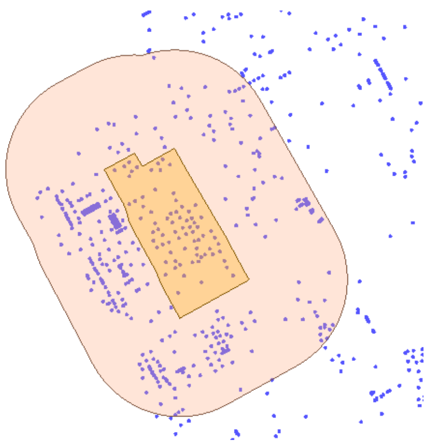


Figure 35 A buffer zone of 800 meters from the neighborhood boundary (in this case T92b, Amstel III deel A/B Noord) that covers the indoor urban amenities of the surrounding areas

Since all information on usage zones/functions and their volumes are stored at the building level in table "Building_info", they are transferred back to the shapefile of BAG PAND. After that, a new layer that contains the central points of all the footprints in BAG PAND with the new information from table "Building_info" is created. Meanwhile, a loop is created in FME that iterates through the neighborhoods, makes a buffer zone of 400/800 meters from the neighborhood boundaries and clips the just created layer of the building's central points. Then, the statistical aggregation in FME was used to get the number of functions and the function's volume within each neighborhood and its buffer zone.

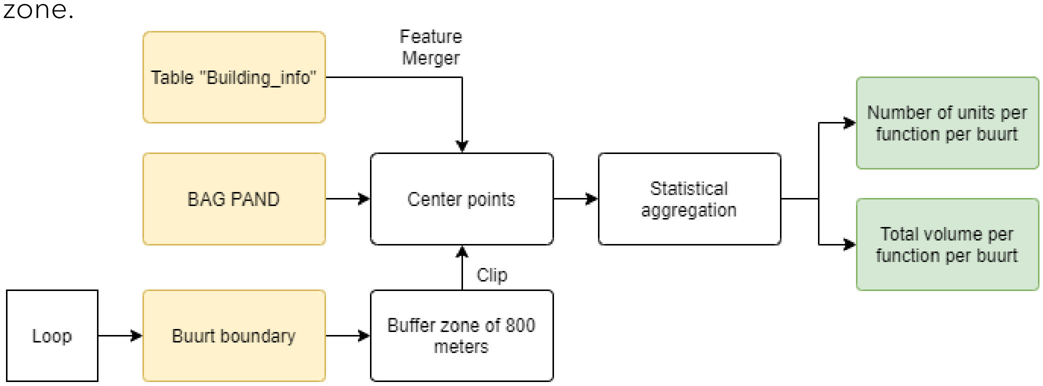


Figure 36 FME workflow to generate Information on indoor urban amenities of the neighborhoods and their buffer zones

[2] Other non-volumetric KPIs

Socio-economic data such as population, household, quality of life, housing price at the neighborhood level were retrieved from different open data portals and were uniformly stored in the project database for analysis and visualization. Regarding outdoor amenities (footpath, bike path, street, green landscape, and water surface), the same buffering approach as the indoor amenities was used on the BGT datasets, only that the buffer distance is set as 400 meters.

The buffer zone of 800 meters (10 minutes walking distance) was chosen for accessibility to indoor urban amenities, whereas it is 400 meters (5 minutes walking distance) for outdoor amenities. It is because people are willing to travel further for purchasing goods or for recreational activities, whereas outdoor urban amenities such as bike path, footpath, greenery is essential to the living quality surrounding the living area.

Figure 37 The buffer zone of 400 meters from the neighborhood boundary (in this case T92b, Amstel III deel A/B Noord) that covers the outdoor urban amenities of the surrounding areas (in this case, the green landscape)

[3] The database for the Urban KPIs

A schema that contains different tables on different urban aspects of the city in 2016 is created. The datasets are recorded either at the building scale or at the neighborhood scale that supports queries for the City Reading to understand the city context comprehensively and comparatively.

Scale	Name of the table	Content of the table
Building	Building_info	All information at the building level (without geometry) is stored according to the building id ("identificatie"). Included are the number of dwellings, usages (per type), net floor area of usages (per type), and volume of usages (per type), age class, and price range. The type usages/functions consist of Culture, Religion, Catering, Hotel, Bar-dancing, Sport and Recreation, Healthcare, Kindergarten Daycare and Primary School, Higher Education, Office, Industry, Store, Transportation, Infrastructure, Housing, Parking & garage, Other, and Unknown.
Neighborhood	Buurt_building	Building information at the neighborhood level. Included are the number of buildings, number of buildings per

Scale	Name of the table	Content of the table
		development period, number of buildings per building type, the volume of building per building type, number of buildings per development period, total building footprint, total building volume, footprint density and volume density.
	Buurt_housing	Housing information at the neighborhood level. Included are the number of dwelling units, number of dwelling units per building type, total, average, and median dwelling volume per building type, indoor amenities volume per dwelling, and outdoor amenities area per dwelling.
	Buurt_indoor_amenties	Indoor amenities at the neighborhood level, included are the total volume per function per neighborhood.
	Buurt_indoor_amenites_ buffer	Same as above, but include the volume of indoor amenities from the surrounding neighborhood (800 m of buffer zone)
	Buurt_outdoor_amenities	Outdoor amenities at the neighborhood level. Included are water surface, footpath, bike path, local street, regional street and green landscape.
	Buurt_outdoor_amenities _buffer	Same as above, but include the areas of outdoor amenities from the surrounding neighborhoods (400 m of buffer zone)
	Buurt_population	Population information at the neighborhood level. Included are the total population, population per age class, population density, dwelling volume per person, indoor amenities (800 m buffer) per person, and outdoor amenities (400 m buffer) per person.
	Buurt_household	Household information at the neighborhood level. Include are the total number of households, number of households per household type, household density, dwelling volume per household, indoor amenities (800 m buffer) per household, and outdoor amenities (400 m buffer) per household.
	Buurt_liveability	Livability index at the neighborhood level.

Table 12 The database structure for the Urban KPIs

4.2.2. Interpretation of the city context

[1] Demographic context

At the city scale, population between 25- and 45-years old accounts for the largest share of the Amsterdam total population, followed by the age class of 45 to 65 years old. At the neighborhood scale, the number of residents and the population density per neighborhood are highest within the area surrounding the old city core. The values decrease in the old city core and in the area towards the city's edges. In addition, the share of the age class of 25-45 years old is also highest in the neighborhood having the highest population density. The densest area located to the North West of the old city core has a very high share of the young working class, with an average of 50% of the total population, the same for the areas located on the South East of the city core. The share of population according to age class is more equally distributed for sites located far away from the city center (see Figure 38).

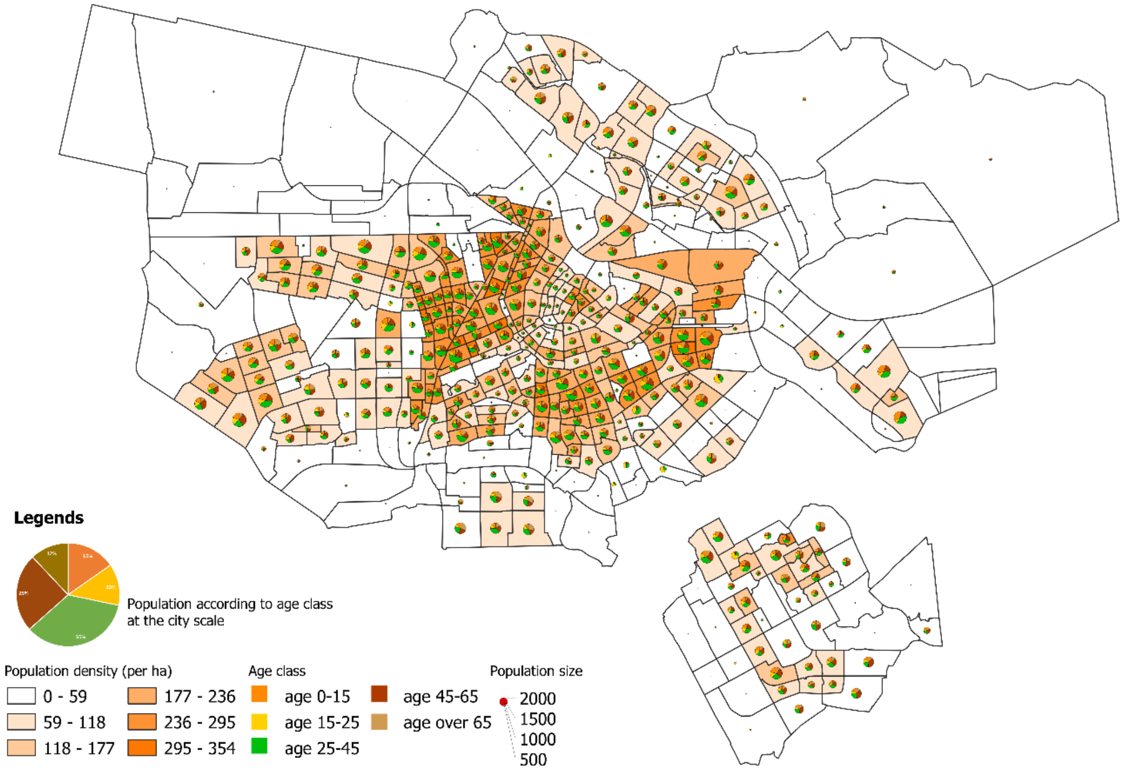


Figure 38 Spatial distribution of population in Amsterdam in 2016

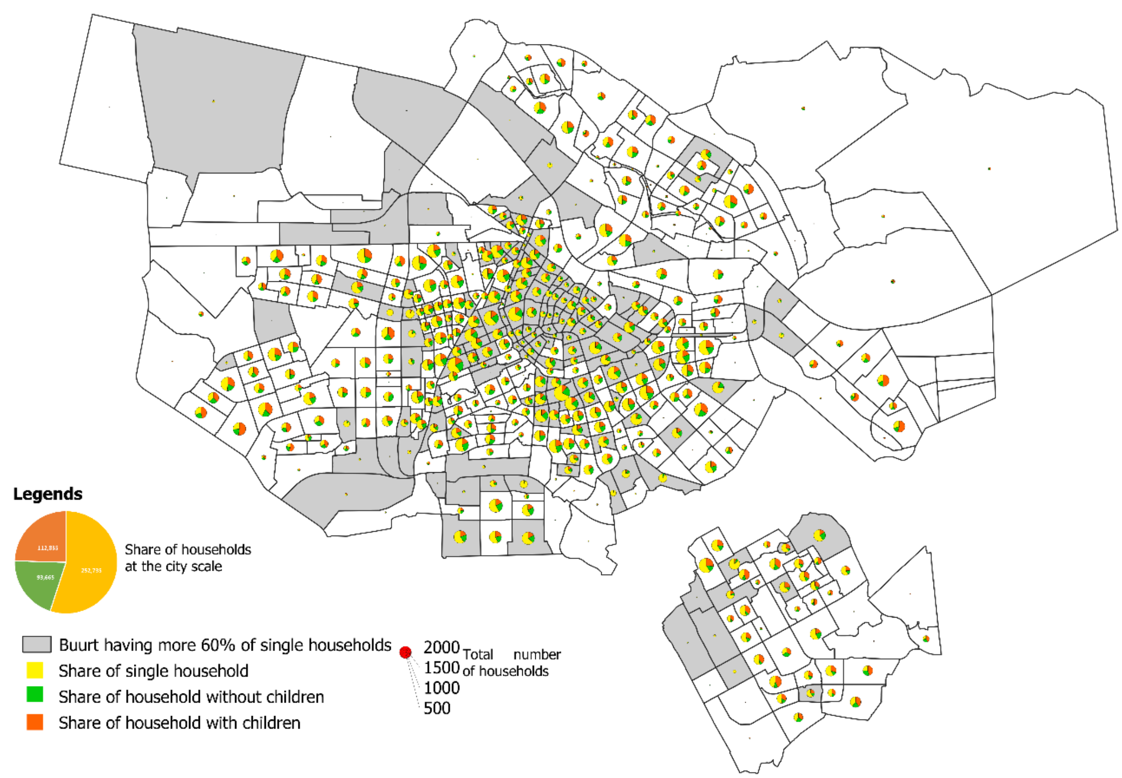


Figure 39 Spatial distribution of households in Amsterdam in 2016

Regarding the distribution of households, single households occupy the largest share with more than 50% of the total number of households, following by households with children and households without children accordingly. Single households also concentrate in the old city core and its close surroundings, whereas households with children are often situated far away from the city center. This distribution also coincides with the distribution of population (see Figure 39).

The demographic context of the city, as a result, reveals the high housing demand from single households and the young working-age class within the city. They also prefer the location within the old city core and especially its close surroundings. Other types of households, especially households with children, prefer the area farther away from the city center.

[2] Buildings and housings

At the city scale

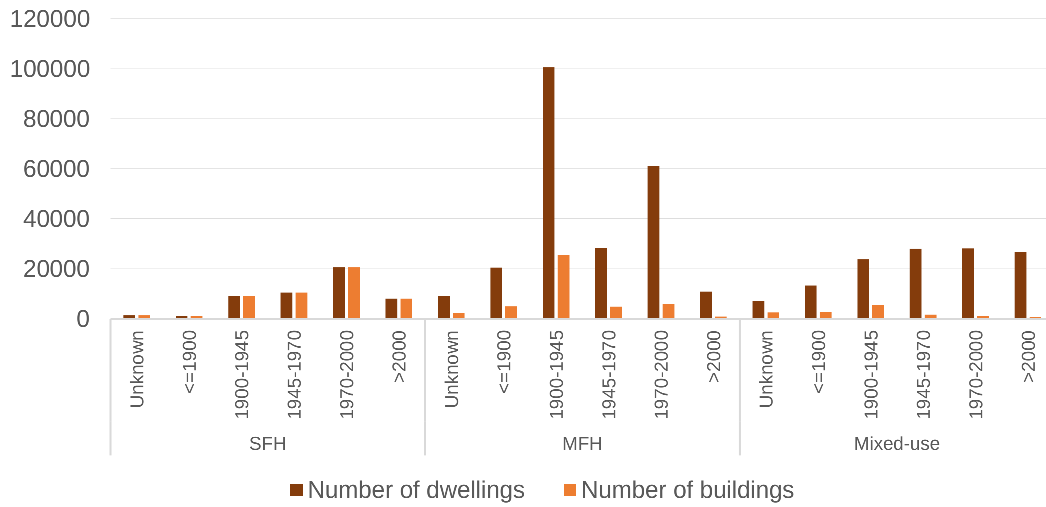


Figure 40 Number of residential buildings and dwelling units according to building type and age class

As can be observed from the above graph (see Figure 40), housing developed strongly from 1900 to 1945 and from 1970 to 2000. In terms of land occupation, while multi-family houses were prioritized between 1900 and 1945, single-family houses were strongly developed between 1970 and 2000. In terms of the number of dwellings, multi-family housing shared the most significant portion in the past, then mixed-use housing has become more frequent since 2000. Regarding multi-family housing and mixed-use housing in particular, the ratio between the number of houses and number of dwellings shows that the residential building in the recent period contains more dwelling units than in the past, indicating a trend of higher physical density development. This argument is also supported by the graph illustrating the total volume of housing buildings (see Figure 41).

In addition to the higher number of dwelling units per building, the dwelling units are also greater in volumetric size. The dwelling volume expands in size for all housing types. In particular, dwelling units that are SFH usually have larger volumetric sizes compare to those from MFH and mixed-use housings. SFH that was built before 1900, moreover, is particularly larger . Apart from the characteristics of a single housing unit that are different from an apartment, the case of more than one dwelling unit sharing the same address could also add to this figure.

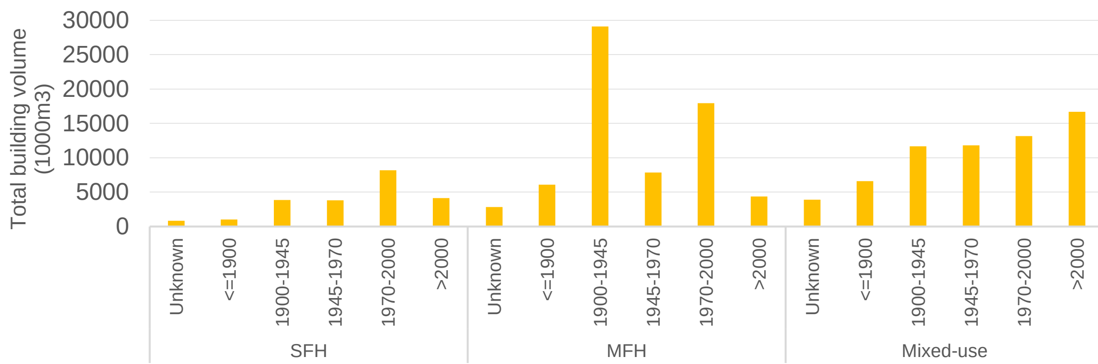


Figure 41 Distribution of total building volume according to building type and age class

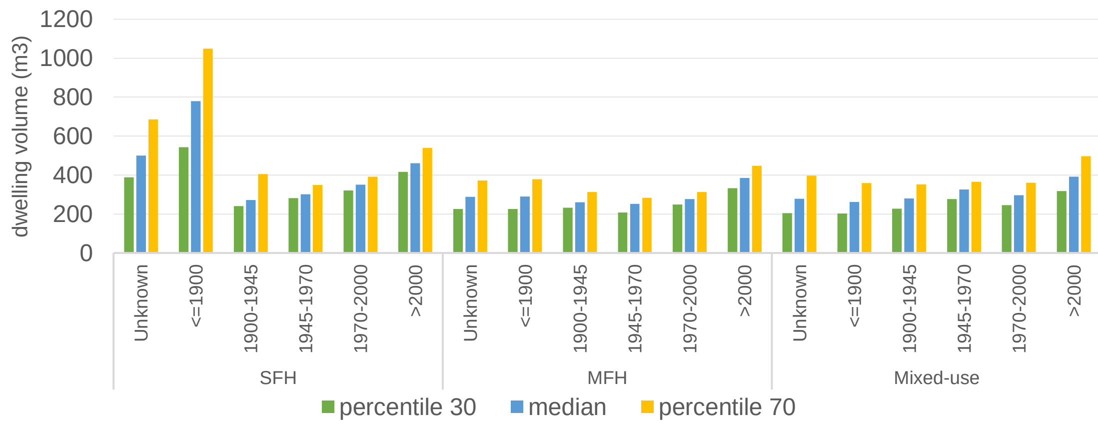


Figure 42 Dwelling size according to building type and age class

The housing price, although highly depends on the location of housing, is also investigated at the city scale. Figure 43 shows that newly built housing in the period after 1970 has a different trend in volumetric size according to price range per square meter. The dwelling volume tends to be highest at the medium price and decreases towards the two ends. Housing from 1900 to 1970, on the other hand, shows a reverse trend. Furthermore, as stated in the previous paragraphs, the dwelling units are becoming more spacious in recent years.

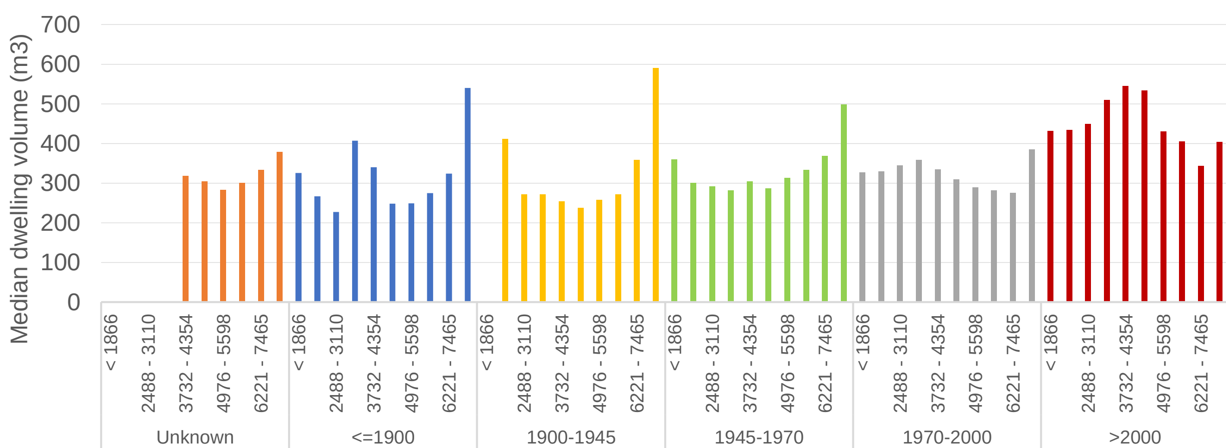


Figure 43 Median dwelling size according to age class and price range

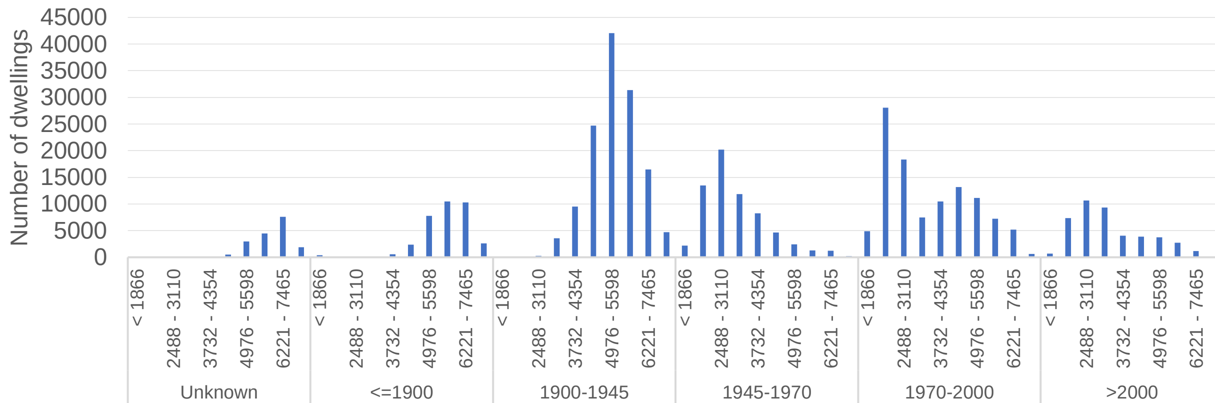


Figure 44 Number of dwelling units according to age class and price range

Regarding the graph on the number of dwelling units according to age class and price range (see Figure 44), old residential buildings (before 1945) that are mostly located within the city core and its close surrounding have a price tendency towards the higher end. On the other hand, housings from 1945 have a price tendency towards the lower end.

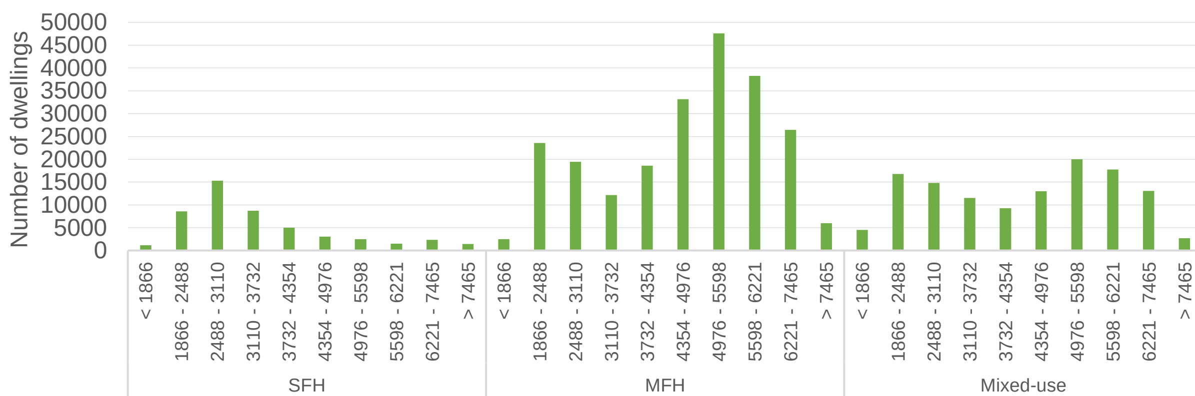


Figure 45 Number of dwelling units according to housing type and price range

The housing price per square meter and the dwelling size are proportional for the single-family house but do not show a clear trend for multi-family housing and mixed-use housing (see Figure 45).

In brief, from the distribution of housing at the city scale, some points emerge as follows:

- There is a trend of densification in housing development since multi-family houses and mixed-use houses with a higher number of dwellings were constructed in the latest period.
- The volumetric size of the dwelling is also becoming larger over time; however, it does not necessarily link with larger floor area but might be related to higher floor height or to more space designed for public uses such as hallways, elevators, community spaces, etc. Hence, volumetric size is more precise as it includes other parameters of a gross space for a dwelling.
- Recent mid-class housing (according to the price range) is greatest in size.

Therefore, the development of input KPIs for new development sites must consider the development period, the price range, the physical density, and the development types within the city. These elements will be the basis for further spatial investigation of the housing development of the city.

Buildings at the neighborhood scale

With regard to the spatial distribution of buildings according to building types at the neighborhood level, the functional composition of the city is highlighted. Firstly, there are three clusters of non-residential functions within the city, one large area located towards the North-West, one cluster located in the South, and one newly developed cluster in the South-East of the city. Secondly, higher-density types of buildings (multi-family house buildings and mixed-use buildings) concentrate within the old urban core and its close surroundings, whereas low-density types of buildings such as single-family house and non-residential building mainly locate far away from the city center. Thirdly, unknown buildings, that mostly have footprints areas lower than 20 m^2 also are found far away from the city center. They are primarily small shed, garages that are detached from the main building. It also supports the statement on the low-density type of building in these areas.

From the building density perspective, the spatial distribution of footprint density and volume density (water surface excluded) is not always proportional. High footprint density and low volume density indicate the inefficient use of land, as large land area is covered by underused space above it. Such type of development concentrates in the Southwestern part of the city, and some neighborhoods to the Northeast of the city core. Low footprint density and low volume density indicate a very sparse development pattern, mostly integrate with agricultural areas locate to the Northeast of the city. High footprint density and high-volume density cases are situated within the city core, indicate a dense and crowded urban pattern. These indicators decrease gradually for the areas surrounding the city core. Low footprint density and high-volume density pattern is not likely the case in the city of Amsterdam, at least in the year 2016.

