Designing a Dutch building energy simulation tool using semantic 3D city models

Energy model testing for a case study area in Rotterdam

MSc Geomatics

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by

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to obtain the degree of Master of Science
in Geomatics
at Delft University of Technology,

Student number:	4596870	
Project duration:	October 1, 2023 – May 30, 2024	
Thesis committee:	C. León-Sánchez	TU Delft, first supervisor
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Cover Image: Photo by Matthew de Livera using Google, Pixel XL
Kalgoorlie WA, Australia. Published on August 09, 2021.

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1 Introduction

1.1. Background

Addressing energy consumption in buildings is currently high on the political agenda for national and municipal governments worldwide. This is particularly the case for the Netherlands, where household energy consumption accounts for an estimated 22% of total final energy usage, of which the majority goes to space heating (van den Brom, 2020). Assessing a building's energy demand can be simulated with the help of building energy simulation (BES) tools. These tools are essential to the architectural design process because they provide information on patterns of energy usage, help determine which renovations are most cost-effective, and calculate the payback periods of energy-saving solutions (van den Brom, 2020). But the state of BES tools today poses a distinct difficulty, especially when it comes to city-level analysis, which calls for a new strategy to handle the delicate balance between scalability and detail in energy demand modeling.

1.2. Problem definition

Although detailed information and established tools are available for single-building analysis, the complexity and computation escalates at the urban level (Agugiaro et al., 2015). This becomes problematic for municipalities that try to predict and create localized solutions that successfully reduce the demand for heating in residential buildings for entire cities. Challenges arise from several factors such as the interplay between changing climatic conditions, evolving building standards, and diverse resident behaviors, which make standardized predictions difficult. In addition, collecting high-quality building-level data for entire neighborhoods or cities also becomes a hindering factor for municipalities to be able to run these types of analyses. Moreover, Dutch buildings are required as of January 1, 2021, to comply with the *Bijna Energie Neutrale Gebouwen* (BENG) standard, which translates to "Almost Energy Neutral Building" (Bodelier and Herfkens, 2021). BENG is grounded in the principles outlined in the NTA 8800 standard, which stands for *Nederlands Technische Afspraak*, translated to the "Dutch Technical Agreement" — a comprehensive method for energy performance assessment. Furthermore, research has shown that existing BES tools compute theoretical consumption values that often deviate significantly from actual consumption values (van den Brom, 2020; Majcen et al., 2013), suggesting that there are limitations with the current approach on how BES tools are being developed.

1.3. Relevance

In response to this challenge, the proposed solution is the development of a BES tool for city-scale analysis tailored to the Dutch context. This tool would provide a more accurate and scalable method of predicting heating demand at the municipal level. It would be based on the NTA 8800 standard and leverage the power of semantic 3D city models. Predicting energy usage more accurately might be achieved by integrating semantic 3D models, which include comprehensive information about the urban environment. This new approach aims to give municipalities a reliable, scalable, and accurate tool for energy simulation, bridging the gap between detailed dynamic models and oversimplified national-scale tools. This will allow for more informed and efficient decision-making in the pursuit of energy efficiency and ultimately contribute to the reduction of the environmental footprint of Dutch cities.

1.4. Objective

This research sets out to implement a method for computing theoretical heat demand estimates that adheres to the NTA 8800 principles and is compatible with semantic 3D city models to enhance city-scale energy analysis. The specific objectives include:

- Implementing a heat demand model for the built environment for city-scale analysis by using semantic 3D city models
- Ensuring compliance with BENG standard and NTA 8800 principles, allowing the tool's utilization in the Dutch context
- Follow the Findable, Accessible, Interoperable, and Reusable (FAIR) science principles

1.5. Reader's guide

The thesis proposal is structured in the following seven sections:

- **Section 2** outlines the core concepts of the research, such as energy modeling approaches, existing tools, semantic 3D city models, and relevant data structures for this research.
- **Section 3** elaborates on the research design approach and research questions.
- **Section 4** discusses the research methodology and study area selection, the methods used, such as concept mapping and heat demand modeling, and the data collection.
- **Section 5** presents some preliminary results of the thesis so far.
- **Section 6** covers the study planning and expected outline.
- **Section 7** displays the expected datasets and tools used for the thesis.

2
Literature review

The research procedure is guided by a brief review of academic studies to outline the essential concepts presented in the thesis. This section is split into two sections: section 2.1 and section 2.2. In section 2.1, subsection 2.1.1 provides an overview of the different urban building energy modeling approaches to provide the context of the existing modeling approaches used in the field. Then, subsection 2.1.2 introduces what a semantic 3D city model is and how to represent a city model through the data model CityGML in subsection 2.1.3, which also explains the main module used in this thesis, the building module, and level of detail. Lastly, subsection 2.1.4 provides a description of the Energy ADE data model, an extension to CityGML that allows for energy modeling. For section 2.2, a brief overview is provided of related work explaining the two main energy model types and elaborates on the details of the NTA 8800 method in subsection 2.2.2. Lastly, an overview of the existing simulation tools in the field in subsection 2.2.4 is provided.

2.1. Theoretical framework

2.1.1. Urban building energy modeling

Urban building energy modeling (UBEM) is becoming more important as areas are urbanizing at a fast pace and the question of reducing energy consumption becomes more urgent. As a response to the situation, several spatial decision-making tools emerged (e.g. *CitySim Pro*, *Simstadt* etc.) However, UBEM is still difficult for a variety of reasons. One reason is that it is difficult to obtain high Level of Detail (LoD) data needed for the analysis. Another reason is that there are also high computational costs tied to the analysis scale combined with high-level data. In addition, setting up these models requires many generalizations and assumptions, creating many uncertainties with the simulation results. Another limitation of UBEM is the modeling of occupant behavior while many research point out that occupancy behavior is the reason theoretical estimates deviate from actual consumption values (van den Brom, 2020; Majcen et al., 2013). All these reasons make it complicated for urban-scale modeling.

Despite that, UBEM can have valuable insight for energy modeling. UBEM is made possible by the development of geometric and geo-data modeling capabilities, enhanced accessibility, and higher quality of spatial and non-spatial data (Allegrini et al., 2015). Several studies outline different UBEM approaches (Allegrini et al., 2015; Swan and Ugursal, 2009; De Rosa et al., 2014; Conti et al., 2020), however, this thesis focuses on the classification definition of UBEM approaches according to Swan and Ugursal, 2009. Based on Swan and Ugursal, 2009, there are two main UBEM approaches: top-down and bottom-up (statistical or engineering).

In top-down, the residential sector is viewed as an energy sink, which does not differentiate energy use based on specific end-uses (Swan and Ugursal, 2009). Top-down models frequently use variables such as macroeconomic data (such as GDP, employment rates, and price indices), weather patterns, rates of home building and demolition, estimates of appliance ownership, and the number of residential units (Swan and Ugursal, 2009). As seen in Figure 2.1, top-down approach has two types of methods: *econometric* and *technological*. The two main foundations of econometric models are income and price, while technological models link the energy consumption to general dwelling stock factors like trends in appliance ownership (Swan and Ugursal, 2009). This method is inadequate for predicting building energy consumption at greater spatial resolutions, as technical aspects of the city are frequently overlooked (Swan and Ugursal, 2009).

Bottom-up models can account for the energy consumption of particular end-uses, individual houses, or groups of houses and are then extended to represent the area or nation depending on the representative weight of the modeled sample (Swan and Ugursal, 2009). Bottom-up models make it possible to calculate end-use consumption in more complex ways. *Statistical* and *engineering* methodologies are other categories into which this bottom-up approach may be divided (Swan and Ugursal, 2009). Statistical methods depend on historical data and various forms of regression analysis to estimate household energy usage to certain end-uses. Within the statistical methods, *Regression*, *Conditional demand analysis*, and *Neural networks* can be employed (see Figure 2.1). Engineering methods account for end-use energy consumption based on power ratings and the utilization of equipment and systems, etc (Swan and Ugursal, 2009). For engineering approaches, there is *Population distribution*, *Archetype*, and *Sample* methods.

For this thesis, a key focus is placed on the *Archetype* modeling, due to its unique beneficial use. High quality, accurate data collection of building characteristics for one building is oftentimes time-consuming or even unavailable completely. Scaling accurate, high quality data collection for an entire neighborhood with various different building types can promptly become unfathomable during the research process. Hence, when the modeling purpose is to simulate multiple different types of buildings while having limited data availability, archetype modeling is an approach that can be used to simplify the data collection for building characteristics. Archetype modeling refers to the method of classifying buildings into different groups (archetypes), with each archetype classification having comparable attributes such as u-values, g-values, building function and construction time (Swan and Ugursal, 2009). Using this approach generalizes buildings characteristics types into stereotypes, which is not accurate but significantly simplifies the energy modeling.

