Galina Voitenko

Method for 3D neighborhood model creation in CityGML standard as basis for urban simulation tools

Master's thesis in Sustainable Architecture
Supervisor: Niki Gaitani
Co-supervisor: Hannes Harter
May 2023

Master's thesis

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Abstract

As cities continue to expand, the availability of basic resources for constructing and maintaining comfortable living conditions in homes becomes increasingly limited. To create a sustainable urban environment, it is crucial to prioritize sustainable construction practices and minimize resource consumption.

Norway has established itself as a leading country in sustainability research, particularly in the construction and architecture sectors. To address the mentioned challenges in Norway, it is necessary to analyze the local building stock, both new projects and renovated, to develop optimization strategies. Evaluating buildings in terms of operational energy needs and conducting a life cycle assessment (LCA) of building technical services (TBS) can significantly contribute to achieving sustainability goals.

As of now, the application of these concepts has resulted in endeavors to utilize contemporary technologies, such as employing 3D city models. While 3D modelling can aid in planning and expedite decision-making, planners often hesitate to use them due to the complexities of data integration and the lack of an efficient building stock evaluation process.

This dissertation aims to promote spatial modelling for sustainable architecture, specifically at the district level, by creating a 3D model of the district and conducting a housing stock assessment using computer-aided urban tools.

The methodology will be illustrated through a case study of a district in Norway, the city of Fredrikstad, which encompasses two areas — one already existing development and the other planned for future development. The life cycle assessment process will rely on 3D city models developed in accordance with the CityGML standard. These models will be utilized in life cycle assessment software, incorporating relevant data specific to Norway. The results will be analyzed mainly in terms of operational energy demand, heat load, and LCA, which will be compared between the results of these two cases. For the newly developed areas, it will also be compared against similar calculations processed by syn.ikia project.

The outcome of this study will be a comprehensive methodology and recommendations for generating 3D models and assessing the building stock based on these models. Furthermore, the study demonstrates the methodology's ability to produce reliable results. It is worth noting that this dissertation does not explore the creation of alternative scenarios for the new developments, but this area presents an interesting potential for future research about reducing energy demand on a life cycle basis.

Keywords: Sustainable Architecture, 3D city model, 3D building models,
Life Cycle Assessment, building simulations, open-source data, free and open-source software, sustainable urban development, sustainable neighborhoods

Preface

This thesis has been submitted to the Faculty of Architecture and Design of the Norwegian University of Science and Technology NTNU (Norges Teknisk Naturvitenskapelige Universitet) for the fulfilment of the requirements for the degree of Master of Science. This work was carried out at the Architecture and Technology Department, Sustainable Architecture program, in the period from January 2023 to May 2023, under the supervision of Professor Niki Gaitani and co-supervision of Postdoctoral Fellow Hannes Harter. The research presented is not funded.

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Galina Voitenko,
Trondheim, May 2023

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List of Abbreviations (or Symbols)

2D	Two-dimensional
3D	Three-dimensional
CAD	Computer-aided design
CityGML	City Geography Markup Language
CityJSON	City JavaScript Object Notation
BAC	Building Age Class
BIM	Building Information Modeling
DEM	Digital elevation model
DSM	Digital surface model
ETL	Extract, transform, and load
FME	Feature Manipulation Engine, Software for integrating spatial data
HVAC	Heating, Ventilating, and Air Conditioning
IFC	Industry Foundation Classes
GIS	Geographic information system
GUI	Graphical user interface
GML	Geographic markup language
LoD	Level of detail
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
TBS	Technical building services
XML	Extensible markup language

1 Introduction to the topic

This part of the thesis provides background information and context for the research. It serves to introduce the reader to the topic of the thesis, establish its significance, and outline the objectives and scope of the study.

1.1 Background

Cities are responsible for a significant share of global greenhouse gas emissions. Cities consume more than two-thirds of the world's energy and generate over 70% of global CO2 emissions (United Nations, 2020). In 2021, the operation of buildings in cities was responsible for 30% of global final energy consumption and 27% of total energy sector emissions. Of this, 8% was attributed to direct emissions from buildings themselves, while 19% was due to indirect emissions resulting from the production of electricity and heat used in buildings. (International Energy Agency report, 2021). In addition, the densification of development in cities often leads to conflicts over the use of limited resources such as space and access to daylight (Dogan & Knutins, 2018).

This highlights the urgent need for adaptation to climate change and sustainable building design, urban planning, and management practices that prioritize resource efficiency, low-carbon energy, and climate resilience to mitigate the negative impacts of urbanization on both human health and the environment. To solve these goals The European Green Deal was created is a comprehensive plan launched by the European Commission to make Europe the world's first climate-neutral continent by 2050. It sets out a roadmap for transforming various sectors, including buildings, to achieve sustainability and combat climate change. For the development sector, the European Green Deal aims to enhance energy efficiency, reduce greenhouse gas emissions, and promote sustainable construction and renovation practices. It recognizes the significant impact that buildings have on energy consumption and emissions, as well as their potential for energy savings and environmental improvements (European Commission, 2022. European Green Deal). There is also EU (European Union) Taxonomy as a classification system that aims to promote sustainable economic activities by providing a framework for assessing the environmental sustainability of various sectors. In the context of buildings, the EU Taxonomy focuses on identifying which types of construction and renovation projects contribute to climate change mitigation and adaptation, as well as resource efficiency. It aims to provide clear guidelines on sustainable building practices and help investors and stakeholders make informed decisions regarding sustainable investments in the built environment. (European Commission, 2020. EU Taxonomy for Sustainable Activities: Technical report)

Adaptation to climate change is indeed a complex task for the construction sector that requires cooperation among various stakeholders. The use of digital tools and the digitalization of urban design processes has been recognized as an essential approach to accelerating the design process and better coordination among stakeholders (Somanath et al., 2021). Furthermore, these tools facilitate the creation of a global repository of data on the current state of cities, which can contribute to the synchronization of efforts by multiple stakeholders to address common risks (IPCC, 2018).

The integration of digital tools and data analysis in urban design and planning can also help identify vulnerabilities and prioritize adaptation measures. For instance, Geographic Information Systems (GIS) have been widely used to map climate risks and vulnerabilities, which can aid in the identification of areas that require attention and investment (Neteler et al., 2012). The same methods could be implemented on a building scale in urban areas. Moreover, the digitalization of the urban environment design process can enhance stakeholder engagement, promote participatory decision-making processes, and enable collaborative approaches to adaptation planning (Zhihang Yao, 2016). These approaches have been increasingly applied in cities worldwide to develop inclusive and resilient communities (UN-Habitat, 2016).

It is crucial to acknowledge that the effective integration of digital tools in urban design relies on the quantity and quality of spatial data utilized. Open-source spatial data is widely used in Europe for various purposes such as urban planning, environmental management, and transportation (Jayaraj et ai., 2018). Many cities and municipalities are using open-source geographic information systems (GIS) software such as QGIS to manage and analyze spatial data (Neteler and Bowman, 2012). There are also already many digital building models for existing buildings available worldwide (Awesome CityGML, 2023). In addition, the European Union has launched several initiatives to promote the use of open data and open-source software for spatial data management, including the INSPIRE Directive, which aims to establish a European Spatial Data Infrastructure (ESDI) for the sharing and integration of spatial data across Europe (European Parliament and Council, 2007). Examples of such a project are EUBUCCO or European Data Portal. They are large projects that distribute open spatial data to the countries of the European Union, Norway, and Switzerland.

Norwegian open-source spatial data development has come a long way in recent years. Norway has been at the forefront of open data policies and has made some types of spatial data freely available to the public. A broader list of data is available for experts. The full list of sources found during this research is explained in the Methodology part with links for sources. The Norwegian Mapping Authority (Kartverket, n.d) is the main organization responsible for managing and providing access to much of this data. Additionally, there are several open-source software tools and platforms that have been developed in Norway, such as Norwegian National Data Directory (Felles datakatalog, n.d.) which is used for spatial data management, analysis, and visualization. However, there is still room for further development and improvement, particularly in the areas of standardization and interoperability of data formats and tools.

Knowledge of how to work with spatial data is not enough; it is crucial to comprehend how experts can apply the obtained data. Urban data has a significant role in urban planning, but it is also crucial to assess planned developments. One of the emerging trends in urban planning is the application of Life Cycle Assessment (LCA) methods at the neighborhood level.

LCA is increasingly being applied to the neighborhood level to evaluate the environmental impacts of urban areas. This approach provides a comprehensive assessment of the environmental performance of buildings, transportation, infrastructure, and other systems within a neighborhood. Several studies have explored the use of LCA to evaluate neighborhoods, including energy use, carbon emissions, and other environmental impacts (Harter et al., 2020).

In Norway, the Life Cycle Assessment (LCA) of buildings is guided by relevant legislation and regulations aimed at promoting sustainable construction practices. The primary legislation governing LCA in Norway is the Planning and Building Act (Plan- og bygningsloven, n.d.), which includes provisions for energy efficiency and environmental considerations in building projects. The act requires that new buildings meet specific energy performance requirements and encourages the use of environmentally friendly materials and technologies. Furthermore, the Norwegian Building Technical Regulations (TEK17) provide detailed requirements and standards for energy efficiency, environmental impact, and sustainability aspects of buildings. These regulations outline specific parameters and performance indicators that need to be considered during the life cycle assessment of buildings.

In addition to Norwegian legislation, the European Union (EU) has introduced directives and frameworks that impact the energy performance and sustainability of buildings. The EU Energy Performance of Buildings Directive (EPBD) sets energy performance standards for buildings across member states, including requirements for energy efficiency, heating and cooling systems, and renewable energy integration. The EU-Taxonomy is a classification system introduced by the European Commission to determine whether economic activities, including building construction and renovation, are environmentally sustainable. It sets criteria for determining the environmental performance of buildings and aims to promote investments in sustainable projects.

Both Norwegian legislation and EU directives play a significant role in shaping the life cycle assessment and sustainability aspects of buildings in Norway. Compliance with these regulations ensures that buildings meet energy efficiency standards, consider environmental impacts throughout their life cycle, and contribute to the overall sustainability goals.

LCA on a neighborhood level varies depending on the region and country. The listed standards, considering the LCA, speak of the active introduction of it into modern building practice. However, the application of LCA to the neighborhood level is still in the early stages and requires further research, data availability, and standardization to become more widespread.

1.2 Research scope

The main objective of this study is to evaluate the use of open-source spatial data in Norway to create a 3D model of a specific neighborhood and analyze it using the Life Cycle Assessment (LCA) tool at an urban scale.

In terms of data sources, the focus is primarily on open spatial data available within Norway. However, if the available open data from Norway is insufficient, consideration of global sources of open data is allowed.

The Urbi+ software has been selected as one of the latest tools for LCA estimation at the district level. By studying the applicability of this software in a Norwegian context, the research aims to assess its suitability for use in Norway.

Regarding 3D modelling, the study emphasizes the use of the CityGML format since it is necessary to conduct urban simulations in the Urbi+ software. It is anticipated that other file formats may need to be generated initially to obtain the required file format.

Given that the study encompasses three subcomponents, the focus is primarily on the 3D modelling aspect using open-source data. This objective is particularly interesting because the resulting models can be further tested on other urban simulation tools in the future. For a more detailed explanation of the objectives of the study, see section 1.4 Aims and Goals.

The selected neighborhood for testing purposes is situated in Fredrikstad. The site boundaries are defined by Sorgenfri Alle to the south, Sarpsborgveien to the east, Grårudveien to the north, and Galtungveien to the west. Specifically, the northern part of the site was selected. This area includes a mix of residential buildings constructed in various years that is remarkably interesting from the point of view of LCA.

The residential area within the site encompasses a building cluster constructed between 1901 and 1990. Additionally, new residential buildings were built in the area in 2016. There are plans for further development starting in 2023, also involving buildings with residential typology. A detailed distribution of buildings on the site by construction year can be found in chapter Application and Methods on the Figures 9-11.

The study was conducted over a period of approximately five months, from January to May 2023.

1.3 Problem statement

The problem statement revolves around the utilization of open-source tools by professionals, particularly architects and planners, and the challenges faced in integrating these tools effectively. Additionally, professionals from various backgrounds express interest in using these tools but often lack the necessary skills.

The current state of active use cases of spatial data is in the developmental phase, but issues arise when considering quality and inclusiveness. It is crucial to evaluate the quality, accuracy, and consistency of open-source spatial data, considering factors such as data sources, collection methods, and processing techniques. Identifying challenges related to data integrity and reliability is also necessary.

In modern design, especially on a large scale, problems arise when assessing numerous new developments within a short time. Digital tools can assist in addressing these challenges, but there are still gaps and disconnections in the process. Therefore, it is important to assess the level of engagement and responsiveness within the open-source spatial data and software community.

Solving of this problem is particularly relevant in Norway, a country with a strong emphasis on sustainability. Moreover, the entire European Union has committed to transitioning to climate neutrality.

Addressing the issue is important because it enables the calculation of global warming potential (GWP) and energy efficiency during the preliminary stages of design. While the gap is still significant, more widespread adoption of this practice will facilitate the implementation of LCA in neighborhoods and will make sustainable development of the construction sector faster.

1.4 Aims and goals

The main goal of this master's thesis is to develop a workflow/method for creating 3D CityGML models using existing and available data in Norway. These models will serve as a foundation for various types of simulations. Additionally, the thesis aims to test and utilize these models for conducting LCA at the neighborhood level.

The objectives of the study are centered around establishing a workflow and providing recommendations to assist individuals in Norway in utilizing 3D city modeling tools for conducting LCA on an urban scale. The case study focuses on both an existing residential district and the case of new development in Norway. To achieve these objectives, the study will involve testing diverse types of spatial data, utilizing software for data processing, and incorporating a new LCA tool.

By accomplishing these objectives, the study aims to contribute to the advancement of LCA methodologies and tools specific to the urban context. The results and findings of the thesis will provide insights for practitioners and researchers involved in urban planning, sustainability assessment, and decision-making processes.

1.5 Overview of the content

Following the introduction to the topic, this master's thesis is divided into five subsequent chapters.

Chapter two “Theory and background” provides the theoretical framework, presenting fundamental principles necessary for comprehending the methodologies. It encompasses Literature review and State-of-the-art parts as well as Research Gap and list of Research questions.

The third chapter “Methods and materials” outlines the methodology employed in the research.

Chapter four “Application of Method and Results” focuses on presenting and analyzing the results obtained from comparing available data and various modeling approaches. Subsequently, the outcomes of the final part of the neighborhood level LCA are presented.

The fifth chapter “Discussion” consists of a critical discussion concerning the implications of the results obtained in the previous chapter. Furthermore, it addresses the limitations of the design and implementation, as well as the shortcomings of the workflow.

The sixth and last chapter “Conclusions and Outlook” summarizes the conclusions drawn in relation to the research questions posed.