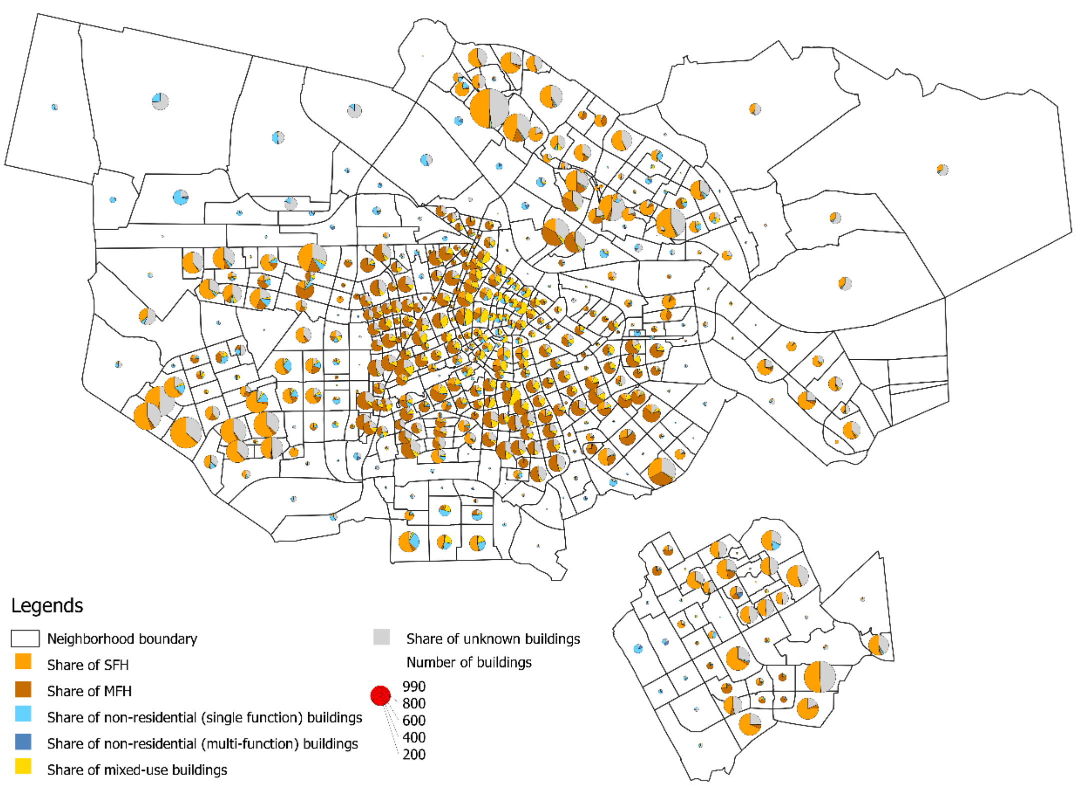


Figure 46 Spatial distribution of number of buildings according to building types

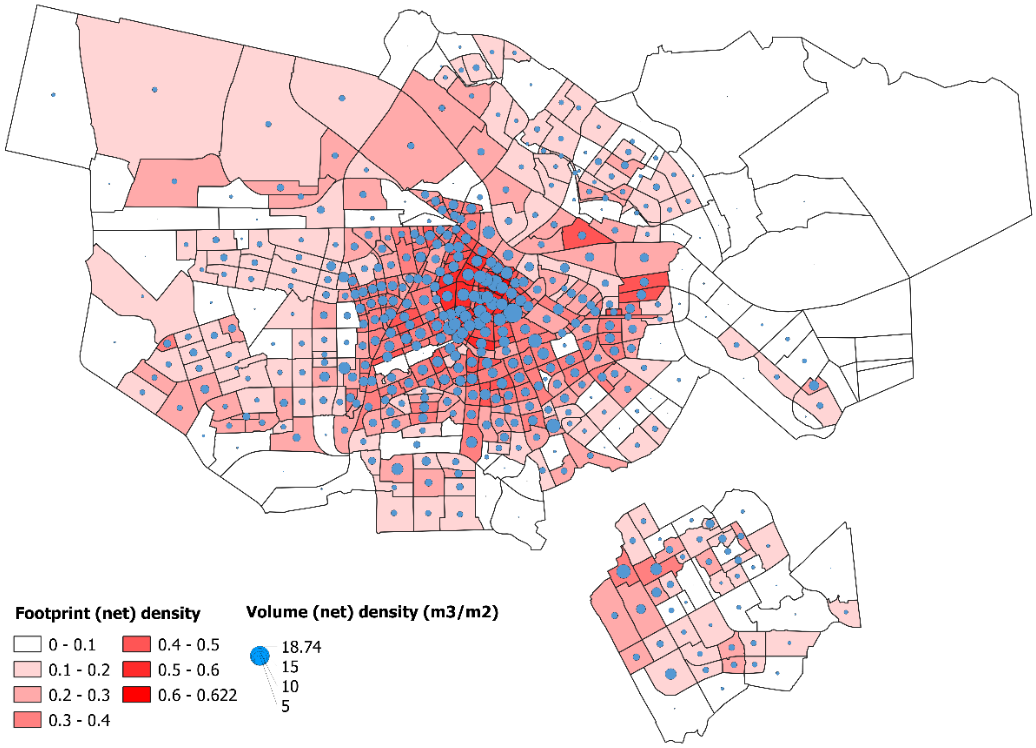


Figure 47 Building density according to building footprint and building volume

Housing at the neighborhood scale

First and foremost, it is essential to distinguish between household and dwelling unit, as one dwelling unit can contain more than one household (see Figure 48). A household is defined as people living together in a living space and who provide for themselves, not commercially, for the daily necessities of life[7]. Hence, it could be the case of single households, which provide for themselves, sharing the same flat. The total number of calculated dwellings accounts for 407745 units, whereas the total number of households in 2016 accounts for 459235 units (CBS Wijken en Buurten 2016). Hence, there is a significant gap between these two values. The use of households to calculate the average dwelling volume in the current Buurt Generator is consequently problematic. Therefore, for the upcoming computation, the number of dwelling units is used instead, as it is difficult to determine the number of households sharing the same dwelling unit. However, it could be the case that a building having more than one dwelling unit but is not registered accordingly. This phenomenon is, however, not detectable with the available data despite being known to exist in reality. On the other hand, there are also cases where the number of dwellings is larger than the number of households (neighborhoods in grey color) indicating the underused housing in some areas. However, there could be cases of misclassification due to the volumetric constraint and also from the unclear registered function (e.g., "woofunctie" and "winketfunctie" for one unit).

[7] https://www.cbs.nl/nl-nl/cijfers/detail/71486NED

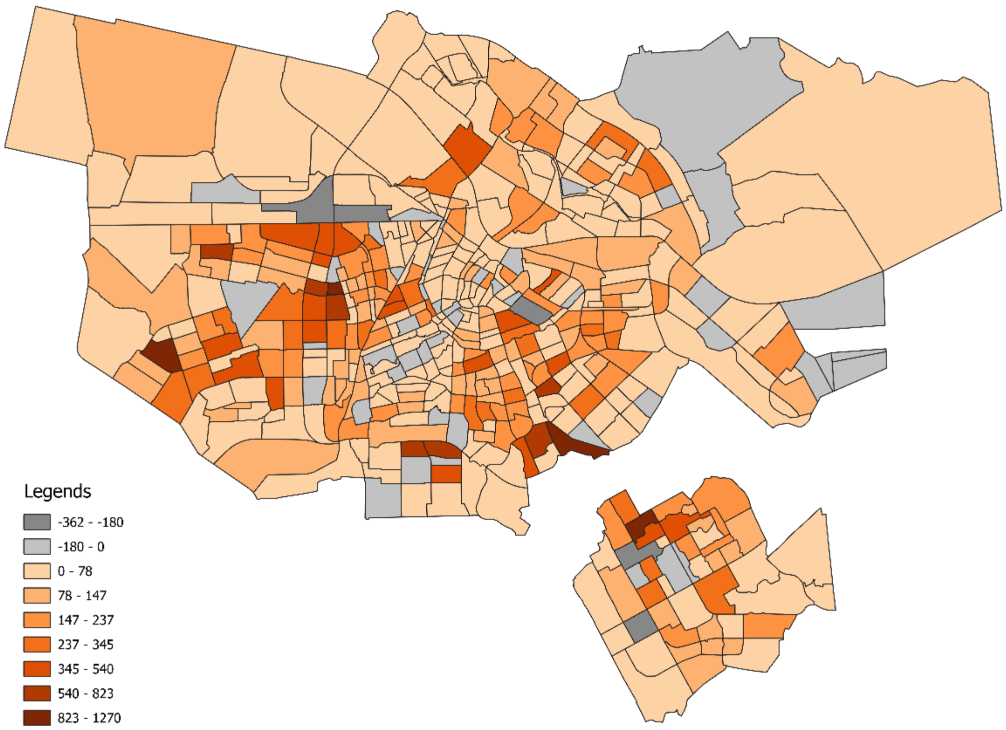


Figure 48 The difference between the number of households and the number of dwellings (household minus dwelling)

The spatial distribution of dwelling types and the number of dwellings resembles building type and building density. The below map Figure 49 shows that dwellings in the city core mainly belong to mixed-use housing, whereas dwellings close to the city core are mostly from multi-family houses. In the second development ring from the city core, mixed-use housing shows a more significant share, together with the multi-family housing. The area towards the city's edge, on the other hand, shows a great share of single-family housing.

Due to data imperfection and reality, there are some very small and very large building units. Hence, the median volumetric dwelling size is used instead of the average dwelling size to avoid bias, although, for most of the cases, they show very close values. In addition, neighborhoods with a very small number of buildings (less than 50) are also excluded from the map to avoid misleading values since there might be missing values from the datasets (see Figure 50). The map on the spatial distribution of dwelling size reveals that single-family house is often greater in volume. The size of the single-family housing within the area surrounding the city core is the largest, while the buildings accounting for a minimal share of dwellings. In general, the dwellings in the city core are smallest for all housing types. Furthermore, some clusters around the city have a larger dwelling size. One locates on the Eastern and Northeastern side of the city. Another locates on the Southwestern side of the city. The mixed-use building in the city core is very different from the other areas. They are mostly shophouses with no clear distinction with the living space, which makes the average dwelling volume of the mixed-use building in this area relatively small.

Figure 49 The spatial distribution of dwelling types and number of dwellings

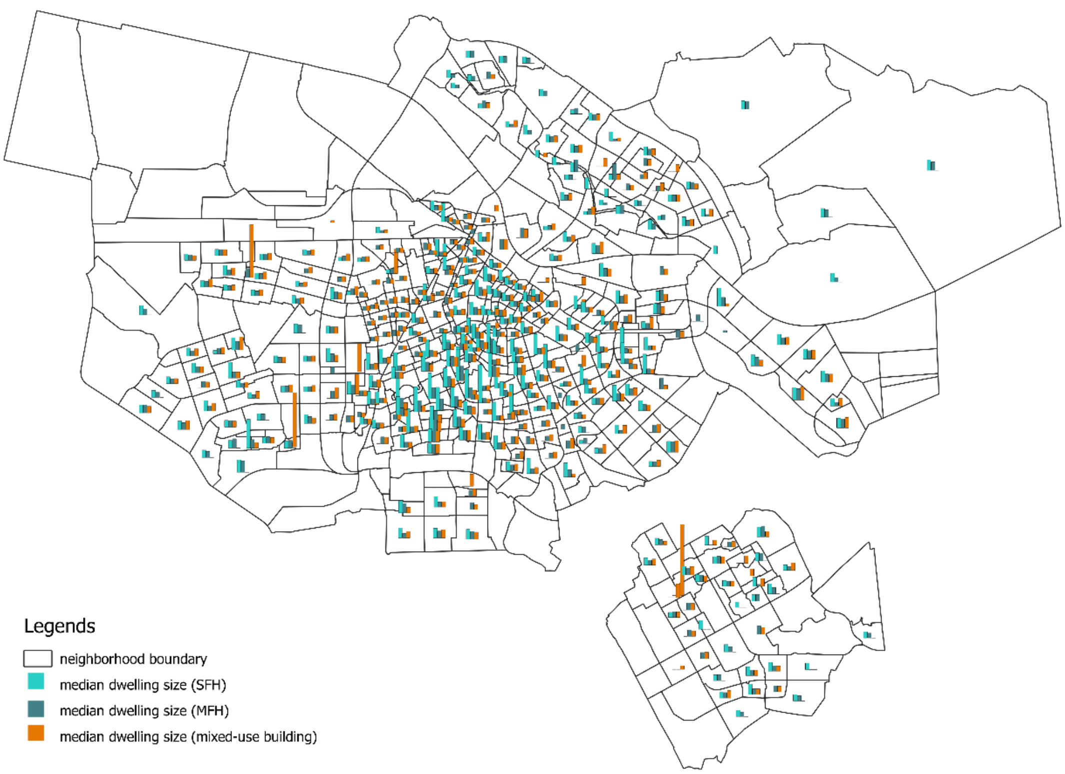


Figure 50 The spatial distribution of dwelling size in volume

[3] Indoor urban amenities

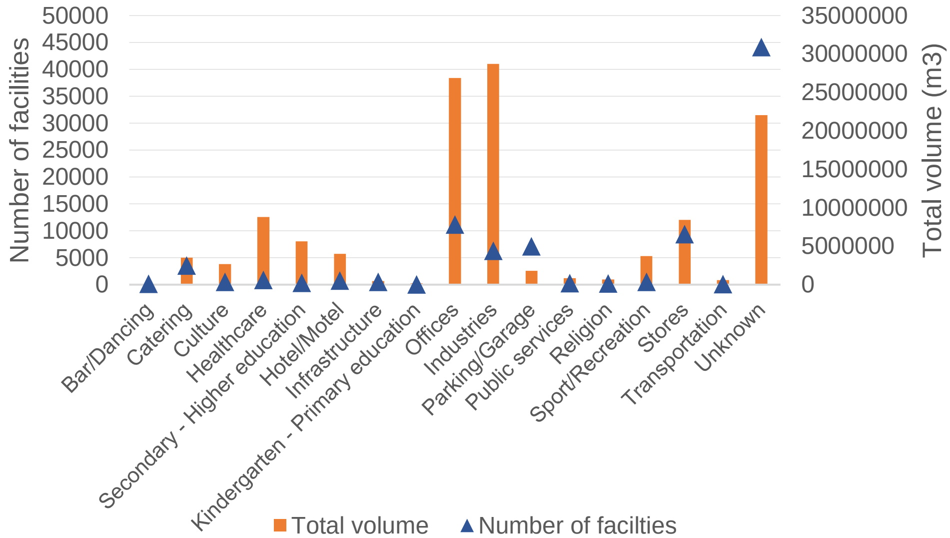


Figure 51 Overview of indoor urban functions with regards to volumetric size m³

The distribution of indoor urban functions at the city scale in terms of total volumetric size reveals the functional components of one city. And by comparing these parameters with other cities (e.g., dividing by the number of population), the roles of different cities within a region could be clarified. As can be observed from the above graph, Amsterdam is a dynamic, multi-functional city that is rich in cultural, educational, recreational, and other services. The city is also a center of commercial and production activities that account for a great share of non-residential functions.

Looking closely at the distribution of indoor functions at the neighborhood level (see Figure 52), the urban core has a more diverse pattern than the outer areas, which have a more mono pattern of amenities. The urban core plays a role of a center of cultural, recreational, tourism and education activities with a variety and large volume of urban functions. The level of diversity and the total volume decrease with distance from the city center. Besides, there are three clusters of office and industry functions locate in the North-Western, the South, and the Southeast of the city that correspond with the distribution of non-residential functions stated above. Some North-Western that are far type from the city center but have a comparable great volume with regard to the surroundings and have a great share of services are likely to be sub-centers of the area.

However, to estimate the accessibility to the urban amenities, it is not reasonable to use the data within the neighborhood boundary but also from the surrounding area (see Figure 53). The second map on indoor urban amenities with a buffer zone of 800 m, as a result, shows an equal distribution of amenities among the neighborhoods. These data will be used for further calculation on accessibility with regards to the dwelling unit. For the neighborhood located at the edge of the city, the amenities from other administrative units are not considered – bt could be easily added as soon as data are provided.

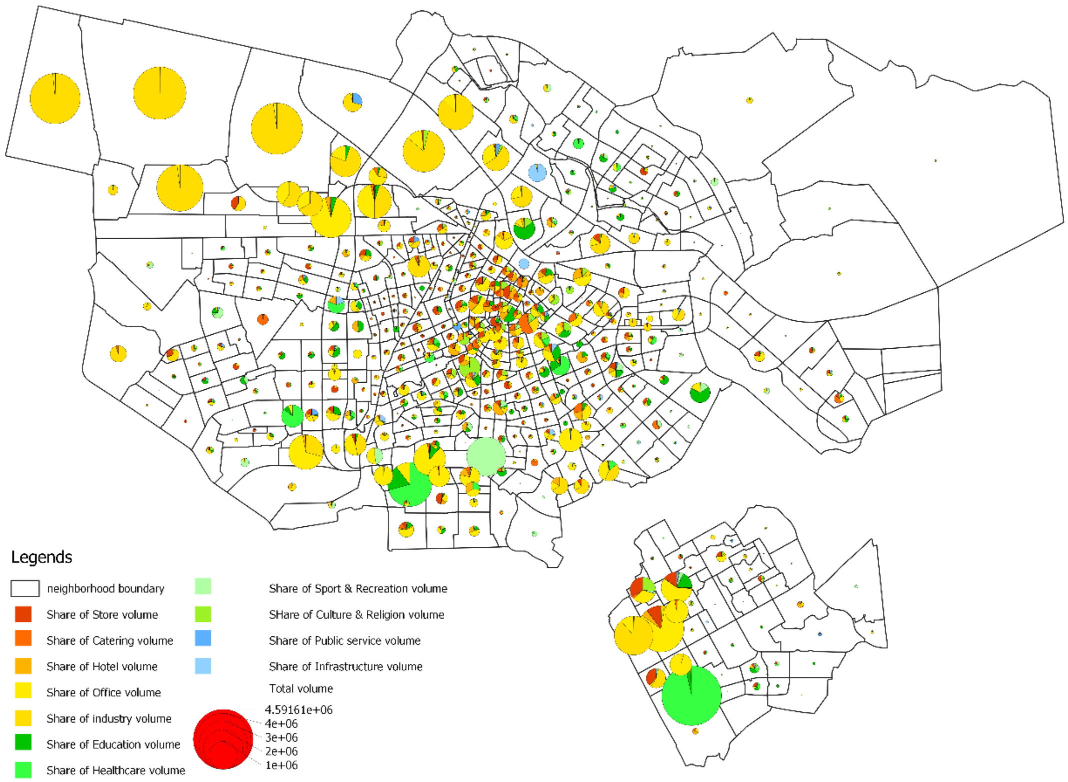


Figure 52 Volumetric distribution of indoor amenities

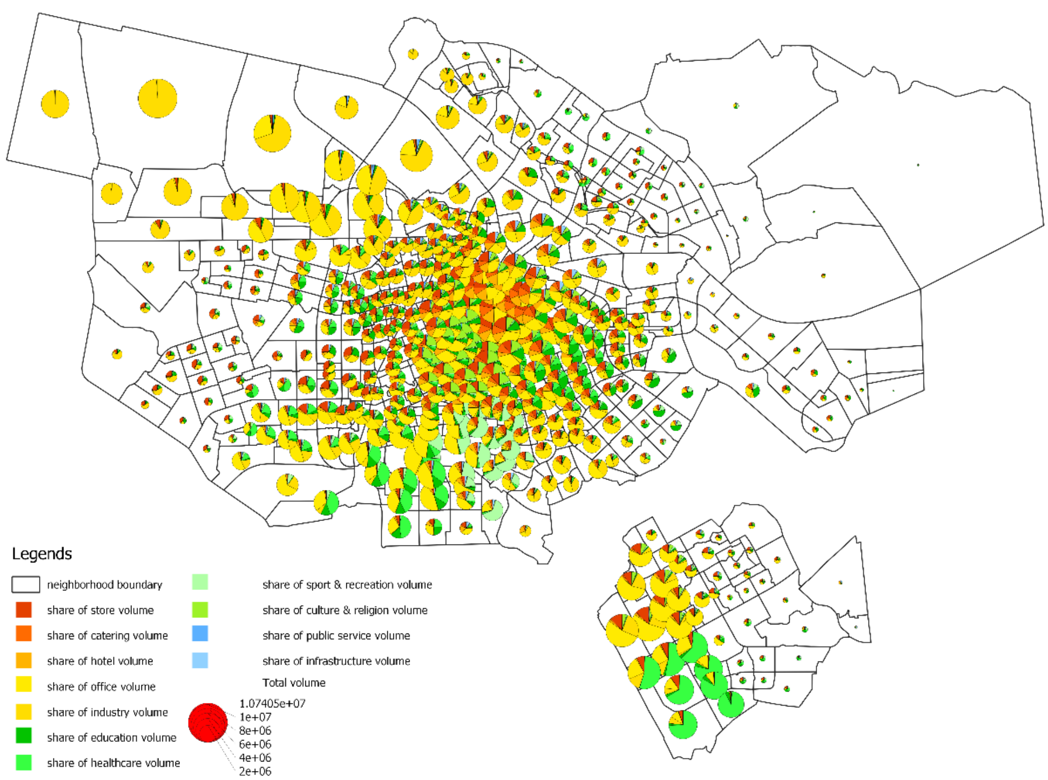


Figure 53 Volumetric distribution of indoor amenities with buffer zone of 800 m (the scale of the pie chart is reduced compared to the above map for visibility)

The map on the ratio between residential and non-residential volume also reflects the distribution of indoor urban amenities, but also shows the functional status of different areas within the city (see Figure 54).

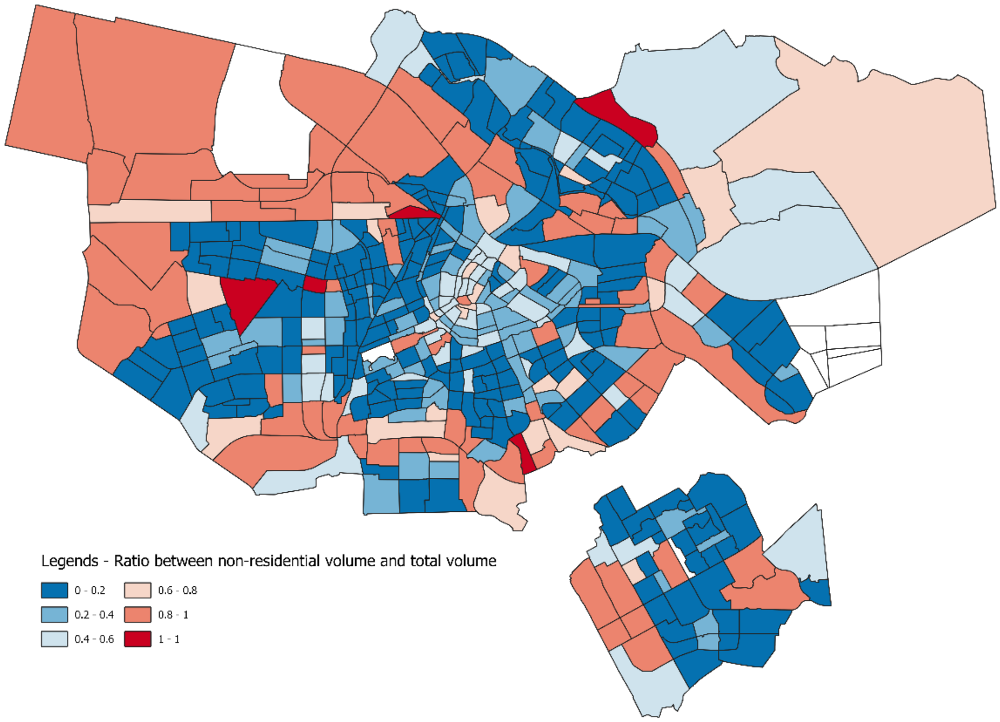


Figure 54 Ratio between non-residential volume and total building volume

[4] Outdoor urban amenities

The distribution of outdoor amenities within the neighborhood boundary itself reflects the status of built-up density. The area having high building footprint density will have a lower outdoor footprint, notably the area within the city core and its close surroundings. The outdoor footprint increases with distance from the city center. Since agricultural land is not included as outdoor urban amenities, the outdoor footprint of the area located on the North-Eastern side of the city is relatively small.

However, as the neighborhood itself is not self-contained, a buffer zone of 400 m from the neighborhood boundary is created that covers the outdoor amenities of the surrounding areas for the calculation. The size of the pie charts and the share of amenities change tremendously and better reflect the accessibility to outdoor urban amenities of the neighborhoods, especially for those located next to large green spaces. As a result, these values will also be used as a base for the calculation of accessibility to outdoor urban facilities with regard to dwelling units within a neighborhood. The neighborhoods located at the city's edge also do not cover the outdoor amenities from other administrative units.

These urban parameters still do not fully reflect the accessibility status, especially for large neighborhoods, where the distribution within the neighborhoods themselves is also important. However, this factor is more related to the spatial arrangement of the local area than the urban context at the city level.

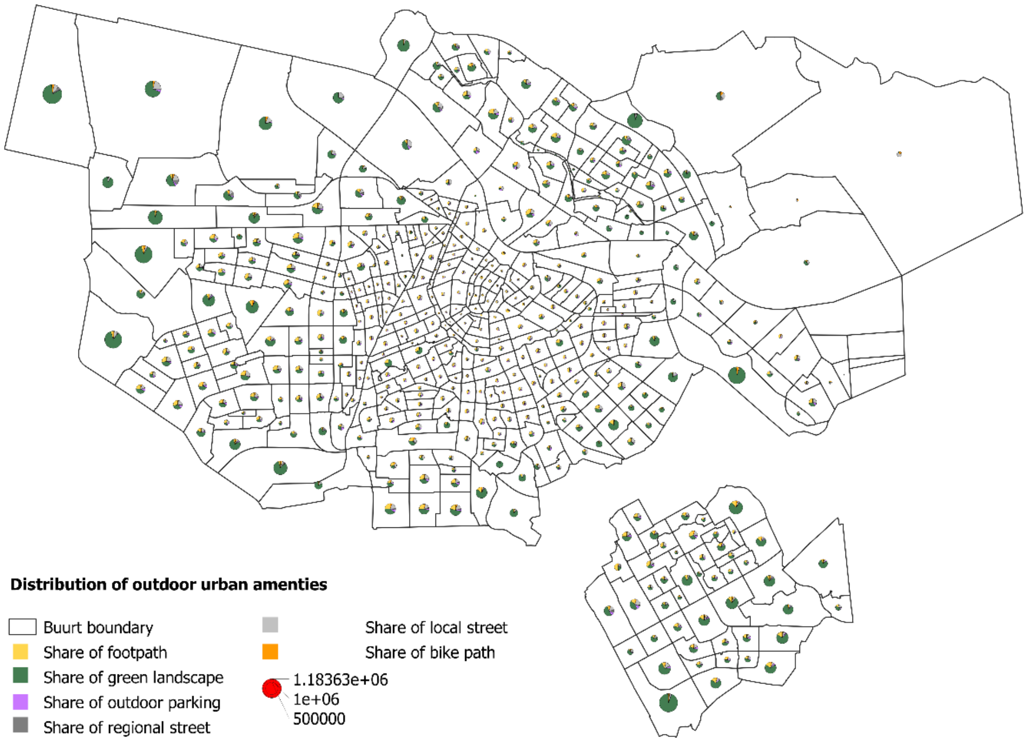


Figure 55 Distribution of outdoor amenities according to area (m2) – water surface excluded

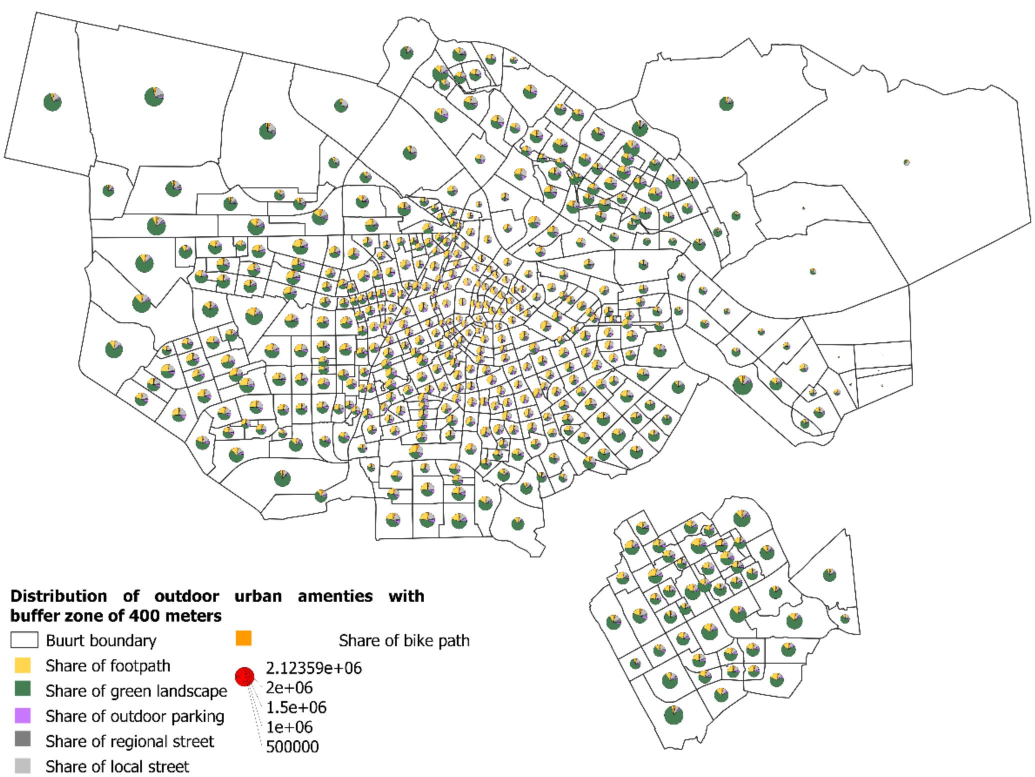


Figure 56 Distribution of outdoor amenities (with buffer zone of 400 m) according to area – water surface excluded

[5] Development periods and urban characteristics

Urban development characteristics are considerably attached to the development periods. The urban core contains mostly buildings built before 1900 and a small portion of rebuilt buildings in the period of 1970-2000. In the period of 1900-1945, the city expanded strongly to the Northeast, across the river, and to the West, Southwest, and the South from the city center with a very high built-up density (mostly multi-family houses). In the period of 1945-1970, the city continued to expand strongly to the West with a high built-up density of multi-family houses and single-family houses. It also grew towards the South and Southeast with a lower built-up density. In the period of 1970-2000, new clusters for office, industry, and urban amenities such as hospitals were the development focus. Referring to the map of indoor amenities, the cluster of offices and industry in the Northwest was developed in this period. Besides, a new urban area that detached from the main city body was developed in the Southeast, it is more likely to be self-contained with housing, offices, and industries, and other sport-recreational, stores facilities. Two other housing clusters to the far West and the Northeast also developed in this period, with mostly single-family houses. In the period from 2000, the development zones from the previous period continue to be filled up. Another new housing cluster is developed locate to the East of the city. The dominant housing types at this period are single-family houses and mixed-use buildings, with a larger dwelling size overall.