To visually summarize the different UBEM approaches, Figure 2.1 shows the top-down and bottom-up classification of the various approaches for UBEM. Table 2.1 summarizes the key advantages and disadvantages of each approach to further explain the main differences between top-down and bottom-up approaches.

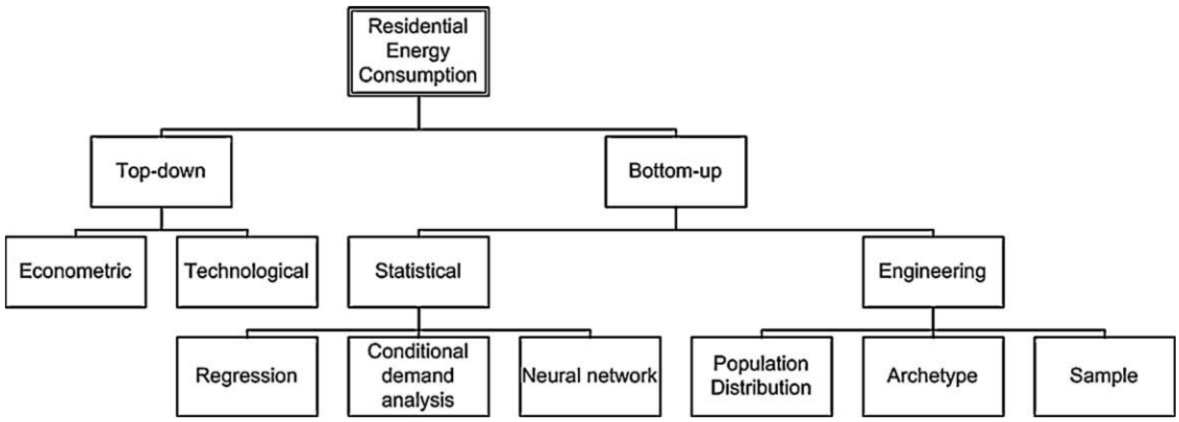


Figure 2.1: Overview of the UBEM approaches according to Swan and Ugursal, 2009.

	Top-down	Bottom-up statistical	Bottom-up engineering
Advantages	• Long term forecasting in the absence of any discontinuity • Inclusion of macroeconomic and socioeconomic effects • Simple input information • Encompasses trends	• Encompasses occupant behaviour • Determination of typical end-use energy contribution • Inclusion of macroeconomic and socioeconomic effects • Uses billing data and simple survey information	• Model new technologies • 'Ground-up' energy estimation • Determination of each end-use energy consumption by type, rating, etc. • Determination of end-use qualities based on simulation
Disadvantages	• Reliance on historical consumption information • No explicit representation of end-uses • Coarse analysis	• Multicollinearity • Reliance on historical consumption information • Large survey sample to exploit variety	• Assumption of occupant behaviour and unspecified end-uses • Detailed input information • Computationally intensive • No economic factors

Table 2.1: Overview of the main urban building energy modeling approaches according to Swan and Ugursal, 2009.

2.1.2. Semantic 3D city models

A 3D city model is described as "*a digital representation, with three-dimensional geometries, of the common objects in an urban environment, with buildings usually being the most prominent objects*" (Ledoux, 2021, p. 1). The structure of city models can vary depending on the acquisition methods used (Ledoux, 2021). A semantic 3D city model is considered as a city data model in which the pertinent objects stored, have characteristics assigned to them and are labeled with the respective meaning (Ledoux, 2021). 3D city models can be stored in different formats such as CityGML and CityJSON formats or even processed and stored in a geographic database management system (DBMS). An example of such DBMS is *3DCityDB*, which is defined as "*an Open Source software suite allowing to import, manage, analyze, visualize, and export virtual 3D city models according to the CityGML standard, supporting both versions 2.0 and 1.0*" (Yao et al., 2018, p. 2). For this thesis, a key focus is placed on the CityGML data model and *3DCityDB* is used for processing and storing.

2.1.3. CityGML

CityGML can be used to represent semantic 3D city models. CityGML is an open standardized data model internationally issued by the Open Geospatial Consortium (OGC) since 2008 (Gröger et al., 2012). CityGML is implemented as a Geography Markup Language (GML) application schema that allows for the exchange format to store 3D city models (Gröger et al., 2012). CityGML supports multi LoD 3D geometry, topology, semantics and appearance and it is extendable to other application domains (Gröger et al., 2012), making it particularly useful for urban planning, architectural design or environmental simulations. The current version of the standard is 3.0 (Open Geospatial Consortium, 2023). However, this thesis works with version 2.0 since Energy ADE V1 is compatible with it.

Core and Building modules

CityGML 2.0 has various modules available for declaring to define in detail objects that exist in a city. There are two main types: *Core* and thematic modules. In *Core*, there is *CityGML Core*, *Generics* and *Appearances* (Gröger et al., 2012). These create the foundation for more specialized thematic modules that cover a range of urban environment facets.

In thematic, there is *Bridge*, *Building*, *CityFurniture*, *CityObjectGroup*, *LandUse*, *Relief*, *Transportation*, *Tunnel*, *Vegetation* and *Waterbody* (Gröger et al., 2012). The *CityObject* serves as the basis class for all thematic modules, and it is defined in the *Core* module together with fundamental data types (Gröger et al., 2012).

The *Building* module is of particular importance in this study. Figure 2.2 provides an UML excerpt overview of how a building is modeled in CityGML. The abstract class *Building* is delineated, which consists of the features *Building* and *BuildingPart*. This distinction of *Building* and *BuildingPart* within the *Building* class allows for scenarios such as two buildings e.g. a house and a garden shed on a land plot to be classified as building parts but both adhere to as one building feature.

A key aspect of the *Building* module is the application of modeling semantic classification of the boundary surfaces of the building. These surfaces can be classified as either *WallSurface*, *RoofSurface*, and *GroundSurface*, and other integral components of the building's structure. The *BoundarySurface* module allows for these surfaces to be modeled with geometry such as MultiSurfaces, defined with its respective LoD. Furthermore, the module facilitates other architectural element representations such as Windows and doors through the *Opening* feature.

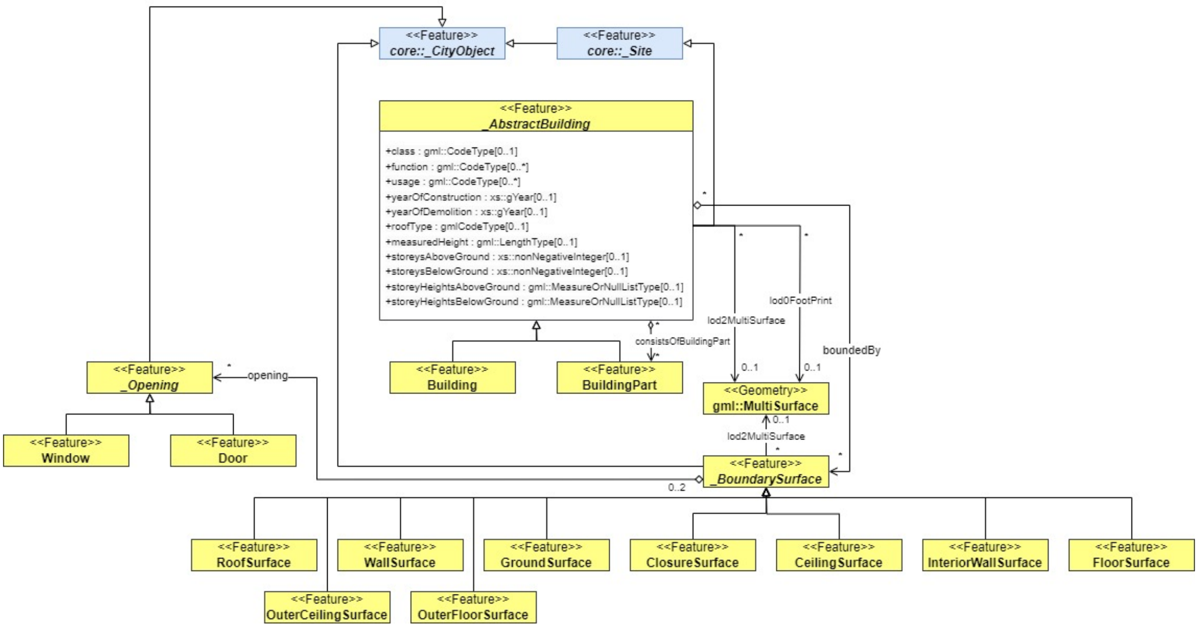


Figure 2.2: Excerpt of the building module (Gröger et al., 2012).