2 Theory and background

The section provides a comprehensive overview of the relevant theoretical concepts, principles, and existing knowledge related to the research topic. It aims to establish a theoretical foundation for the study and contextualize the research within the broader academic and practical framework.

2.1 Literature review

The literature reviewed for this thesis was chosen based on the main components of the thesis. The papers were categorized into three sections: progress in developing big urban data and the advantages of digital city models, working with spatial data and the software used for processing and modeling it, and recent advancements in LCA at the neighborhood level. This section provides a brief overview of the most important articles for the study.

2.1.1 Trends in Spatial Modelling

In general, the current trends in spatial modelling for cities include the use of big data, digital city models, and 3D urban geometry. Spatial modelling is being used to evaluate the life cycle energy demand and greenhouse gas emissions of cities, as well as to assess the energy efficiency and potential of buildings. The development and use of open-source tools and software, as well as collaboration between different disciplines, are also trends in spatial modelling for cities.

The article "City Digital Twin Potentials: A Review and Research Agenda" provides a comprehensive review of the concept of the city digital twin (CDT) and its potential in improving urban sustainability, resilience, and livability. The authors argue that a CDT, as a digital replica of a city, can support various urban applications such as urban planning, management, and decision-making processes. The review also highlights the challenges and limitations of CDT development, including data integration, privacy, and security concerns, and the need for interdisciplinary collaboration to address these challenges. Finally, the authors propose a research agenda that identifies key research topics for CDT development and suggests directions for future research. Overall, the article provides a useful overview of CDTs potential and challenges and outlines important research areas for their development and deployment in urban contexts.

2.1.2 Spatial data and its processing

Various data models are used for defining, storing, managing, manipulating, and utilizing building and spatial data digitally, based on their intended applications. These data models are utilized extensively in various research, analysis, and implementation projects for both building and geographical scale information. Energy performance simulation is carried out by simulation scientists, urban planners, researchers, and engineers using different applications, tools, and formats.

The paper “Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: The cases of Bergen, Norway, and Zürich, Switzerland” (De Koning et al., 2020) aims to enhance the understanding of how urban structure and forms contribute to sustainable development. The authors utilized spatial data and an automated workflow to examine the urban structures and forms of Bergen, Norway, and Zürich, Switzerland. The georeferenced datasets used in the study, including urban structures, urban forms, building density, road center lines, and transport energy usage, were obtained from OpenStreetMap and collaborating local and national authorities. Whenever possible, open-source data was used, and data gaps in proprietary data were supplemented with proxies or open-source data. This article considers urban modeling for purposes other than those of this paper. However, the article considers an interesting case of using open data for a Norwegian city.

"Technical report: Literature Review concerning Industry Foundation Classes (IFC), gbXML and CityGML data models for Energy Performance Simulation" presents an extensive literature review of the IFC, gbXML, and CityGML data models, focusing on their formats, version releases, usage platforms, example files, and energy simulation tools and software that utilize these data models. The report provides valuable insights for simulation scientists, urban planners, researchers, and engineers who use different formats, applications, and tools for energy performance simulation.

The paper "CityJSON: a compact and easy-to-use encoding of the CityGML data model" presents the creation and expansion possibilities of CityJSON data format. CityJSON is a JSON-based encoding used to store 3D city models. Its goal is to provide a compact and developer-friendly format that allows easy viewing, processing, and modification of files. It was specifically designed with programmers in mind, enabling efficient development of tools and APIs to support it (CityJSON, n.d.). The aim is to reduce data complexity, enhance interoperability, and make 3D solutions more accessible to a wider audience. CityJSON is a text-based data format that simplifies the deep structure of CityGML while retaining its functionalities (Ledoux et al., 2019).

CityJSON is a subset of the CityGML data model and is related to it. JSON, like GML, is a text-based data interchange format that is human-readable and machine-understandable. JSON was chosen as an alternative encoding to GML for several reasons. Firstly, JSON is widely used on the web, making it the preferred choice when sharing data between different types of applications (instead of XML). Secondly, JSON geometry has a single standard representation, making it efficient and easy to interpret. Thirdly, JSON enjoys broad adoption among developers, resulting in a larger number of libraries and applications supporting it and ensuring its ongoing maintenance. Lastly, JSON is based on two fundamental data structures found in nearly every programming language: an ordered list of elements and objects consisting of key/value pairs (Ledoux et al., 2019).

Additionally, bidirectional conversion between CityGML and CityJSON is possible, allowing for seamless integration and compatibility.

2.1.3 LCA at the neighborhood level

The objective of sustainable development is to reduce the demand for non-renewable resources and the resulting environmental impact, and buildings contribute significantly to this goal. To achieve a climate-neutral building stock, lifecycle-based assessment of buildings is essential. However, the existing approaches and tools consider the operational energy demand of buildings and not a lifecycle-based approach when assessing technical building services (TBS).

In the paper "Life cycle assessment of technical building services of large residential building stocks using semantic 3D city models" (Harter et al., 2020) presents a methodical approach for the life cycle-based assessment of TBS of large residential building stocks, based on semantic 3D city models. The article explains the methodology developed for this purpose, describes the procedure for calculating the operational energy demand, the dimensioning of the TBS components, and the calculation of the life cycle assessment. The methodology was applied in a case study with over 115,000 residential buildings from Munich, Germany, and it produced reliable results. The study showed that a significant reduction of the lifecycle-based energy demand can be achieved by refurbishment measures. However, the goal of achieving a climate-neutral building stock is still a challenge from a life cycle perspective.

The article "Uncertainty Analysis of Life Cycle Energy Assessment in Early Stages of Design"(Harter et al., 2020) discusses the importance of Life Cycle Energy Assessment (LCEA) in evaluating the energy demand of buildings in the preliminary stages of design. However, the design and related information are subject to uncertainty, which can affect the LCEA and decision-making. The study proposes a method that uses uncertainty analysis to assess the influence of uncertainty on LCEA and prioritize decisions to reduce uncertainty. The method is embedded in a multi-Level of Development (LOD) modelling approach and is applied to seven different building shapes. The study concludes that the method can provide valid results to assess project-specific uncertainty in LCEA.

This study from the paper "Developing a roadmap for the modernization of city quarters - Comparing the primary energy demand and greenhouse gas emissions"(Harter et al., 2017) presents a new method to evaluate the energy demand and greenhouse gas emissions during the different life cycle stages of a city quarter, based on 3D urban geometry in CityGML format. The method was applied to a case study in Stuttgart, Germany, considering specific building characteristics. Four different scenarios were assessed to reach a similar building standard for all residential buildings, involving refurbishment, demolition and reconstruction, or a combination of both. The study found that refurbishment to a high building standard is better than reconstruction from a life cycle energy perspective, provided that the structural condition of the building allows it.

The order of refurbishment or reconstruction also has a high influence on the energy demand reduction of the city quarter over time.

Apart from the articles, a considerable number of online resources related to the topic of this study were analyzed. These resources include conference reports, software manuals, and open-source data web sources. The approach presented in this paper utilizes the knowledge gained from these resources and describes a novel application of open data and innovative software for both model building and energy simulations in Norwegian cities.

2.2 State-of-the-art

The initial section provides a state-of-the-art of the key concepts related to the topic, including open-source data for spatial modelling, spatial data in Norway, software tools to process the data, other elements and concepts related to the thesis topic.

2.2.1 Open-source spatial data

The use of open-source spatial data by building professionals has become increasingly prevalent and is considered a state-of-the-art approach in the industry. The key trends and practices are as follows:

Data integration and visualization: Building professionals are leveraging open-source spatial data to integrate various datasets, such as geospatial information, building footprints, infrastructure data, and environmental factors. These data sources are combined and visualized using Geographic Information Systems (GIS) software to gain insights into urban planning, site analysis, and building performance.

Open data platforms: Open data platforms, such as OpenStreetMap (OSM), provide building professionals with access to crowdsourced geospatial data. They can contribute to and extract data from these platforms, allowing for collaborative data creation and utilization. OSM data can be used for a wide range of applications, including building footprints, road networks, and land use information.

Building energy performance simulation: Open-source tools like EnergyPlus, OpenStudio, and Ladybug Tools are widely used for building energy performance simulation. These tools allow building professionals to assess and optimize energy efficiency, thermal comfort, and daylighting strategies. Open-source spatial data, combined with these simulation tools, enables more accurate and detailed analysis of building performance.

Data Analytics and Machine Learning: Building professionals are utilizing open-source spatial data for data analytics and machine learning applications. By combining spatial data with other datasets, they can gain insights into building performance patterns, occupancy behavior, energy consumption trends, and predictive maintenance. Open-source libraries like TensorFlow and scikit-learn provide tools for data processing, feature extraction, and predictive modeling.

2.2.2 Spatial Data sources in Norway, EU and worldwide

Norway's efforts to make spatial data publicly available and accessible have been recognized as a best practice by the United Nations. The UN's Global Geospatial Information Management (GGIM) initiative has highlighted Norway's approach as an example for other countries to follow.

The Norwegian Mapping Authority (Kartverket) plays a significant role in collecting, managing, and distributing spatial data in Norway. According to a report by the European Union's Joint Research Centre, Kartverket has "established an efficient and coordinated national mapping program" that has led to the creation of a comprehensive and high-quality dataset. The data collected by Kartverket, including topographic data, elevation data, and aerial photographs, is made available through several online portals, including Geonorge.no which is a central repository for geospatial data in Norway and provides access to datasets from a variety of sources, including public authorities, research institutions, and private companies.

The other source of the data is Geonorge - a Norwegian national mapping and geodata portal that provides access to a wide range of geospatial data and services from various public and private organizations. It is managed by the Norwegian Mapping Authority and is intended to be a one-stop-shop for geospatial data and related services in Norway. Geonorge offers access to data such as topographic maps, aerial imagery, nautical charts, and other spatial data from various government agencies and organizations. The portal also provides tools for searching, viewing, and downloading geospatial data and services, as well as metadata and documentation about the data.

The availability of open spatial data has enabled a range of innovative applications and services in Norway, including the development of smart cities and sustainable urban planning initiatives. The use of open spatial data in urban planning has been shown to improve the efficiency and effectiveness of planning processes, and to enable greater collaboration and engagement with citizens and other stakeholders.

Overall, while Norway's approach to making spatial data available is viewed as positive, there is room for improvement in terms of accessibility, quality control, and transparency.

According to a report by the Norwegian Ministry of Local Government and Modernization, there have been criticisms of the accessibility and usability of Norway's publicly available spatial data, particularly for non-experts. The report suggests that efforts should be made to simplify access and use of the data.

In the European context, there is a big open-source data distributor called The European Data Portal (EDP). It is an online platform that provides access to a vast collection of open data from various European countries and institutions. The Portal offers a wide range of datasets covering various topics, including economy, environment, society, transportation, health, and more. These datasets are contributed by national and regional governments, as well as other public sector organizations across Europe. The portal aggregates and harmonizes the data, making it easier for users to search, explore, and compare datasets from different countries and domains. The EDP aims to promote the use of open data to drive innovation, research, and decision-making processes.

There is also geographic data available for the whole world, including data on physical features such as land cover, topography, and bathymetry, as well as data on human features such as population density, transportation networks, and land use. One of the well-known examples is OpenStreetMap (OSM) - a collaborative, open-source project that aims to create a free and editable map of the world. It was created and maintained by a community of volunteers who contribute data such as roads, buildings, landmarks, and other features using GPS devices, aerial imagery, and other sources. OSM data is stored in a standard format and can be downloaded and used for free by individuals and organizations for various purposes, such as mapping applications, research, and disaster response. OSM data is available under an open license, which allows for its use, distribution, and modification without restrictions.

In addition to the mentioned data sources, there are other data providers included in this study. A comprehensive list of the studied data sources is presented in the table () in Methodology chapter. Although this chapter describes a large number of open spatial resources,, there is still room for further development and improvement, particularly in the areas of standardization and interoperability of data formats and tools.

2.2.3 3D city models

A 3D city model refers to a digital representation of a city that is constructed using 3D geospatial data, encompassing information on terrain, buildings, vegetation, transit systems, and more. City models serve the purpose of showcasing, examining, analyzing, and managing urban data (Döllner, Baumann, & Buchholz, 2007). Among the components within a 3D city model, buildings hold significant importance for various applications, albeit presenting challenges in terms of accurate depiction due to their complexity (Lancelle & Fellner, 2004). Consequently, several countries have recognized the need for a standardized representation of buildings and have developed national standards that define 3D building models based on their specific requirements (e.g., Gruber, Riecken, & Seifert, 2014; Stoter et al., 2013).

2.2.4 CityGML

CityGML has been the worldwide open standard for representing and distributing 3D city models under the Open Geospatial Consortium (OGC) since 2008. In 2012, an expanded version 2.0 was accepted, and in 2021, OGC announced CityGML 3.0. Apart from being an OGC standard, CityGML has gained widespread acceptance in the software industry, with interfaces provided by prominent companies (Gröger & Plümer, 2012).

Gröger and Plümer (2012) highlighted CityGML as one of the most widely used information models for representing objects and structures in city simulations. CityGML is an open, structured, XML-based standard for storing and exchanging data. It is built on the foundation of the Geography Markup Language (GML) and represents the physical representation, topological information, and semantic data of real-world objects (Gröger & Plümer, 2012). CityGML facilitates the integration of urban geodata for various applications in Smart Cities and Urban Digital Twins, including urban and landscape planning, building information modeling (BIM), and disaster management (OGC, n.d.). Additionally, CityGML allows for storing objects at different levels of detail (LoD), enabling a more detailed representation of city models (Gröger & Plümer, 2012).

When users gather data for applications, they often encounter data from multiple sources. These sources may have been collected at different times, using different techniques, and with varying levels of detail and geometric and semantic models. Consequently, data heterogeneity becomes a challenge for users. One of CityGML's primary objectives is to address data heterogeneity issues through standardization (Gröger & Plümer, 2012).