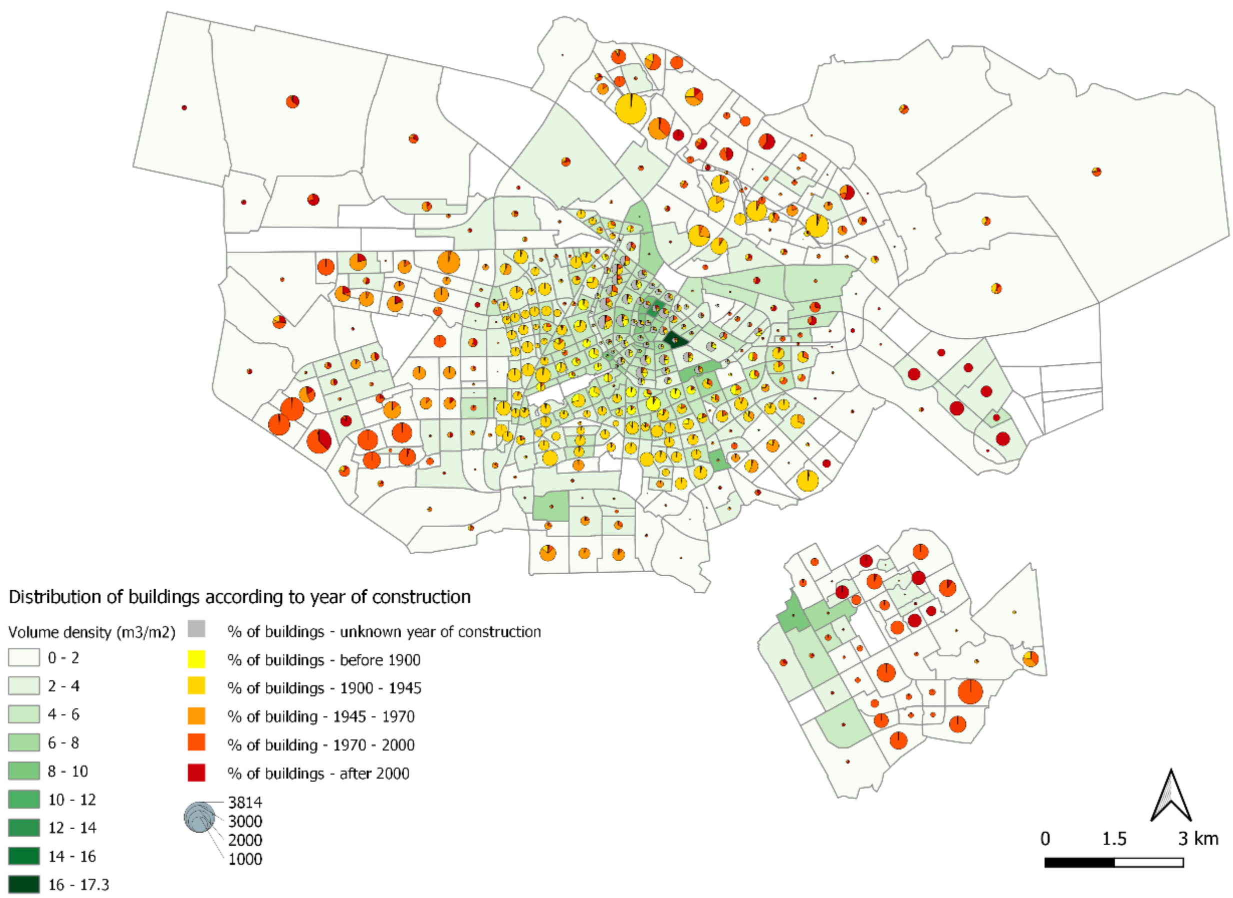


Figure 57 Distribution of buildings according to the year of construction

[6] Housing prices and urban characteristics

The spatial distribution of the number of dwellings according to the price range reveals a clear trend. The housings with the highest price range concentrate within the city core. The price then decreases gradually with distance from the center except for the areas surrounding Vondel Park, especially its Southern neighborhoods. The newly developed area that is located at the city's edge has the lowest housing price per square meter.

Apart from being a historical center with many tourist attractions, the city center and its close surroundings also contain many urban facilities, workplaces with a limited housing supply that make it highly-priced compared to other areas. The Southern neighborhoods (the Amsterdam-Oud Zuid and Amsterdam Zuid area), on the other hand, is bounded by the Vondel Park to the North, and a cluster of offices, universities, attractions, sport and recreation facilities to the South, and a better distribution of green landscape. The median dwelling size in this area is also comparatively higher than others. These factors contribute to the high housing price within this area. Newly built urban areas have limited access to indoor urban facilities and are far away from workplaces and are one reason for the low housing price per square meter. Besides, the high footprint density and a high share of single-family houses in these areas also contribute to the housing status.

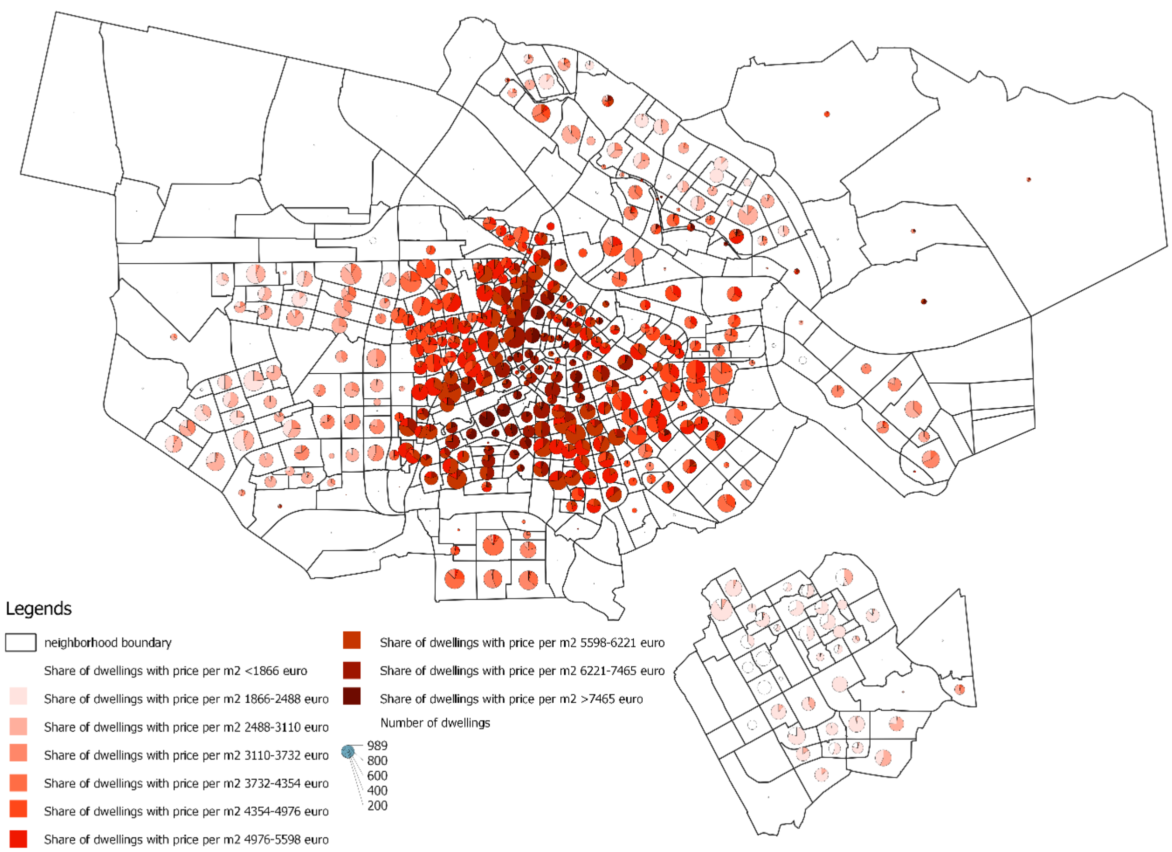


Figure 58 Spatial distribution of dwellings according to housing price per m2

[7] Quality of life and urban characteristics

With regard to housing quality, the houses built within the period from 1945 to 1970 are generally less satisfying than other areas. Some neighborhoods located to the North East of the city that was developed in the period of 1900-1945 are the worst concerning housing quality. Housings within the city core rank the highest. The housing quality index decreases with distance from the center, except for two newly developed housing clusters in the Eastern and Western side of the city. The housing quality, as a result, does show a clear relationship with the development period and distance from the city. Housing with lower rank, furthermore, does also relate to lower housing prices, except for the two newly developed clusters (the western cluster and the eastern cluster). Regarding the dwelling size, areas that have higher median dwelling size also gain higher score in housing quality, except for the area developed between 1945 and 1970.

The quality of facilities shows a clear trend according to distance from the city center and the distribution of indoor urban facilities. The area with a higher total volume and a higher level of variety scores higher in satisfaction. With regard to safety, areas with lower population density and lower built-up density score higher in the level of satisfaction. However, the city, in general, scores lower in safety compared to the national average. The satisfaction towards the environment shows no clear pattern nor relationship with other urban parameters.

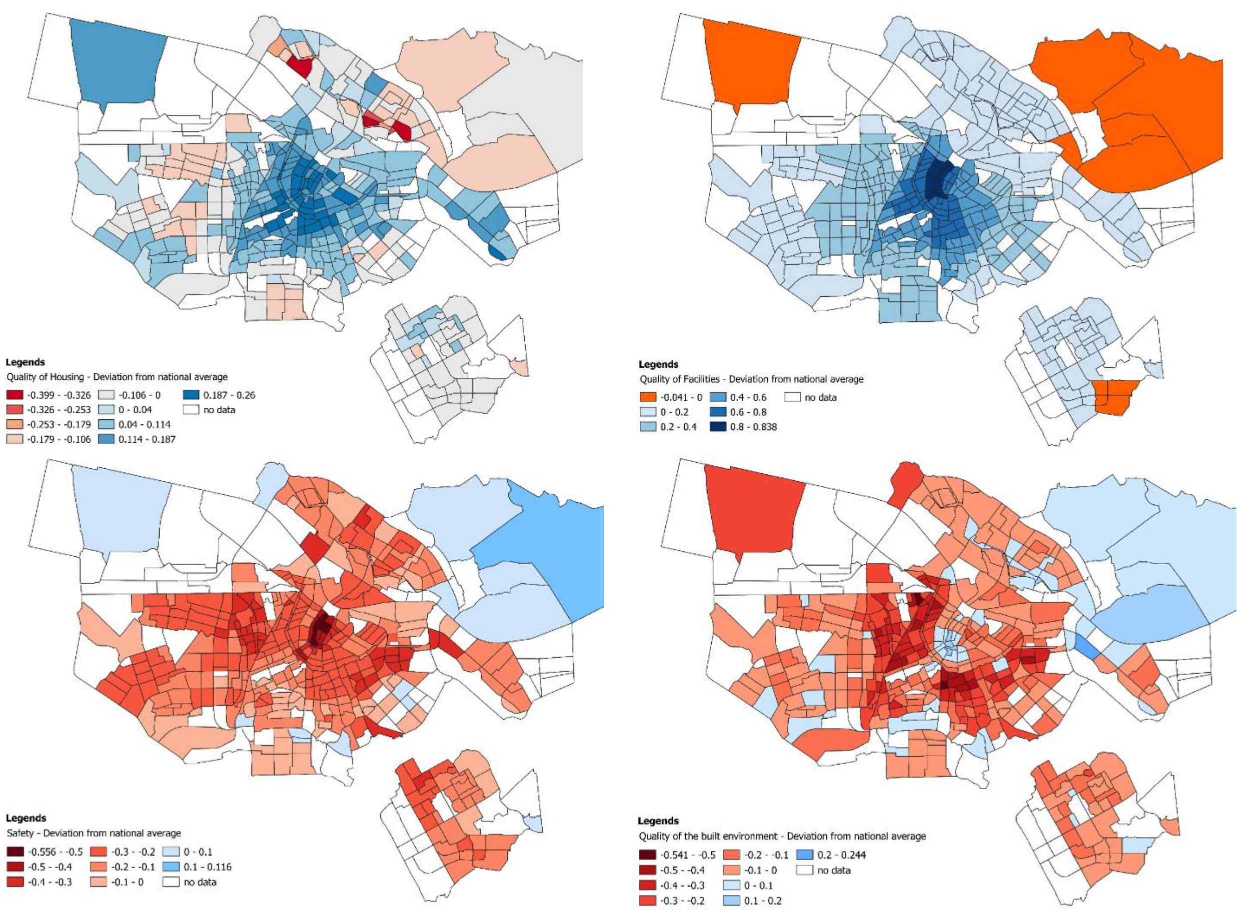


Figure 59 Livability index according to the deviation from the national average with regards to housing, amenities, safety, and the built environment

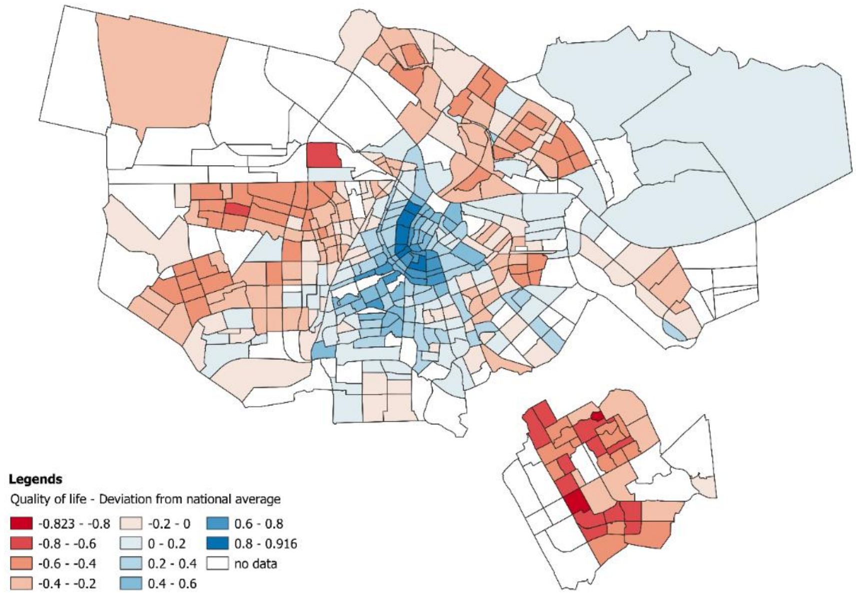


Figure 60 Livability index according to the deviation from the national average (overall)

In short, a good living environment depends on many factors. Among those is the personal perception of the investigated subject. Therefore, the quality-of-life index should not be a base factor to extract urban indicators for the design KPIs. For example, the housings in the city center score highest in terms of housing quality but it should not be a model for the new urban development due to the inefficient use of land.

[8] Urban parameters according to the dwelling density

The urban parameters at the neighborhood level are then translated to the dwelling level by dividing the parameters at the neighborhood level by the number of dwellings of the neighborhood. All information is stored in the table "buurt_housing" to assist the query by the user. For the indoor urban amenities and outdoor urban amenities, the values from the buffered neighborhood are used.

For example, a simple query could be carried out to find out the possible volume of catering services per dwelling from a neighborhood that has high satisfaction in terms of facilities:

```
SELECT a.buurt_code, a.catering_vol_per_dwelling
FROM data_ams_n.buurt_housing AS a JOIN data_ams_n.buurt_liveability AS b
ON a.buurt_code = b.buurt_code
WHERE b.facilities > 0.5;
```

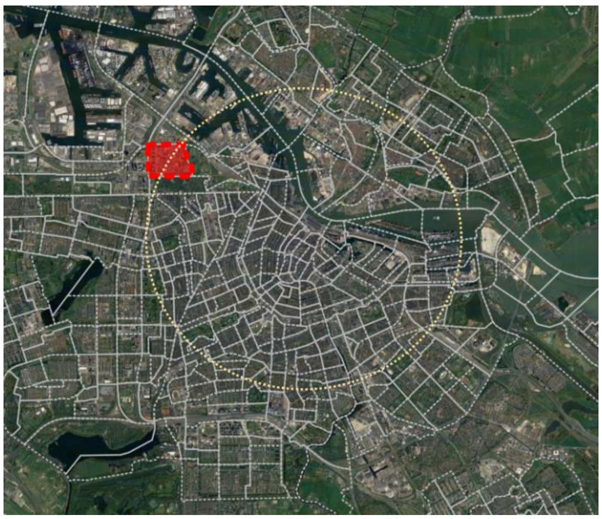
4.3. Design KPIs for the new development project

The above stage helps to understand the development pattern of the city comprehensively and comparatively, and in parallel derives a set of urban KPIs to be used in the later steps. It is, however, found that the selecting of a perfect neighborhood that fits the development goal of the new site is not persuasive. Each neighborhood that was developed in different periods of time and context (location, available construction technologies and materials, architectural trend) has its own trademark, pros and cons.

As a result, the thesis proposes a different approach, that is, to position the development site within the city context and to use the derived urban KPIs at the city scale and at the neighbor scale to find the best-fit design KPIs for the new development. The thesis uses the same case study as in the current "Buurt Generator" tool for further comparison and development.

4.3.1. Current status of the new development site

The neighborhood to be redeveloped that was chosen as a case study is Sloterdijk One located within the Haven-Stad project area in the western part of the city of Amsterdam, with the neighborhood code as "E36b". To study the current status of the new development site, queries are performed on the project database that stores a set of urban KPIs of the city of today.



Location: The area is within the same region with the second development ring (1900-1945) with regard to the distance to the city center. There is a tram terminal within the area that make it easily accessible using public transportation.

Demographic

Subjects	Values
Number of population (0 – 15 years old)	5
Number of population (15 – 25 years old)	5
Number of population (25 – 45 years old)	50
Number of population (45 – 65 years old)	40
Number of population (over 65 years old)	5
Total population	105
Population density (ex. Water surface) / ha	1.55235
Number of households	40
Number of single households	30
Number of households without children	5
Number of households with children	5
Household density (ex. Water surface) /ha	0.59

Livability

Subjects	Values
Overall (deviation from the national average)	-0.72997
Housing (deviation from the national average)	-0.14357
Resident (deviation from the national average)	-0.25479
Facilities (deviation from the national average)	0.0815
Safety (deviation from the national average)	-0.12889
Built environment (deviation from the national average)	-0.28421
Livability score	1

Building

Subjects	Values
Number of buildings	167
Number of buildings built between 1900-1945	6

Housing

Subjects	Values
Number of dwellings (SFH)	3
Number of dwellings (MFH)	0

Number of buildings built between 1945-1970	77
Number of buildings built between 1970-2000	48
Number of buildings buiit after 2000	36
Total footprint area (m^2)	196163
Total building volume (m^3)	1.65E+06
Footprint density (ex. Water surface)	0.29
Volume density (m3/m2) (ex. Water surface)	2.44
Number of SFH	3
Number of MFH	0
Number of non-residential (single function) buildings	91
Number of non-residential (multi-function) buildings	22
Number of mixed-use buildings	11
Number of unknown buildings	45

Number of dwellings (mixed-use)	6
Total number of dwellings	9
Average volumetric size of dwelling (m3)	7036
Median volumetric size of dwelling (m3)	5891
Total dwelling volume (m3)	63325
SFH- Average volumetric size of dwelling (m3)	7140
SFH- Median volumetric size of dwelling (m3)	5891
SFH- Total dwelling volume (m3)	21421
MFH- Average volumetric size of dwelling (m3)	0
MFH- Median volumetric size of dwelling (m3)	0
MFH- Total dwelling volume (m3)	0
Mixed-use- Average volumetric size of dwelling (m3)	6984
Mixed-use-Median volumetric size of dwelling (m3)	2149
MFH- Total dwelling volume (m3)	41904
Percentage of housing volume / total volume	3.8%

Urban Amenities

Outdoor amenities	Values	Values (400m buffer)
Water surface area (m2)	4818.36	150953.5
Green landscape area (m2)	121480	563880.2
Local street area (m2)	49818.72	119691
Outdoor parking area (m2)	21068.22	39567.85
Bike path area (m2)	12359.57	39222.3
Foot path area (m2)	33375.99	136071.5
Regional street area (m2)	19932.99	45598.65
Indoor amenities	Values	Values (800m buffer)
Number bar/dancing clubs	0	0
Total volume of bar/dancing clubs (m3)	0	0
Number of catering services	3	25
Total volume of catering service (m3)	40671	108091
Number of cultural attractions/destinations	1	6
Total volume of cultural attractions/destinations (m3)	6432.53	11643.4
Number of healthcare services	1	7
Total volume of healthcare services (m3)	8267.91	12732.2
Number of general educations facilities	3	10
Total volume of general educations facilities (m3)	52697	266603
Number of hotels	0	163
Total volume of hotels (m3)	0	152868
Number of infrastructures	0	14
Total volume of infrastructures (m3)	0	13334.5
Number of kindergarten and primary school	0	10

Total volume of kindergarten and primary school (m3)	0	43394.6
Number of offices	69	638
Total volume of offices (m3)	707155	3.78E+06
Number of industries	120	360
Total volume of industries (m3)	688888	2.31E+06
Number of parking/garages	0	9
Total volume of parking/garages (m3)	0	85934.3
Number of public services	1	7
Total volume of public services (m3)	131.15	44547.9
Number of religion buildings	1	4
Total volume of religion buildings (m3)	2261.01	28733.3
Number of sport/recreation facilities	1	8
Total volume of sport/recreation facilities (m3)	6459.6	24091
Number of stores	1	53
Total volume of stores (m3)	15963.9	127889
Number of transportation facilities	0	3
Total volume of transportation facilities (m3)	0	91224

Urban Amenities per person / per dwelling (buffer zone included)

Urban amenities volumes	Per person	Per dwelling
Bar/Dancing clubs (m3)	0	0
Catering services (m3)	1029.44	12010.1
Cultural attractions/destinations (m3)	110.889	1293.71
Healthcare services (m3)	121.259	1414.69
General education facilities (m3)	2539.08	29622.6
Hotels (m3)	1455.89	16985.4
Infrastructure (m3)	126.995	1481.61
Kindergarten and primary school (m3)	413.282	4821.62
Offices (m3)	36033.2	420387
Industries (m3)	21976.6	256394
Parking / Garages (m3)	818.422	9548.25
Public services (m3)	424.265	4949.76
Religion (m3)	273.651	3192.59
Sport – Recreation facilities (m3)	229.446	2676.87
Stores (m3)	1217.99	14209.9
Transportation facilities (m3)	868.803	10136
Bike path (m2)	373.546	4358.03
Foot path (m2)	1295.92	15119.1
Green landscape (m2)	5370.29	62653.4
Outdoor parking (m2)	376.837	4396.43
Local street (m2)	1139.91	13299
Regional street (m2)	434.273	5066.52
Water surface (m2)	1437.65	16772.6

The project area is currently an office and industry cluster, with very few population, housings, and facilities. Facilities within the neighborhood boundary include catering services and sport facilities. The area, however, is adjacent to a commercial cluster and benefits from a variety of services. For the redevelopment purposes, the industry/storage function would be removed to leave space for housing and urban amenities development.

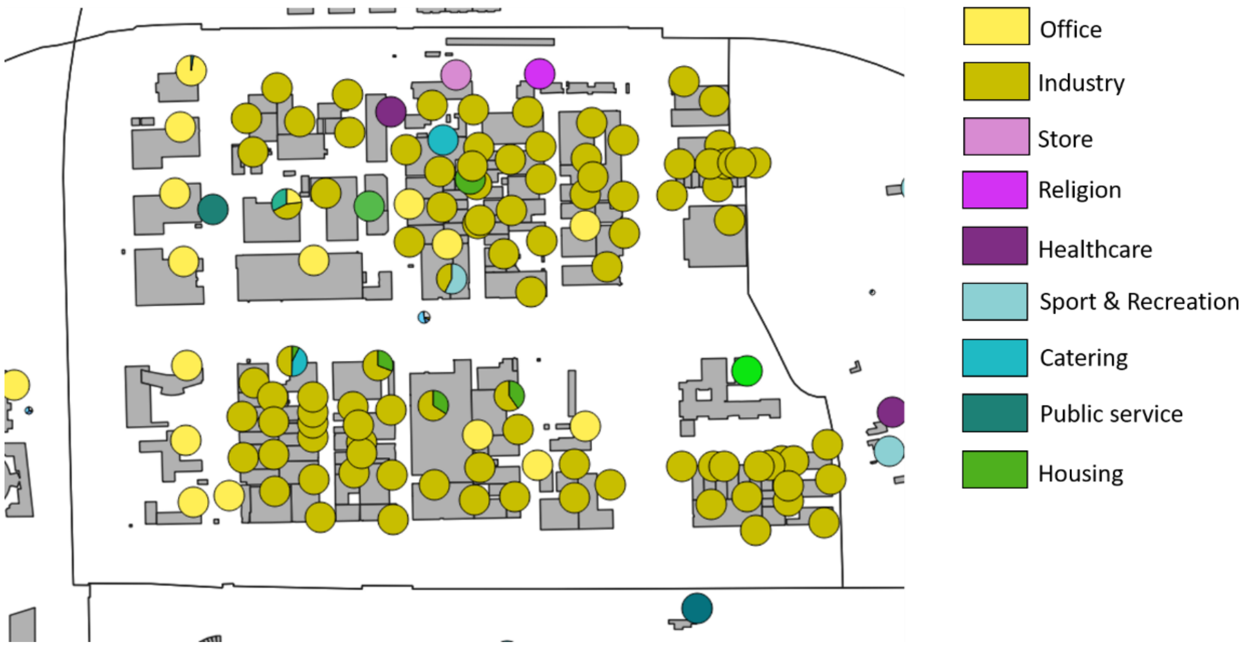


Figure 61 Current status of the development site (share according to volume)

4.3.2. Future status

[1] Total number of dwellings to be developed

With the planned development density of 192 households/ha Table 9, the total number of dwellings for a net area (excluding water surface) of 67.64 ha (query from table "buurt_outdoor_amenties") would be approximately 12864 households maximum. To convert the number of households to the number of dwellings, a conversion factor is generated. Since the project site locates within the second development ring according to the distance from the city center and is close to the workplace, it is expected that the area is attractive to the young working-class and single household, with the same living characteristic as the neighborhood within the second development rings (neighborhood code begins with E or K). For that reason, the average ratio between the number of households and the number of dwellings in these areas is used as the conversion factor.

```
SELECT avg(a.huishoudenstotaal::numeric/b.no_dwelling_total::numeric)
FROM data_ams_new.buurt_household AS a JOIN data_ams_new.buurt_housing AS b
ON a.buurt_code = b.buurt_code
WHERE (left(a.buurt_code, 1) = 'E' or left(a.buurt_code, 1) = 'K')
AND b.no_dwelling_total >50;
```

The query results in 1.16, which means the maximum number of dwellings for the new development site would be approximately 11074 units. The next step, then, is to derive the input for the dwelling size and the indoor/outdoor facilities volume/area per dwellings.

[2] Buildings to be kept

With a set of criteria, building's id (and later their geometries) could be selected directly from the database to be integrated in the Grasshopper workflow in the design stage. In this example, buildings that are built after the year 2000 and are occupied by office, religion, store, education and healthcare functions are selected to be kept and exported to the Grasshopper environment.

```
SELECT identificatie FROM data_ams_n."Building_info"
WHERE year_of_construction >= 2000
AND (usage_office is not null OR usage_store is not null OR usage_healthcare is not null
        OR usage_religion is not null OR usage_highedu_research is not null
        OR usage_edu_sec_voc is not null)
AND buurt_code = 'E36b';
```

The query results in six buildings, the 3D geometries of these buildings can be queried using either FME or directly in Grasshopper (the query of geometries in Grasshopper will be addressed later in Chapter 5).