Level of Detail

A key characteristic in CityGML is that the same object can be represented in different LoDs at once (Gröger et al., 2012). It is also possible to merge or combine two different CityGML datasets with the same object but different LoDs (Gröger et al., 2012). In essence, there are five LoD levels (e.g. LoD0, LoD1, LoD2, LoD3 and LoD4) that buildings can be represented by. LoD0 buildings refer to either a building footprint or rooftop representation, and LoD1 buildings are shown as blocks (Gröger et al., 2012). LoD2 buildings are blocks that also incorporate thematic surfaces such as e.g. walls and incorporate the specific roof geometry, and LoD3 buildings is similar to LoD2 but now also include windows and doors (Gröger et al., 2012). LoD4 buildings include level of information as LoD3 and also rooms, stairs, and furniture (Gröger et al., 2012). Figure 2.3 visualize displays the LoD 0-3 representation of buildings explained before and, in addition, shows the further developments of the LoD representation developed by the *TU Delft 3D Geoinformation*. (Biljecki et al., 2016). Despite having LoD4 data storage capabilities available in CityGML, most 3D city models do not go up to LoD4. Most 3D city models do not have information such as the number of rooms or furniture types there are in each building, which is attributed to LoD4, the most advanced ones currently are at LoD2.2.

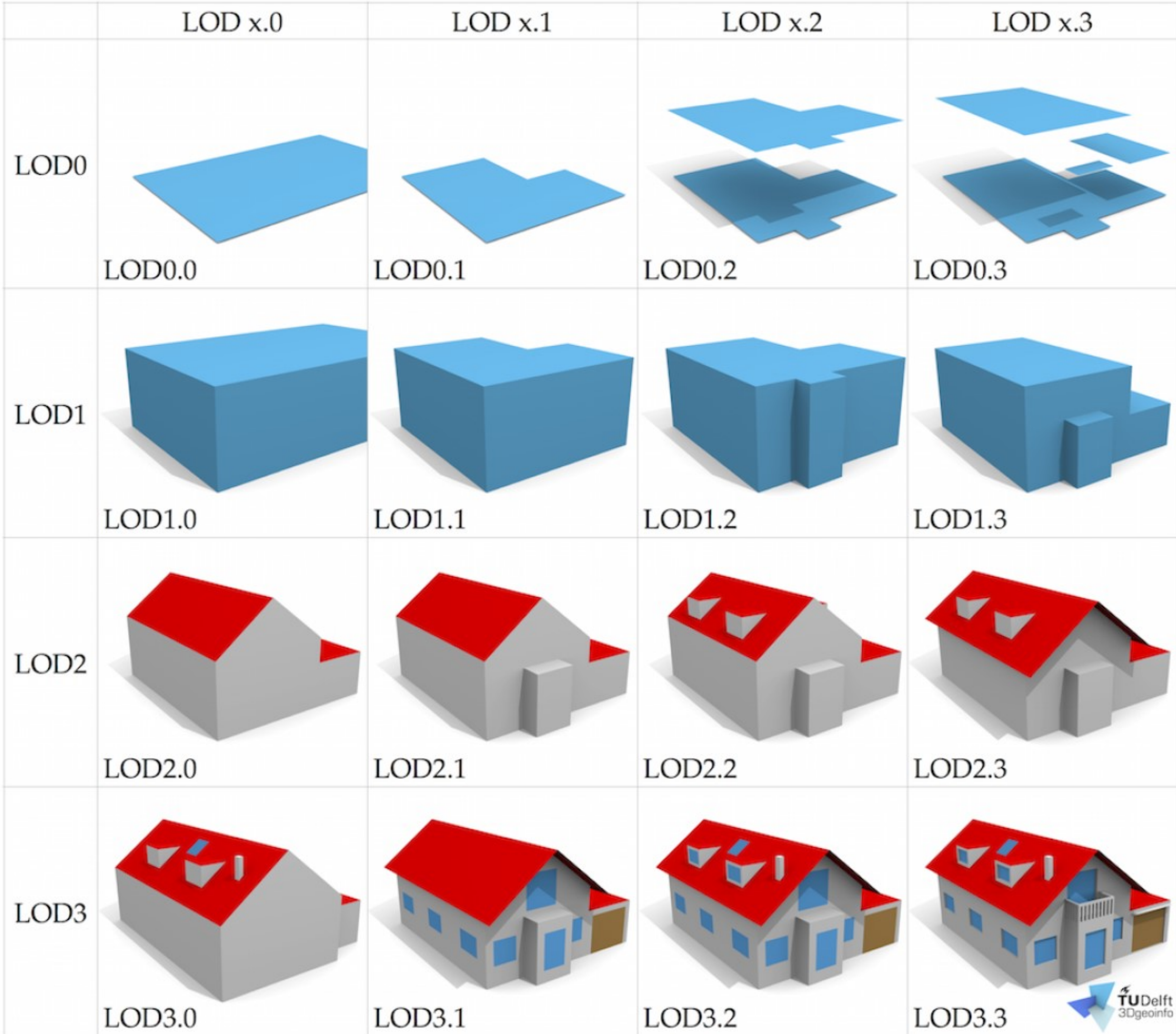


Figure 2.3: Overview of the different LoDs. Figure from Biljecki et al., 2016.

2.1.4. Energy Application Domain Extension

CityGML can be extended by Generic Attributes and Objects and in addition, it is extendable to another data model named Energy Application Domain Extension (ADE) which allows for storing and managing energy-related information for buildings (Benner, 2018). There are three versions (e.g. V0.8, V0.9 and V1) and this thesis focuses on Energy ADE version 1. In essence, Energy ADE is an extension package for CityGML to enrich city models, Figure 2.4 shows the 6 new packages added to the CityGML model through Energy ADE. The packages are only extended to *CityGML Core* and *Building* modules (Benner, 2018). The 6 packages are *Energy ADE Core*, *Supporting Classes*, *Occupant Behavior*, *Material and Construction*, *Energy Systems* and *Building Physics*. To provide a brief explanation of the packages (Benner, 2018):

- The *Energy ADE Core* module includes abstract base classes for the four primary theme modules, as well as a variety of generic data types, enumerations, and codelists.
- The *Supporting Classes* module contains classes to classify time series, weather data, and schedules

- The *Occupant Behavior* module facilitates the modeling of energy-related behaviors among occupants.
- The *Material and Construction* module allows for physical properties of the building materials be modeled.
- The *Energy Systems* module allows for the representation of a building's energy conversion system, distribution system, and storage system.
- The *Building Physics* module enables the ability for single- or multizone building energy simulations.

Despite this development in CityGML energy modeling, the Energy ADE has a complicated structure. In an effort to simplify the Energy ADE while still maintaining its relevancy with energy modeling, the Karlsruhe Institute of Technology has developed a simplified version known as the KIT profile. This version eliminates specific modules or classes from the original data model, resulting in a more user-friendly subset (Leon-Sanchez et al., 2021). The key distinctions between the original Energy ADE and the KIT profile are the elimination of the *Energy Systems* module, the extreme simplification of the *Supporting Classes* module, and the removal of several characteristics.