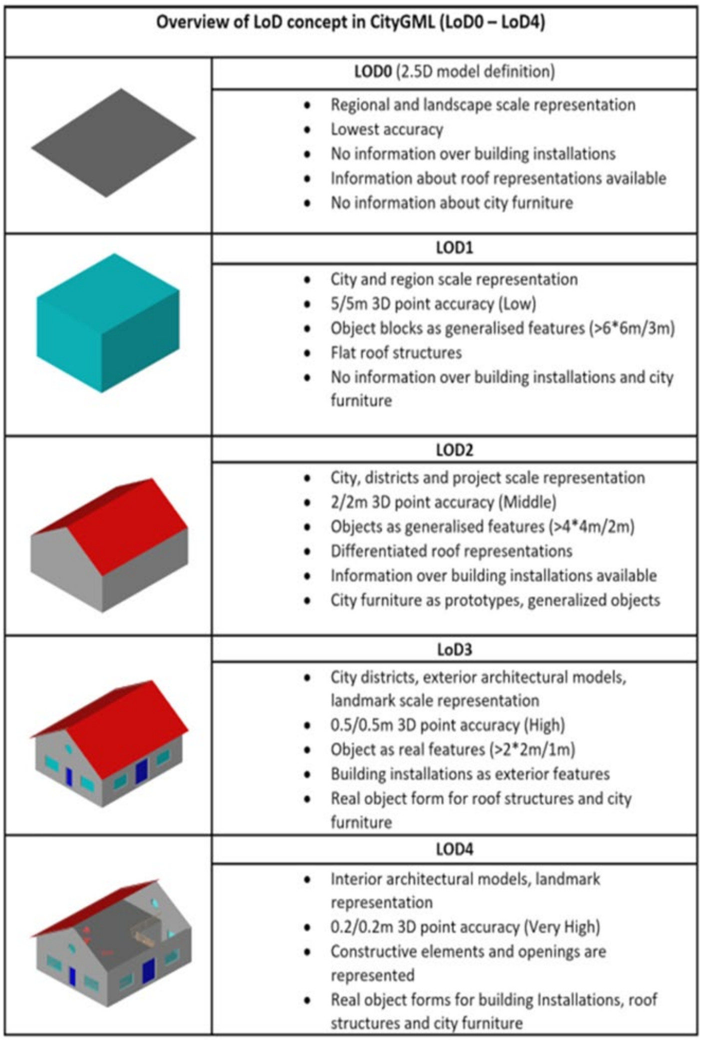
Several studies have observed compatibility issues between CityGML data and the software used to manage it, despite the increasing popularity of city models represented in CityGML (Noardo et al., 2021). Noardo et al. (2021) mention two main reasons for this. First, the geometries describing objects in CityGML can be represented in various ways, which poses a challenge for software developers in handling different interpretations of the same object's geometry. Second, CityGML's hierarchical data structure can become complex as datasets grow.

2.2.3 Level of detail (LoD)

CityGML 2.0 was the most used version, offering different LoDs (Level of Development) to represent urban objects with varying complexities. The format allowed for the representation of not only buildings but also terrain, vegetation, transportation networks, and other urban features. As the LoD increases, the complexity of the models also increases (Gröger, Kolbe, Nagel, & Häfele, 2012). The concept of LoD is defined by four key characteristics:

- Objects of the same LoD can be seamlessly integrated through data interoperability.
- Each level satisfies the requirements of different applications, making it adaptable to diverse needs.
- The LoD structure aligns with contemporary data-capturing methods.
- An object can be represented in multiple LoDs, enabling the selection of the most suitable LoD dynamically for specific tasks (Gröger & Plümer, 2012)

Gröger and Plümer (2012) define five distinct LoDs what is shown in the Figure 1.



Overview of LoD concept in CityGML (LoD0 – LoD4)	
	LOD0 (2.5D model definition) • Regional and landscape scale representation • Lowest accuracy • No information over building installations • Information about roof representations available • No information about city furniture
	LOD1 • City and region scale representation • 5/5m 3D point accuracy (Low) • Object blocks as generalised features (>6*6m/3m) • Flat roof structures • No information over building installations and city furniture
	LOD2 • City, districts and project scale representation • 2/2m 3D point accuracy (Middle) • Objects as generalised features (>4*4m/2m) • Differentiated roof representations • Information over building installations available • City furniture as prototypes, generalized objects
	LoD3 • City districts, exterior architectural models, landmark scale representation • 0.5/0.5m 3D point accuracy (High) • Object as real features (>2*2m/1m) • Building installations as exterior features • Real object form for roof structures and city furniture
	LOD4 • Interior architectural models, landmark representation • 0.2/0.2m 3D point accuracy (Very High) • Constructive elements and openings are represented • Real object forms for building Installations, roof structures and city furniture

Figure 1. Overview of the five Levels of Detail for CityGML. Information retrieved from (Malhotra, et al. 2019)

2.2.4 Software tools for processing spatial data

The field of software tools for processing spatial data has seen significant advancements in recent years. Here are some state-of-the-art aspects of this domain.

Open-Source Software: Open-source tools have gained prominence due to their accessibility, flexibility, and community-driven development. Tools like GDAL (Geospatial Data Abstraction Library), PostGIS (spatial database extension for PostgreSQL), and GeoServer (open-source server for sharing geospatial data) have become widely used in spatial data processing workflows.

Integration of Remote Sensing Data: Software tools have evolved to handle various types of remote sensing data, including satellite imagery, LiDAR data, and aerial photography.

Geographic Information Systems (GIS): GIS software tools remain fundamental in spatial data processing. Leading GIS software such as ArcGIS by Esri, QGIS, and GRASS GIS offer comprehensive capabilities for data management, analysis, visualization, and geoprocessing. QGIS is free and widely used open-source software, while ArcGIS is proprietary software developed by Esri. Both software can handle a variety of data formats and offer a wide range of tools for spatial analysis, mapping, and data visualization. However, ArcGIS has a more extensive set of tools and is commonly used in larger organizations, while QGIS is often used by smaller organizations or individuals due to its accessibility and cost-effectiveness.

3D Visualization and Modeling: Advanced software tools for 3D visualization and modeling have emerged, allowing the creation and analysis of realistic 3D representations of spatial data. Tools like SketchUP, Rhinoceros, Blender, and CityEngine offer capabilities for visualizing, simulating, and analyzing complex 3D environments.

Workflow Automation and Scripting: Tools that enable workflow automation and scripting have gained popularity to streamline repetitive tasks and enhance productivity. Python, R, and JavaScript, along with libraries like arcpy, geopandas, and rasterio, provide scripting capabilities for spatial data processing.

FME (Feature Manipulation Engine) is also one of the tools for processing and transforming spatial data. It is a software platform developed by Safe Software for extracting, transforming, and loading (ETL) data between different formats and systems. FME is designed to support a wide range of data formats, including geographic information system (GIS) formats such as ESRI Shapefile, GeoJSON, and KML, as well as non-spatial formats like CSV, XML, and databases. The tool allows users to automate data workflows, perform data quality control, and perform complex spatial data transformations. FME is used in a variety of industries such as urban planning, environmental management, and transportation. It is commonly used by GIS professionals and data analysts to process and manage substantial amounts of spatial data efficiently.

2.3 Reserch Gap

The research gap between open-source spatial data and its use in building practice can be characterized by several key aspects:

Data Quality and Reliability: While open-source spatial data provides a wealth of information, there is often a lack of quality control and standardization. Research is needed to address data accuracy, completeness, and reliability issues to ensure that open-source data can be confidently used in practical applications.

Integration and Interoperability: Open-source spatial data sources often come in various formats and structures, making it challenging to integrate and harmonize different datasets. Bridging the gap between diverse data sources and enabling seamless interoperability is an ongoing research area.

Data Processing and Analysis: Although open-source tools and libraries exist for processing and analyzing spatial data, there is still a need for advanced techniques and methodologies to extract meaningful insights from large and complex datasets. Research efforts are focused on developing efficient algorithms, data mining approaches, and machine learning techniques tailored for open-source spatial data.

Closing the research gap between open-source spatial data and its real-world use involves interdisciplinary collaboration, involving experts from geospatial sciences, computer science, data management, and domain-specific fields. This collaboration can drive innovation, address challenges, and bridge the gap to unlock the full potential of open-source spatial data for practical applications.

2.4 Research Question

The research questions for this thesis project are as follows:

- How open-source spatial data from Norway can conduct to the creation of 3D model of the neighborhood in LOD2 for life cycle-based assessments?

This study includes auxiliary questions that are formulated as components in addition to the main research question:

- How to work with available open-source data and how this data can help stakeholders with the project development process?
- What specific 3D model generated from open-source data is necessary to conduct LCA analysis on a neighborhood scale?
- What kind of other parameters do we need to know about neighborhood to conduct LCA?

3 Methods and materials

In this chapter, the overall approach and procedures used to conduct the study and achieve the research objectives are described. This section outlines the specific methods and assumptions used to conduct the research as well as the steps taken to address the research questions or hypotheses. It also contains delimitations and limitations of the process.

3.1 Research method and used tools

This study focused on the process of creating a 3D model from open spatial data in Norway, followed by an analysis of the model using LCA. The research aims to understand and go through this process and draw conclusions contributing to existing knowledge or practice. To conduct the study, a methodology consisting of five main steps was developed.

The first step involves analyzing the potential use of spatial data in Norway and studying the compatible formats of these spatial data for the software. Additionally, it explores how LCA can be performed at the neighborhood level and what data format will be needed at the end of the process.

The second step involves collecting data directly for a specific district selected for the study, which in this case is the "Verksbyen" area in Fredrikstad. As this area is undergoing rapid residential development, existing building datasets are collected and analyzed. For new construction, the project drawings by the architectural bureau GRIFF. and development company Arca Nova are examined.

The third step focuses on modelling the buildings in the neighborhood using specialized software. Two modelling experiments are conducted using different programs for the existing district part. A model is manually created for the new district using SketchUp software based on existing design data.

In the fourth step, a unified neighborhood model in the CityGML standard is created by combining the existing 3D models of buildings and the new construction. GEORES software is used for this purpose. Manual adjustments are made to the model, and additional data such as the year of construction and the type of roof used are added to the GML file. For the further analysis of the model in an LCA tool Urbi+ Norwegian definitions for energy consumption, emission values, HVAC and constructional systems are researched and included.

The full list of used software with links and brief explanations are presented in “Software overview” part of chapter “Application method”

The final step involves summarizing the results of the case study and exploring its growth potential. The data obtained from the LCA analysis at the new district level is used to compare with the existing one and assess building's potential areas for improvement.

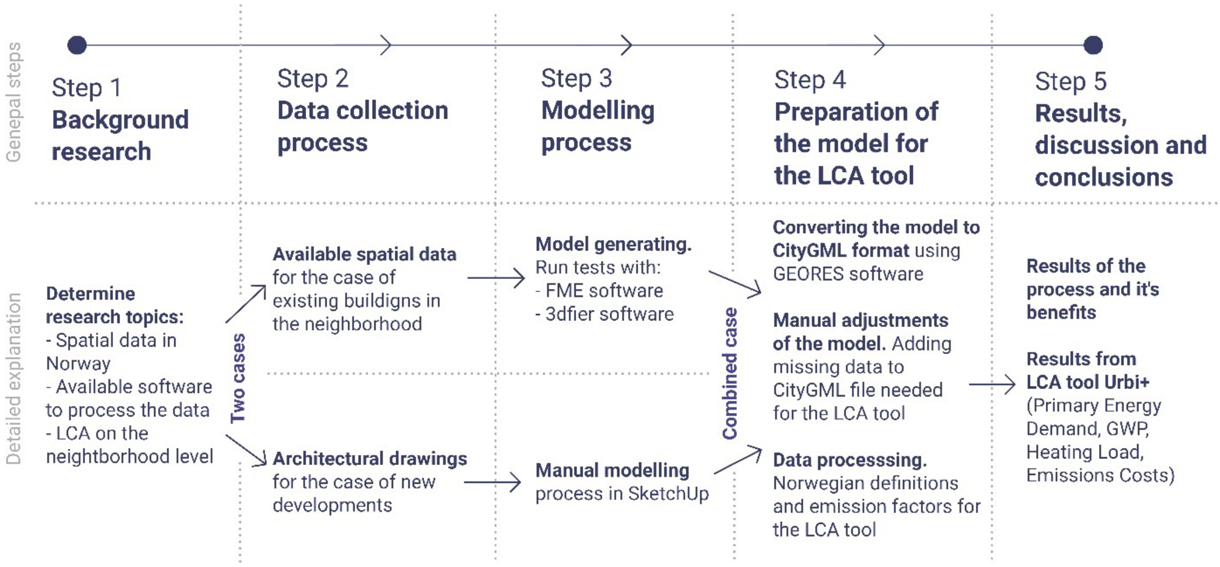


Figure 2. Developed methodology for the master's thesis process.

3.2 Assumptions

The described methodology is founded on several assumptions. These assumptions are formulated after gaining initial familiarity with the research topic and conducting a thorough review of relevant existing research and the global state of the art in the field of the thesis.

Firstly, based on the research on open-source spatial data from Norway, it is assumed that this process can be replicated. It is also based on research about software for the generation of models. Various file formats and software were discovered in the public domain, and the process of generating a 3D model can be successful thanks to them.

Secondly, it is assumed that converting a 3D model into the CityGML format is achievable. Tools that facilitate this process have also been identified, implying that the desired final file format can be obtained based on current practices.

Thirdly, regarding using the LCA tool, it is assumed that with the generated model and the identified definitions for Norwegian case calculation that is necessary for the tool, the conducting LCA can be obtained. This assumption is based on the description of an LCA calculation process carried out in Munich, Germany (Hannes, 2021).

3.3 Limitations

There are some limitations that reflect the shortcomings of the study, based on practical or theoretical constraints that were faced:

Timeframe. The research was prolonged from January to the end of May. It is likely that the result will be recorded taking into account the time available for the study.

The availability of spatial data and software. Some of the data sources or software products weren't free or open to use. All the steps of the methodology are based on free and open-source data and software. There are also some student versions of commercial software that were used.

Software skills of thesis author. There is an assumption that some parts of the process need more skills or time to develop the skill for working with software used during the research.

The result of the modelling process could become a limit for the next steps. For example, the quality and utilization of the model for the LCA tool can influence the result of calculations.

3.4 Delimitations

There are several delimitations that reflect the choices described in the thesis in terms of the focus and scope of the research aims and research questions:

The size of the study area. The area is restricted to the “Verksbyen” area in Fredrikstad due to time and computational constraints.

Level of detalization of 3D model. The 3D city models used in this thesis are limited to LoD2, which represents buildings with building elements like the ground floor, walls, and roof without incorporating landscape features.

File format. It is known that for the final calculation of the LCA, a file with the CityGML extension is required. The resulting extension may define the scope for using any date or date in the previous steps.

The focus of this thesis is primarily on the input data, software to process data, workflow, and comparisons, and does not delve into the creation of the data itself or the specifics of the LCA tool (Urbi+) and associated processes. This sets some framework regarding the size of "The Application of Method".

4 Application of Method and Results

It is demonstrated in this part how the chosen methodology was implemented and applied to the research problem. This section provides a detailed account of the actual execution of the study, including the data collection process, 3D modelling process, LCA assessment and any modifications or adjustments made to the original methodology. After the methodology, the results from the process carried out are given.

4.1 Application of Method

4.1.1 Data collection

The table provides information about the name of the resource, its internet address, the prevalent file formats available on the resource, the availability of the data, and a brief description.