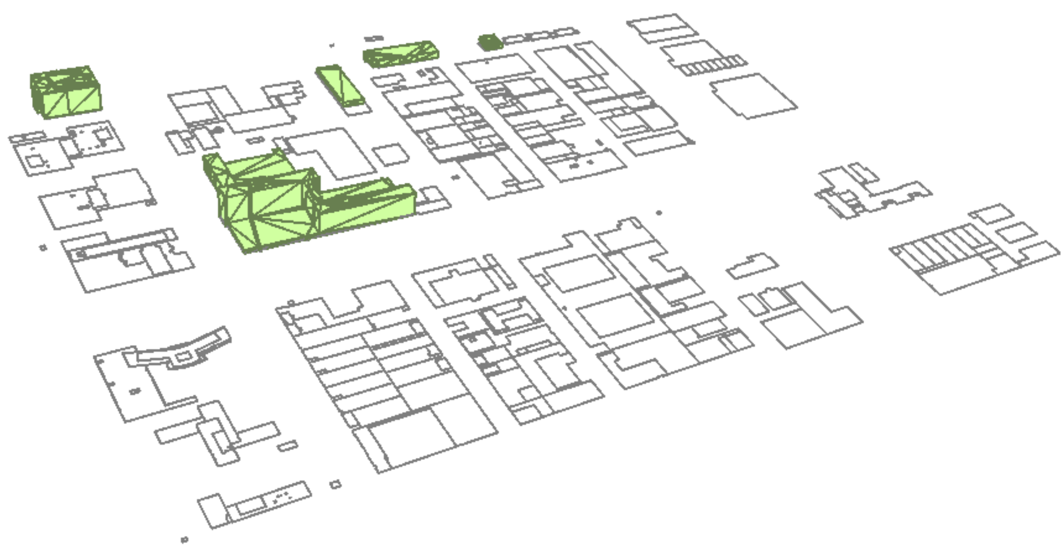


Figure 62 Kept buildings (in 3D) - 3D shapefile is queried and generated using FME

[3] Average dwelling size

With regard to the dwelling size, the overlaying of the information on dwelling size and the quality of housing reveals that the neighborhoods that have a higher median dwelling size usually have a higher perceived quality of housing. Moreover, the distance from the urban core and the period of development also affects the housing quality. In the previous work (see Figure 63), the template neighborhoods that were chosen to extract the average dwelling size are not lying in the top areas considering housing quality, the median dwelling volumes are also smaller compared to the neighborhoods with higher housing quality. The figures also differ between the neighborhoods.

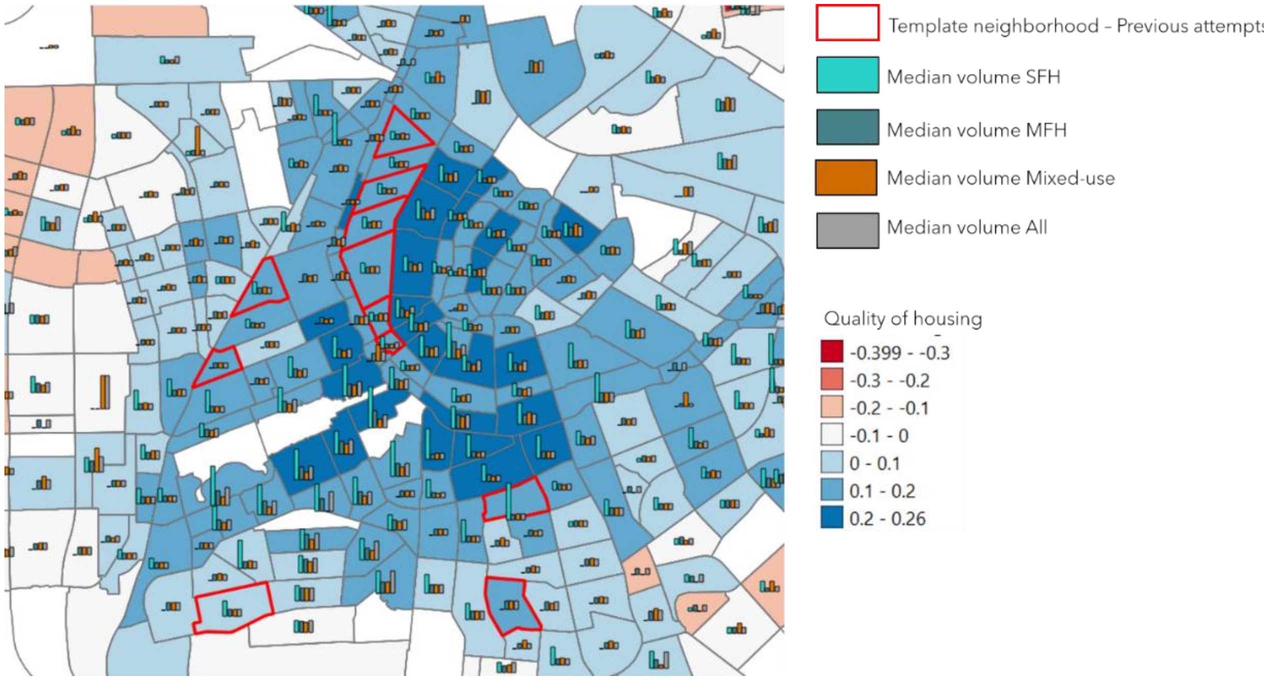


Figure 63 Template neighborhoods from the previous work

The thesis, as a result, proposes a solution that is not based on template neighborhoods, but the statistical figures of the median dwelling size at the neighborhoods having high housing quality. The median dwelling size are retrieved also based on the housing types (SFH, MFH, and mixed-uses).

Query median dwelling size of neighborhood with high housing quality

```
SELECT a.med_dwelling_size, a.med_dwelling_size_sfh, a.med_dwelling_size_mfh,
a.med_dwelling_size_mixed
FROM data_ams_n.buurt_housing AS a JOIN data_ams_new.buurt_liveability AS b
ON a.buurt_code = b.buurt_code WHERE b.housing >= 0.1;
```

According to the histograms (see Figure 64), the values of the median size of dwellings fall in the range from 250 m^3 to 500 m^3, with the highest frequency lies in the value of 300 m^3. Some rare cases having the values greater than 500 m^3. The result suggests that the starting value for the average size of dwellings for the new development should be 300 m^3. Regarding SFH dwellings, the highest frequency lies in the median dwelling size of more than 900 m^3, other cases range from 400 m^3 to 800 m^3. Regarding MFH dwellings, the highest frequency also lies on the 300 m^3 but the number of neighborhoods having the median dwelling size of 250 m^3 is also very high. Median size of 350-450 m^3 also occupy a significant amount. For mixed-use dwellings, the highest frequencies lie from 250 to 350 m^3. These numbers can be used as reference for the further elaboration of dwelling sizes within the development area. These values with will be used as references for determining the total residential volume of the new development area in the following step.

It should be emphasized that the city's regulation towards the minimum size of dwelling is 25 m^2 net, which is 90 m^3 in volume (with conversion factor from net to gross of 1.2 and average story height of 3.5 meters). Hence, the median dwelling volumes extracted from the data are qualified to use.

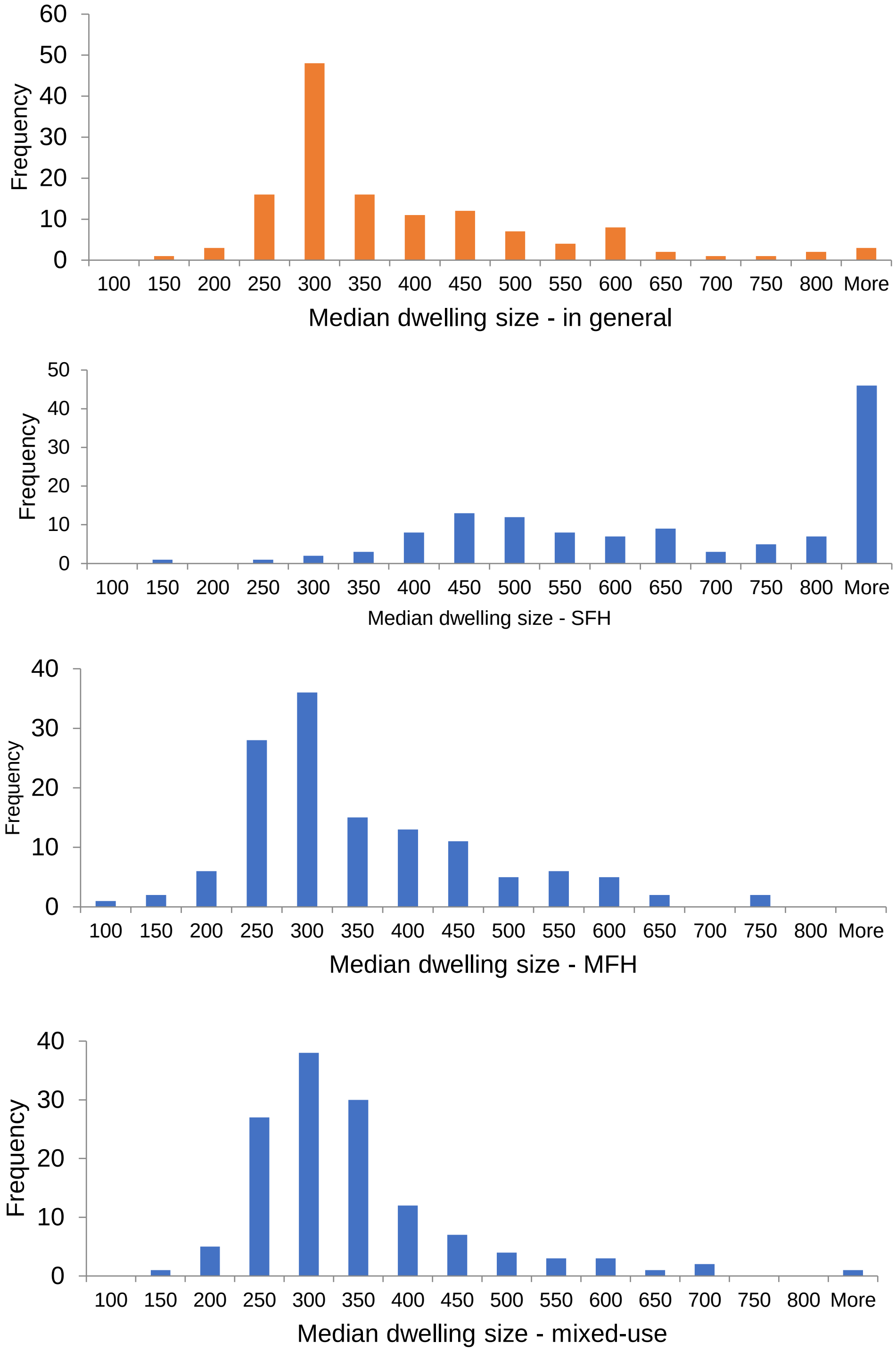


Figure 64 Histogram of median dwelling size of the chosen neighborhoods according to types

[4] Elaboration of design KPIs as input for the design stage

The current building footprint density (exclude water surface) at the development site is 0.293. The current infrastructure/transportation that accounts for 38% of the total area, however, are required to be left untouched. To provide more space for greenery and other outdoor amenities, this number should be kept as high as possible. Hence, an optimization problem between the dwelling size, the number of dwelling, and the land parcel for development is raised.

Density	Values
Footpath	0.049
Bike path	0.018
Local street	0.073
Regional street	0.029
Outdoor parking	0.031
Green landscape	0.18
Sum	**0.38**

The FAR is calculated as:

$$\frac{((Number\ of\ dwelling * Dwelling\ volume) + \ (Number\ of\ dwelling * Dwelling\ volume) * 0.25)}{Total\ buurt\ area\ (ex.water) * percenatage\ of\ land\ for\ development * Storey\ height}$$

$$= \frac{Number\ of\ dwelling * Dwelling\ volume * 1.25}{Total\ buurt\ area\ (ex.water) * percentage\ of\ land\ for\ development * Storey\ height}$$

$(\boldsymbol{Number\ of\ dwelling * Dwelling\ volume) * 0.25})$ is the non-residential volume according to the requirement from the municipality.

With the following constraints:

- Number of dwelling <= 11047 units
- Dwelling volume from 300 m^3
- Percentage of land for development <= 0.62
- FAR from 2.2 to 3.5 (Table 9 Development requirements of the new development site (Garcia González, 2019)Table 9)
- Story height of 3.5 meters (average values)

For the relationship between the dwelling volume and the story height, additional knowledge from the field or regulations might help. Within the scope of this thesis, an average value of 3.5 meters is chosen.

Priority	Dwelling number	Dwelling volume	Footprint density	FAR
Environmentally friendly and super high housing quality	5400	500	0.4	3.56
Environmentally friendly and high housing quality	6000	450	0.4	3.56
Environmentally friendly and high housing quality	7000	420	0.45	3.45
Neutral	8400	400	0.5	3.55

Neutral	9000	380	0.5	3.61
Neutral	9500	350	0.5	3.51
Accommodation capacity level 3, medium housing quality	10000	330	0.5	3.48
Accommodation capacity level 2, medium housing quality	10500	320	0.5	3.55
Maximize accommodation capacity	11000	320	0.55	3.38
Max. number of households	12864	300	0.6	3.40

Table 13 Example of KPIs for different scenarios

In order to select the design KPIs, an agreement between the stakeholders should be made. For example, in this thesis, the “Accommodation capacity level 2” scenario is selected. The total number of dwelling accounts for 10500, the average dwelling size accounts for 320 m3, and the land parcel for buildings account for 50% of the total area, the resulted FAR will be 3.55.

With regards to the indoor urban amenities, the total volume for the new development will be 840000 m3 (20% of the total volume). The values per dwelling (buffer zone included) are recalculated based on the total number of dwellings of 10500, and the above buildings in the previous step are kept.

The calculated indoor amenities per dwelling per functions are then compared with the values from the neighborhood that score very high in facilities quality (see Figure 59).

Query total indoor volume based on average values from neighborhoods with high satisfaction in amenities.

```
SELECT avg(bar_dancing_vol_per_dwelling)*10500, avg(catering_vol_per_dwelling) )*10500,
avg(culture_vol_per_dwelling) )*10500, avg(heathcare_vol_per_dwelling) )*10500,
avg(highedu_vol_per_dwelling) )*10500, avg(hotelier_vol_per_dwelling) )*10500,
avg(infra_vol_per_dwelling) )*10500, avg(kindergarten_primaryschool_vol_per_dwelling) )*10500,
avg(office_vol_per_dwelling) )*10500, avg(industry_vol_per_dwelling) )*10500,
avg(parking_garage_vol_per_dwelling) )*10500, avg(publicservice_vol_per_dwelling) )*10500,
avg(religion_vol_per_dwelling) )*10500, avg(sport_recre_vol_per_dwelling) )*10500,
avg(store_vol_per_dwelling) )*10500, avg(transport_vol_per_dwelling) )*10500
FROM data_ams_new.buurt_housing
WHERE  left(buurt_code, 3) = 'K24' or left(buurt_code, 3) = 'K25'
or left(buurt_code, 3) = 'E17' or left(buurt_code, 3) = 'E19' or left(buurt_code, 3) = 'E20' or left(buurt_code, 3) = 'E22';
```

Indoor amenities	From the 800m buffer zone	Kept from the current site	Current status (include 800m buffer)	Expectation (from sample neighborhood)	To be developed (rank 1-4)
Total volume of bar/dancing clubs (m^3)	0	0	0	177556	3
Total volume of catering service (m^3)	67420	0	67420	6890150	2
Total volume of cultural attractions/destinations (m^3)	5211	0	5210.87	4154463	2
Total volume of healthcare services (m^3)	4464	8268	12732.2	2163454	2
Total volume of general educations facilities (m^3)	213906	10290	224196	7781413	3
Total volume of hotels (m^3)	152868	0	152868	6100540	3

Indoor amenities	From the 800m buffer zone	Kept from the current site	Current status (include 800m buffer)	Expectation (from sample neighborhood)	To be developed (rank 1-4)
Total volume of infrastructures (m^3)	13335	0	13334.5	256492	3
Total volume of kindergarten and primary school (m^3)	43395	0	43394.6	2601929	1
Total volume of offices (m^3)	3072845	159519	3232364	21201879	2
Total volume of industries (m^3)	1621112	0	1621112	3089823	4
Total volume of parking/garages (m^3)	85934	0	85934.3	782145	1
Total volume of public services (m^3)	44417	0	44416.75	1006713	3
Total volume of religion buildings (m^3)	26472	2261	28733.3	626993	3
Total volume of sport/recreation facilities (m^3)	17631	0	17631.4	4120915	1
Total volume of stores (m^3)	111925	15964	127889	12679171	2
Total volume of transportation facilities (m^3)	91224	0	91224	21271	4
Total (m^3)	5572159	196302	5768460.92		643698

Table 14 KPIs for indoor facilities for a given non-residential volume of 840000 m^3

As can be seen from Table 14, for the given space of 840000 m^3, the project site will be far less qualified compared to the areas with high facility amenities index. Hence, it is first questioned that whether the proportion of 20% for non-residential function is a reasonable number for a high quality of life area. And then, by comparing the existing values with the expected values, the result suggests the level of priorities in arranging different types of urban amenities. For the actual implementation in the design stage, there should be a consensus between the stakeholders on the volumes assigned for the facilities based on the data. Furthermore, it could be the case that adjacent areas could also provide new facilities for the region.

4.4. Chapter conclusion

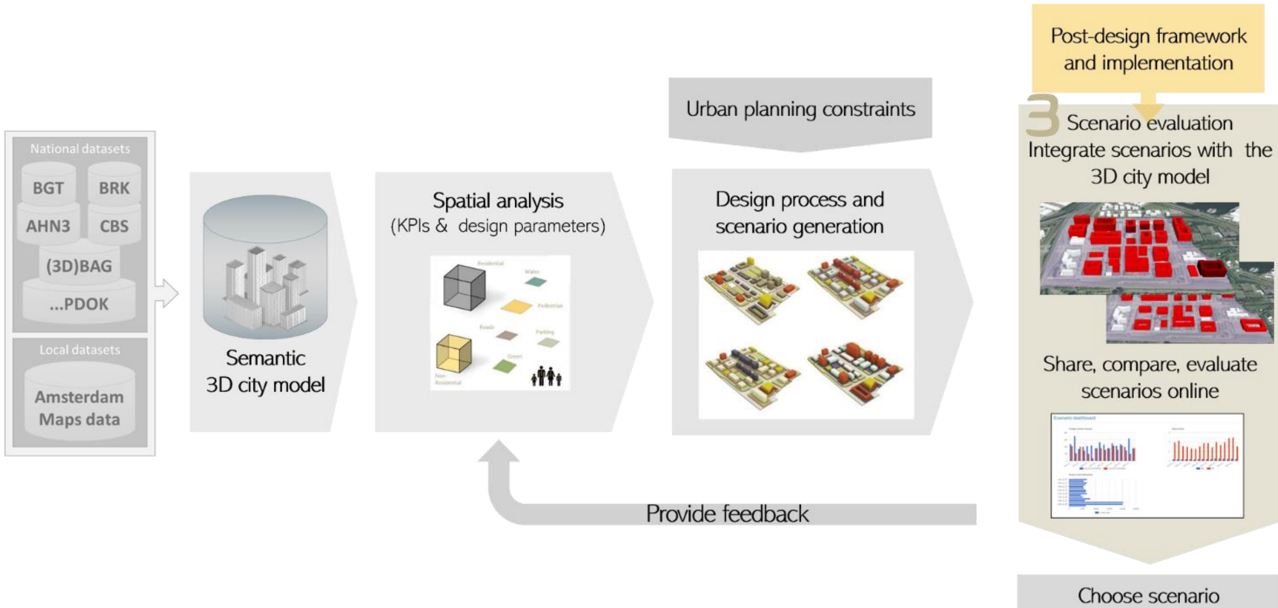
In this chapter, the thesis expands the list of urban KPIs for a more comprehensive approach to explore and describe the city context and to deliver KPIs for the new urban development sites. The first part covers the generation of a database of the city of Amsterdam, where various urban parameters are gathered and treated. It allows the extraction of different information and the visualization of different urban aspects in thematic maps. The second part focuses on the case study – the development site – first to understand its context, and second to develop KPIs for the design stage.

(Spatial) data-driven approach plays a vital role in the success of urban planning activities, but only if it is based on reliable datasets and the data manipulation process is correctly done. During the process, the thesis adds some constraints to remove some data that are not qualified (e.g., data on net floor area) or also make some assumptions on the data (e.g., conversion factor from net area to gross area, story height, etc.). It , however, might lead to misleading results. As a result, two further approaches could be further elaborated. On the one hand, further in-depth investigation on the datasets could be conducted to find a way to balance the mismatches between them. On the other hand, official reports on the detected problems could be generated to be submitted to the authorities.

Furthermore, since a city is a complex living entity, two further remarks are made to conclude this chapter. Firstly, apart from spatial data, series of temporal (spatial) data would expand the breadth and depth of the understanding towards cities. Currently, only social-economic data are available as serial data. Secondly, most of the datasets that are incorporated in this chapter are quantitative data. The quality-of-life index are also quantified based on a set of quantitative indicators. Further (spatial) qualitative data could be collected and introduced to the database of the city. These might come from the wide public or groups of specific experts that give opinion on different aspects of the cities, for example the level of livability, lovability, walkability, etc. On the other hand, more detailed quantitative or descriptive data could also be added to further clarify the relationship between the datasets. For example, people's perceptions on livability, lovability might be associated with the architectural details, the urban furniture, or the landscape of one area. These qualitative data together with the collected quantitative data could talk more about the city and could further assist the decision making towards urban development.

Lastly, the tool does not substitute the traditional approaches of the pre-design stage, including on-site empirical research and professional knowledge towards the site. The tool acts as a guideline for the extraction and development of KPIs for the design stage. The chosen KPIs must meet an agreement between the stakeholders and must also comply with the existing regulations and constraints from the municipalities. However, findings from the data could also be used to reflect back to the cities on the suitability of development indicators assigned for the urban areas for further consideration.

5 Post-design evaluation



5.1. Chapter introduction

From the pre-design stage, the thesis moves to the post-design stage of the tool. The design stage, which will employ the new input KPIs and other built-in constraints and options, will not be further investigated as it is beyond the scope of this thesis.

According to the review work of (Gil and Duarte, 2013), the general structure of sustainable urban development evaluation tools consists of five hierarchical levels: sustainability dimensions (environment, social, and economy), then the themes of concerns (e.g., accessibility, resource efficiency) of each dimension, evaluation criteria of each theme (e.g., access to public transport in the theme accessibly), design indicators for each criteria (e.g., walking distance to the nearest public transit stop), and finally benchmark values (e.g., the distance shouldn't exceed 500 meters). Among the tools, two products employ GIS for spatial analysis and visualization, which are CityCAD (that allows user inputs for assessment parameters) and Index (that employs indicators from the Leed Neighborhood – Leed-ND US rating system). Some approaches also focus on some specific urban aspects for impact assessments, notably the urban micro-climate field. Any changes in the urban form of an urban area will indeed lead to changes in the air movement pattern, air temperature and the level of exposure to solar radiation. For that, the integration of the micro-climate assessment tools with urban planning and design tools was proposed in many pieces of research so that planners can directly access the impacts of their designs (Reiter, 2010; Wong et al., 2011).

Based on the hierarchy of a general structure of sustainable urban development evaluation tool and additional literature review on impact assessments of urban projects, the thesis proposes a post-design assessment framework to be integrated with the "Buurt Generator" as shown in Table 15. The assessment framework informs urban practitioners and stakeholders on different aspects of the scenarios for decision making and guides the detailed design solution in the next step of project development and implementation. The framework, however, only focuses on spatially related indicators that can be generated based on the integration of the 3D scenario models into the existing 3D city model. It does not give a direct ranking for the scenarios but only information and suggestions.

Themes		Criteria	Indicators	Method/Tool
Environment	Weather	Energy efficiency	Global solar radiation for the scenarios and the surrounding	Grasshopper/Ladybug radiation study
		Outdoor thermal comfort	Outdoor thermal comfort within the scenarios and the surroundings	Grasshopper/Honeybee thermal comfort study
	Green infrastructure	Greenspace	Distribution of private and public green space	2D Spatial statistical analysis (multiple tools available)
		Roadside greenery	Distribution of roadside greenery	2D Spatial statistical analysis (multiple tools available)
	Built landscape	Views	Viewsheds from new buildings and old buildings Height differences compared to the surrounding and compared to the city	3D visibility analysis (multiple tools available)
		Level of compactness	Building volume density	Calculation (multiple tools available)
Social	Accessibility	To green space	Catchment volume of new green spaces	Network analysis (multiple tools available)
		To kindergarten and primary school	Catchment volume of kindergartens and primary schools	
		To public transportation	Catchment volume of public transport stations	
		To leisure destinations	Catchment volume of leisure destinations	
		To health care amenities	Catchment volume of health care amenities	
	Integrity	Level of mixed-uses	Distribution of housing types Distribution of amenities	Spatial statistical analysis (multiple tools available)
		Evenly distribution	Distribution patterns and the average distance from inhabitants to amenities	Spatial analysis (multiple tools available)
Economic	Local economic, real estates, and jobs	Office, commercial, housing	The net floor area of each function	Calculation (multiple tools available)

Table 15 Post-design evaluation framework

The evaluation results should be stored in the project's database and should be readily available for queries and web-based, interactive visualization, e.g., as dashboards, ideally embedded or integrated with CesiumJS. Due to the time scope of the thesis, only the first indicator – the global radiation – is selected for further elaboration in the following steps. Since the thesis does not cover the design stage, the scenarios generated in the previous works are used for the analysis.

The solar radiation analysis is conducted in Grasshopper with the 3D models of the scenarios as the analysis targets, and the surrounding buildings and trees as the analysis context. The 3D objects are stored in the 3D database and can be queried in Grasshopper. Firstly, a connection between the 3DCityDB and the Grasshopper environment is established that allows the query and import of geometries in Well-Known Text (WKT) format. Secondly, the buildings and trees geometries are reconstructed in the Grasshopper environment. Thirdly, the solar radiation analysis component of Ladybug is run to get the monthly radiation value at the wall/roof surface level. Finally, the radiation values are stored back in the 3DCityDB in the form of energy-related values. Thus, the CityGML Energy ADE (Agugiaro et al., 2018) is employed. The gmlid of the object/geometry (unique id of the object in CityGML) is the primary key that keeps track of the import, simulate and export of data throughout the process.

5.2. Overview on the methodology

As previously introduced, CityGML and 3DCityDB were employed to manage the semantic 3D City model as well as the 3D model of the scenarios. The model is then imported in Grasshopper for solar radiation analysis. In this thesis, before diving into the complex database of the project, a 3D model of a simplify, simple called Alderaan is employed to test the feasibility of the approach as well as to debugging.

5.2.1. Set up

The newest versions of the 3DCityDB (version 4.3.0)[8] and the Energy ADE extension for the 3D City Database (version 1.3)[9] are first downloaded. The Energy ADE extension must be located within the "ade-extensions" folder of the 3DCityDB package. After creating a database in PostgreSQL and installing necessary extensions, an instance of the 3DCityDB is set up in the database. Then, Energy ADE related schema is created and registered to the 3DCityDB instance using the 3DCityDB Importer/Exporter ADE Manager (see Figure 65).

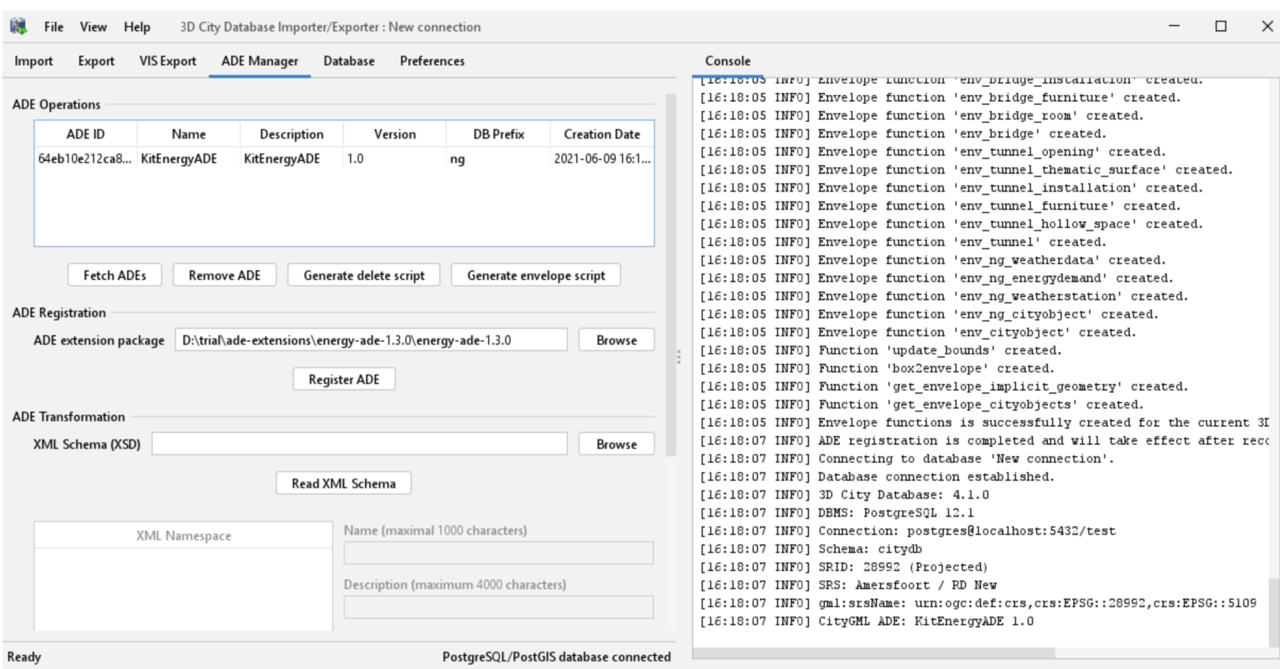


Figure 65 Create Energy related schema using 3DCityDB Importer/Exporter - ADE Manager

[8] https://www.3dcitydb.org/3dcitydb/downloads/
[9] https://github.com/3dcitydb/energy-ade-citydb

Then, using the import tool of the 3DCityDB Importer/Exporter, import the CityGML file of the Alderaan dataset into the 3DCityDB instance in the PostgreSQL database. Meanwhile, in Grasshopper, the GH Python remote plugin is installed. It allows writing a script using Psycopg2 - a package that provides access to PostgreSQL in Python. Hence, the building geometry can be queried and retried in the form of WKT.