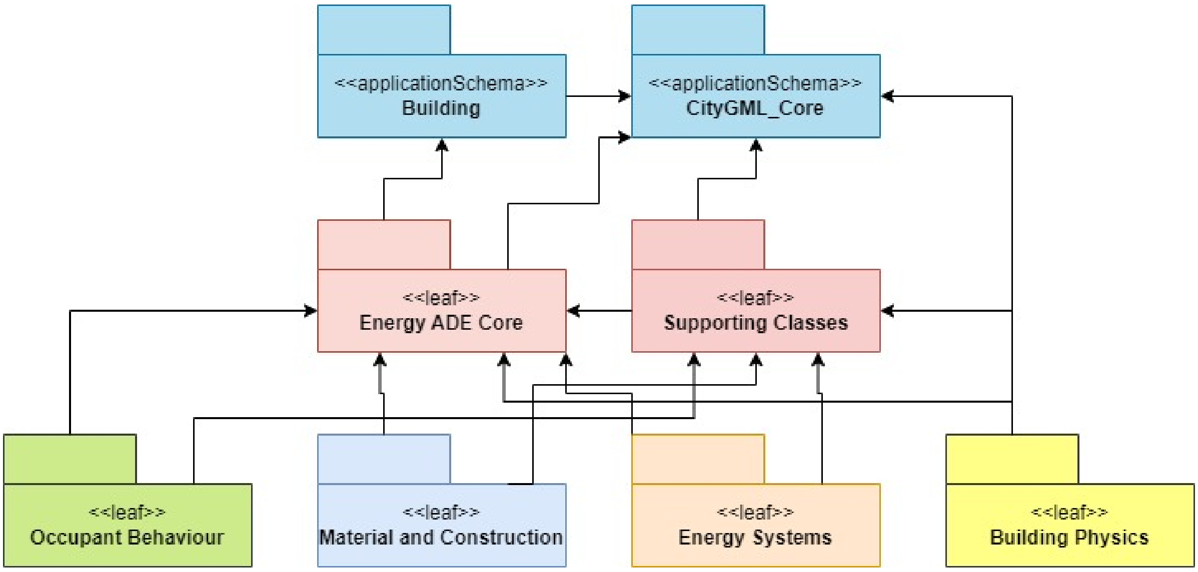


Figure 2.4: Overview of the Energy ADE packages (Benner, 2018).

2.2. State of the art

In this section, a focus is placed on the state of the art of energy models. To put it simply, an energy model is a set of computer-generated computations that offer data on the expected energy usage of a building and its systems. An energy model is an essential tool that can help designers or policymakers understand how to manage energy consumption within the building. To further understand an energy model tool, a distinction should be clarified between energy model types. Specifically, for thermal building models, there is a difference between statistical (hybrid) building models and dynamic building models (transient heat transfer). In the next sections, the differences between the two are explained.

2.2.1. Statistical (hybrid) building models

Statistical (hybrid) building models employ the energy balance method. The energy balance method is predicated on a quasi-stationary monthly computation of the building's useful heat gains and heat loss (Conti et al., 2020). The computation utilizes the monthly averages for the outside temperature and solar radiation (Conti et al., 2020). It also accounts for heat gain from people, objects, lights, and equipment, as well as the building's ability to store heat (Conti et al., 2020). Figure 2.5 provides a representation of the energy flows typically considered in the energy balance method. Figure 2.5 also shows the conversion of energy from utility companies extracting the raw materials (primary energy) which get processed and transported to residential homes where the final energy can be consumed. This is also part of the energy balance method, but outside the scope of the thesis research.

Long-term calculations using steady-state models are typically utilized for scenario studies and early construction design, usually ignoring the inertia effect (or taking certain correction factors into account) (De Rosa et al., 2014). The degree-days approach is a quick and easy way to do quick calculations in order to get an estimate of how much energy a structure uses (De Rosa et al., 2014). Their underlying premise is that, in the long run, energy usage will always be proportionate to the difference in temperature between the inside and outside (De Rosa et al., 2014).

The data requirements typically needed for the energy balance method include (Agugiaro et al., 2015):

- Building geometry data (thermal boundaries, etc.) retrievable through semantic 3D city model
- Building physics data (U-values, g-values, etc.) retrievable through archetype modeling
- Building usage data (average internal gains, set-point temperatures, etc.) which can be retrievable from norm standard

The energy balance method is a norm based method used for calculating the energy performance calculation, which varies across countries due to national standards. Each country adopts its own guidelines of computation and fixed values appropriate for the country's situation. For instance, Germany employs the DIN 18599 standard (Monien et al., 2017) which uses different average temperature values in comparison to Italy which uses the UNI-TS 11300 standard (Agugiaro et al., 2015) with their corresponding temperature values. For this thesis, the NTA 8800 standard is consulted, which is the standard used in the Netherlands (NEN, 2023).

2.2.2. NTA 8800

Based on the European Union (EU)'s Energy Performance of Buildings Directive (EPBD), NTA 8800 seeks to provide a transparent and policy-free technique for determining the energy performance of buildings (NEN, 2023). The NTA 8800 employs one determination method, using norms and values from the Dutch NEN 8800, so that it can be used for assessing energy performance of building stock for Dutch building regulation. The determination method has fixed degree of accuracy that can be used for calculations of existing and new buildings (NEN, 2023). The manual offers fixed values (e.g. building usage data) to be used when the data is not available or becomes time-consuming to compute (NEN, 2023). Calculations are performed on the monthly method e.g. monthly average values are used for computation (NEN, 2023). Certain components of modeling such as building parts, installation and climate variables are generalized to utilization factors (NEN, 2023). The fixed values can be substituted for higher quality values if available. The NTA 8800 was published in July 2021 and is considered a precursor to the requirements of BENG on January 1, 2021. There are three versions of the NTA 8800 (2020, 2022, 2023) released. This thesis considers the principles explained in the latest version 2023. Some important terms from the NTA 8800 manual (NEN, 2023) to consider:

- Use function: The category of the building (e.g. residential or commercial)
- Thermal zone: Building or group of building parts for which energy performance is calculated (see Figure 2.6 for an example of the thermal zone classification of a building).
- Calculation zone: Portion of a building that may be considered as one unit for the purpose of calculating energy requirements for heating.
- Usable area: Area of room or a group of spaces - for example:
  - Use area of the thermal zone: The total area of use of the thermal zone is determined as the sum of the areas of use of all calculation zones in the building or building section over which the energy performance is determined
  - Usable area of the calculation zone: The usable area of a calculation zone is determined as the sum of the usable areas of all (groups of) non-common areas and the (groups of) common areas lying within the calculation zone

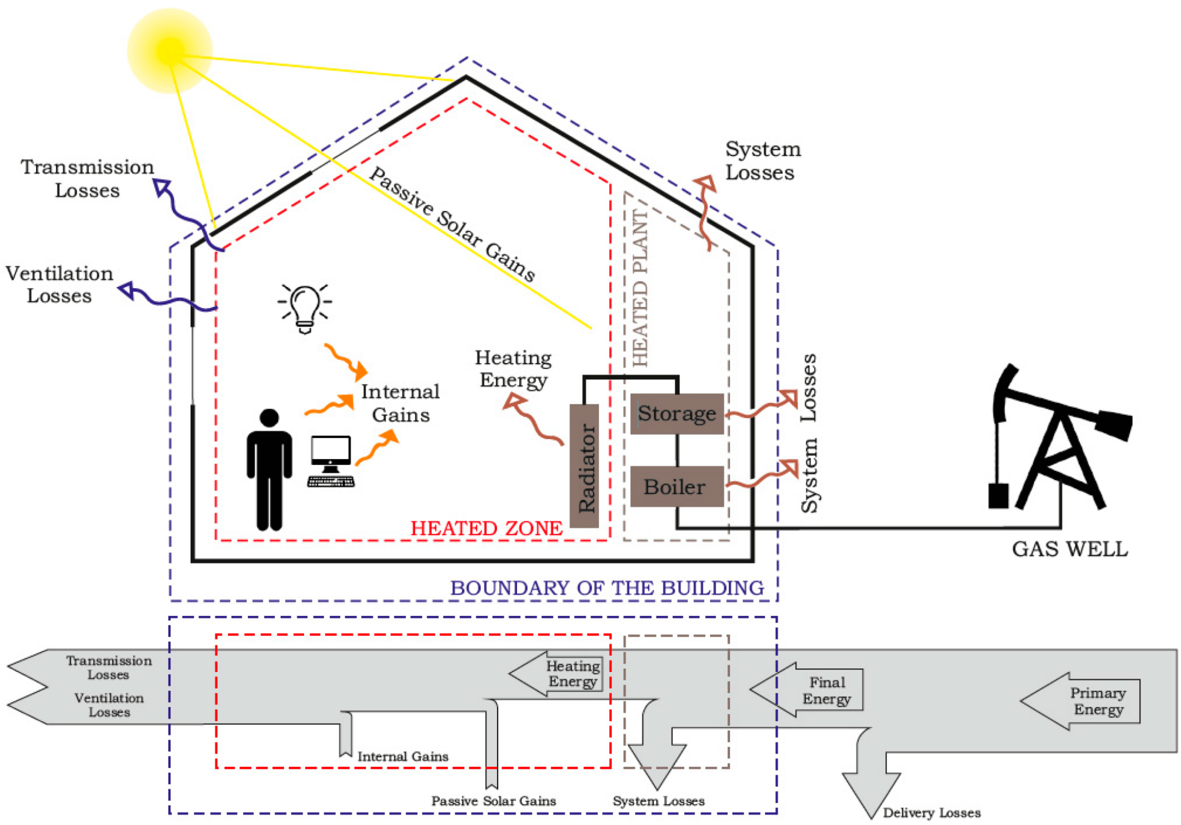


Figure 2.5: Simplified overview of the thermal energy balance of a building and the primary energy conversion to final energy (Borowski et al., 2020).