Source of data	**Format of data**	**Availability**	**Other details/comments**
Norwegian sources			
Høydedata *www.hoydedata.no*	Point clouds: LAZ or ZLAS DTM, DOM: Grid-format (Geotiff)	Open source	Geospatial dataset that provides information about the height or elevation of the Earth's surface in each area.
Norwegian Open Data *data.norge.no*	XML, JSON, CSV, Javascript, HTML etc.	Open source	The official portal for open data in Norway, offering a wide range of datasets, including building data from different sources.
Geonorge *www.geonorge.no*	SHP, GeoJSON, GML, KML, TIFF, ASCII Grid, WMS etc.	Open source	Norway's national infrastructure for spatial data, providing access to open geospatial data, including building information, from different government agencies and organizations.

Kartverket (Norwegian Mapping Authority) *www.kartverket.no*	SHP, GeoJSON, XML, KML, TIFF, ASCII Grid, WMS	Access only to licensed parties	The national mapping agency of Norway provides various open spatial data, including building footprints and cadastral information (Matrikkelen and FKB)
Norkart *www.norkart.no*	DTM, DSM etc.	Commercial	The source supplies terrain models (DTM) that cover all or parts of Norway. The models can be delivered in various formats, themed, and with additional information such as building bodies and simulated forests (DSM).
Geodata *www.geodata.no*	FKB as SOSI, Shape, DXF or Esri File Geodatabase etc.	Commercial data provider	Through the source, there is access to data based on Norwegian conditions. The maps and data are tailored to the software from Esri but can also be used by other clients and standardized interfaces.
Terratec *www.terratec.no*	DTM/DEM, DOM/DSM etc.	Commercial data provider	Terratec can deliver object based and "mesh" 3D city models in LOD1, LOD 2, LOD3 or LOD4 (BIM). They could offer 3D models of terrain, coastlines, buildings, entire cities, infrastructure, and more.
EU sources			
European Data Portal *data.europa.eu*	CSV, Esri File Geodatabase, XML, JSON, HTML, SHP etc.	Open source	The official portal for European data with the datasets available for 36 countries.

Global sources			
OpenStreetMap (OSM) *www.openstreetmap.org*	OSM	Open source	Collaborative mapping platform provides building footprints and other spatial data contributed by volunteers.

Table 1: Representation of available spatial data with the explanations of file extensions, availability and sources

4.1.2 Modelling process

The modelling process includes the generation of a model of existing buildings from open-source spatial data and the manual modelling of the new developments in the area. These processes will be described in this part of method application.

Software overview

To achieve the objectives of the thesis, an extensive exploration of software options was conducted. Preference was given to freely available tools during the investigation. In cases where free alternatives were unavailable, several commercial products were examined using student licenses. The research helped to develop a table of available software and scenarios for utilizing these tools, along with an assessment of their technological capabilities. The findings of the study are presented in the table ().

Software name	Main data format	Availability	Details / Comments	Use case
Cloud Compare *www.danielgm.net/cc*	LAZ	Free	3D point cloud and mesh processing software to check the spatial data	View the point cloud data
QGIS *www.qgis.org*	OSM	Free	The cross-platform desktop geographic information system application can be used to generate the footprint file from OSM data and then export into a variety of formats	Extract footprints from OSM

FME *fme.safe.com*	LAZ, DWG to OBJ, XML	Commercial software, a student license was used	FME is a geospatial extract, transformation, and load software platform. It can be used to generate 3D model into 3D format (OBJ) or directly generate CityGML file (XML)	Generate 3D model for existing buildings
3dfier *tudelft3d.github.io/3dfier*	LAZ, DWG to OBJ	Free	The open-source tool for creation of 3D models by utilizing 2D GIS datasets and extracting elevation information from a point cloud, it transforms them into 3D representations.	Generate 3D model for existing buildings
MeshLab *www.meshlab.net*	OBJ	Free	The 3D mesh processing software system focuses on handling and manipulating unstructured large meshes. It offers a range of tools for tasks such as editing, cleaning, healing, inspecting, rendering, and converting this type of mesh.	View generated OBJ file
SketchUP *www.sketchup.com*	SKP	Commercial software, a student license was used	3D modeling software used for architectural, interior design, and construction projects. It offers a variety of tools and features for drawing, shaping, and manipulating objects in the virtual 3D environment	Manual 3D modelling for new development
GEORES plugin for SketchUP *www.geoplex.de/geores*	SKP to XML	Free	The plugin allows users to import and export CityGML files in SketchUP software. It also provides functionalities to annotate meshes and faces with the according CityGML classes and attributes.	Generate CityGML file in LoD2

FZKViewer *www.iai.kit.edu/english/1648.ph*	XML, GML	Free	A viewer of semantic data models in IFC, CityGML, gbXML, LandXML, CIM (IEC) formats	CityGML viewer to check the result
Notepad++ *www.notepad-plus-plus.org*	XML, GML	Free	Free and open-source text and source code editor	CityGML code edition
Urbi+ *www.github.com/tum-gis/LCA-TGA*	CityGML	Free	The tool to carry out LCAs and LCCs of large residential building stocks using semantic 3D city models	Urban simulations

Table 2: An overview of software to process spatial data generation for different use cases

The data about building footprints were not found in Norwegian sources, but they can be extracted using the OpenStreetMap data source and QGIS software. The data from OpenStreetMap is initially composed of geometries with assigned key-value pairs. The buildings can be easily filtered from all the geometries within an OSM file. The following steps were taken to create the file:

Add a new layer for the buildings. In opened QGIS software in the OSM file containing the downloaded area a new vector layer should be added (Menu->Layers->Add Layer->Add Vector layer).

When prompted to choose the layer to add, only the multi polygons layer can be selected (adding all layers is also acceptable, but the buildings are specifically found in this layer).

Filter the buildings. The Layers Panel filter should be selected for the multi polygons layer that was just added. In the dialogue window, "buildings" should not be null (this effectively filters out polygons without a building key). Now, only the buildings are displayed on the map. The example of the file presented on the Figure 3 with the buildings marked with the red color.

Save the footprint file. From the Layers Panel, the multi polygons layer should be selected. In the dialogue window for saving the file, the ESRI Shapefile format should be chosen, and the output file is specified as DWF. It may be necessary to reproject the geometries to a different Coordinate Reference System (CRS) if the elevation data is not in the same system.

After saving, a file with the footprint of the buildings for the specified area and the specified CRS is obtained. This file can be used as an input for the next steps.

Figure 3: Screenshot from OSM software: footprint file view

3D model creation with FME software

The FME tool was initially chosen for the direct generation process. Working with many file formats, as well as many modifiers for working with them, discovered in the process, gave a lot of space for experimenting with the tool.

In addition to the tool, a large knowledge base is also provided by the FME software distributors. One of the scripts suitable for the purpose of modelling a 3D model in the software has been tested (Figure 4). The full tutorial can be evaluated on the software platform (FME, 2020). The following text will describe the main steps of the process.

- Read Source Point Cloud and Buildings. A reader for the LAZ file and another for the building_outlines DWG file were added. It is important to ensure that both files are in the appropriate coordinate system to match each other.
- Store Building Geometry. The GeometryExtractor was added and connected the building footprints to store the current geometry in an attribute. The parameters for the GeometryExtractor were set to encode the geometry as FME Binary and store it in the _geometry attribute.
- Filter the Point Cloud for Buildings. The PointCloudFilter was used to filter out points classified as Buildings or Ground based on their classification attribute. The result is presented on the Figure 5.
- Clip the Point Cloud by the Buildings. The Clipper transformer was added and connected to the filtered Buildings points to the Candidate port and the building outlines to the Clipper port. The Clipper parameters were configured to merge attributes and resolve conflicts, preserving the point cloud attributes.
- Get Building Heights. The Inside output port from the Clipper to a PointCloudStatisticsCalculator transformer was connected. The Median was enabled for the z Component to calculate the median height of the buildings from the point cloud.
- Restore the Geometry. The GeometryReplacer was used to restore the original geometry from the _geometry attribute.

- Set Building Base Heights. The output from the GeometryReplacer to a 3DForcer was connected. The base heights of the buildings were set using the base_height attribute from the source DWG building outlines. Since there was no such attribute in the source DWG file the attribute was added with the AttributeCreator transformer with the base_heigh equal to 6m.
- Extrude the Buildings. An Extruder transformer was added and connected to the output of the 3DForcer. The rooftop height derived from the point clouds was used and the base elevation to extrude the buildings into 3D.
- Surface creator. The TINGenerator transformer was added and connected to the Ground output port from the PointCloudFilter to generate a surface. The surface tolerance parameter was set to determine which input points are added as vertices to the model.
- Write the Result. A suitable format for writing the result can be chosen (such as Sketchup, OBJ or 3D PDF) Connect the extruded buildings and the TINSurface output to their respective feature types in the writer.
- In the end, the workspace to generate the output file should be run.
-

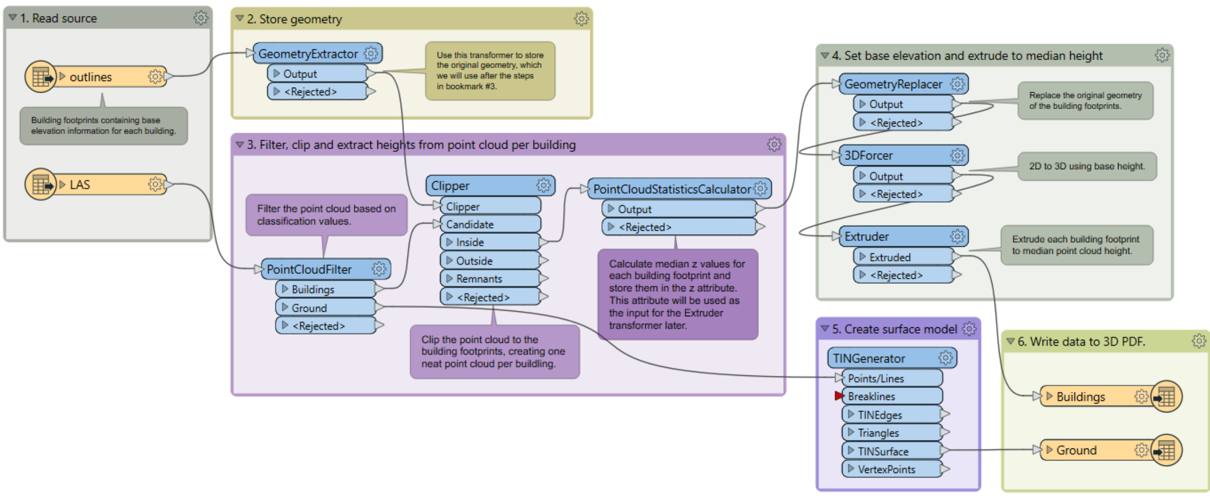


Figure 4. Screenshot from FME workspace: used modifiers for 3D model generation process.

Figure 5. Input data for 3D model generation in FME software: 2D footprint file (left) and point cloud Lidar file with filtered out points classified as Ground based (right).

3D model creation with 3dfier software

To generate a 3D model using 3dfier, it is needed to provide 2D datasets and elevation datasets as input. The 2D datasets can be in various formats like SHP or GML, while the elevation datasets should be in LAS/LAZ format. In this simulation, the 2D footprint data from QGIS was exported as an SHP file, and the elevation data was in the form of a point cloud stored in a LAZ file.

To define the input datasets and other parameters, a configuration file with a .yml extension was used. There is a sample config file provided with 3dfier that can be modified to suit the specific case. Here is an overview of the main steps involved in generating a 3D model:

- Installation and preparation. After downloading the 3dfier software, there will be an "example_data" directory containing all the necessary files for creating a 3D city model. The file for configurations "testarea_config.yml" is already prepared with the required information.
- Dataset generation. The prepared 2D footprint data is used as input for the buildings' outlines, while the LAZ file containing the point cloud data is used for elevation information. In the configuration file, there could be specified certain classes in the point cloud to omit (e.g., vegetation) and adjust point thinning to speed up the process. In this case, all lidar points were considered (Figure 6).
- Adjustment of 3dfier options. There is the flexibility to adjust various options in 3dfier. One important option is determining the elevation of each building's top. In this case, the "height_roof" values were chosen using the percentile-50, which represents the median of all points. Another crucial option is selecting the format of the resulting 3D city model. 3dfier supports formats like CityJSON, OBJ, and more. For this case, OBJ was chosen as the final output format.
- 3D model generation. To generate the 3D model, there is a command to simply execute in the program ("3dfier testarea_config.yml --OBJ output/testarea.obj").

This command initiates the process and generates the 3D model in the specified format (OBJ in this case).

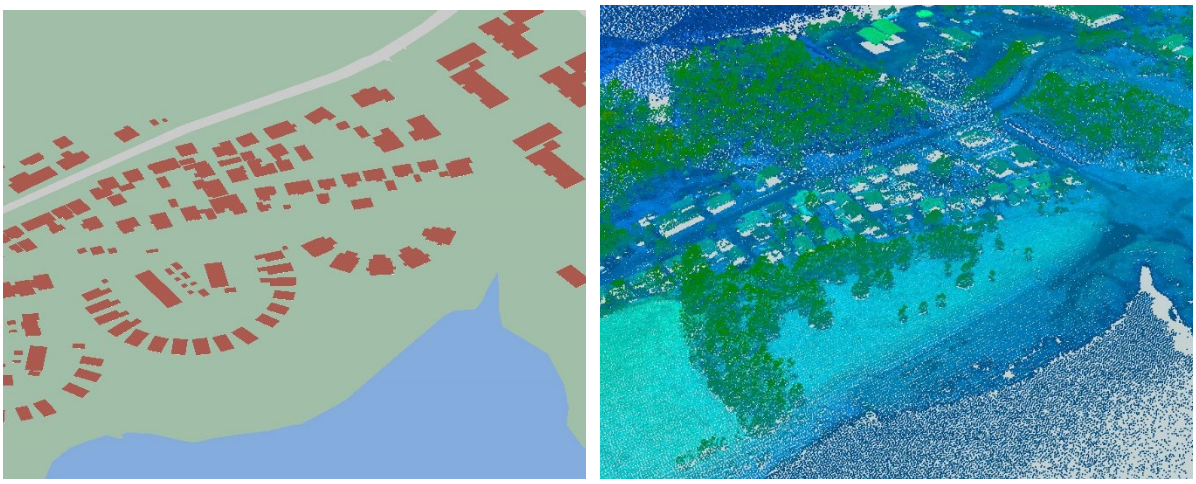


Figure 6. Input data for 3D model generation in 3dfier software: 2D footprint file (left) and point cloud Lidar file (right).