5.2.2. The Alderaan City

The Alderaan sample dataset is in CityGML format, it contains 23 "fictive" buildings in LOD0, LOD1. Additionally, the 12 "core" buildings are available also in LOD2 (see Figure 66). The dataset also contains tree geometries in LOD1, LOD2, and LOD3. The query of buildings' geometries in 3DCityDB is relatively straightforward, whereas, for the trees' geometries, further information on how they are stored in the database is studied.

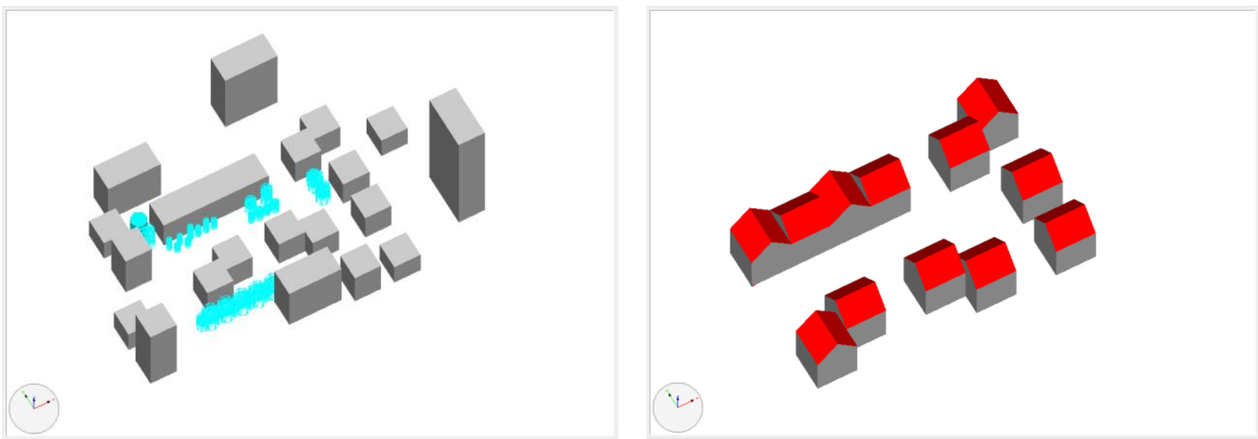


Figure 66 The Alderaan dataset (image on the left: buildings in LOD1 and trees in LOD3, image on the right: 12 "core" buildings in LOD2

As can be referred from the CityGML UML diagram of vegetation object in Figure 67 and the illustration in Figure 68, each tree record (i.e., each object derived from the SolitaryVegetationObject) can have multiple types of geometry. The second modelling approach consists in using templates that are then reused by means of a "cloning" mechanism (in addition to a 3D affine transformation). In CityGML, such geometries are called ImplicitGeometries. The template geometry is generally stored in a local coordinate system and (generally) centered in [0, 0, 0]. Every time such geometry is instantiated, a 3D affine transformation is applied. All trees in Alderaan dataset are modelled using the ImplicitGeometry approach, e.g., using a distinct template model for LoD1, LoD2 and LoD3.

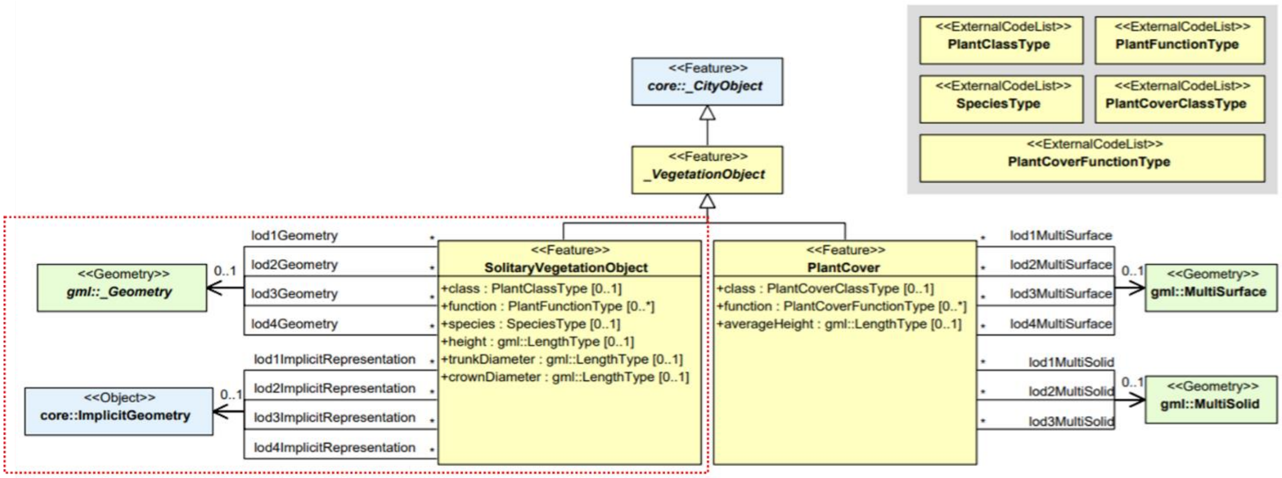


Figure 67 CityGML UML diagram - Vegetation object

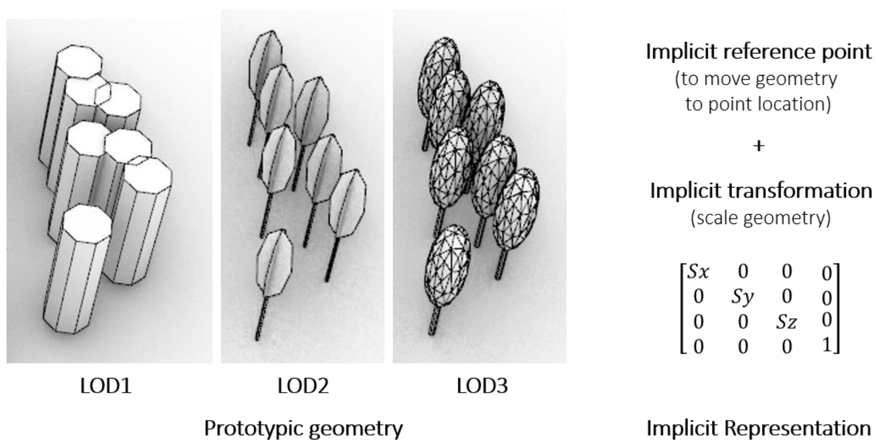


Figure 68 Solitary Vegetation Objects in CityGML

Hence, the query of tree geometries includes two components, the prototypic geometry (generally centered in [0, 0, 0]), the real position of the trees (3D points), and the 3D affine transformation matrices. The implicit representation information is stored in the "solitary_vegetat_object" table in 3DCityDB (see Figure 69). The prototypic geometry is stored in the "surface_geometry" table (see Figure 70) with parent_id referred to the id of the level of detail in the "implicit_geometry" table (see Figure 71).

lod1_implicit_rep_id... integer	lod2_implicit_rep_id... integer	lod3_implicit_rep_id... integer	lod4_imp integer	lod1_implicit_ref_point geometry	lod2_implicit_ref_point... geometry	lod3_implicit_ref_point... geometry	lod4_impl geometry	lod1_implicit_transformation... character varying (1000)	lod2_implicit_transformation... character varying (1000)
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		6.0 0.0 0.0 0.0 0.0 6.0 0.0 0.0...	10.02 0.0 0.0 0.0 0.0 10.02 ...
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		4.0 0.0 0.0 0.0 0.0 4.0 0.0 0.0...	6.68 0.0 0.0 0.0 0.0 6.68 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		4.0 0.0 0.0 0.0 0.0 4.0 0.0 0.0...	6.68 0.0 0.0 0.0 0.0 6.68 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		3.0 0.0 0.0 0.0 0.0 3.0 0.0 0.0...	5.01 0.0 0.0 0.0 0.0 5.01 0....
1	2	3	[null]	01010000A04071000000000...	01010000A04071000000000...	01010000A04071000000000...		2.0 0.0 0.0 0.0 0.0 2.0 0.0 0.0...	3.34 0.0 0.0 0.0 0.0 3.34 0....

Figure 69 The solitary_vegetat_object table of the Alderaan dataset that store the information on the implicit_ref_point (position of the tree) and the implicit_transformation (the 3D transformation matrix)

id [PK] integer	gmlid character varying (256)	gmlid_codespace character varying (	parent_id integer	root_id integer	is_solid numeric	is_composite... numeric	is_triangulated... numeric	is_xlink numeric	is_reverse numeric	solid_geometry... geometry	geometry... geometry	implicit_geometry geometry
678	id_lod3_poly_tree_trunk_132	[null]	674	674	0	0	0	0	0			01030000800100000005000...
679	id_lod3_poly_tree_trunk_133	[null]	674	674	0	0	0	0	0			01030000800100000005000...
680	id_lod3_poly_tree_trunk_134	[null]	674	674	0	0	0	0	0			01030000800100000005000...
681	id_lod3_poly_tree_trunk_135	[null]	674	674	0	0	0	0	0			01030000800100000005000...
682	id_lod3_poly_tree_trunk_136	[null]	674	674	0	0	0	0	0			01030000800100000005000...
683	id_lod3_poly_tree_trunk_137	[null]	674	674	0	0	0	0	0			01030000800100000005000...
684	id_lod3_poly_tree_trunk_138	[null]	674	674	0	0	0	0	0			01030000800100000009000...
685	id_lod3_poly_tree_crown_1	[null]	674	674	0	0	0	0	0			01030000800100000004000...

Figure 70 The surface geometry table of the Alderaan dataset

id [PK] integer	mime_type character varying (256)	reference_to_library character varying (4000)	library_object bytea	relative_brep_id integer	relative_other_geom geometry
1	[null]	[null]	[null]	644	
2	[null]	[null]	[null]	665	
3	[null]	[null]	[null]	674	

Figure 71 The implicit_geometry table where the parent id of the tree geometry in the surface geometry table is linked to the relative_brep_id of the LODs

5.2.3. Energy ADE

To effectively store the monthly solar radiation data for the thematic surfaces, the Energy Application Domain Extension (Energy ADE) for CityGML is used. The Energy ADE data model extends the CityGML model with extra features and properties to perform energy simulation, to store and exchange energy-related information[10]. Its implementation for the 3DCityDB then supports managing, importing, and exporting Energy ADE data using the 3DCityDB importer/exporter[11]. Although the current implementation of the Energy ADE is limited to the KIT profile[12], it is adequate to be used within the scope of this master thesis.

The monthly radiation value can be mapped to a WeatherData class and needs to be stored as regular time series. City objects, in this case, thematic surfaces, can be associated with multiple WeatherData objects of different types (global solar radiation, daylight illuminance, etc.). The weather data values, furthermore, are of "AbstractTimeSeries", and are in the form of RegularTimeSeries (see Figure 72 Figure 73). For that, a PostgreSQL script is created to insert relevant data into a series of tables. First, the cityobject_id values of the thematic surfaces are stored in the table NG_CITYOBJECT, which extends the CITYOBJECT table for the Energy ADE. After that, weather data and regular time series attached to the thematic surfaces are inserted into the city object table. Then, table NG_TIMESERIES, NG_REGULARTIMESERIES and NG_WEATHERDATA are filled accordingly.

There are, however, some drawbacks to using the Energy ADE kit. Firstly, the time series data are stored as text instead of an array. For example, for a series of monthly data, instead of having an array of twelve values, the data are concatenated as text using the space as values separator. Hence, it is quite inconvenient getting statistic figures directly from the stored energy data. Secondly, there are limited built-in functions for inserting energy data. The Energy ADE, however, is convenient in supporting the import/export of CityGML data format with integrated energy data.

[10] https://www.citygmlwiki.org/index.php?title=CityGML_Energy_ADE
[11] https://github.com/3dcitydb/energy-ade-citydb
[12] https://www.citygmlwiki.org/images/4/41/KIT-UML-Diagramme-Profil.pdf

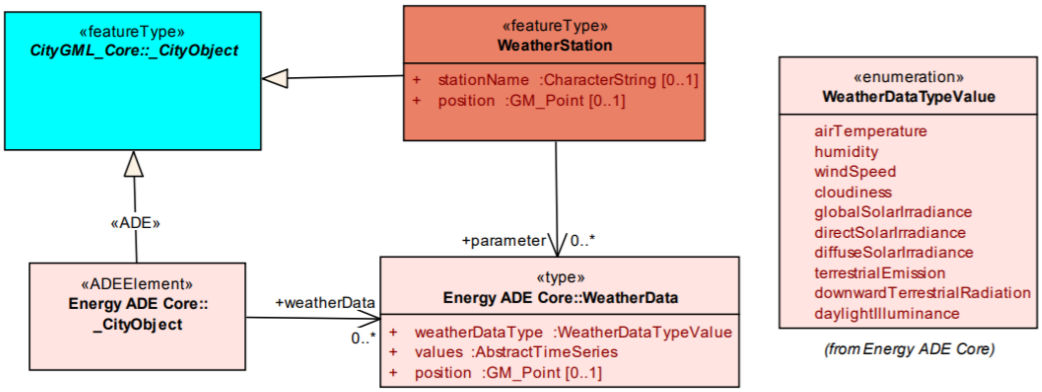


Figure 72 Weather data in Energy ADE UML diagram

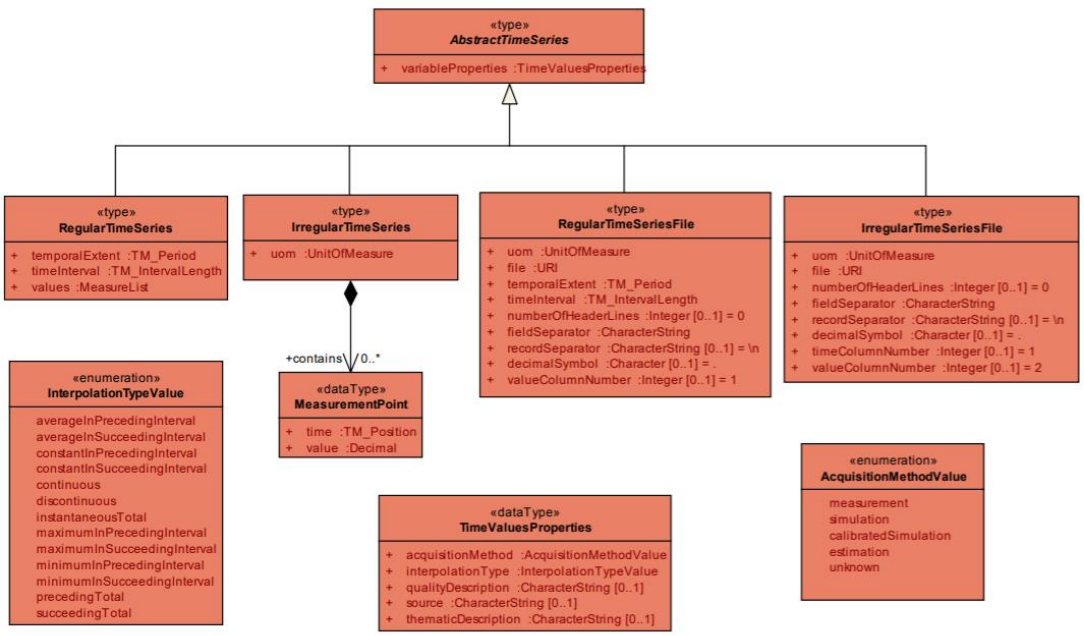


Figure 73 Time series in Energy ADE UML diagram

5.2.4. Workflow

Figure 74 illustrates the workflow to get the solar radiation of each thematic surface (roof and wall surfaces) of the target buildings. In Grasshopper, a script is written in GH Python remote component to connect to the 3D database and query the geometries in Well Known Text (WKT). The script also transforms the coordinates from WKT to Rhino's 3D Point as outputs. Other attributes such as the gmlid of the geometries are also queried. Then, the 3D geometries are reconstructed in Grasshopper and are then baked to the Rhino environment. They then become inputs for the solar radiation analysis using Ladybug plugin. The results are then written back to the database with another Python script, the radiation values are attached with the gmlid of the thematic surfaces having the values. Finally, in PostgreSQL, the results are written following the Energy ADE data model.

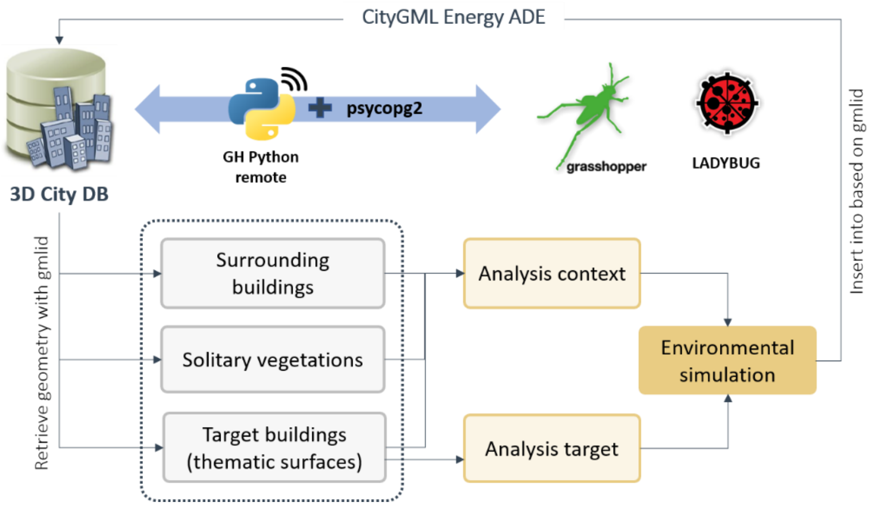


Figure 74 Workflow of the radiation analysis of the scenarios

For surrounding buildings that act as the analysis context, the LOD1 building solids are queried and are transformed to Rhino point lists. The points are then connected to form bounded surfaces. In the Alderaan dataset, buildings that are not classified as "habitation" are queried.

SELECT b.id, st_astext(a.geometry) FROM (citydb.surface_geometry AS a JOIN citydb.building AS b ON a.cityobject_id = b.id)
WHERE b.lod1_solid_id = a.root_id AND a.geometry is not null AND b.class is null;

For buildings that are the analysis target, the LOD2 thematic surfaces (roof, wall) are queried, as it is expected that the solar radiation value is estimated for each surface of the buildings. The queried WKT are transformed to Rhino point lists to form bounded surfaces accordingly. The gmlid of the thematic surfaces are also kept track with the geometry for the following step in storing the solar radiation back to the database.

SELECT st_astext(a.geometry), b.gmlid FROM citydb.surface_geometry as a JOIN citydb.cityobject as b ON a.cityobject_id = b.id
WHERE a.geometry is not null and (left(b.name, 4) = 'Roof');

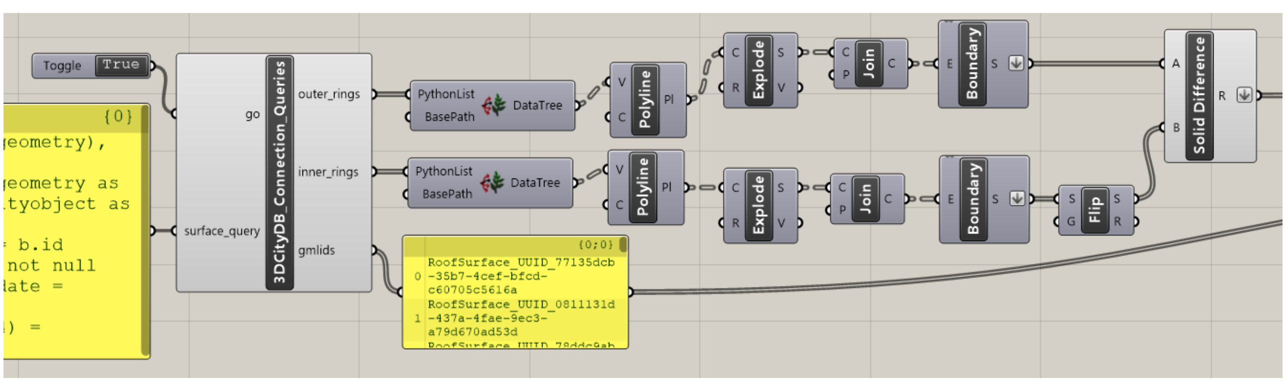


Figure 75 Grasshopper workflow to query and reconstruct surface geometry (Roof surfaces)

Importing the existing vegetation (or designed vegetation) from the 3DCityDB is a bit different from the buildings. In Grasshopper, the tree's prototypic geometry is first queried from 3DCityDB and is reconstructed accordingly. In this example, the LOD3 geometry is addressed. In parallel, the implicit representation of the trees is queried and treated; the outputs of this step include the Rhino's point where the tree should be located, and the x, y, z scale factors of the tree at that point.

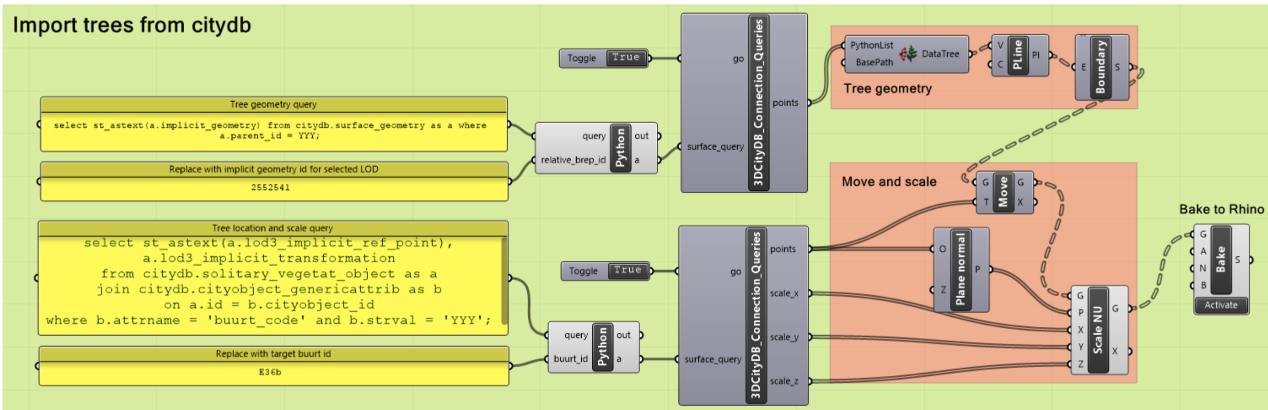


Figure 76 Grasshopper workflow to query and reconstruct tree geometry

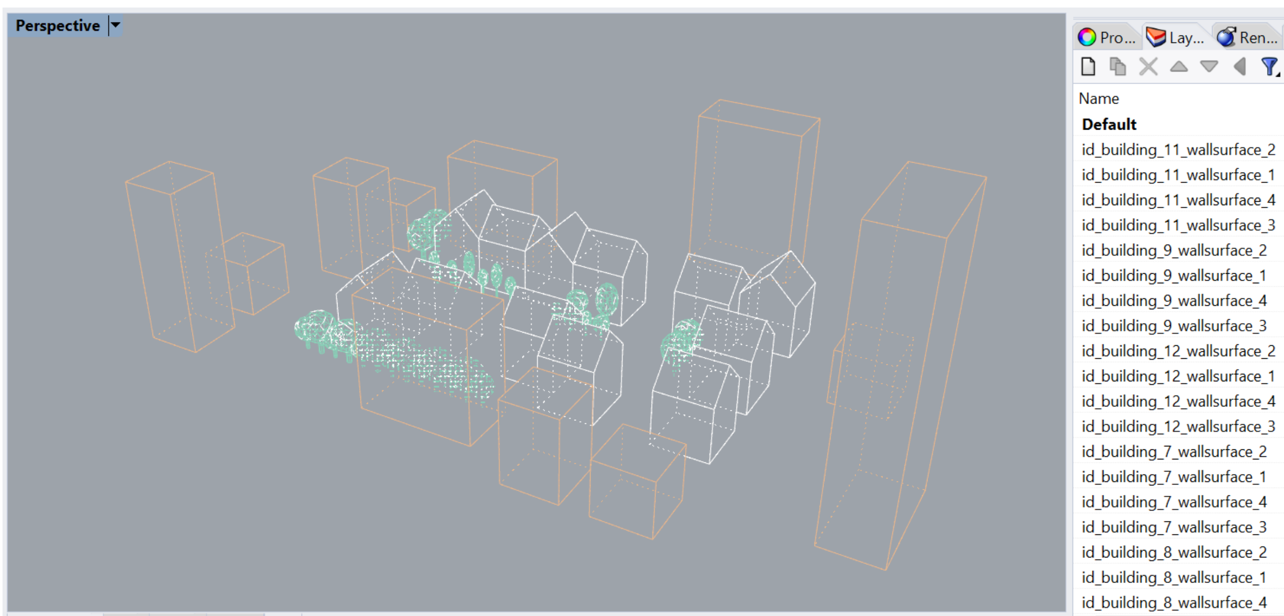


Figure 77 Geometries in Rhino with gmlid attached (white buildings in LOD2 – analysis targets, orange buildings in LOD1 – context, vegetation – analysis context)

All building and tree geometries are "baked" into the Rhino's environment. The gmlids of the thematic surfaces of the scenarios are attached to the layers in Rhino using the Grasshopper's plugin Elefront. All of the "baked" geometries are used as inputs for the radiation analysis context, whereas the "baked" geometries of the thematic surfaces are also used as the analysis targets. Then, monthly radiation values are generated using Ladybug's radiation analysis component. Some manipulations are added to get the radiation results at the surface level that are linked with the surface's gmlid. They are then written to a temporary table in the project's database before being translated to the 3DCityDB Energy ADE format. The tree geometries are not used in the winter months (December to March) for the simulation because it is assumed that they have no foliage during this time of the year.