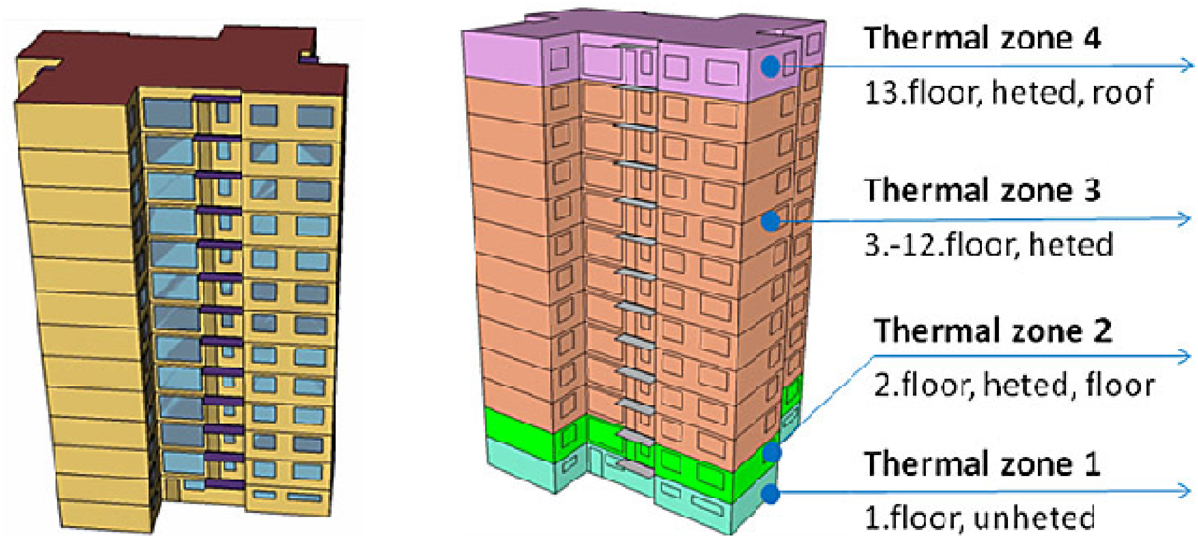


Figure 2.6: Example of a thermal zone classification of an apartment model (Kmeťková et al., 2018).

2.2.3. Dynamic building model

Dynamic building models (transient heat transfer) is an alternative method to energy balance modeling, which presents more detailed results since more factors in buildings, such as occupant behavior, household composition, and climate patterns are modeled with more details. These models also, therefore, require more high-level detailed data sets as inputs. Dynamic models typically also operate on daily or hourly values instead of monthly estimates like in the energy balance method, in which the computation time ends up taking longer. There are several tools available that use the dynamic modeling method: *CitySim Pro*, *EnergyPlus*, and *TRNSYS*. There is always a trade-off to be made between computational costs and the quality of input data. Dynamic models are typically preferred when the input data is available. When modeling on a city-scale level, data availability can become scarce and hence the energy balance method is more attractive and considered as the modeling method in this thesis.

2.2.4. Building energy simulation tools

An example of an energy model is a building energy simulation (BES) tool. BES tools are developed to model building performances, for example, determining the energy demand of a building. They can be used to model strategies to lower the energy consumption in the building stock. Although a lot of tools can do complex energy models, they frequently need a lot of precise data and take a long time to compute. Which tool to use will depend on the modeler's purpose of study. To help with this, 20 distinct BES tools were evaluated by Allegrini et al., 2015, who categorized each BES tool into four detail levels: not included (1), link to other program (2), simplified program (3) or detailed model (4) over 17 energy modeling category results. Figure 2.7 summarizes the important findings of the BES assessment as reported by the author and provides an overview of the various BES tool's detail level and modeling capability, which helps determine the trade-offs between various tools to evaluate which tool to use depending on the study use case.

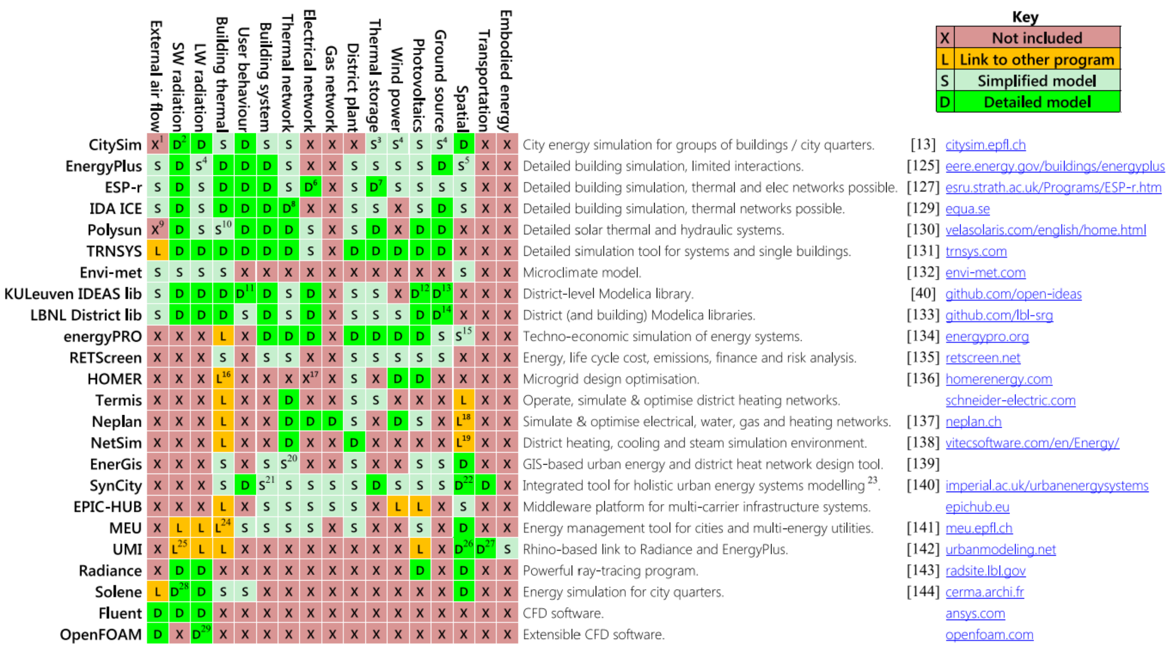
Of the 20 tools specified in the Allegrini et al., 2015 paper, a closed look is taken at the two tools; *EnergyPlus* and *TRNSYS*, which scored highly on the detailed model category on multiple sections, indicative of being a sophisticated model for energy modeling. *EnergyPlus* is a dynamic building-level modeling tool (Allegrini et al., 2015). It can be used to simulate district networks, renewable technologies, longwave radiation exchange, and external air movement (Allegrini et al., 2015). Some key strengths of *EnergyPlus* include the capability of extensive detailed energy analysis for various building phases, integration with other CAD tools such as SketchUp through plugins, and a strong technical foundation valued for its empirical validation and precise capabilities (Attia et al., 2009; Crawley et al., 2008). Some downsides for the *EnergyPlus* tool is the high learning curve for users due to its complexity and text-based interface and its limited early design phase capabilities (Attia et al., 2009; Crawley et al., 2008). It is typically more suitable for later stages of design, not so much for the conceptual stages. In short, *EnergyPlus* is a significant tool for in-depth energy analysis for the later design stage of buildings.

Then, there is *TRNSYS*, which is also considered a dynamic building-level modeling tool but this one can simulate thermal and electrical energy systems (Allegrini et al., 2015; Monien et al., 2017; Crawley et al., 2008). It was created to simulate solar water heating systems (Allegrini et al., 2015). One of its strengths is that it offers flexibility in configuring HVAC systems and also is capable of simulating a wide range of discrete HVAC components (Crawley et al., 2008). However, similarly to *EnergyPlus*, *TRNSYS* has a high learning curve due to its complexity and lack of graphical interface and is also limited in its early design phase capabilities (Crawley et al., 2008). So it is also more suitable for the later design stage, specifically ideal for simulating various types of renewable energy technologies (Crawley et al., 2008).