3D model creation with SketchUP software

New housing stock can be constructed using manual modeling based on drawings from architects and developers. The documentation was analyzed and incorporated accordingly. The resulting file for this line was merged with the generated file for the existing housing stock (Figure 7)

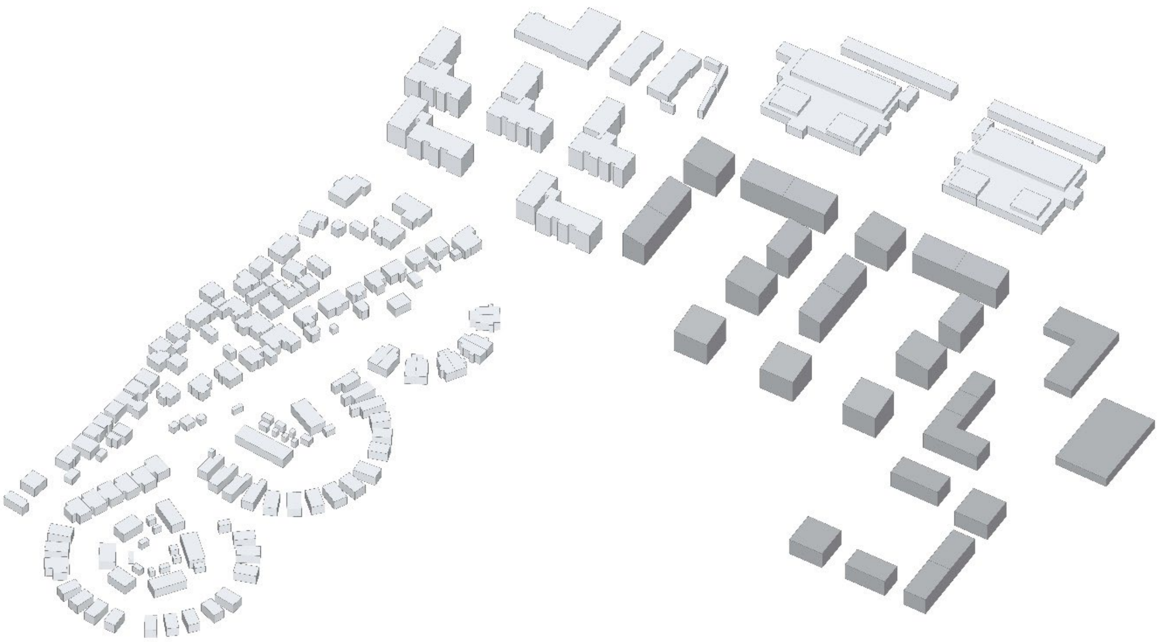


Figure 7. Combined model with 3D models of existing buildings (light grey) as well as new developments (dark grey). Screenshot from SketchUp software.

4.1.3 Transferring into CityGML model with GEORES plugin

Following the two modelling processes, the next step involves converting the model into the GML format. In this case, the GEORES Sketchup plugin was utilized to test this process.

- The GEORES SketchUp CityGML Plugin offers functionalities for importing and exporting CityGML files. It also provides tools for annotating meshes and faces based on CityGML classes and attributes. The following operations were carried out within the program:
- Building attribution. The initial step involves assigning a unique code attribute to each building in the model.
- Building part attribution. To create a model compliant with the LoD2 standard, the plugin allows for determining the ground floor slab, walls, and roof for each building using its built-in functions.
- Model export. Once all the attributes are set, the model can be exported according to the CitiGML 2.0 standard. During the export process, the typology of the 3D model objects (in this case, buildings) and the desired level of detail (LoD2) need to be specified. Clicking the "Start" button initiates the process of saving the model.

4.1.4 Adjustments of the CityGML model for LCA tool Urbi+

After creating the CityGML model, it was discovered that to utilize the model in the Urbi+ LCA tool, certain attributes needed to be added for each building in the model. The models of the buildings are represented as a code. An example of the code for one building could be found in the Appendices (Appendix 3). The following extracts from the building code should be specifically checked:

The function of the building: This attribute defines the function of the building and is represented as" <bldg:function>1111</bldg:function>" (Figure 8). It allows Urbi+ to identify which buildings should be analyzed. Currently, the program only works with residential buildings, so all residential buildings in the calculation were identified with 1111 id number.

Year of construction: This attribute represents the year of construction for each building and is given as "<bldg:yearOfConstruction>2018</bldg:yearOfConstruction>" (Figure 8). It is necessary for calculations as the program considers the Construction Age Class of the building. The program allows for setting 11 age classes, and U-values may vary based on the age of the building. This provides more accurate results in calculations, such as costs and harmful emissions for energy maintenance. In this case, information about the year of construction was taken from the open resource geodata.no and manually added as an attribute for each building. Figure 9 shows the distribution of buildings according to their building age class. Figure 10 shows the distribution of number of the buildings by their building age class (BAC), while Figure 11 shows the distribution of the buildings with different BAC of the case by total living area.

Type of roof: The attribute is written as "<bldg:roofType>3100</bldg:roofType>"(Figure 8). Since the program assumes calculations at the LoD2 level of detail, the type of roof can vary among the buildings in the model. This attribute increases the accuracy of calculations. However, for this study, a simplification is adopted, and all buildings in the model are considered to have flat roofs.

It is important to note that the base floor, walls, and roof are defined in the CityGML model, and the calculations in the Urbi+ LCA program are performed based on the LoD2 level of detail. However, the 3D model itself has a simplification, where buildings with pitched roofs in the model are represented with flat roofs.

```
<bldg:Building gml:id="UUID_Building_687_72569_115690">
<bldg:function>1111</bldg:function>
<bldg:yearOfConstruction>2018</bldg:yearOfConstruction>
<bldg:roofType>3100</bldg:roofType>
<bldg:measuredHeight uom="urn:adv:uom:m">6.0</bldg:measuredHeight>
<bldg:lod2Solid>
```

Figure 8. Fragment of building code in CItyGML file. Screenshot from NotePad++ software.

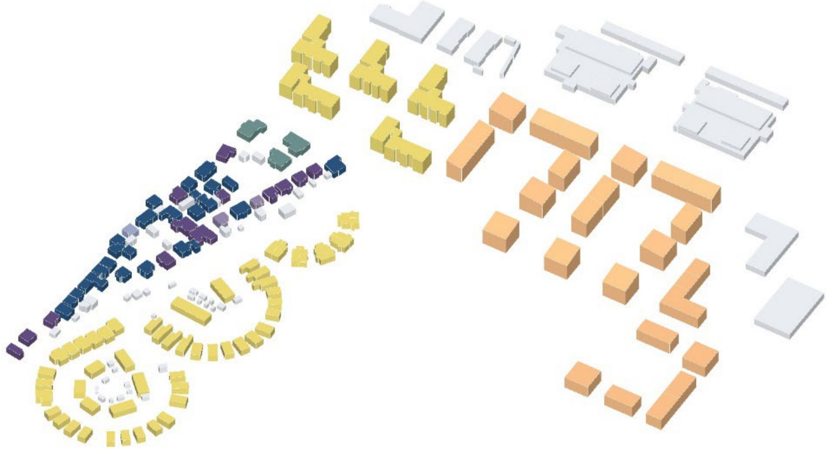


Figure 9. 3D view of the model with coloring of buildings by building age class (BAC)

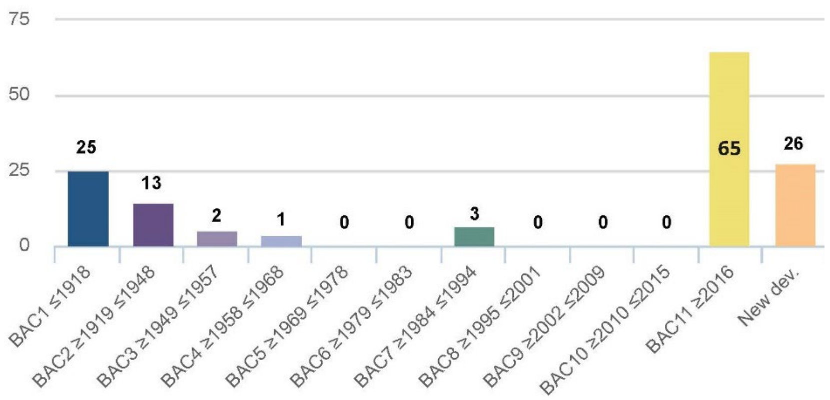


Figure 10. Distribution of the buildings of the case by BAC

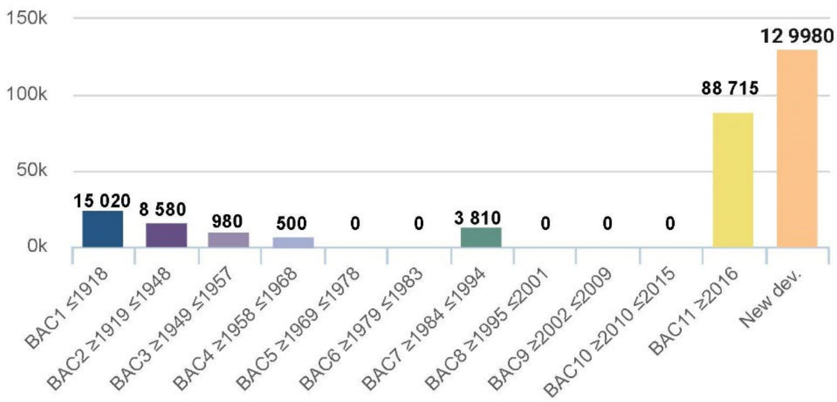


Figure 11. Distribution of the buildings with different BAC by total living area

4.1.5 Norwegian definitions for and emission factors for LCA tool Urbi+

The Urbi+ program was used to calculate the LCA. For this calculation, it takes a systematic approach to conduct a thermal building system (TBS) life cycle assessment in large housing stocks using 3D Semantic City Models (CityGML). The calculation is carried out according to the operating energy consumption, thermal load, sizing of TBS components and life cycle assessment.

It is also important to mention, that the calculations are conducted based on the following general assumptions:

- The calculations are performed using a single-zone model, which does not consider building-specific floor plans or zoning.
- The calculations utilize a Level-of-Detail 2 CityGML building model as the input data.
- Basements and underground car parks are excluded from the calculations, focusing solely on above-ground areas and residential buildings.

For calculation, in addition to the model, it is necessary to enter into the program the values for the thermal systems of the building that are relevant to the specific area in the case. The program carried out 2 calculations for the existing neighborhood area and for the new development.

Figure 12 shows the screenshots of the interface with definitions for the existing neighborhood area, while Figure 13 shows definitions for the new development. There is a full list of values with sources for both areas presented in the table of the Appendix 3.

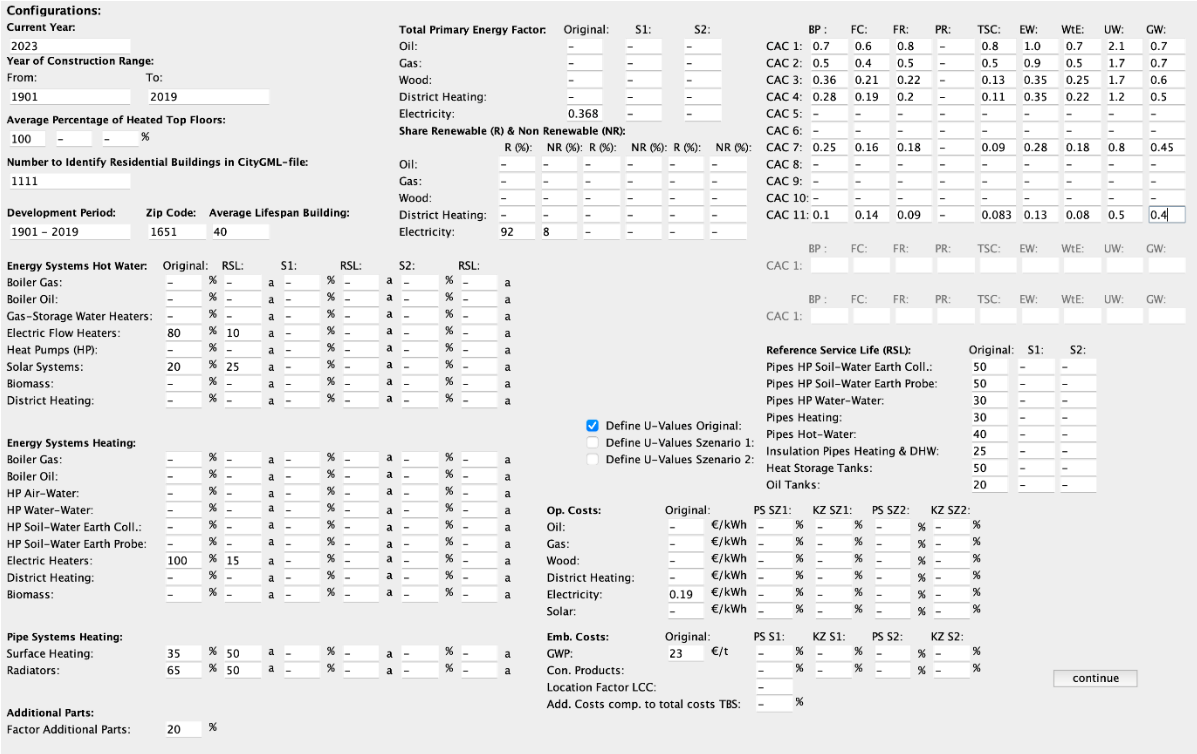


Figure 12. Screenshot of applied definitions into LCA tool Urbi+ for existing neighborhood