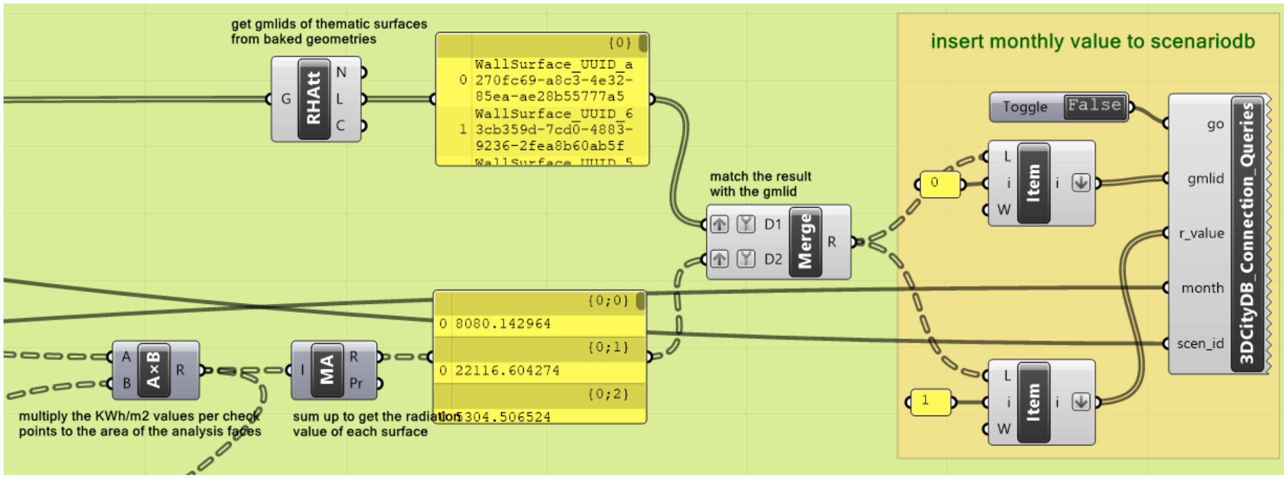


Figure 78 Grasshopper workflow to insert monthly radiation value to the database

In 3DCityDB, the following steps are done to complete the storage of radiation values:
[1] Insert into the "ng_cityobject" table the id of the thematic surface (roof and wall) which the radiation values are attached;

	id [PK] integer
1	10959
2	10960
3	10963
4	10965
5	10968
6	10975

Figure 79 Screenshot of the "ng_cityobject" table

[2] Insert into the "cityobject" table the corresponding data on weather data and time series;

id [PK] integer	objectclass_id integer	gmlid character varying (256)	gmlid_codespace character varying (1000)	name character varying (1000)	name_codespace character varying (4000)	description character varying (4000)
12022	50005	Weatherdata_GS_11591	[null]	[null]	[null]	[null]
12023	50005	Weatherdata_GS_11592	[null]	[null]	[null]	[null]
12024	50005	Weatherdata_GS_11594	[null]	[null]	[null]	[null]
12025	50005	Weatherdata_GS_11595	[null]	[null]	[null]	[null]
12026	50005	Weatherdata_GS_11597	[null]	[null]	[null]	[null]
12027	50033	Timeseries_GS_10959	[null]	[null]	[null]	[null]
12028	50033	Timeseries_GS_10960	[null]	[null]	[null]	[null]
12029	50033	Timeseries_GS_10963	[null]	[null]	[null]	[null]

Figure 80 Screenshot of "cityobject" table

[3] Insert into the "ng_timeseries", "ng_weatherdata" and "ng_regulartimeseries" table the corresponding information and values. The radiation values are stored as a string of twelve concatenated values of twelve months in a year; thus the time interval would be 1/12 (0.0833).

id [PK] integer	objectclass_id integer	timevaluesprop_acquisitionme character varying (1000)	timevaluesprop_interpolation character varying (1000)	timevaluesprop_qualitydescri character varying (1000)	timevaluesprop_thematicdescr character varying (1000)
12027	50033	simulation	[null]	[null]	[null]
12028	50033	simulation	[null]	[null]	[null]
12029	50033	simulation	[null]	[null]	[null]
12030	50033	simulation	[null]	[null]	[null]
12031	50033	simulation	[null]	[null]	[null]

Figure 81 Screenshot of the "ng_timeseries" table

id [PK] integer	cityobject_weatherdata_id integer	position geometry	values_id integer	weatherdatatype character varying (1000)	weatherstation_parameter_id integer
11623	11102		12052	globalSorlarIrradiance	[null]
11624	11106		12053	globalSorlarIrradiance	[null]
11625	11111		12054	globalSorlarIrradiance	[null]
11626	11126		12055	globalSorlarIrradiance	[null]
11627	11131		12056	globalSorlarIrradiance	[null]

Figure 82 Screenshot of the "ng_weatherdata" table – values_id is the foreign key that links to the "ng_timeseries" and the "ng_regulartimeseries" table

id [PK] integer	timeinterval_ numeric	timeinter integer	timeint integer	timeinterval_unit character varying (10	timeperiodprop_beginposition timestamp with time zone	timeperiodproper_endposition timestamp with time zone	values_ text	values_uom character varying (1
12027	0.0833	[null]	[null]	year	2020-01-01 00:00:00+01	2020-01-31 23:59:00+01	899.061 1621.06 6947.29 10655.1 11948.4 12742...	KWh
12028	0.0833	[null]	[null]	year	2020-01-01 00:00:00+01	2020-01-31 23:59:00+01	5251.32 11573.6 28062 37532.7 34347.2 38952.5...	KWh
12029	0.0833	[null]	[null]	year	2020-01-01 00:00:00+01	2020-01-31 23:59:00+01	900.633 1597.7 5770.57 10591 10692.5 9597.67 ...	KWh
12030	0.0833	[null]	[null]	year	2020-01-01 00:00:00+01	2020-01-31 23:59:00+01	10719.9 20412.4 48453.2 75156.6 70373.7 67033...	KWh
12031	0.0833	[null]	[null]	year	2020-01-01 00:00:00+01	2020-01-31 23:59:00+01	1760.29 2697.94 7004.62 10597 11269.5 10143 8...	KWh
12032	0.0833	[null]	[null]	year	2020-01-01 00:00:00+01	2020-01-31 23:59:00+01	12283 25186.9 59914.9 78684.9 71539 79454.9 7...	KWh

Figure 83 Screenshot of the "ng_regulartimeseries" table

In the last step, the appearance illustrating solar radiation is also added to the model at the surface geometry level according to CityGML standard. Due to the time scope of the thesis, the texture images of solar radiation are not visualized but instead diffuse color based on the range of radiation values are applied for each surface.

5.3. Solar radiation analysis on the scenarios

After testing the approach with the Alderaan dataset and resolve, debug most of the possible problems, the solar radiation analysis approach is applied for the new urban development, with the scenarios as the analysis targets and the surrounding areas and the vegetations as the context.

The integration of design scenarios back to the 3D city model of today allows quantifying the radiation values of the scenario and the impacts on radiation values of the surrounding context. In the design stage of the "Buurt Generator", the 3D models of the design scenarios in Grasshopper were stored in the 3DCityDB (FME was used to translate the model to CityGML format, 3DCityDB importer was then used to import the CityGML file to the database). Two scenarios in the project's database (Scenario 65 and Scenario 71) are selected for testing the workflow of the post-evaluation regarding solar radiation. Scenario 65 prefers bigger and fewer numbers of building footprints whereas Scenario 71 prefers a smaller and higher number of building footprints. The statistical distribution of the solar radiation can be queried from the 3DCityDB database.

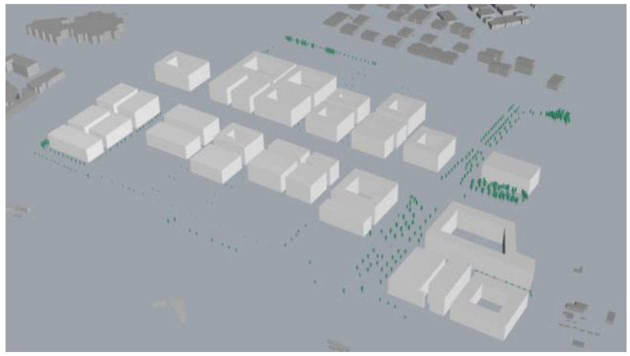


Figure 84 Screenshot of the baked geometries in Rhino (Scenario 65 in a bright color)

	Scenario 65	Scenario 71
Total volume (m³)	3906243	3844546
Footprint area (m²)	114137.66	122593.57
Total wall surface area (m²)	369114.06	405959.1
Wall area facing North-West	99766.99	109275.03
Wall area facing North-East	84674.17	93897.63
Wall area facing South-West	83494.9	93594.8
Wall area facing South-East	101178	109191.64

Table 16 General information of the two scenarios

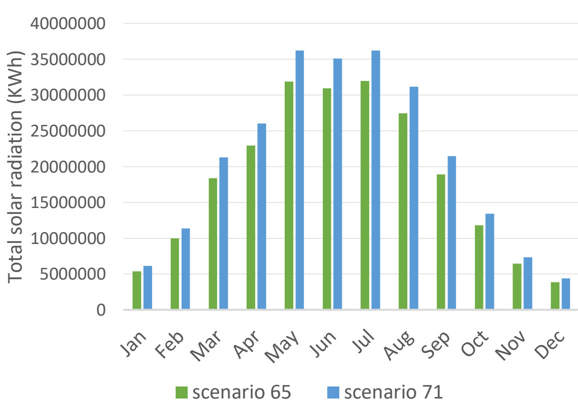


Figure 85 Total solar radiation of the two scenarios

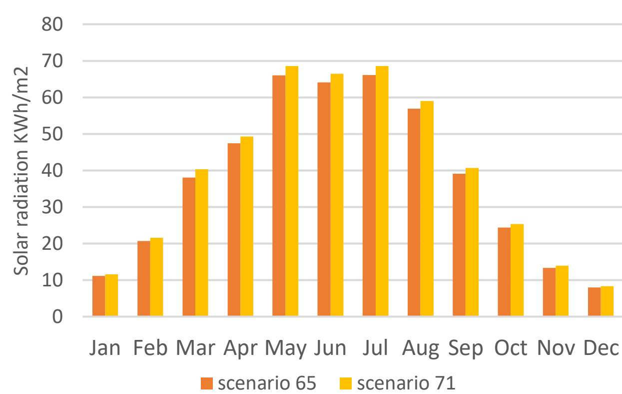


Figure 86 Solar radiation per m² of the two scenarios

In general, Scenario 71 receives a larger amount of solar radiation. On the one hand, Scenario 71 is smaller in volume but has a larger total building footprints area and total wall surface area. As a result, the total surface area having contact with the sun is larger. On the other hand, when the solar radiation per square meter is considered, the value from Scenario 71 is also larger due to the spatial arrangement of the buildings. As can be observed, the buildings in Scenario 71 are considerably smaller in size and are scattered around the development area. The distances between the buildings are also larger compared to Scenario 65.

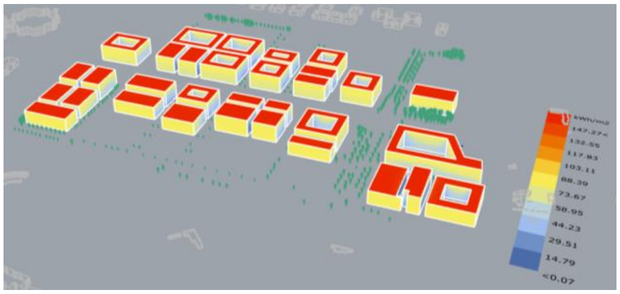


Figure 87 Screenshot of radiation analysis of scenario 65 in June

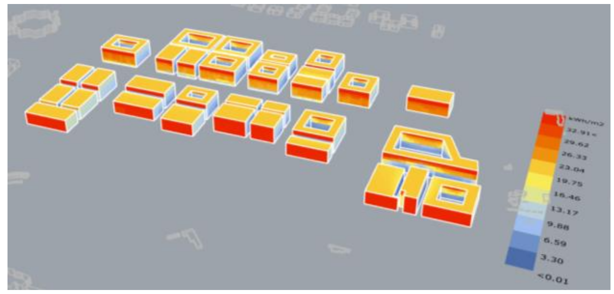


Figure 88 Screenshot of radiation analysis of scenario 65 in January

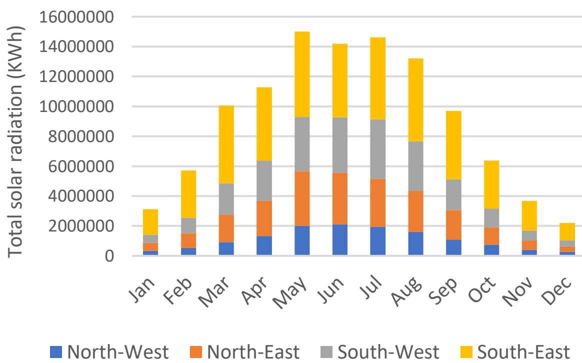


Figure 89 Total solar radiation on wall surfaces according to the wall's azimuth – scenario 65

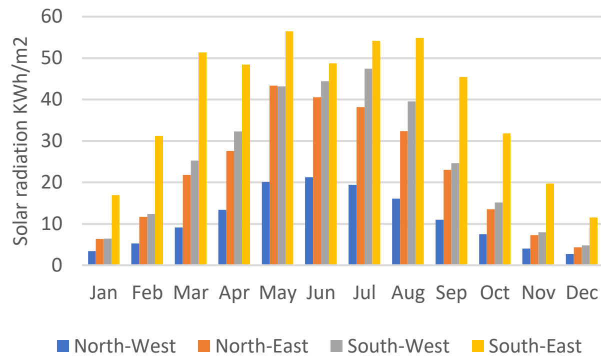


Figure 90 Solar radiation per m^2 on wall surfaces – scenario 65

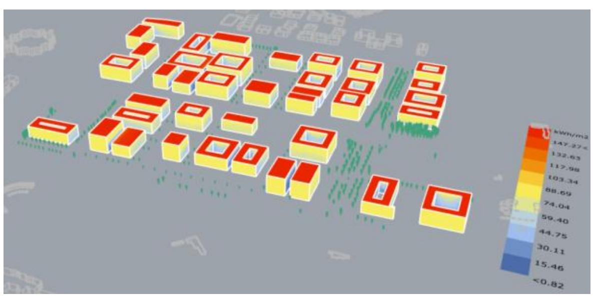


Figure 91 Screenshot of radiation analysis of scenario 71 in June

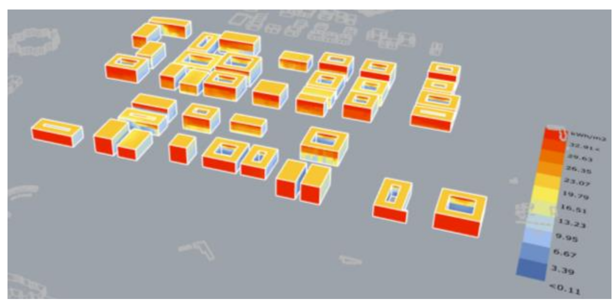


Figure 92 Screenshot of radiation analysis of scenario 71 in January

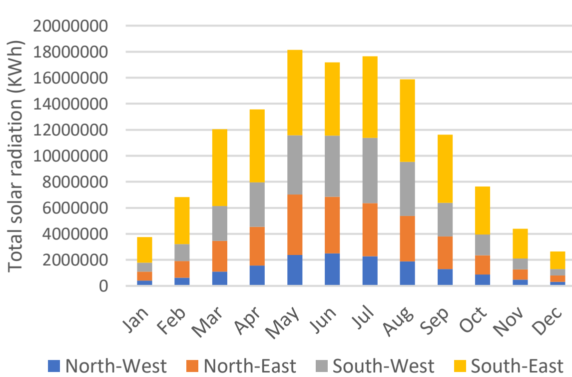


Figure 93 Total solar radiation on wall surfaces according to the wall's azimuth - scenario 71

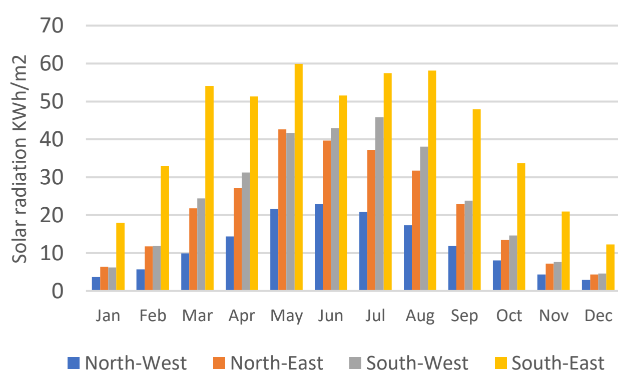


Figure 94 Solar radiation per m^2 on wall surfaces – scenario 71

For each of the wall surfaces of the development scenarios, their azimuths and surface areas are calculated and stored in the cityobject_genericattrib table together with the cityobject_id of the wall surfaces as a foreign key. This allows further investigation of the solar radiation distribution between the scenarios at the wall surface level. For both scenarios, the walls facing South to Southeast receive a considerably larger amount of total solar radiation. The values decrease for walls facing South-West, North-East, and North-West accordingly. The solar radiation per square meter also reflects the same pattern.

Hence, a test is conducted for a single building without surrounding context that reveals stronger solar radiation from the South. Apart from that, the spatial distribution of the buildings also affects the solar radiation pattern. The buildings in Scenario 65 are volumetrically large and quite close together whereas those in Scenario 71 are smaller in size, have more units, and are evenly distributed across the development site. As a result, the post-evaluation of the design regarding solar radiation suggests some additional constraints for the design stage such as the minimum distance between the buildings concerning the azimuth of the wall surfaces and the height of the wall. It can also suggest the placements of vegetation that minimize the solar radiation in the summer months and maximize the values in the winter months. In this case, the area adjacent to the façade facing the South should be considered for plantations.

On the one hand, the spatial arrangement of building clusters and external shading elements (e.g., trees) should optimize the solar radiation at the building's surface in different seasons. The buildings should have a reasonable ratio between building height and the void between them. Introducing the optimization problem of solar radiation in the design stage could be over complicated. Hence, this element is evaluated in the post-design stage as an indicator to choose between the scenarios or to find weak points in the workflow of the design stage that should be improved. On the other hand, the introduction of new constructions could considerably affect the solar radiation hitting the surface of existing buildings, especially in the case of relatively high buildings in a dense existing urban fabric. Hence, it is one important aspect that should be considered in the context of sustainable development. Furthermore, the post-evaluation also allows the comparison between scenarios for decision-making purposes. The difference between the numbers could be directly transformed into quantitative indicators in a decision-making framework.

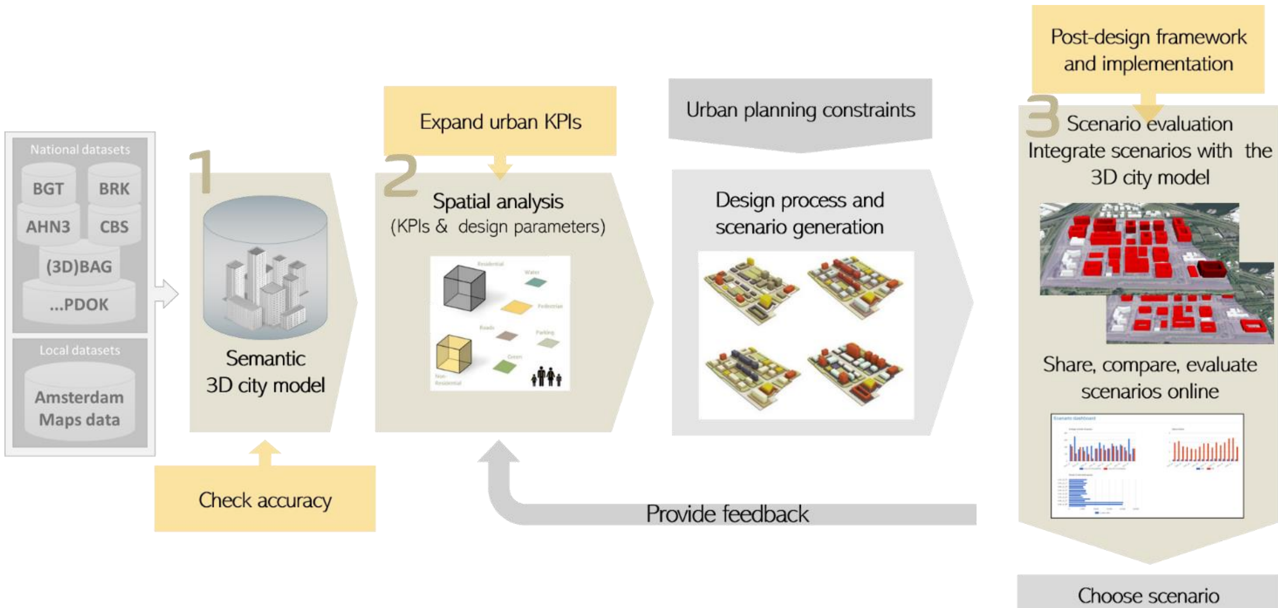
5.4. Chapter conclusion

Urban simulation is a fast-growing field with many applications and plugins being developed for different environmental aspects of the built environment. In recent years, Grasshopper and its extensions/plugins are renowned for a wide array of options not only for parametric design but also for urban simulation such as solar radiation analysis, shadow analysis, view analysis, thermal comfort analysis, wind analysis, etc. 3DCityDB and its ADE, on the other hand, offers a solution for generating, storing semantic 3D city model (includes buildings, urban infrastructure, urban furniture, and vegetation, etc.) and its expansions (energy, noise, wind, etc.).

As a result, bridging the gap between Grasshopper and 3DCityDB (that eventually lead to the semantic 3D model of the city of today and also future spatial intervention) would open up a wide range of applications as an attempt to understand the present context of the city as well as to predict impacts of new developments on the existing environment. With the web map client package offered together with the 3DCityDB, the simulation results could also be disseminated via web interfaces. The viewers can request detailed information via a dashboard or via interacting directly with the objects in the interface.

In the context of the "Buurt Generator", the above workflow opens up further applications in post-evaluation of the design solutions. With the same approach, other aspects such as urban thermal comfort, energy demand, wind simulation, and view analysis can be conducted. This work has also contributed to testing the existing implementation, finding bugs, reporting them, and having them solved.

6 Conclusion and Recommendation



6.1. Conclusion

This thesis contributes to the further development of the "Buurt Generator" by testing and expanding some of its functionalities. In terms of testing, the whole concept of the tool through the lens of urban planning is first reviewed. Then, the fundamental component of the tool, which is the 3D city model of today, is checked in terms of its accuracy to be used in analyzing the urban context and generating urban KPIs in the latter steps. After that, the list of design KPIs is expanded by considering different spatial and non-spatial, volumetric, and non-volumetric urban indicators from the existing data context in the Netherlands. Lastly, the research focuses on expanding the functionalities of 3D GIS in the post-design stage.

Accordingly, three research questions are generated to guide the thesis as follows:
[Question 1] How accurate the 3D model is in estimating the residential and non-residential volumes within the city?

[Question 2] What key performance indices could be introduced as new inputs for the design stage of the tools? How to develop them in the pre-design stage?

[Question 3] In which aspects the developed scenarios could be evaluated in the post-design stage? How to utilize the 3D models of the scenarios, the 3D city models, and other spatial data for the evaluation?

In the second chapter, after briefly describe the current package of the GIS-supported design tool for new urban development project (the "Buurt Generator"), the thesis critically reviewed the tool in terms of its function, its target user, its pre-design stage, design stage, and post-design stage. The tool is developed based on the data context of the Netherlands that requires a group of users of different expertise and is operated in different software and applications. Regarding the pre-design stage, the accuracy of the 3D city model of today is questioned as it is one of the important components to derive volumetric urban KPIs. Moreover, the list of urban KPIs is also limited to the requirements of the development project rather than the development context of the city, the project site and its surrounding. Regarding the design stage, further built-in constraints and options could be introduced to the Grasshopper script to enrich the design product to meet the requirements not only from the development KPIs but also the city's regulation and other aesthetic, social, and environmental aspects. For the post-design stage, the current product is limited to visualization and dissemination via a web interface, with dashboards presenting the design outcomes in numbers. Therefore, further post-evaluation options could be introduced to the product package to review the design product, to assist the decision making, and to guide the further elaboration of the design in the implementation stage. Furthermore, the literature review on urban planning in general and computer-assisted tools in urban planning introduces directions for the further development of the "Buurt Generator".

In the third chapter, the thesis answered the first research question on the accuracy of the 3D City model generated within the "Buurt Generator" package. A volumetric comparison approach between the 3D model of the "Buurt Generator" and those of a newly developed 3D model by Kadaster and TU Delft (BAG3D 2.0) was conducted. It was revealed that the volume of the buildings from the "Buurt Generator" is very close to the volume of the BAG3D 2.0 in LOD2.2. However, there are some specific cases where a huge volume difference occurs. On the one hand, it is because of some errors in the 3D reconstruction of the BAG3D 2.0, notably the case of multi-parts buildings. On the other hand, the approach of the "Buurt Generator" is error-prone in the case of very small footprint buildings and very large footprint buildings. Small footprint buildings are mostly garage, shed, that might fall under vegetation or other structure that makes the median height to be extruded ambiguous. However, these buildings are not that important for deriving urban KPIs. The case of the large building footprint, however, is concerned as they are important in calculating urban KPIs. The thesis suggests that the median height to be used to extrude a large building footprint might underestimate the building size. Residential buildings, which are the key ingredient of the urban KPIs, are fortunately having the most stable and correct derived volume. In brief, the thesis contributes to give an insight into the overall quality of the 3D models (the "Buurt Generator" and also the 3D BAG 2.0), to identify errors and understand the common sources of errors.

In the fourth chapter, the second research question is addressed. New urban KPIs are calculated that cover different urban aspects of the city and offer a more comprehensive approach in understanding the city context. Accordingly, a list of urban aspects and their KPIs are first generated. After that, different spatial and non-spatial datasets are collected and treated to get meaningful values in describing the city context. Compared to the current "Buurt Generator", new urban KPIs address the context of the surrounding areas by applying a buffer zone for calculating the urban amenities provided for neighborhoods, also the classification of different housing types and types of indoor amenities, the demographical context, and also the measured quality of different urban aspects. The KPIs are then arranged in the project database that facilitates the queries and spatial data visualization from the users/urban practitioners. Based on the project database, the chapter then attempts to describe the city regarding the demographic context, the built-up status, the housing context, the provision of urban amenities (both indoor and outdoor amenities), the livability status, and the development periods. Input KPIs for the new urban development project, as a result, will be drafted based on the current urban context and the development goals of the project site. The new approach obtains a different result from the current "Buurt Generator" approach. In brief, the thesis contributes first to expand the list of KPIs that helps to refine the descriptive capabilities of the tool, and second to assist the extracting of data at different urban scales for the development of KPIs for the design stage.

It should be emphasized that the pre-design stage in the tool assists in understanding the urban context and assists the site analysis of the new urban development project. It does not substitute the traditional approaches including on-site empirical research and professional knowledge towards the site. Furthermore, the tool also acts only as a guideline for the extraction and development of KPIs for the design stage. The chosen KPIs must meet an agreement between the stakeholders and must also comply with the existing regulations and constraints from the municipalities. However, findings from the data could also be used to inform the cities on the suitability of development indicators assigned for the urban areas for further consideration.

The thesis skips the design stage of the project package and moves to the post-design stage (as it is out of the scope of this thesis). In the fifth chapter, the thesis deals with the third research question, the development scenarios (that were generated in the current "Buurt Generator") are integrated into the 3D city model of today for post-evaluation purposes. Firstly, a post-evaluation framework is developed based on a literature review. The framework, however, focuses mainly on the integration of the 3D city model in the urban planning process, that other social and economic factors might not be included. Possible technical solutions for each of the criteria/indicators in the framework are also introduced. The thesis then chooses the solar radiation analysis to be the focus for development. For that, a workflow in Grasshopper is developed that retrieves geometries of the scenarios and the urban context from the 3DCityDB and reconstructs them in the Rhino/Grasshopper environment. After that, monthly solar radiation simulation for the scenarios is conducted using the Ladybug plugin. The results are then written back to the 3DCityDB at the thematic surface level employing the Energy ADE. The workflow has contributed to bridging the gap between urban simulations offered in Grasshopper and 3D city models in general (3DCityDB and CityGML in particular) that suggest further urban simulations to be operated in urban development applications.

Overall, the thesis further explores the values of the 3D city model in the urban planning process, from the pre-design stage to the post-design stage. 3D city model not only helps to understand the city context in a visual manner but also in a spatial data-driven manner. Moreover, the integration of 3D models of new design solutions to the existing 3D urban context offers a wide range of post-evaluation approaches that are conveniently disseminated among the stakeholders for the decision-making process. The thesis, however, only covers some parts of the "Buurt Generator" package and paves the path for further development of the tool.

6.2. Recommendation

As also mentioned by (Garcia González, 2019) and (Agugiaro et al., 2020), the "Buurt Generator" can be further improved in different aspects. In the short term, it was recommended that there should be some rounds of questionnaires and interviews with the intended users to test the usability of the tool. Furthermore, the spatial parameters and indicators should continue to be enriched, same for the constraints and the design options and typologies for the design stage. In the long term, the complete chain of the tool could be incorporated in one interface for data modeling, spatial analysis, scenario generation, visualization, and interaction (probably via web interface) instead of using different GIS packages simultaneously as it is now.

From the perspective of the thesis work, the recommendations are tailored to each of the research problems. First and foremost, since the 3D modeling approach of the "Buurt Generator" is error-prone to large footprint buildings that affect the derived building volume, further investigation should be conducted to choose an appropriate value as height to be extruded from the building footprint instead of the median value.

Secondly, further suggestions should be provided to the authority with regard to the storing and disseminating of semantic urban datasets that facilitate urban practitioners in data mining, manipulating, and analyzing. For example, the data on building functions/usages and associated net floor areas are ambiguous as there might be the case one function/usage of more than one building is assigned for only one building or the register net floor area is wrong. The datasets also do not record the start and end date of the functions/usages. Still, only the date it was registered into the database is stored, which does not support the spatial-temporal analysis of the dataset. Furthermore, apart from quantitative datasets, other descriptive or qualitative datasets that are spatially based could also be generated and disseminated for different uses. For example, there could be information on the architectural period and architectural details that attached to different spatial location, or other qualitative data on the perceived livability, lovability, or the perceived density of different urban areas.

Thirdly, the design stage should be enriched with new suggestions from the design stage and from the product review. New design KPIs, building typologies, and constraints could be introduced to the current Grasshopper workflow in generating development scenarios semi-automatically. Hence, the design would be more detailed in terms of functional allocation and be more realistic with design parameters such as setbacks according to road types and building heights, more options for building typologies and building arrangement within a block, etc. Furthermore, detailed information such as vegetated surfaces (horizontally and vertically), glazing surfaces, the material used, etc. could enable further port-evaluation options. For example, with information on thermal transmittance (u-value) from the building's material and thickness of the walls and other building' design details, the energy demand for the new development scenario could be generated. Another example is the simulation of urban thermal comfort based on the spatial arrangement of building blocks, vegetations, and building materials. Hence, the more detailed the design, the more information we will have for the post-evaluation of the design.