Comparing both tools, it can be concluded that both offer detailed analysis capabilities that do require some higher level technical expertise since both lack a user-friendly graphical interface. Both are more suitable for the later stages of design, while *TRNSYS* stands out for renewable energy system simulations and *EnergyPlus* for more comprehensive building and environmental systems simulations. Both tools require detailed data input and can have labor-intensive computation times just at the building level alone, making these programs not appropriate for modeling broad energy flows at the district or city level (Allegrini et al., 2015).

For modeling city-scale level, it is better to use the BES tool such as *CitySim Pro* or *SimStadt*, which offer this capability. *CitySim Pro* is developed in Java and C++ by the Swiss Federal Institute of Technology Lausanne (CitySimPro, 2023), designed to facilitate sustainable urban planning decision-making (Allegrini et al., 2015; CitySimPro, 2023; Robinson et al., 2009; Ferrando et al., 2020). It is composed of a radiation model for shortwave radiation to detect solar gains on facades and roofs, and a basic resistor-capacitor thermal model to simulate the energy performance of the building stock (Allegrini et al., 2015; Robinson et al., 2009; Ferrando et al., 2020). It takes into consideration the exchange of longwave radiation and shortwave radiation (Allegrini et al., 2015). *CitySim Pro* considers subspaces in buildings and links them through wall conductance (Ferrando et al., 2020). To account for tenant behavior uncertainty inside the buildings, a stochastic model of occupant behavior is provided (Allegrini et al., 2015). *CitySim Pro* allows the user to import 3D city models through CityGML files or other formats (Mutani et al., 2018) and compute calculations in an hourly unit (Leon-Sanchez et al., 2021).

The previously explored BES tools were examples of dynamic building models, however, there are also tools that employ the energy balance method, one being *SimStadt*. *SimStadt* was created as a Javascript at HFT Stuttgart to assist decision-makers in the energy sector by executing energy simulations (Monien et al., 2017; Ferrando et al., 2020; SimStadt, 2023). *SimStadt* calculates the monthly energy demand of buildings using a steady-state technique based on the German standard DIN V 18599 (Monien et al., 2017; SimStadt, 2023). It supports the fast creation and evaluation of energy scenarios for urban planning using refurbishment rates and time horizons (Ferrando et al., 2020). The program takes 3D city models through CityGML files as input data but also uses pre-built libraries to model climate patterns or building physics (Leon-Sanchez et al., 2021; Monien et al., 2017; Ferrando et al., 2020). It can facilitate solar potential analysis with the help of online databases (Ferrando et al., 2020). It was designed for large-scale analysis, making it less suitable for building-level assessment. To compare, both tools are suitable for urban-scale modeling, with *CitySim Pro* offering more detailed thermal modeling capabilities in hourly time horizons and *SimStadt* allowing for more scenario creation capabilities in monthly time horizons.



Tool	External air flow	SW radiation	LW radiation	Building thermal	User behaviour	Building system	Thermal network	Electrical network	Gas network	District plant	Thermal storage	Wind power	Photovoltaics	Ground source	Spatial	Transportation	Embodied energy	Description	Ref.	Link
CitySim	X[1]	D[2]	D	S	D	S	S	X	X	X	S[3]	S[4]	S	S[4]	D	X	X	City energy simulation for groups of buildings / city quarters.	[13]	citysim.epfl.ch
EnergyPlus	S	D	S[4]	D	D	D	S	X	X	S	S	S	S	D	S[5]	X	X	Detailed building simulation, limited interactions.	[125]	eere.energy.gov/buildings/energyplus
ESP-r	S	D	S	D	D	D	S	D[6]	X	S	D[7]	S	S	S	S	X	X	Detailed building simulation, thermal and elec networks possible.	[127]	esru.strath.ac.uk/Programs/ESP-r.htm
IDA ICE	S	D	S	D	D	D	D[8]	X	X	S	S	X	S	D	S	X	X	Detailed building simulation, thermal networks possible.	[129]	equa.se
Polysun	X[9]	D	S	S[10]	D	D	D	S	X	S	D	X	D	D	X	X	X	Detailed solar thermal and hydraulic systems.	[130]	velasolaris.com/english/home.html
TRNSYS	L	D	D	D	D	D	D	S	X	D	D	D	D	D	X	X	X	Detailed simulation tool for systems and single buildings.	[131]	trnsys.com
Envi-met	S	S	S	S	X	X	X	X	X	X	X	X	X	X	S	X	X	Microclimate model.	[132]	envi-met.com
KULeuven IDEAS lib	S	D	D	D	D[11]	D	S	D	X	S	S	X	D[12]	D[13]	X	X	X	District-level Modelica library.	[40]	github.com/open-ideas
LBNL District lib	S	D	D	D	S	D	S	D	X	S	S	S	D	D[14]	X	X	X	District (and building) Modelica libraries.	[133]	github.com/lbl-srg
energyPRO	X	X	X	L	X	D	D	D	X	D	D	D	D	S	S[15]	X	X	Techno-economic simulation of energy systems.	[134]	energypro.org
RETScreen	X	X	X	S	X	S	S	X	X	S	S	S	S	S	X	X	X	Energy, life cycle cost, emissions, finance and risk analysis.	[135]	retscreen.net
HOMER	X	X	X	L[16]	X	X	X	X[17]	X	S	X	D	D	X	X	X	X	Microgrid design optimisation.	[136]	homerenergy.com
Termis	X	X	X	L	X	X	D	X	X	S	S	X	X	X	L	X	X	Operate, simulate & optimise district heating networks.		schneider-electric.com
Neplan	X	X	X	L	X	X	D	D	D	S	X	D	S	X	L[18]	X	X	Simulate & optimise electrical, water, gas and heating networks.	[137]	neplan.ch
NetSim	X	X	X	L	X	X	D	X	X	D	X	X	X	X	L[19]	X	X	District heating, cooling and steam simulation environment.	[138]	vitecsoftware.com/en/Energy/
EnerGis	X	X	X	S	X	S	S[20]	X	X	S	X	X	S	S	D	X	X	GIS-based urban energy and district heat network design tool.	[139]	
SynCity	X	X	X	S	D	S[21]	S	S	S	S	D	S	S	S	D[22]	D	X	Integrated tool for holistic urban energy systems modelling [23].	[140]	imperial.ac.uk/urbanenergysystems
EPIC-HUB	X	X	X	L	X	S	S	S	S	S	X	L	L	X	S	X	X	Middleware platform for multi-carrier infrastructure systems.		epichub.eu
MEU	X	L	L	L[24]	S	S	S	S	X	S	X	X	S	X	D	X	X	Energy management tool for cities and multi-energy utilities.	[141]	meu.epfl.ch
UMI	X	L[25]	L	L	X	X	X	X	X	X	X	X	L	X	D[26]	D[27]	S	Rhino-based link to Radiance and EnergyPlus.	[142]	urbanmodeling.net
Radiance	X	D	D	X	X	X	X	X	X	X	X	X	D	X	D	X	X	Powerful ray-tracing program.	[143]	radsite.lbl.gov
Solene	L	D[28]	D	S	S	X	X	X	X	X	X	X	X	X	D	X	X	Energy simulation for city quarters.	[144]	cerma.archi.fr
Fluent	D	D	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	CFD software.		ansys.com
OpenFOAM	D	X	D[29]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Extensible CFD software.		openfoam.com

Key	
X	Not included
L	Link to other program
S	Simplified model
D	Detailed model

Figure 2.7: Overview assessment of the various BES tools by Allegrini et al., 2015.

3

Research approach and questions

There is limited academic research regarding energy demand modeling using semantic 3D city models for the built environment in compliance with NTA 8800 standards in the Netherlands. Therefore, the main research question is formulated as:

To what extent can a heat demand model be developed that adheres to the NTA 8800 principles for semantic 3D city models?

The overarching research question is divided into the following sub-questions:

1. What are the relevant components for computing the theoretical heat demand estimates according to the NTA 8800 principles?
2. How do you implement a model that computes the heat demand for a semantic 3D city model using CityGML and Energy ADE?
3. To what extent can the model heat demand results be validated by comparing them with the CitySim heat demand calculations and CBS statistical consumption values?

To answer the research questions formulated above, the thesis employs a scientific concurrent descriptive mixed-method research approach following the principles according Bhattacherjee, 2012 and Creswell and Clark, 2017. To answer the *what*, *where*, and *when* types of research questions, descriptive research focuses on making meticulous observations and thorough documentation of the phenomena of interest based on repeatable and accurate observations (Bhattacherjee, 2012). Converging quantitative and qualitative research methods to provide a comprehensive assessment of the research problem is known as a concurrent mixed methods approach (Creswell & Clark, 2017).