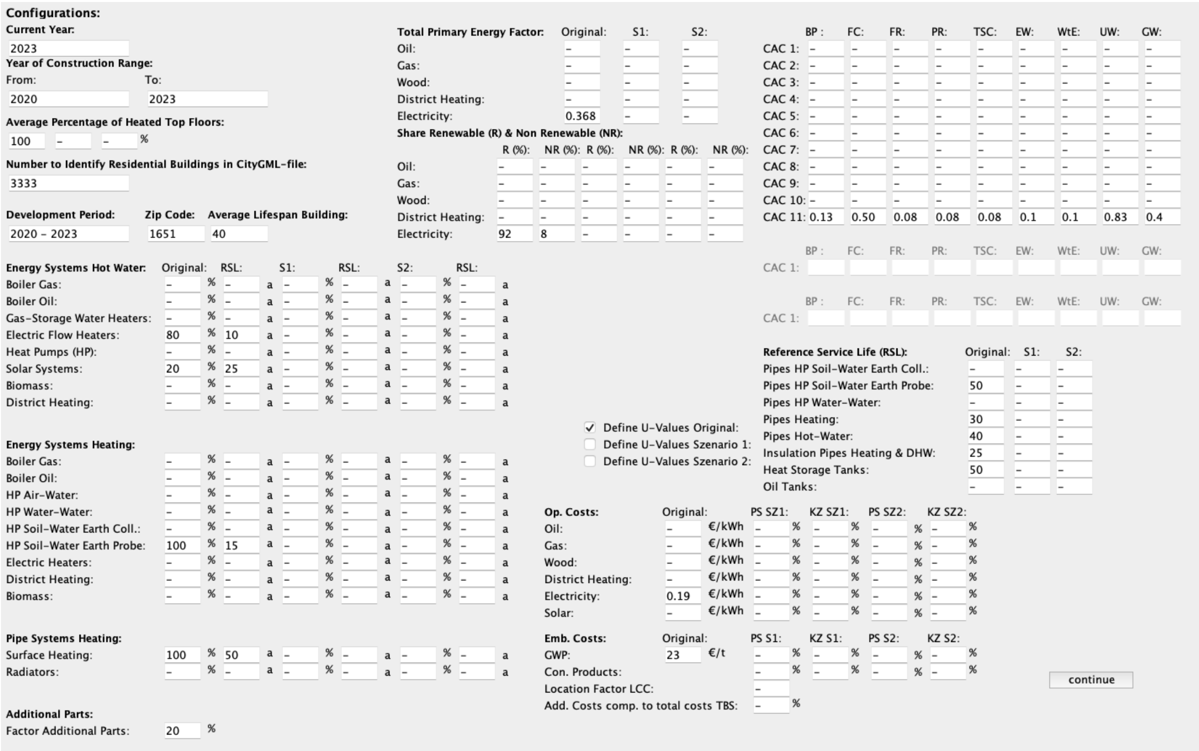


Figure 13. Screenshot of applied definitions into LCA tool Urbi+ for existing neighborhood

4.2 Results

4.2.1 Used open-source spatial data

After analyzing various sources of spatial data in Norway (full list presented in Methodology chapter in Table ()) and considering factors such as file formats and data quality, the following datasets have been identified as the most accessible in Norway and suitable for use:

- Lidar data from Høydedata platform (*www.hoydedata.no)*: This dataset provides detailed information about the elevation and topography of the area. Lidar data is collected using laser scanning technology and can be valuable for various applications, including terrain analysis and building height estimation.
- Building footprints from OSM (*www.openstreetmap.org)*: The OpenStreetMap dataset includes building footprints, which outline the shape and boundaries of buildings. OSM is a popular platform for accessing and contributing to geographical data, and the building footprint dataset is widely utilized by many users.

Accessing the data from these platforms typically involves navigating through the platform's menu options. The interface of the program, along with a view of the provided data, can be seen in the Figures 14, 15.

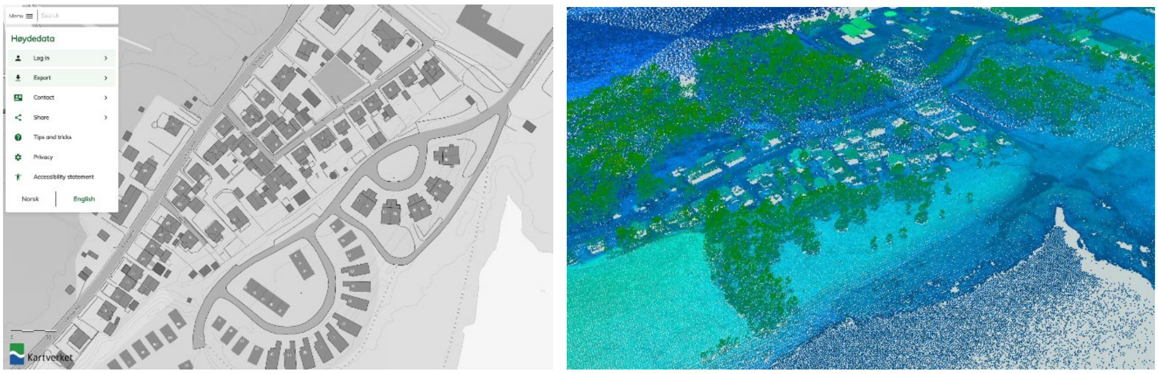


Figure 14. The interface of the spatial data source Høydedata (left). View of the received point cloud Lidar data from this source (right).

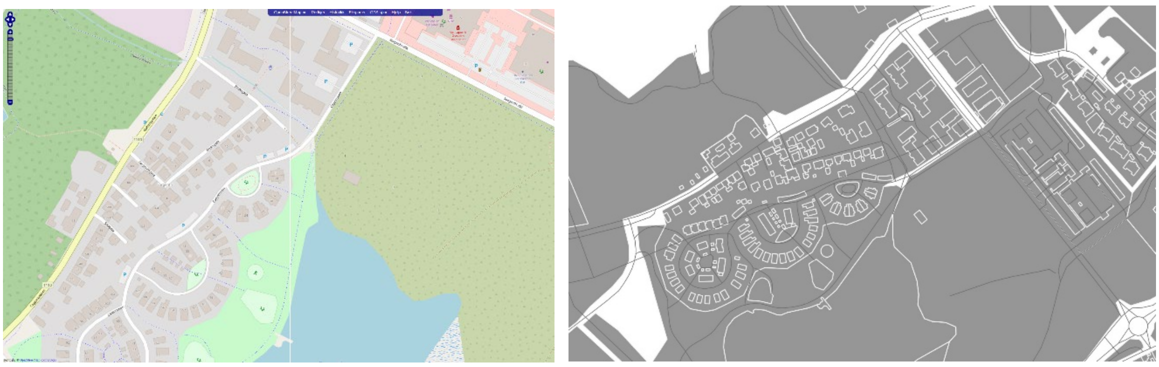


Figure 15. The interface of the spatial data source OSM (left). View of the received building footprint data from this source (right).

4.2.2 Created models of the neighborhood

Footprints of the buildings from QGIS

Through the utilization of QGIS, a file containing building footprints was obtained for the existing development in the designated area for design purposes. This file will play a crucial role in the subsequent steps of generating 3D models, as it considers the extrusion of shapes based on the footprint data.

Created volumes of the buildings

The 3D modeling process resulted in the creation of two models for the site. Below are more detailed descriptions of the outcomes for each case. Both cases were tested using the data collected for the Fredrikstad neighborhood case study.

FME. Using the FME software, a workspace was set up to generate a 3D model of the city and the Earth's surface. However, the "transformers" of the program could not be adjusted to accurately extrude the buildings based on the intended point cloud data. Due to time limitations, this method was tested but did not achieve the desired outcome of accurately extruding buildings to their required heights. Nevertheless, the resulting file is readable in other programs and can be utilized for models with lower accuracy requirements.

3dfire. The model generation process using 3dfire resulted in a model where the heights of buildings were adjusted based on the point cloud data of the district. This model was successfully imported into the Sketchup program and selected for further development due to its higher level of detail compared to the model obtained through tests with the FME software. A more comprehensive comparison of these processes is provided in the Discussions chapter.

Figure 16. The view of the 3D model for existing buildings in the neighborhood was generated with FME software.

Figure 17. The view of the 3D model for existing buildings in the neighborhood generated with 3dfier software.

Final model in CityGML standart

The model obtained after using the GEORES program consists of buildings recorded with a unique ID and has a ground floor, walls and roof related to each building.

The resulting model can be viewed and inspected later using the free FKZ viewer software. The provided screenshot in Figure 18 showcases different elements of the model, such as walls and roofs, which are distinguished by their respective colors.

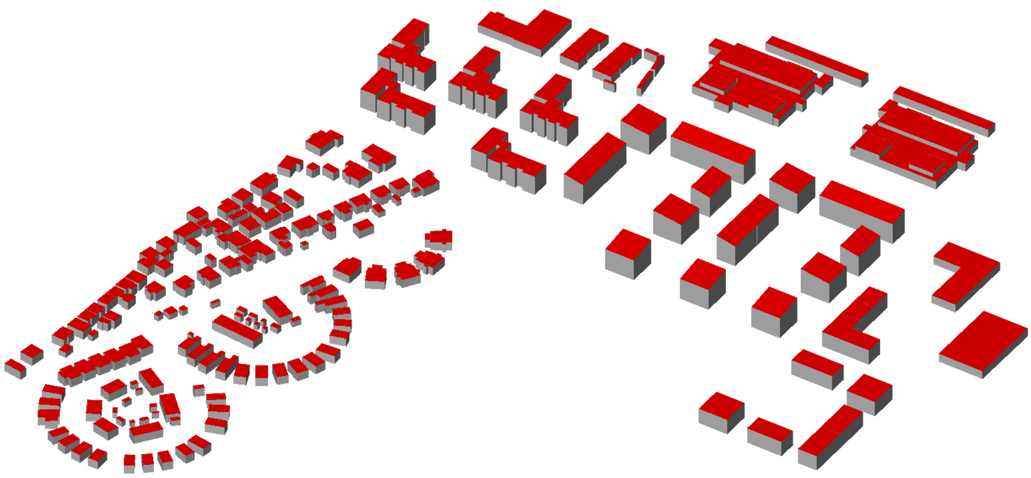


Figure 18. The view of the final CityGML model created in SketchUp with GEORES plugin.

4.2.3 LCA in Urbi+ tool

The LCA calculation in the Urbi+ software generates a text document that presents a variety of calculated indicators essential for LCA analysis. These indicators include:

- Primary Energy from non-renewable resources (PENRT) [kWh]
- Primary Energy from renewable resources (PERT) [kWh]
- Heating Load [kW]
- Global Warming Potential (GWP) [kg CO2-eq.]
- Emissions Costs (related to GWP) [€]
- Life Cycle Costs (for the technical building services components) [€]

To visualize the results, these indicators are graphically represented using Microsoft Excel. Figures 19-22 in the thesis depict the calculation outcomes, which are provided separately for existing buildings and new developments.

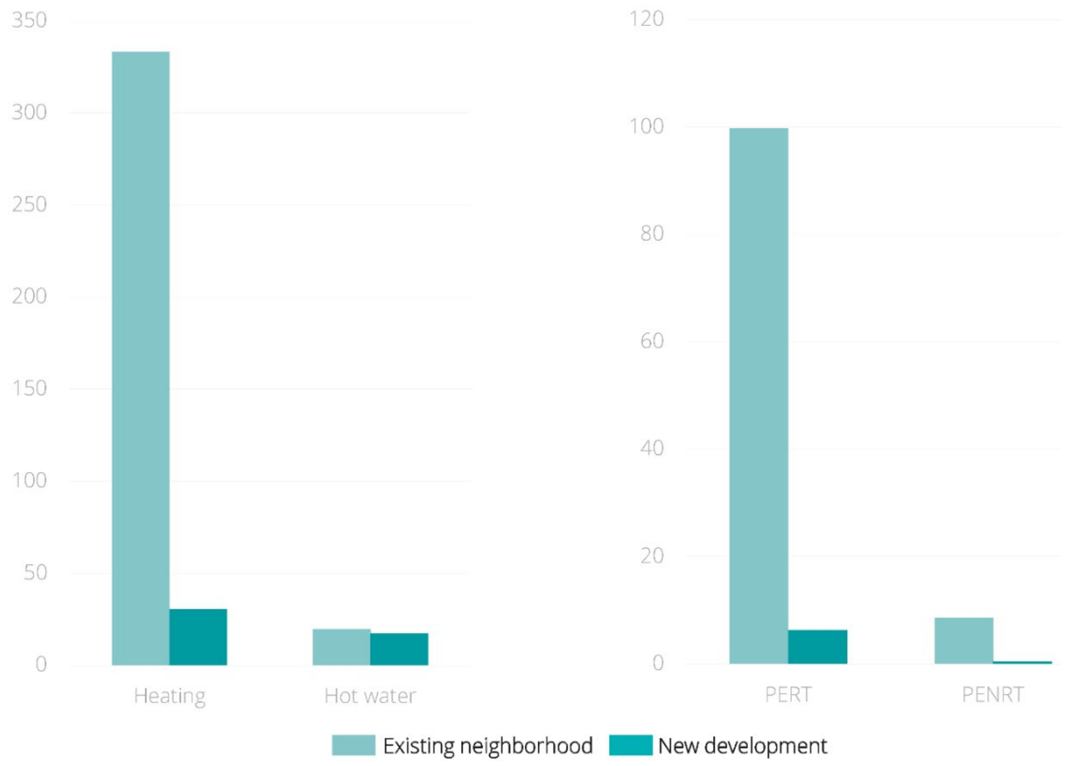


Figure 19. Average specific final energy demand for heating and DHW [kWh/(m2yr)] (left) and primary energy from non-renewable (PENRT) and renewable (PERT) resources [kWh/m2] (right) for existing neighborhood and new development.

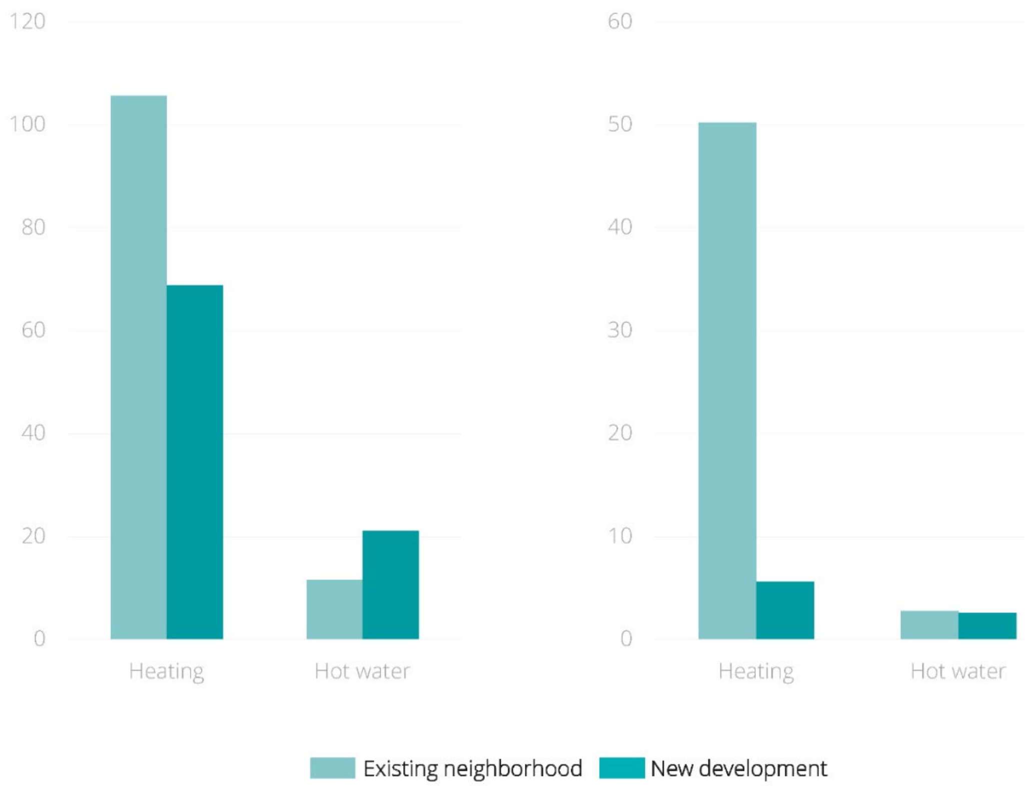


Figure 20. Heating Load [kW/m2] (left) and Costs Energy for heating and DHW (related to GWP) [€] (right) for existing neighborhood and new development.