6.3. Personal reflection

Even though the master thesis is conducted during the inconvenient event of the Covid-19 pandemic, my experience during the process is valuable and still quite enjoyable. First of all, I had the chance to work with an exciting research topic that combines both my interest in urban development and geomatics. Secondly, I learned a lot from my supervisors, my colleges, and also from my own work. I could broaden my horizon both theoretically and technically and challenge myself with different concepts and research approaches. What I gained during the process definitely pertains to my expected career path in spatial data-driven approach in urban planning. Thirdly, although I could not meet my supervisors face to face, we maintained a regular virtual meeting scheme that helped me with the thesis progress and my motivation to keep up with the work. Other occasional meetings with my colleges also helped me get through the difficulties along the way.

In the first stage of the research, it took me time to understand the concept of the current GIS-supported design tool, to identify the problems to be solved within the scope of the master thesis.

I learned that background research is fundamental to point out the gaps in the current approach and to develop the research problems accordingly. Furthermore, asking the right research questions is equally important in guiding the research body to solve the issues identified. In this thesis, I address three problems for three different stages of the "Buurt Generator" and pose three research questions. The questions are theoretically linked in the "Buurt Generator" product package, but they require different research approaches. As a result, I got to deal with three rather separated problems in my thesis that allow me to work on them simultaneously. Furthermore, since the master thesis deals with a hybrid topic, I had to balance the geomatics-related contents and urban planning contents but still meet the objective in testing and developing the "Buurt Generator", which I found the most challenging.

I worked on the volume comparison of different 3D models in the first research question. From that, I learned about different approaches in generating 3D city models. Besides, the research not only checks the accuracy of the volume but also detects the cases where the 3D model went wrong and the reason behind it.

For the second research question, I learned about the open (spatial) data in the Netherlands and Amsterdam in particular. It was pretty challenging as there are many datasets available from different portals and most of the information is in Dutch. Moreover, while working with data, there are cases where errors or inconsistencies occur, so that I had to make some assumptions and filter out inappropriate data. Some errors were detected at the end of the process, causing the replication of the workflow.

For the third research question, I worked with 3DCityDB and Grasshopper which I found very interesting. I received help from other colleagues when first working with Grasshopper and expanded the existing approach in bridging 3DCityDB and Grasshopper (and the Ladybug tool).

Overall, it has been an exciting and rewarding journey working on the master thesis. I gained new knowledge and experiences working with spatial data (2D and 3D) and urban planning issues that will certainly help me prepare for my upcoming career. Moreover, the work also helps me develop the research aptitude and the endurance working solely from home.

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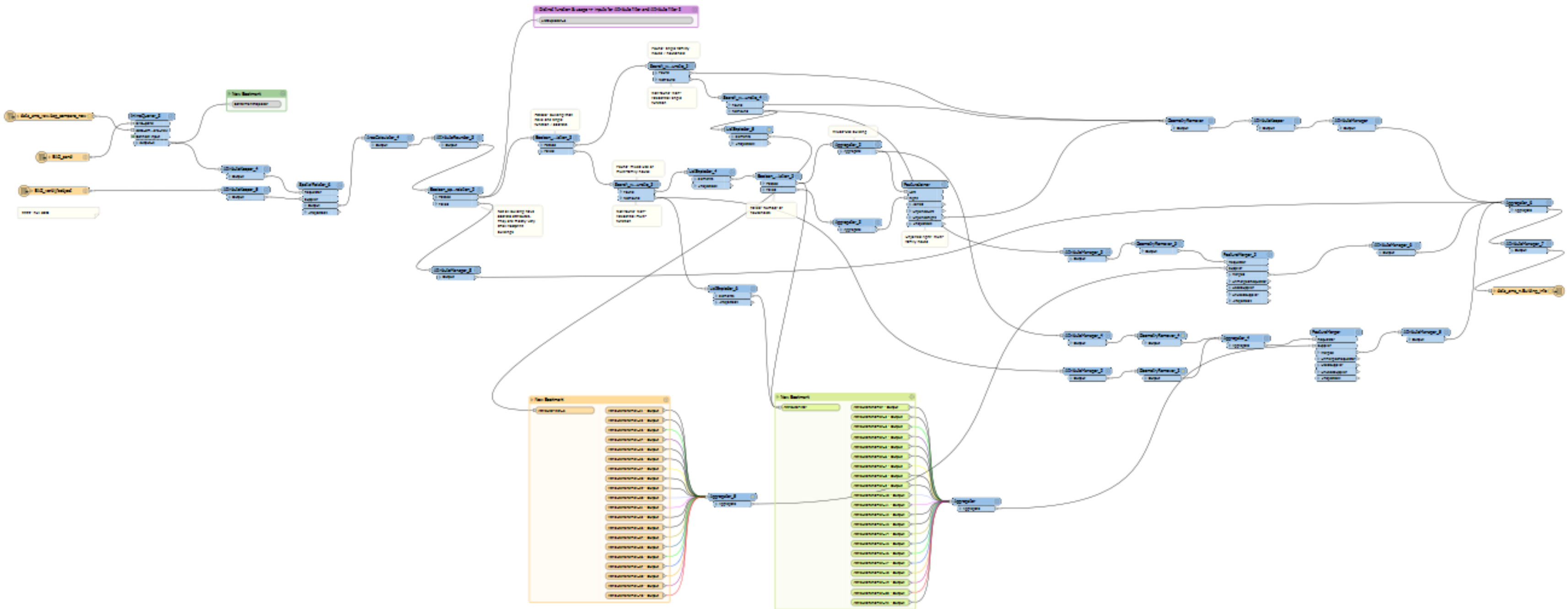
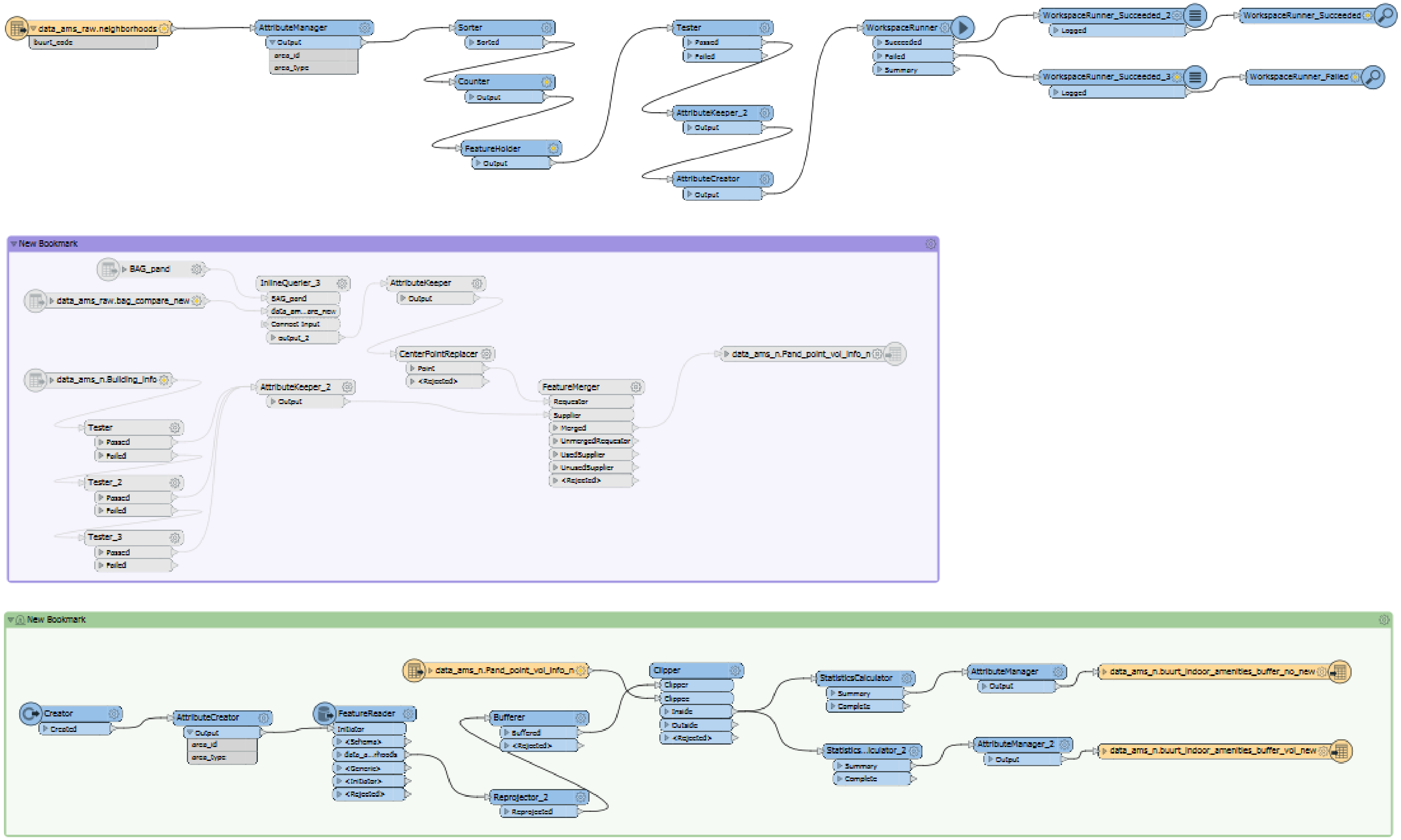
Appendix 1: List of data

Datasets	Descriptions	Link to sources
Basisregistratie Adressen en Gebouwen (BAG): BAG Pand	Dataset on buildings and addresses in the Netherlands that contains information on current main use, construction date, and registration status.	https://bag.basisregistraties.overheid.nl/
Basisregistratie Grootschalige Topografie (BGT)	Topographic map of the Netherlands that provides information on open space components (e.g., road, pedestrian path, bicycle lanes, etc.)	https://www.pdok.nl/introductie/-/article/basisregistratie-grootschalige-topografie-bgt-
CBS Wijken en Buurten 2016	Socio-economic data at the buurt and wijk level, those include the number of people, number of households, average incomes, number of cars registers, housing stocks, etc.	https://www.cbs.nl/nl-nl/maatwerk/2017/31/kerncijfers-wijken-en-buurten-2017
Leefbaarometer 2016	Dutch dataset on the quality of life at the buurt level. There are also details aspects towards housing, safety and security, amenities, and personal quality of life.	https://www.leefbaarometer.nl/page/Open%20data
Map datasets Amsterdam	A collection of urban development, housing, neighborhood, and amenities maps. Among them, the FunctieKaart that indicates different non-residential usages is valuable for the deriving of non-residential KPIs for the tool.	https://maps.amsterdam.nl/open_geodata/?LANG=en
Woningwaarde 2016	Dataset on the average price per square meter of residential construction in Amsterdam. The dataset is available in shapefile of price zone.	https://maps.amsterdam.nl/woningwaarde/
Boomkadaster	Dataset on the tree kadastre of the city of Amsterdam.	https://www.amsterdam.nl/wonen-leefomgeving/bomen/#hb9571386-1365-753f-7973-bca6faf97545

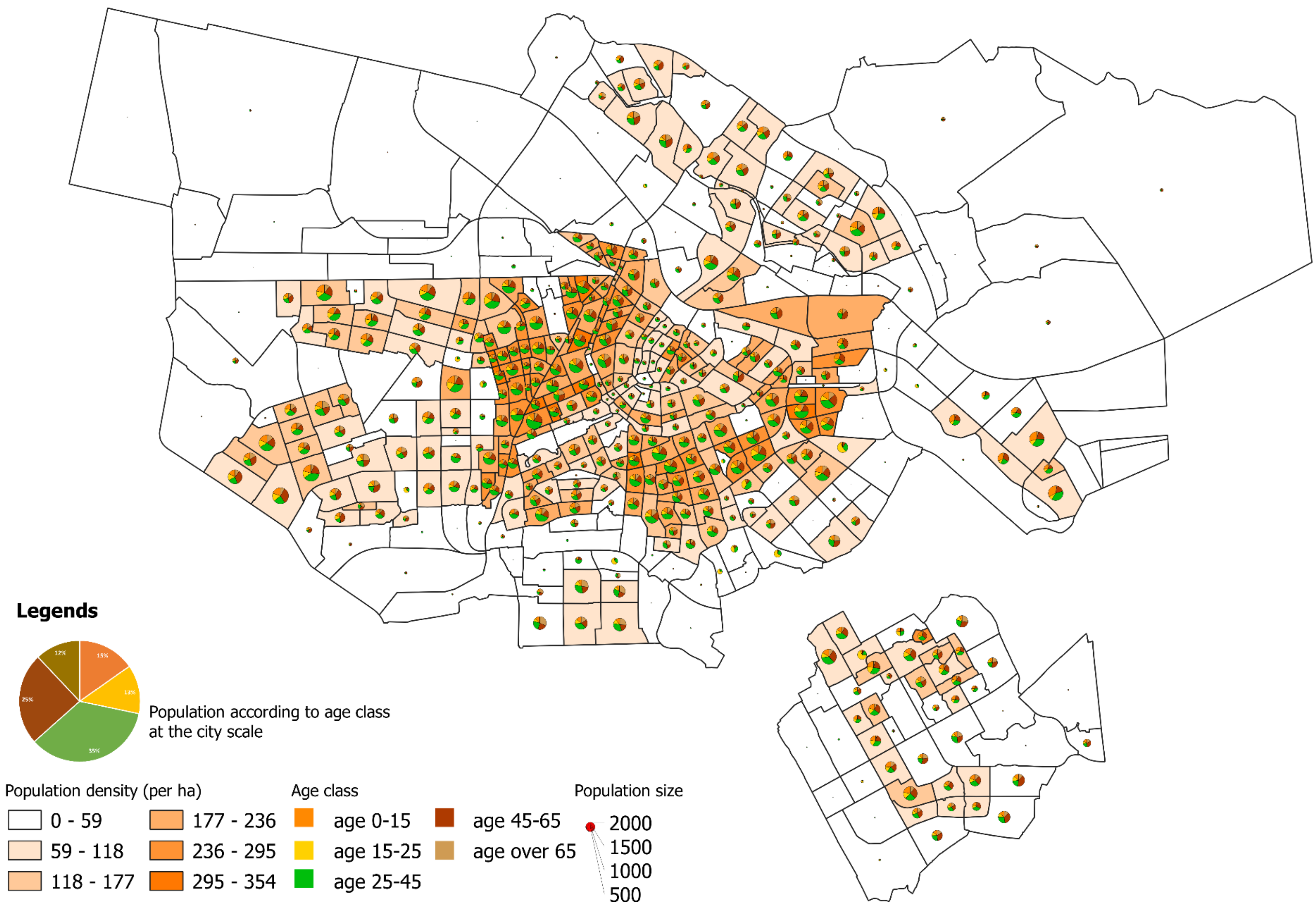
Appendix 2: Chapter 4



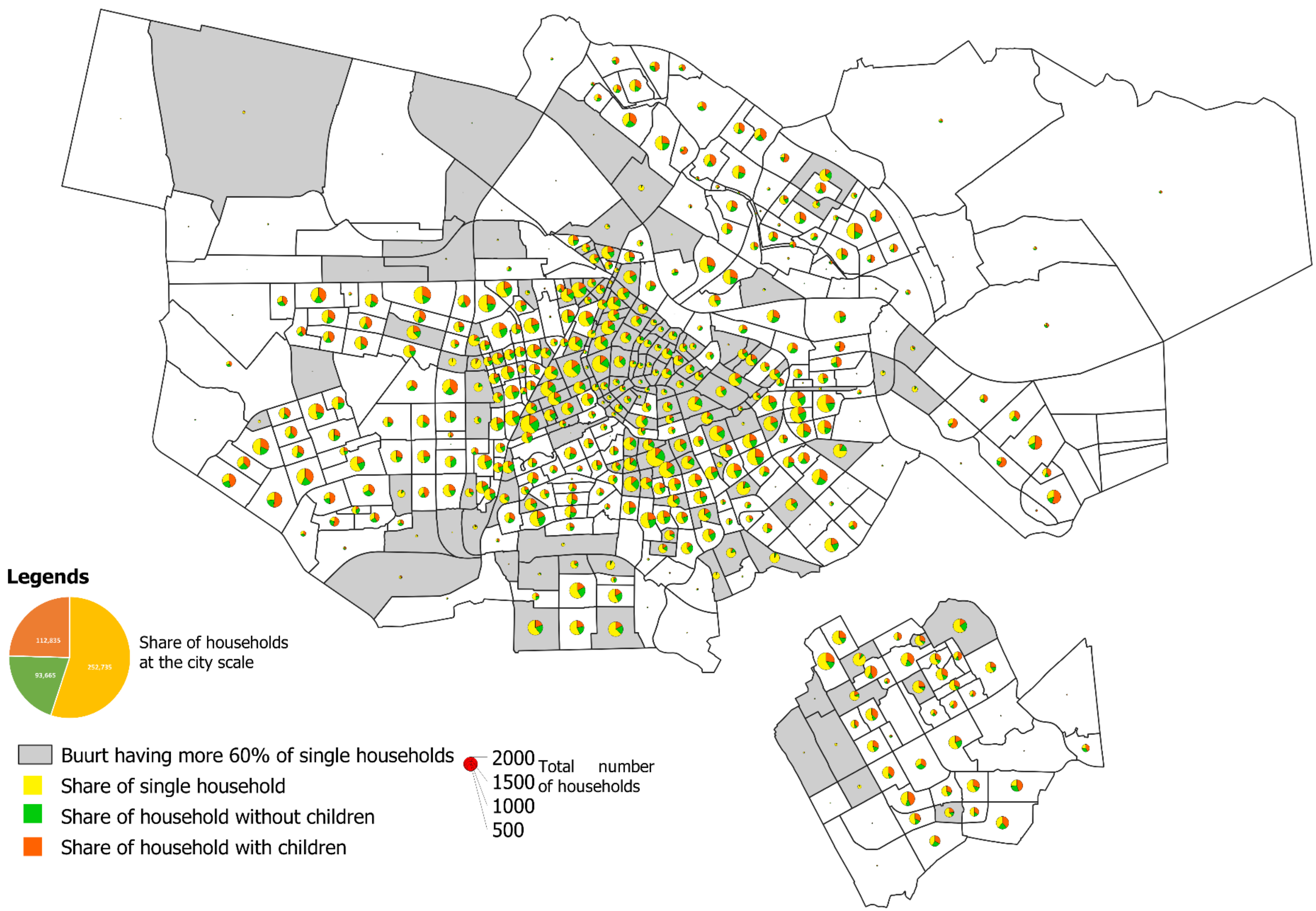
Appendix 1 FME workflow for building and building function classification



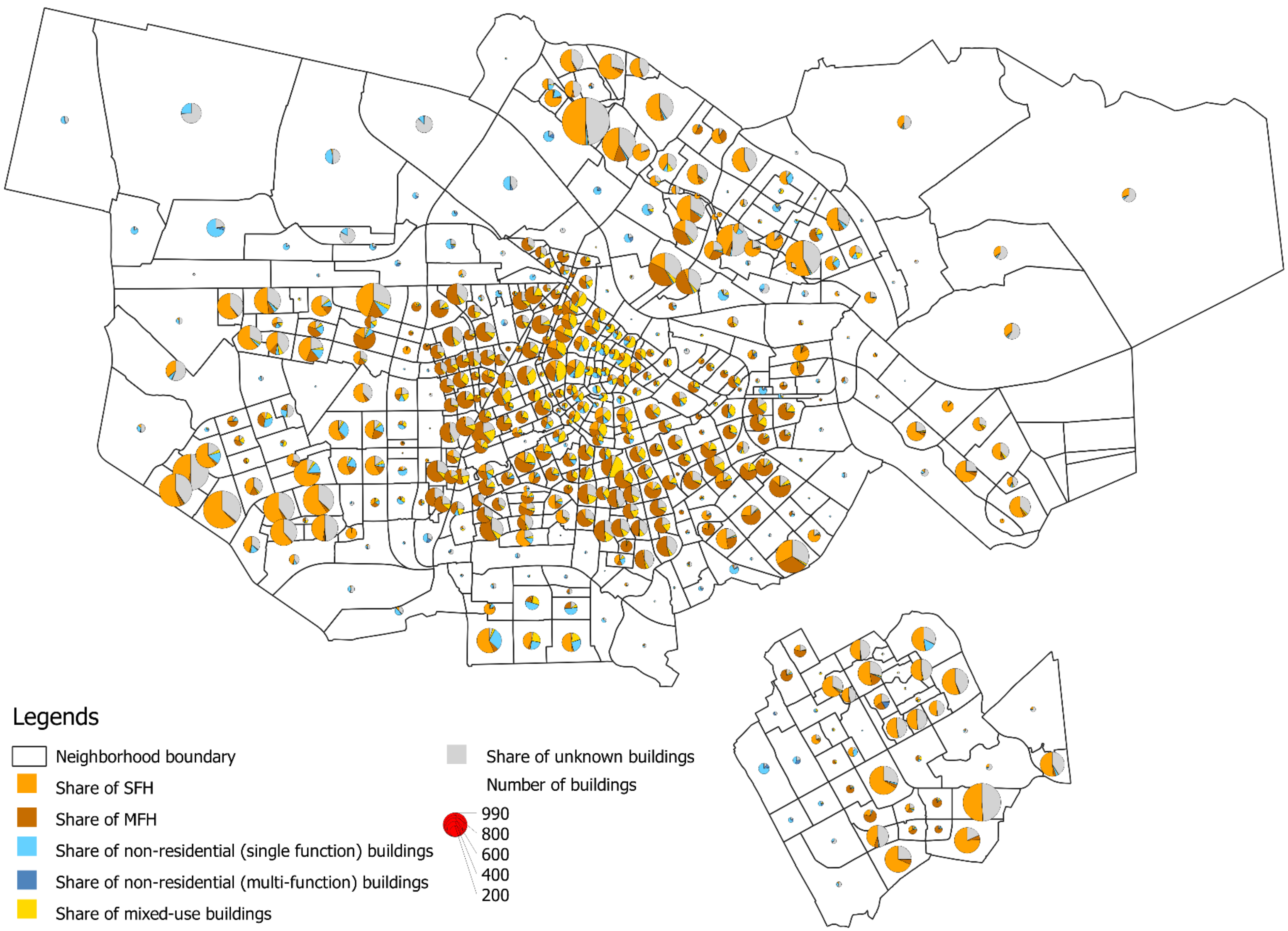
Appendix 2 FME workflow to calculate indoor amenities of the buffered neighborhoods



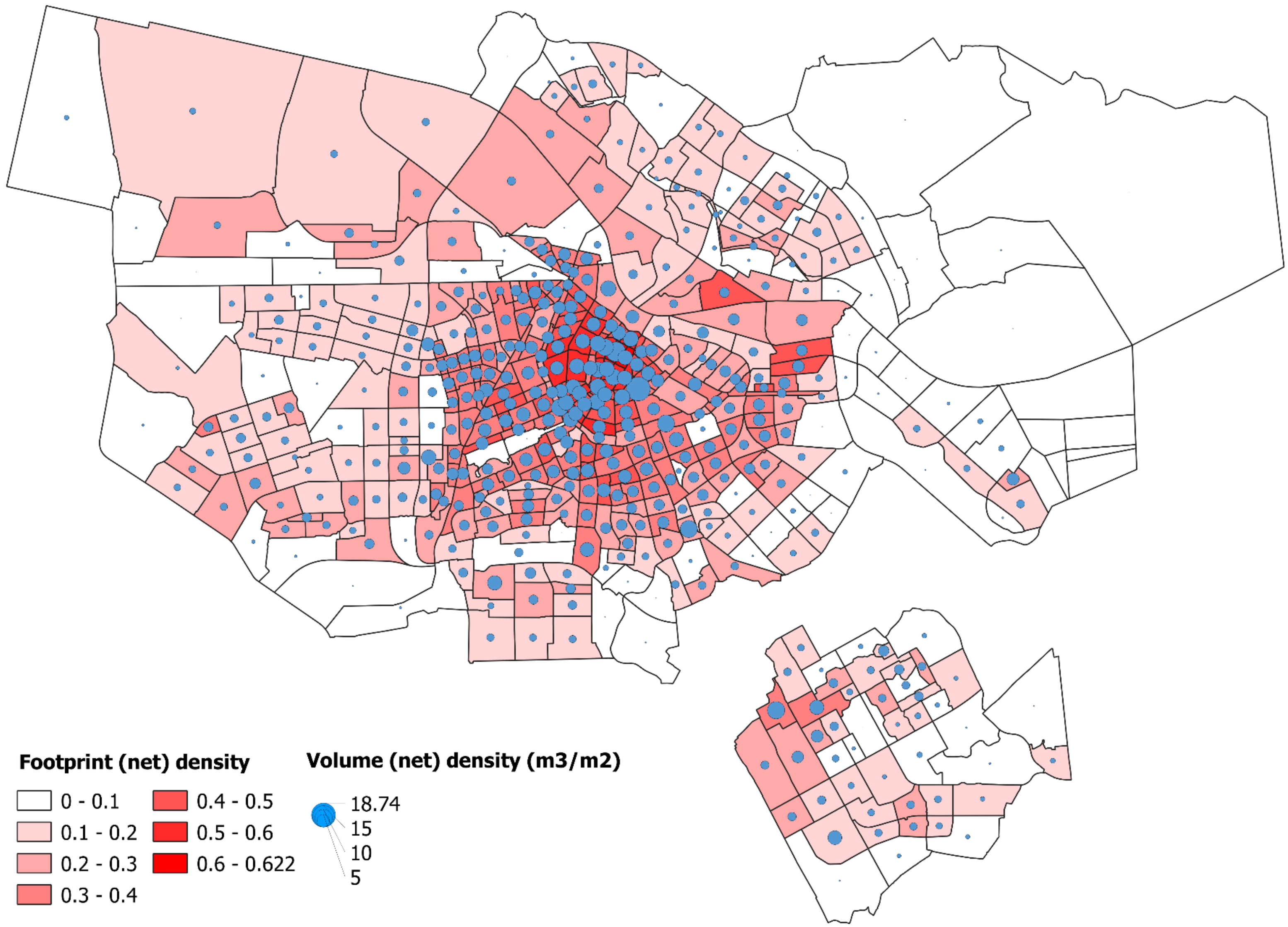
Appendix 3 Spatial distribution of population in Amsterdam in 2016



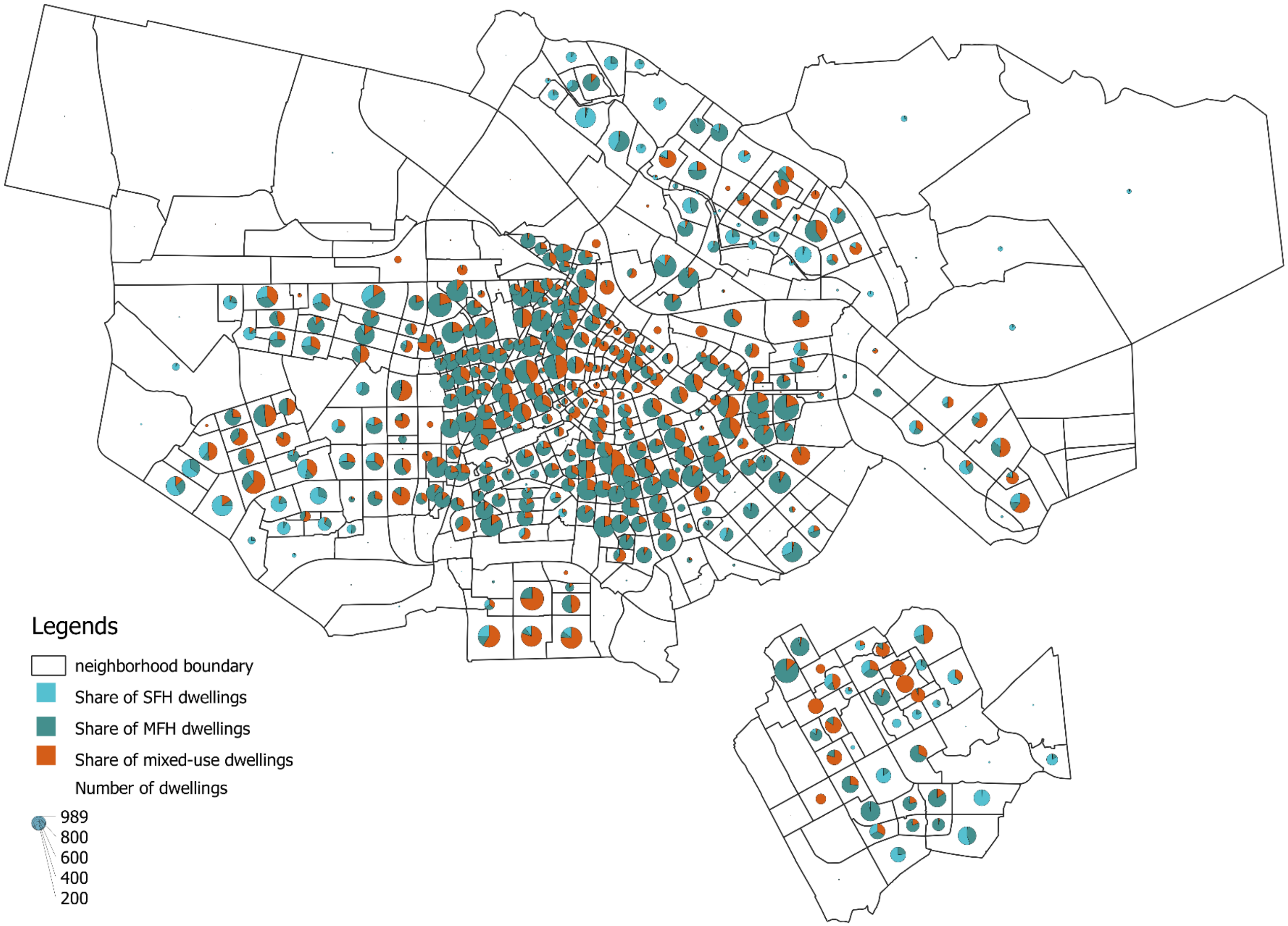
Appendix 4 Spatial distribution of households in Amsterdam in 2016