4 Methodology

4.1. Research framework

The research flow diagram is depicted in Figure 4.1. The first step includes conducting a literature review on the NTA 8800 norm on heat demand modeling and developing a mind map of all the relevant components necessary for modeling heat demand according to the standard. The second step is applying the lessons learned from the first step into a working heat demand model with as input data, a semantic 3D city model. This step will require implementing the theoretical model into a Python script. The third step consists of comparing the Python model heat demand estimates with another energy simulation tool and ground truth data consisting of a statistical consumption dataset to potentially validate the developed model.

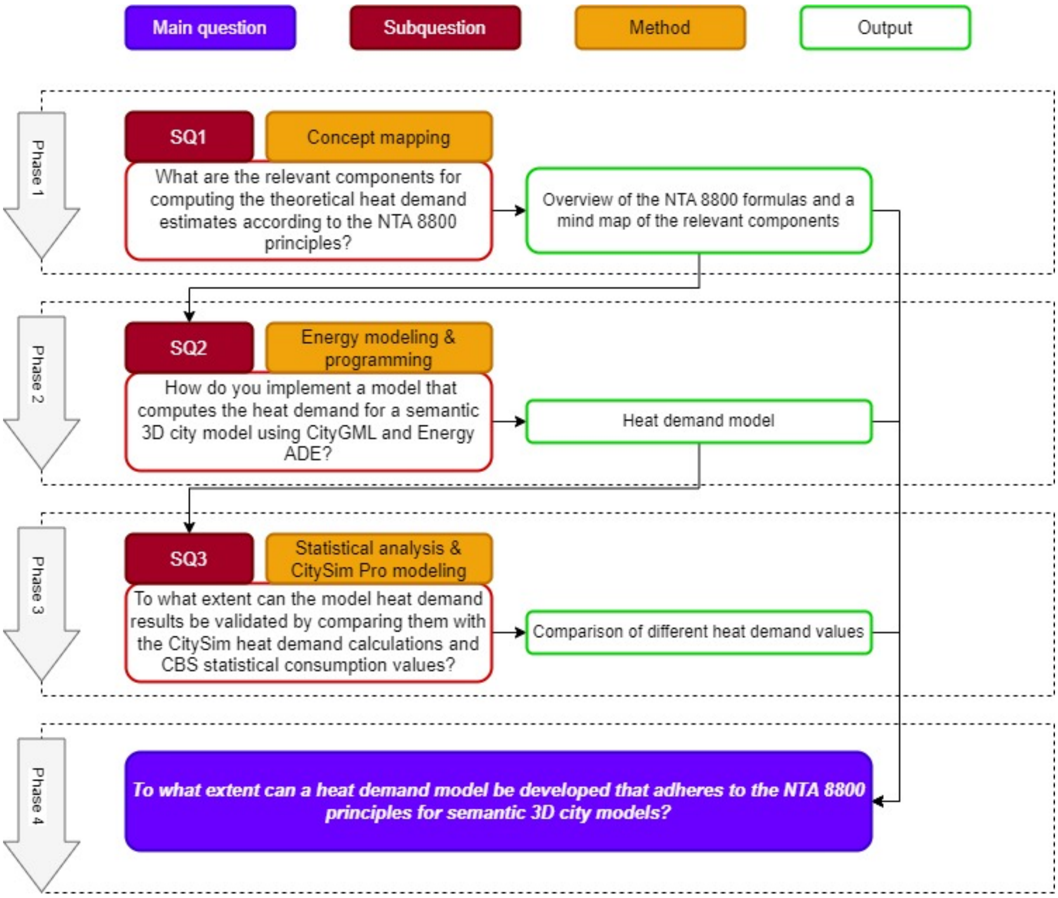


Figure 4.1: The research flow diagram.

4.2. Area of investigation

Rotterdam, a Dutch harbor city, serves as the case study location. The coordinate system EPSG 28992 for the Netherlands, or UTM zone 31N (Morton, n.d.), is where Rotterdam is located. For the heat demand modeling, the script is tested on a case study neighborhood, Wielewaal, Rotterdam. As can be seen in Figure 4.2, it is a small neighborhood with 641 buildings (AllCijfers.nl, 2023). Some key building characteristics of the case study area is that the majority of the buildings have a construction year before 2000 (AllCijfers.nl, 2023), the majority of the buildings have one floor.

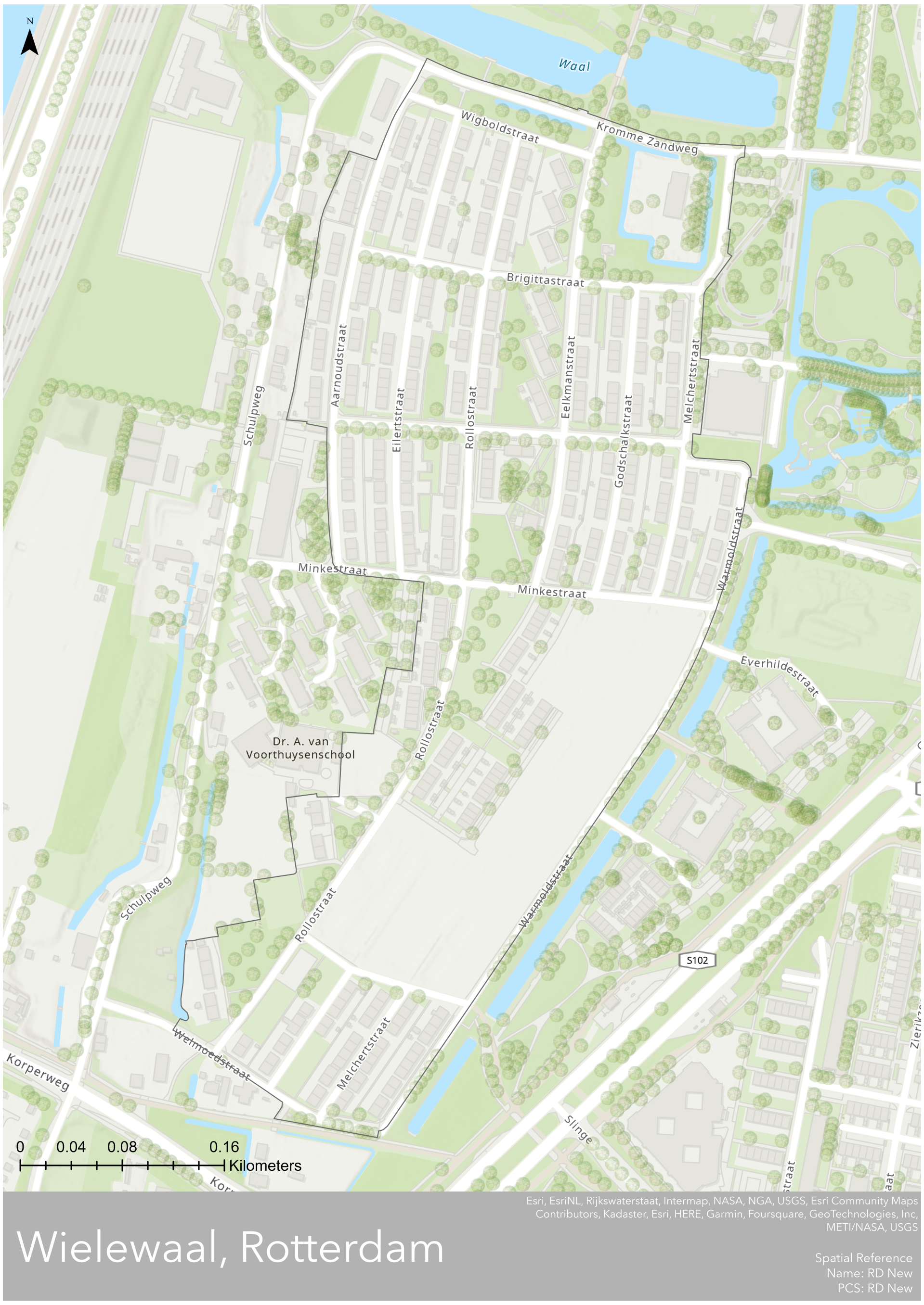


Figure 4.2: Overview of the study area Wielewaal, Rotterdam.