Figure 21. Comparison GWP for two cases by different TBS [kg CO_2-eq.]

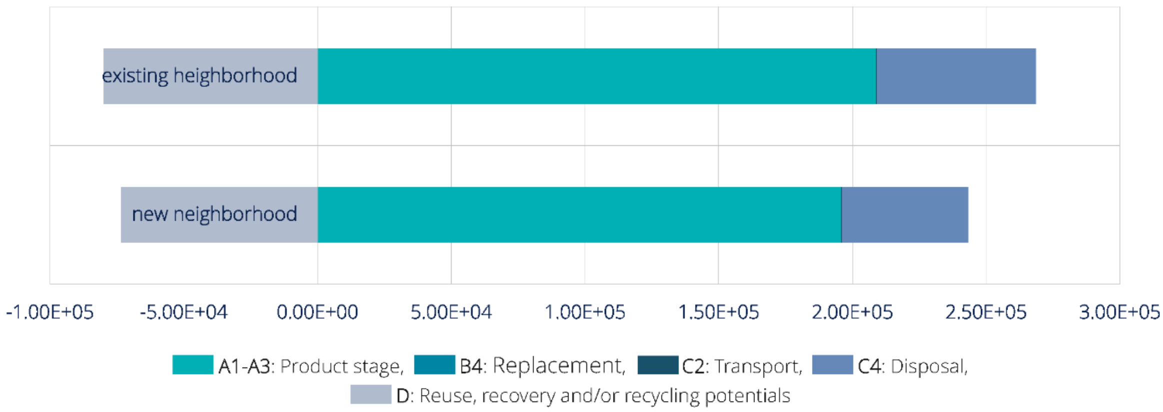


Figure 22. Total GWP for two cases [kg CO_2-eq.]

4.3 Achieving goals

The research process proceeded as scheduled and addressed all the intended aspects. The initial phase involved conducting a comprehensive review of relevant theoretical literature pertaining to the thesis topic. This encompassed an exploration of the latest advancements in the field of open spatial data creation and its application in expediting design processes and promoting sustainable planning. Furthermore, various software applications capable of constructing 3D building models using this data were examined. The study revealed the potential of open data for developing urban simulations that focus on sustainable district-level development. The concept of Life Cycle Assessment (LCA) at the neighborhood level emerged as an adopted framework applicable to this process through the special software tool Urbi+. Drawing upon the findings of the theoretical investigation, the study's objectives, goals, scope, and limitations were defined.

Following the theoretical phase, the research methodology was outlined based on the insights gained from the literature review. To illustrate the methodology, a case study was selected, which centred around an area in the city of Fredrikstad comprising both existing buildings and planned residential development. The methodology delineated the steps undertaken, remaining within the predetermined scope of the task.

Subsequently, the application of the methodology to the selected case study was presented, offering a comprehensive explanation of the procedures performed. This involved leveraging Norway's open spatial data in conjunction with available software. The section provided a general overview of the modelling process and the subsequent analysis of the resulting 3D model using the LCA tool. A key conclusion drawn from this phase was the successful implementation of the planned process, yielding outcomes that serve as a foundation for further work.

Additionally, the LCA was further evaluated, and the results were presented through graphical representations. Furthermore, a comparison was made between the results obtained and the existing calculations for the same area from the syn.ikia project. The comparison demonstrated the ability to achieve accurate calculation results, which undoubtedly facilitates the decision-making process for urban specialists.

Based on the findings of the study, it can be concluded that the main goals outlined in the research were accomplished. The methodology guided the progression from data and information collection to the analysis of the generated model using the LCA tool, yielding meaningful results.

4.4 Contribution to knowledge and independent input

Regarding to original contributions or unique findings from the study there is one significant outcome is the development of a comprehensive methodology and a detailed explanation of the process for selecting open spatial data, creating 3D models in the CityGML standard, and conducting Life Cycle Assessment (LCA) of the neighborhood's building stock based on these models. The methodology devised in this study offers a novel approach to address the research problem and demonstrates the original contribution to the field.

Moreover, the study showcases the reliability of the methodology by generating consistent and dependable results for LCA calculations. The researcher's ability to provide accurate and trustworthy outcomes through the proposed methodology adds value to the existing knowledge in the field.

5 Discussion

5.1 Open-source spatial data

Used datasets, point cloud in LAZ format and building footprints in OSM format, have demonstrated their usability.

In contrast, some of the other mentioned data sources either have limited availability or require advanced spatial data handling skills to utilize effectively. These factors make the identified datasets more favorable options for the purposes of this study.

5.2 3D Modelling process

The comparison of results between FME and 3Dfire software for the 3D generation of existing buildings is based on the modelling experience of the same Fredrikstad area. It is important to note that both models were created with certain simplifications, such as flat roof modelling and LoD1 detail level in spatial modelling. Each generation method has demonstrated its advantages and disadvantages.

Regarding the FME program, it is worth noting that the result was only partially achieved. However, the program itself offers promising opportunities for work. It supports a wide range of file types and can manipulate them using file transformation tools and a well-structured workspace. During the study of the program, numerous training materials on working with spatial data were discovered. With more advanced knowledge of the program, it is possible to create models with higher levels of detail, such as displaying pitched roofs. Another potential advantage is the program's ability to generate a CityGML model without relying on other software.

In contrast, 3dfier produced a result that was closer to the desired outcome, as it considered the varying heights of the buildings. This tool is user-friendly and can be easily applied to similar modelling tasks. It does not require a long learning process, making it advantageous for shorter-term use. However, the main limitation of this program is that it can only generate models in LoD1 without the ability to create models with higher levels of detail. This restriction may limit its applicability, especially in the context of urban simulation tools where a higher level of detail could be preferred. Also, the program cannot write the file directly to the CityGML format, although it does support CityJSON format which also can have attributes as a model with different LoDs.

5.3 LCA in Urbi+ tool

The results obtained from the LCA calculation provide insights into the current state of the building stock, encompassing both existing buildings and new developments. These results offer the opportunity to assess different scenarios for construction development. To conduct the calculations, relevant values specific to the Norwegian context were gathered for both existing buildings and new developments. The Urbi+ tool proved to be efficient and useful, providing a wide range of indicators for building assessments, including factors such as energy availability, use of renewable energy sources, energy pricing, and construction.

A comparison of the calculations between existing developments and new constructions reveals the performance gap between existing buildings and new developments (the results of the calculations in the "Results" section). This comparison can inform plans for the renovation and reconstruction of existing housing stock. It is evident that modern buildings demonstrate higher energy efficiency and better alignment with the challenges of sustainable development.

For new developments, multiple calculations were conducted to achieve results aligned with sustainable development goals. Each calculation involved testing different indicator values to attain the desired outcomes. The specific definitions for these calculations can be found in Appendix 3 of this thesis paper. The benchmark for these calculations was the results obtained from the sin.ikia project report, which conducted calculations for a similar new residential neighborhood (Shahabaldin Tohidi et al. 2022). Table 3 provides a comparison of the key indicator values that had the most significant impact on the calculations. As a result, the estimated energy requirement for heating in Urbi+ closely matched the value from the sin.ikia project (Table 3). This means that with a certain skill of using the Urbi+ program, a qualitative result of the calculation according to the listed indicators can be obtained.

	syn.ikia demo case	**Urbi+ calculations**
Comparison of important calculation data		
Share of renewables	100%	
Types of renewables	Photovoltaics, Ground source heat pump	Photovoltaics, Ground source heat pump
Energy storage: sizes and strategies	DWH, ground, building structure	DWH, ground, building structure, solar thermal collectors
U-values [W/m2K]	exterior wall = 0.1 roof = 0.08 external floor = 0.13 internal floor = 0.50 windows and doors = 0.83	
Heating degree days	4600	
Set point for heating and cooling	Heating: 21 ˚C, Cooling: n/a	
Results of the calculations		

Estimated energy need for heating (space and DHW)	**45 kWh/(m2yr)**	**47,4 kWh/(m2yr)**

Table 3. Comparison of important calculation data and calculation result for estimated energy need for heating from Urbi+ tool with the results from syn.ikia (Shahabaldin Tohidi et al. 2022)

In relation to the LCA Urbi+ tool itself, it is crucial to acknowledge that it is currently undergoing improvement and development. When utilizing the tool for calculations, it is essential to maintain communication with the program developers. It is also important to verify the accuracy of the results and ensure their alignment with the CityGML model. In the process of conducting calculations for this particular case, inconsistencies in the results were identified, necessitating repeated checks to ensure the correctness of the results.

The calculated indicators in Urbi+ contribute to an integrated assessment system that supports crucial urban planning processes and political decision-making. For example, energy demand and heat load calculations can guide municipal planning efforts in providing power plants for district heating. Parameters related to Global Warming Potential (GWP) facilitate the analysis of climate change aspects and the important consideration of climate neutrality. While development scenarios were not specifically calculated in this study, they represent a significant potential for further exploration, which is discussed in more detail in the Exploration Potential section.

6 Conclusions and Outlook

There is summarizes of the main findings and outcomes of the research project in this section. A final reflection on the research and a broader perspective on the implications of the study is offered. Insights into potential future directions or areas of further investigation are also provided.

6.1 Conclusions

In general, the research for this thesis project proceeded according to plan and covered all the intended aspects. The initial stage involved conducting a thorough review of relevant theoretical works related to the topic, focusing on advancements in open spatial data and its utilization in design processes and sustainable planning. Various software applications capable of generating 3D building models using this data were also examined. It was found that open data can be used for urban simulations at the district level, specifically in the context of Life Cycle Assessment (LCA) in neighborhoods. Based on the theoretical findings, the study's goals, objectives, scope, and limitations were established.

The research methodology was then described, drawing upon the examined theoretical material. A case study was selected to illustrate the methodology, focusing on an area in the city of Fredrikstad comprising existing buildings and planned residential development. The methodology outlined the steps taken and remained within the defined scope of the task.

Next, the application of the methodology to the case study was presented, providing a detailed explanation of the actions performed. This involved utilizing open spatial data from Norway in conjunction with software applications. The section provided an overview of the modelling process and the analysis of the resulting 3D model using the LCA tool. The key conclusion from this phase was that the planned process was successfully implemented and achieved the desired outcome.

It is worth noting that the thesis involved a significant amount of work, and there are opportunities for further exploration in several areas. In terms of open spatial data, the study focused on two primary data sources, but there may be other sources capable of generating 3D models. The section on 3D building modelling provided insights into specific software applications, with a focus on FME, 3dfire, and Sketchup. FME exhibited greater flexibility and potential for generating models from open sources, but further investigation is required for simulation and advanced utilization. On the other hand, the specialized software 3dfire allowed for the quick creation of models with a limited level of detail, suitable for specific requirements.

The LCA calculations in the Urbi+ program required additional information, including a 3D building model in CityGML format and data for direct calculations. Collaboration with the program's creator, Hannes Harter, and adjustments for the Norwegian context enabled the successful completion of the calculations. The obtained results were crucial for analysis and demonstrated the potential of the program in expediting the sustainable design process.

Regarding the research questions, it can be concluded that open-source spatial data from Norway can indeed be used to generate a 3D model for LCA, although achieving a complete Level of Detail 2 with roof slopes was not accomplished within the limited timeframe of the study. The study also highlighted the importance of readable datasets in compatible formats for software utilization in 3D modelling and LCA. The CityGML format was specifically focused on in this study, but other programs may use different formats. Additionally, the study emphasized the need for indicators, such as building energy supply, renewable energy sources, building structures, and construction year, for LCA calculations in the studied neighborhood.

In addition to the reflections outlined in this thesis, a few recommendations for similar works are suggested. Firstly, it is advisable to employ open spatial data for simulations. Secondly, the selection of the most suitable method for 3D generation of existing buildings should consider time efficiency. For instance, while the FME program demonstrated significant potential, it required substantial time for users to become proficient. On the other hand, the 3dfire program yielded quick results and did not necessitate extensive user knowledge since it was tailored to a specific process. Finally, it can be concluded that the results obtained in Urbi+ closely aligned with the calculations provided for the syn.ikia case study. This suggests that the tool can be recommended for use and further testing. However, it is important to note that the program is still in the development phase and only a limited number of individuals can currently utilize it for calculations.

In summary, this thesis comprehensively describes the process of 3D modelling and LCA analysis for the area using various software programs, exploring their potential utilization by specialists. The study provides reflections, references, and recommendations, including the use of open spatial data for simulations, consideration of time efficiency in selecting 3D generation methods, and the recommendation and further testing of the Urbi+ program, keeping in mind its ongoing development phase.

6.2 Potentials of the research

Some potential areas for further research, development, or improvement based on the findings and limitations of the current study are explored. It is important to emphasize that the thesis covered a significant amount of work and various areas of study that could be developed in the future.

Firstly, when examining open spatial data, two primary data sources were selected, but there is potential to explore other sources for generating 3D models. Norway has a large amount of spatial data. Of particular interest are data for specialists from the Norwegian cadaster. The use of datasets containing the year of construction of buildings or some data on the engineering condition of buildings can be very interesting for research.

The section focusing on the 3D building modelling process provided detailed insights into specific software applications and described the process extensively. The main modelling procedures involved the use of FME, 3dfire, and Sketchup. The results of the process indicated that FME showed greater flexibility and potential for generating models from open sources. Further long-term investigation of the program is required for simulation and advanced utilization. On the other hand, the specialized software 3dfire allowed for the quick creation of models with a limited level of detail, suitable for further work in an urban simulation tool. However, upon completing both processes, the results did not achieve the ideal model creation in a fully established LoD2. The greatest potential of the study would be to continue working in the FME program until the model is obtained in the required level of detail in CityGML format.

Another potential way of study could be the creation of a CityGML model using a different site as an example to analyze possible differences in the process based on the location of the buildings and energy and building construction definitions for this location.

A third potential idea is to engage in more intensive work with the existing model and the Urbi+ tool. The program offers significant potential for calculating LCA for the area, so further testing of the tool would be beneficial. Diving into the details of the calculations as well as refining how the tool works in the Norwegian context can be an important study.

The mentioned ideas serve as a forward-looking component of the thesis, providing suggestions and recommendations for future research endeavors, improvements, and potential areas of impact or application.