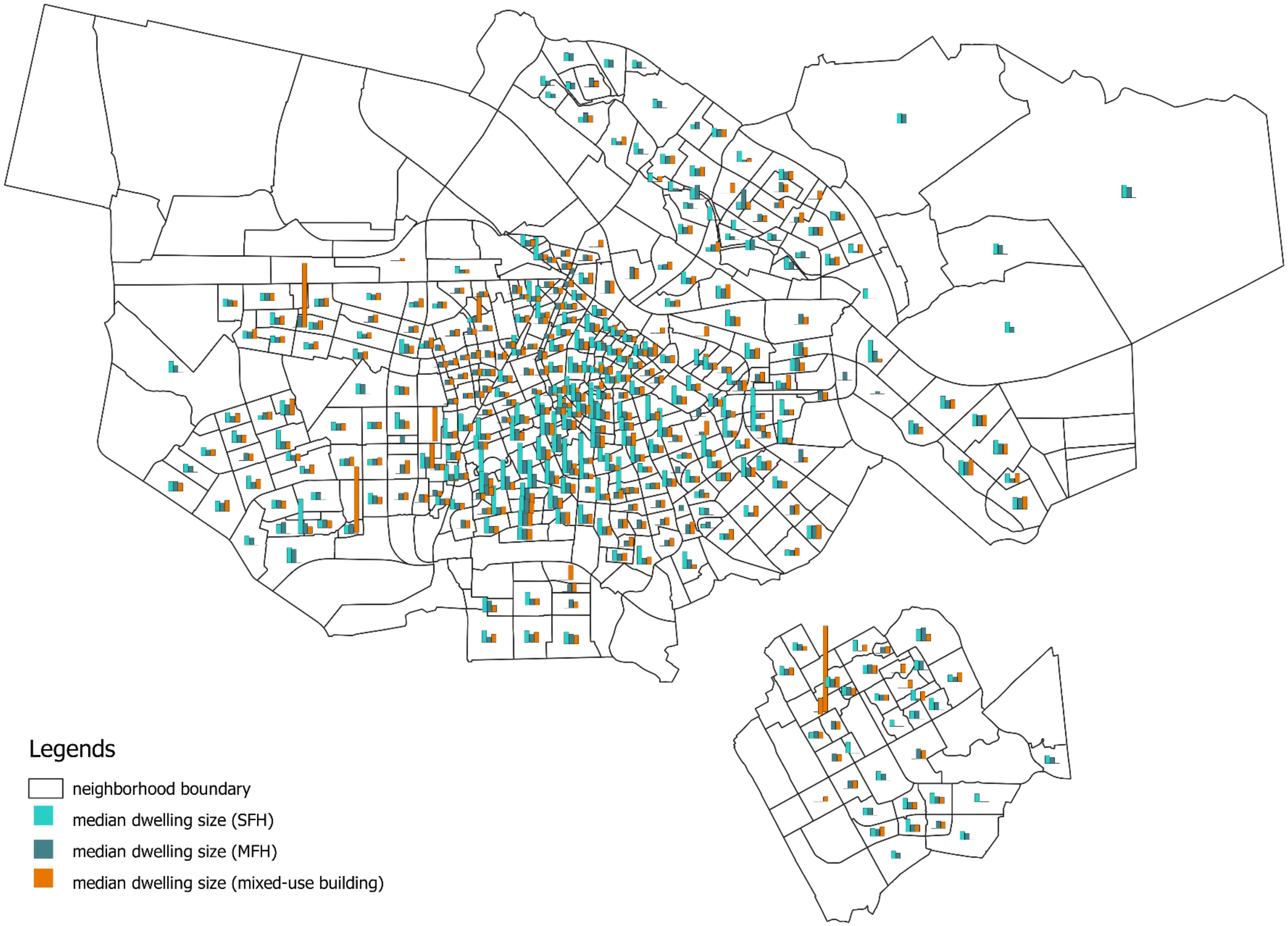
Appendix 5 Spatial distribution of number of buildings according to building types



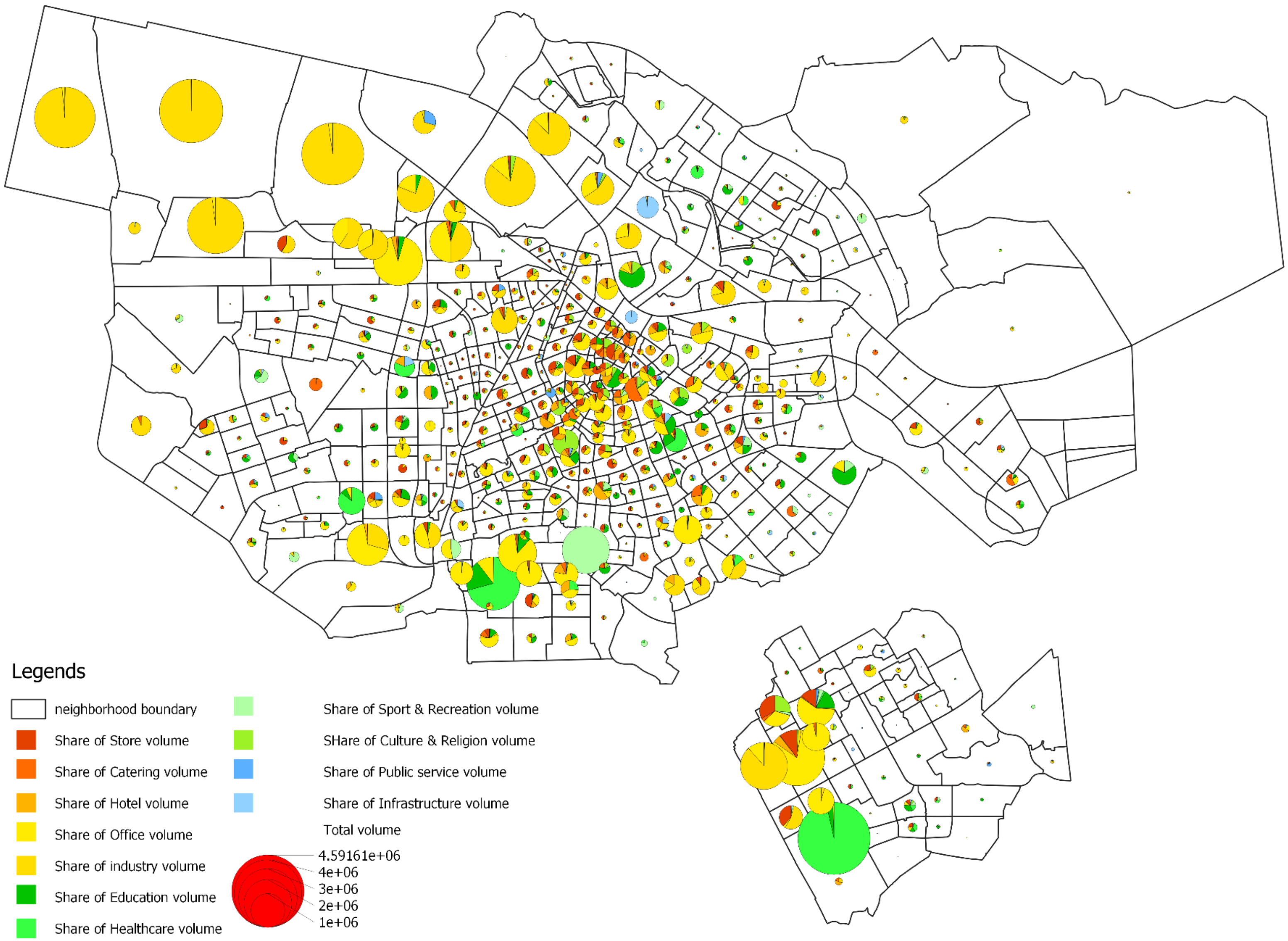
Appendix 6 Building density according to building footprint and building volume



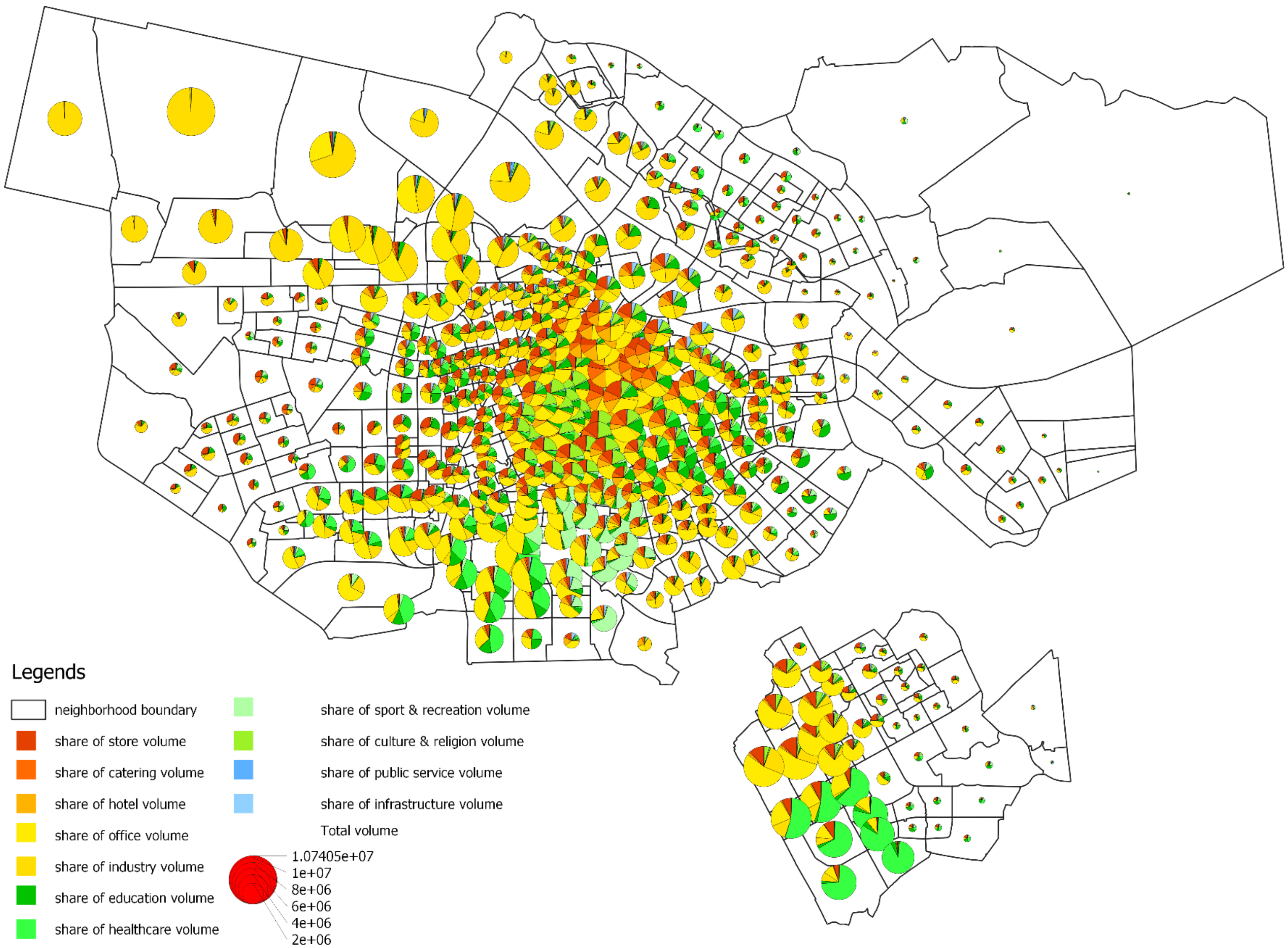
Appendix 7 The spatial distribution of dwelling types and number of dwellings



Appendix 8 The spatial distribution of dwelling size in volume

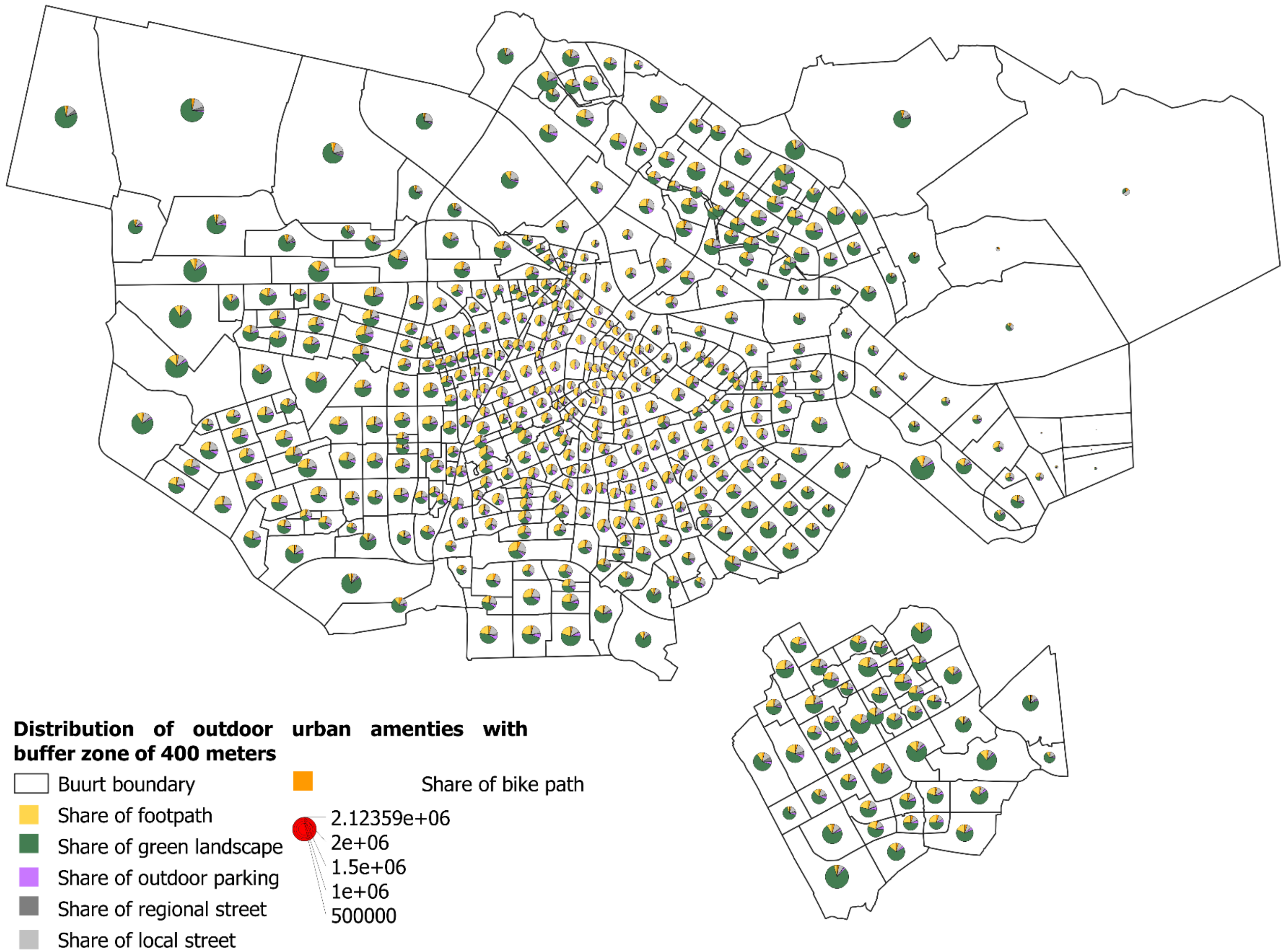


Appendix 9 Volumetric distribution of indoor amenities according to volume

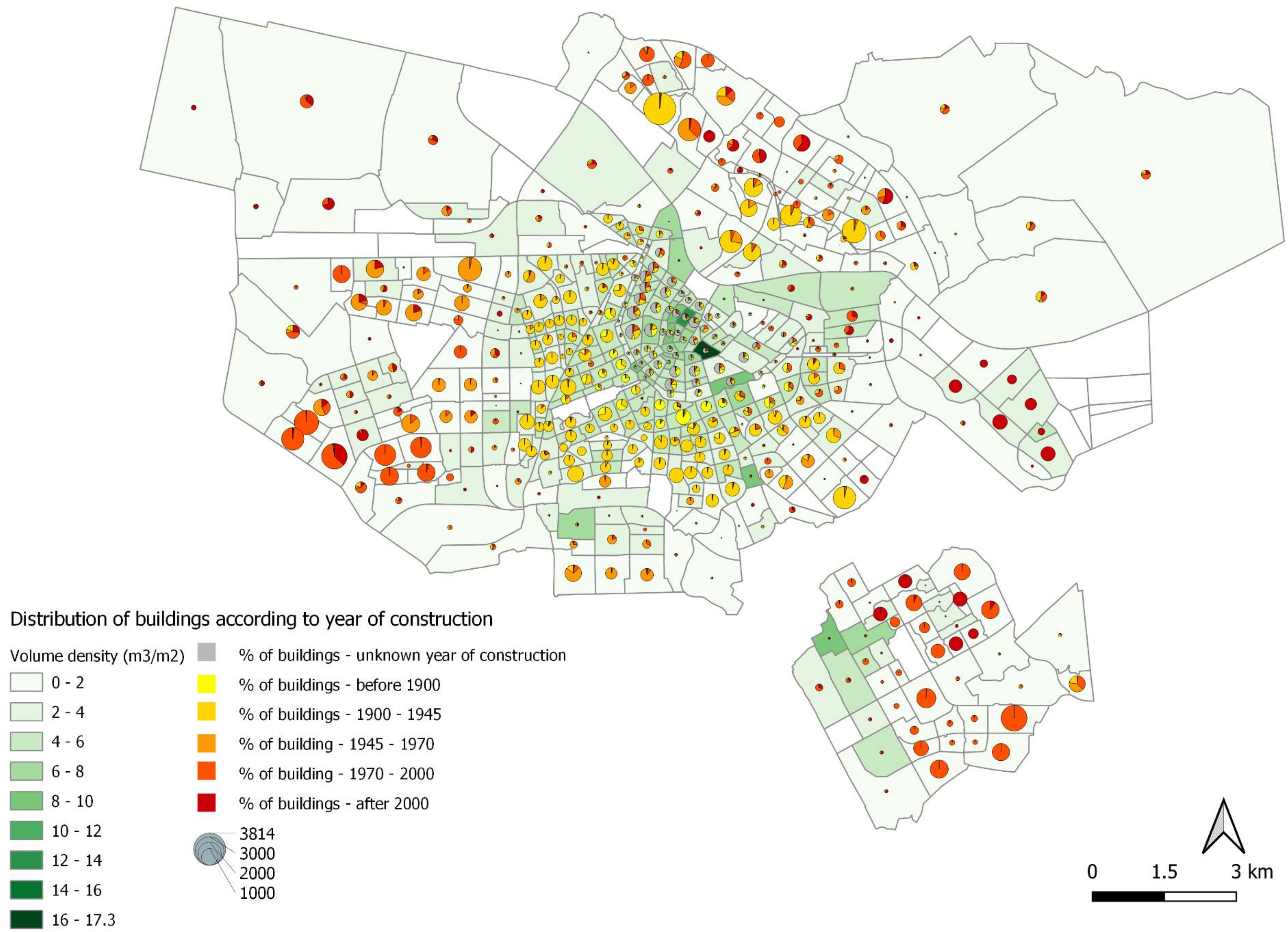


Appendix 10 Volumetric distribution of indoor amenities with buffer zone of 800 m (the scale of the pie chart is reduced compared to the above map for visibility)

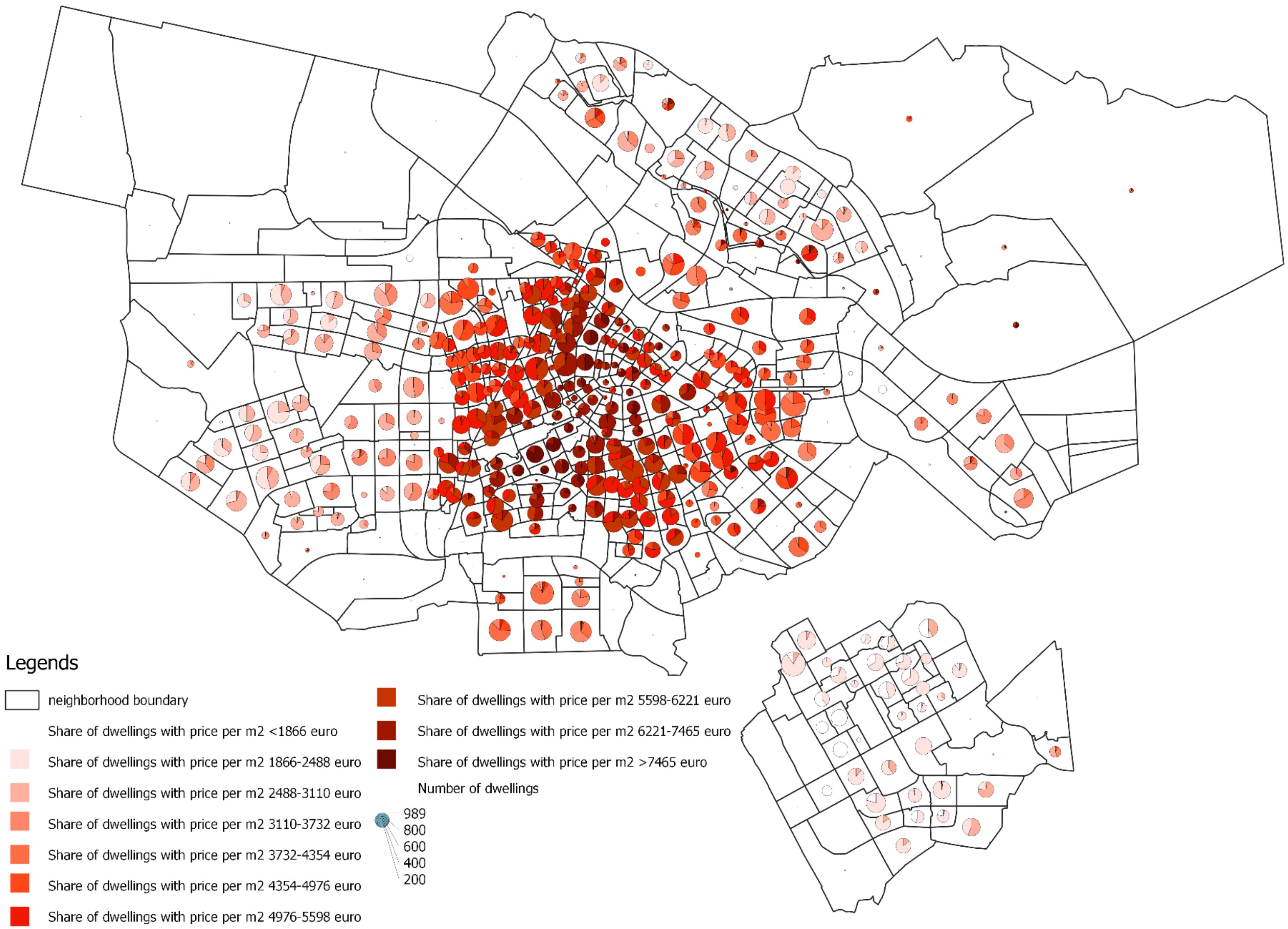
Appendix 11 Distribution of outdoor amenities according to area (m2) – water surface excluded



Appendix 12 Distribution of outdoor amenities (with buffer zone of 400 m) according to area – water surface excluded

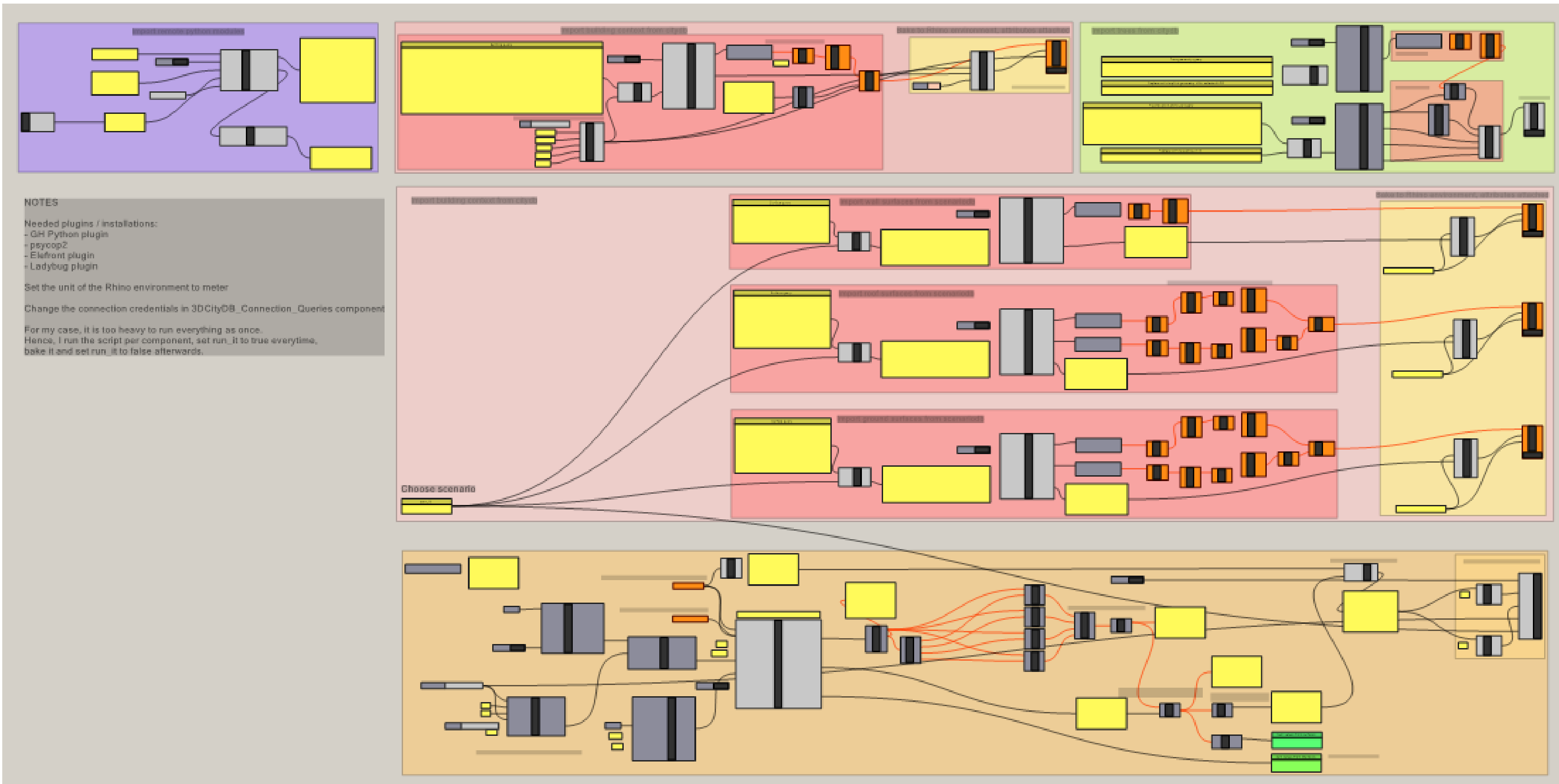


Appendix 13 Distribution of buildings according to the year of construction



Appendix 14 Spatial distribution of dwellings according to housing price per m2

Appendix 3: Chapter 5



Appendix 15 Grasshopper workflow for solar radiation analysis