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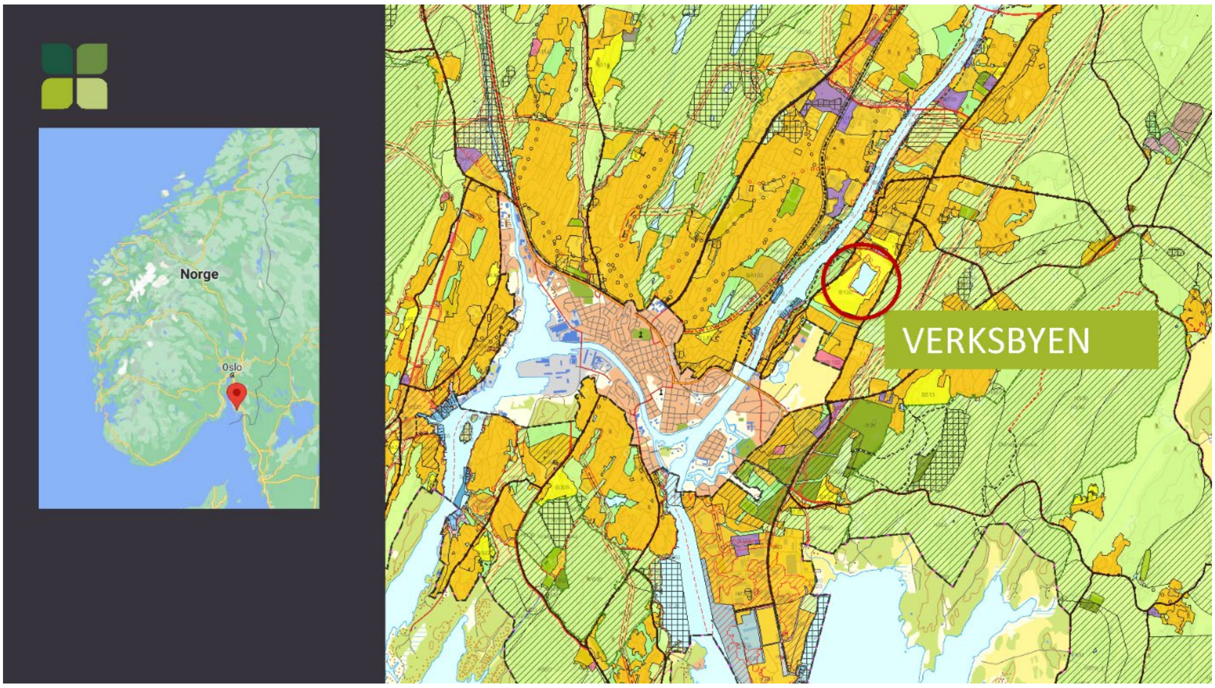
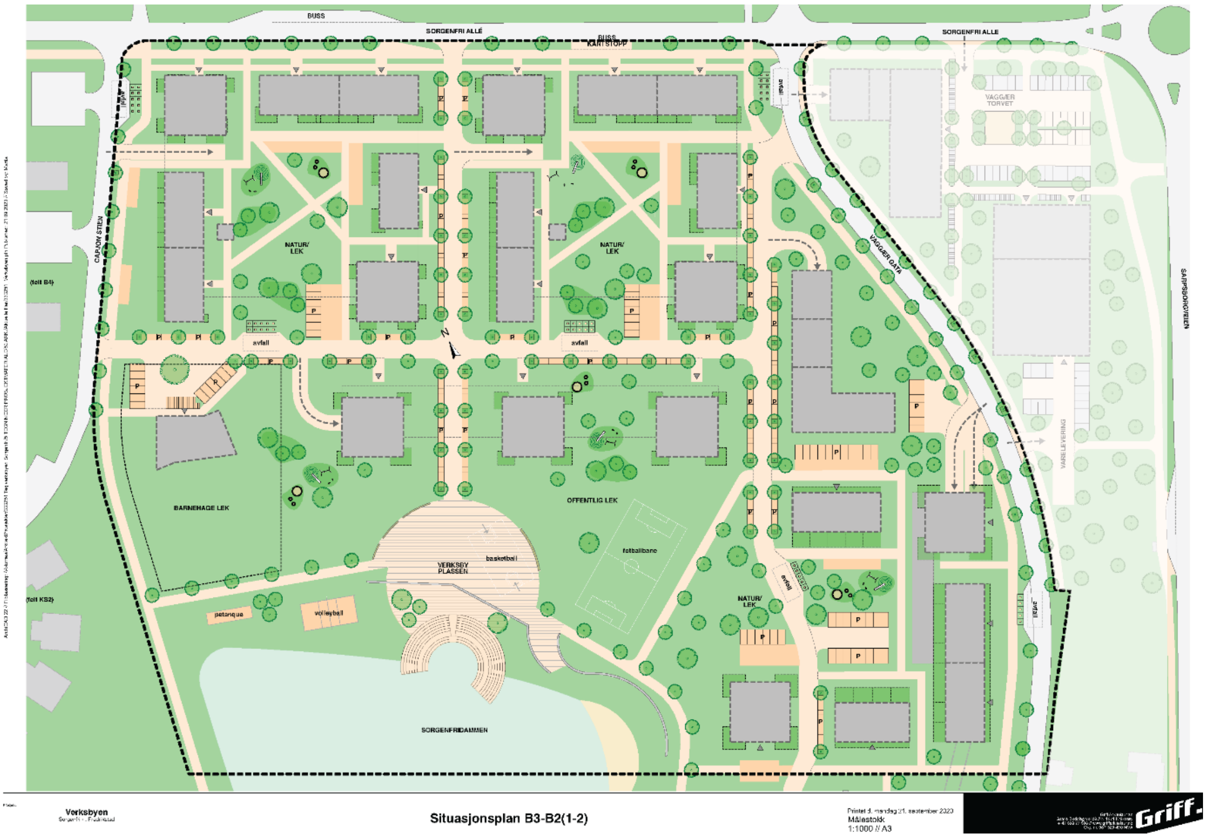
Appendices

Appendix 1: Project documentation for Verksbyen new neighborhood




VERKSBYEN
Future Living
ARCA NOVA
GRUPPEN


BUSS
SORGENFRI ALLÉ
SORGENFRI ALLE
NATUR/
LEK
avfall
BARNEHAGE LEK
OFFENTLIG LEK
VERKSBY
PLASSEN
basketball
fotballbane
petanque
volleyball
SORGENFRIDAMMEN
Verksbyen
Situasjonsplan B3-B2(1-2)
Målestokk
1:1000 // A3
Griff.

Appendix 2: Pictures of the buildings from existing neighborhood and U-values for its walls. There is one picture of the building for each Building Age Class.

BAC1 ≤1918

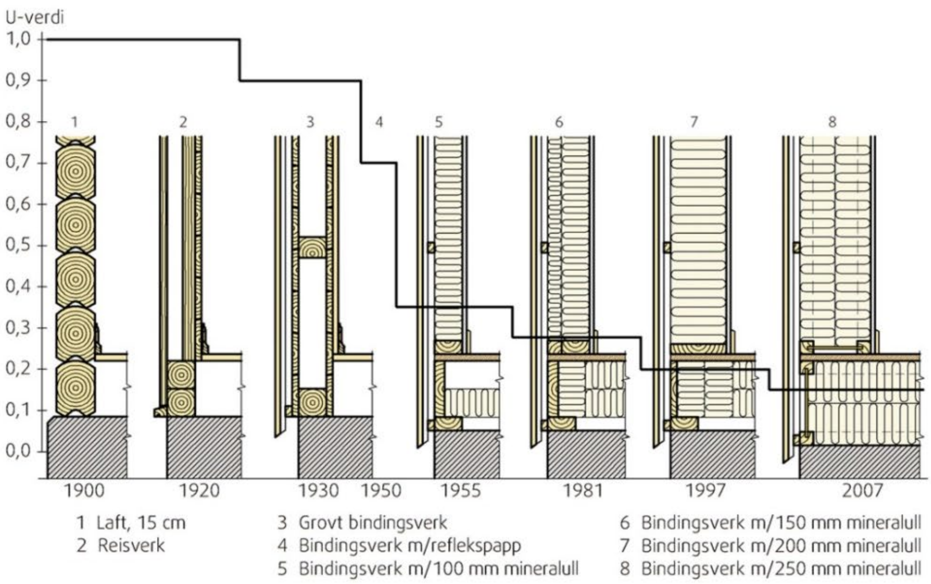
BAC2 ≥1919≤1948

BAC3 ≥1949≤1957

BAC4 ≥1958≤1968

BAC7 ≥1984≤1994

BAC11 ≥2016



U-values for walls of the buildigns from different age classes. Information retrieved from (SINTEF. 2022. Teknisk Godkjenning.)

Appendix 3: Full list of definitions for urban simulations in LCA tool Urbi+ with sources of the definitions

Configuration	Definition	Source
Existing buildings		
Current year	2023	-
Year of Construction Range	1901 - 2019	https://geodataonline.maps.arcgis.com
Average Percentage of Heated Top Floors	100 %	https://geodataonline.maps.arcgis.com
Number to Identify Residential Buildings in CityGML-file	1111	-
Development Period	1901-2019	https://geodataonline.maps.arcgis.com
Zip Code	1651	https://www.posten.no
Average Lifespan Buildings	40	*based on the calculations
Energy Systems Hot Water		
Electric Flow Heaters	80% with RSL = 10 y	https://energifaktanorge.no/en/norsk-energiforsyning/varmeforsyning/ https://www.iea.org/reports/renewables-2019/heat
Solar Systems	20% with RSL = 25 y	
Energy Systems Heating		
Electric Heaters	100% with RSL = 15 y	https://www.iea.org/fuels-and-technologies/heating
Pipe System Heating		
Surface Heating	35% with RSL = 50 y	https://www.ssb.no/energi-og-industri/energi/statistikk/fjernvarme-og-fjernkjoling/artikler/nye-rekorder-for-fjernvarme
Radiatiors	65% with RSL = 50 y	
Reference Service Life (RSL)		
Pipes HP Soil-Water Earth Coll	50 y	https://www.base-inies.fr/iniesV4/dist/tableau-de-bord
Pipes HP Soil-Water Earth Probe	50 y	
Pipes HP Water-Water	30 y	
Pipes Heating	30 y	
Pipes Hot-Water	40 y	

Insulation Pipes Heating & DHW	25 y	
Heat storage Tanks	50 y	
Oil Tanks	20 y	
Factor Additional Parts		
Additional Parts	20 %	* An assumption about the percentage of additional parts
Building Age Classes U-values for different building parts		
BAC 1 (1918)	Base plate = 0.7 Floor ceiling = 0.6 Flat roof = 0.8 Top floor ceiling = 0.8 External wall = 1.0 Wall to earth = 0.7 U-value win = 2.1 G-value win =0.7	TABULA, Typologier for norske boligbygg - Eksempler på tiltak for energieffektivisering SINTEF, Utvikling av varmeisolasjonsevnen i yttervegger SINTEF, U-verdier Vegger over terreng
BAC 2 (1919-1948)	Base plate = 0.5 Floor ceiling = 0.4 Flat roof =0.5 Top floor ceiling = 0.5 External wall = 0.9 Wall to earth = 0.5 U-value win = 1.7 G-value win = 0.7	
BAC 3 (1949-1957)	Base plate = 0.36 Floor ceiling = 0.21 Flat roof = 0.22 Top floor ceiling = 0.13 External wall = 0.35 Wall to earth = 0.25 U-value win = 1.7 G-value win = 0.6	
BAC 4 (1958-1968)	Base plate = 0.28 Floor ceiling = 0.19 Flat roof = 0.2 Top floor ceiling = 0.11 External wall = 0.35 Wall to earth = 0.22	

	U-value win = 1.2 G-value win = 0.5	
BAC 7 (1984-1994)	Base plate = 0.25 Floor ceiling = 0.16 Flat roof = 0.18 Top floor ceiling = 0.09 External wall = 0.28 Wall to earth = 0.18 U-value win = 0.8 G-value win = 0.45	
BAC 11 (2016+)	Base plate = 0.1 Floor ceiling = 0.14 Flat roof = 0.09 Top floor ceiling=0.083 External wall = 0.13 Wall to earth =0.08 U-value win = 0.5 G-value win = 0.4	
Total Primary Energy Factor		
Electricity	0.368	ISO 2017 – Table B.16 - Weighting factors
Share Renewable (R) & Non-Renewable (NR)		
Electricity	R=92%, NR=8%	https://app.electricitymaps.com/map
Op. Costs		
Electricity	0.19 €/kWh	https://www.strompris.no/spotpriser
Embodied Costs		
GWP	23 €/t	https://carbonpricingdashboard.worldbank.org/map_data
New development		
Current year	2023	-
Year of Construction Range	2021 - 2023	https://www.arcanova.no/verksbyen
Average Percentage of Heated Top Floors	100 %	https://geodataonline.maps.arcgis.com
Number to Identify Residential Buildings in CityGML-file	3333	* the number is set by the user of the program

Development Period	2021 - 2023	https://www.arcanova.no/verksbyen
Zip Code	1651	https://www.posten.no
Energy Systems Hot Water		
Electric Flow Heaters	80% with RSL = 10 y	https://energifaktanorge.no/en/norsk-energiforsyning/varmeforsyning/ https://www.iea.org/reports/renewables-2019/heat
Solar Systems	20% with RSL = 25 y	
Energy Systems Heating		
HP Soil-Water Earth Probe	100% with RSL = 15 y	Shahabaldin Tohidi S. et al., 2022
Pipe System Heating		
Surface Heating	100% with RSL = 50 y	Shahabaldin Tohidi S. et al., 2022
Reference Service Life (RSL)		
Pipes HP Soil-Water Earth Probe	50 y	https://www.base-inies.fr/iniesV4/dist/tableau-de-bord
Pipes Heating	30 y	
Pipes Hot-Water	40 y	
Insulation Pipes Heating & DHW	25 y	
Heat storage Tanks	50 y	
Factor Additional Parts		
Additional Parts	20 %	* An assumption about the percentage of additional parts
Building Age Classes U-values for different building parts		
BAC 11 (2016 ≥)	Base plate = 0.13 Floor ceiling = 0.5 Flat roof = 0.08 Top floor ceiling = 0.08 External wall = 0.1 Wall to earth = 0.1 U-value win = 0.83 G-value win =0.4	Shahabaldin Tohidi S. et al., 2022
Total Primary Energy Factor		
Electricity	0.368	ISO 2017 – Table B.16 - Weighting factors

Share Renewable (R) & Non-Renewable (NR)		
Electricity	R=92%, NR=8%	https://app.electricitymaps.com/map
Op. Costs		
Electricity	0.19 €/kWh	https://www.strompris.no/spotpriser
Embodied Costs		
GWP	23 €/t	https://carbonpricingdashboard.worldbank.org/map_data

Appendix 3: An example of code for one building in CityGML file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