4.3. Concept mapping

Concept mapping is a method to visually represent information. It can be in the form of charts, tables, flowcharts, Venn Diagrams, timelines, or decision trees. This method is included as the qualitative research component of the mixed-method approach applied after reading the NTA 8800 and noting down all the relevant formulas, variables, and assumptions. The final outcome expected is a mind map overview of the relevant components necessary for heat demand modeling which is useful for the second research phase where the mind map is used to create an UML diagram. The UML diagram provides a conceptual illustration for heat demand computation using CityGML-based semantic 3D models so that, eventually, a Python script model is created.

4.3.1. NTA 8800 calculation method

The NTA 8800 determination method is deployed for this thesis. As mentioned in subsection 2.2.2, the NTA 8800 calculations are based on the steady-state energy balance method (NEN, 2023), which simply refers to the balance of heat losses and gains within the building. Heat demand is formulated as the monthly energy requirement for heating in the NTA 8800 which is computed as:

- If $\gamma_{H;zi;mi} \leq 0$ and $Q_{H;gn;zi;mi} > 0$:
$$Q_{H;nd;zi;mi} = 0 \tag{4.1}$$
- If $\gamma_{H;zi;mi} > 2.0$:
$$Q_{H;nd;zi;mi} = 0 \tag{4.2}$$
- In other cases:

$$\begin{aligned} Q_{H;nd;zi;mi} = & Q_{H;ht;zi;mi} \\ & - [\eta_{H;gn;zi;mi} \cdot Q_{H;gn;zi;mi} \\ & - \Delta\eta_{H;gn;zi;mi} \cdot Q_{H;gn;zi;mi} \\ & - \eta_{H;gn;zi;mi} \cdot (Q_{H;ls;rbl;zi;mi} - Q_{C;ls;rbl;zi;mi})] \end{aligned} \tag{4.3}$$

Where for each calculation zone zi and each month mi:

- $Q_{H;nd;zi;mi}$ is the monthly energy requirement for heating for the calculation zone zi and month mi, in kWh.
- $\gamma_{H;zi;mi}$ is the dimensionless heat balance ratio for heating
- $Q_{H;ht;zi;mi}$ is the total heat transfer for heating, in kWh
- $\eta_{H;gn;zi;mi}$ is the dimensionless utilization factor for the heat gain
- $Q_{H;gn;zi;mi}$ is the total heat gain for heating, in kWh
- $\Delta\eta_{H;gn;zi;mi}$ is the difference in the utilization factor for the heat gain when calculated with and without considering the internal heat gain due to recoverable losses from or to the space heating and cooling system
- $Q_{H;ls;rbl;zi;mi}$ is the sums of all recoverable losses from or to the space heating systems in the calculation zone zi, and month mi, in kWh
- $Q_{C;ls;rbl;zi;mi}$ is the sums of all recoverable losses from or to the space cooling systems in the calculation zone zi, and month mi, in kWh

The recoverable losses to or from the space heating and space cooling system have been added in the above formula, instead of directly to the internal heat gain, to avoid iterations in the calculation.

Total heat transfer for heating

For each calculation zone and each month, the total heat transfer for heating $Q_{H;ht;zi;mi}$, in kWh, is calculated using the following formula:

$$Q_{H;ht;zi;mi} = Q_{H;tr;zi;mi} + Q_{H;ve;zi;mi} \tag{4.4}$$

Where, for each calculation zone zi and month mi:

- $Q_{H;ht;zi;mi}$ is the total heat transfer for heating, in kWh
- $Q_{H;tr;zi;mi}$ is the total heat transfer through transmission for heating, in kWh
- $Q_{H;ve;zi;mi}$ is the total heat transfer through ventilation for heating, in kWh

Total heat gain for heating

The total heat gain for heating $Q_{H;gn;zi;mi}$, in kWh, is calculated using the following formula:

$$Q_{H;gn;zi;mi} = Q_{H;int;zi;mi} + Q_{H;sol;zi;mi} \tag{4.5}$$

Where, for each calculation zone zi and month mi:

- $Q_{H;gn;zi;mi}$ is the total heat gain for heating, in kWh
- $Q_{H;int;zi;mi}$ is the total internal heat gain for heating, in kWh
- $Q_{H;sol;zi;mi}$ is the total solar heat gain for heating, in kWh

Utilisation factor

The difference in the utilisation factor for heat gain is calculated as follows:

$$\Delta\eta_{H;gn;zi;mi} = \eta_{H;gn;incl.rbl;zi;mi} - \eta_{H;gn;zi;mi} \tag{4.6}$$

Where:

- $\Delta\eta_{H;gn;zi;mi}$ is the difference in the utilization factor for heat gain calculated with and without considering internal heat gain due to recoverable losses to and from the space heating and cooling system
- $\eta_{H;gn;incl.rbl;zi;mi}$ is the dimensionless utilization factor for heat gain
- $\eta_{H;gn;zi;mi}$ is the dimensionless utilization factor for heat gain, where recoverable losses to or from the space heating and cooling system are not included

4.4. Heat demand modeling with semantic 3D city models

The quantitative research component of the mixed-method approach includes implementing heat demand principles as described in the qualitative research component into a Python-based model that uses as input semantic 3D city models. With the help of the mind map which serves as the theoretical baseline of the Python-based model implementation, another additional diagram is created before coding to see which NTA 8800 principles are needed for heat demand modeling that can be implemented with semantic 3D city models using CityGML 2.0 and the Energy ADE V1 data model. The second diagram created is in the form of an UML diagram. After the creation of an UML diagram, a Python-based model is created using Python 3.11. The research outcome in this phase is to develop a script that allows any user to calculate the total heat demand of each building in the city model dataset using the NTA 8800 energy balance method. For this phase, the Python script was tested using the case study neighborhood, Wielewaal, Rotterdam.

4.4.1. Data collection

Several datasets had to be retrieved to be able to perform heat demand modeling using the NTA 8800 energy balance method. Performing heat demand modeling requires information on:

- Building geometries
- Building physics
- Terrain
- Weather patterns

Building geometries were retrieved through CityGML building datasets. Two available datasets were found: 3D BAG LoD2.2 (Peters et al., 2022) and Rotterdam3D (GemeenteRotterdam, N.A.) of which the Rotterdam3D was used for this thesis. The Rotterdam3D dataset is retrievable through the contact form in XML format from the website: https://www.rotterdam.nl/bestelformulier-3d-rotterdam. The Rotterdam3D dataset was sent over by the Municipality of Rotterdam on November 14, 2023, for the entire neighborhood Wielewaal. Building geometrical properties such as surface areas, building volume, number of floors and surface orientations were obtainable through the CityGML dataset. Figure 4.3 displays the number of buildings available in the Rotterdam3D dataset of Wielewaal for the thesis.

Figure 4.3: CityGML building dataset displayed in FZKViewer.

Not all components that are required for the heat demand calculations based on the NTA 8800 can be model since some of the computations require building physics data not available for the buildings in the case study area. Hence, assumptions and generalizations had to be made for the building physics using archetype modeling. The building physics data for the archetype modeling is retrieved from an excel "Voorbeeldwoningen 2022" Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023.

The dataset AHN DTM was used to model the terrain and Lawrie and Crawley, 2022 was used to retrieve relevant weather information for the case study area.

4.5. Heat demand estimate comparison

4.5.1. With CitySim Pro

A BES tool was deployed to compare with the NTA8800 energy balance model's heat demand estimations. For this, CitySim Pro was used, which requires an active license in order to run (Mutani et al., 2018). In subsection 2.2.4, a short description can be found for CitySim Pro. Figure 4.4 displays the software interface, as can be viewed in the interface, on the top left, the building geometries can be loaded in (Mutani et al., 2018). To run the simulations, the bottom right "simulate" button has to be pressed (Mutani et al., 2018). After the simulations are done, at the top right, the user can select which results parameter to display where the legend will be updated based on the parameter chosen (Mutani et al., 2018). The results were exported and visualised as a map. The energy simulation took around 30 minutes to run in CitySim Pro (section 7.1 outlines the computer technical specification used for this analysis).

Figure 4.4: CitySim Pro interface.

Figure 4.5: Overview of the CitySim Pro workflow outlined by Jin, 2022.

Several datasets need to be collected to be able to use the CitySim Pro software (see Figure 4.5 for an overview of the CitySim workflow steps) and significant data pre-processsing had to occur before running the simulations.

Data preparation
The following data preparation needed to occur:

1. Climate file (Mutani et al., 2018; Jin, 2022)
2. Horizon file (Mutani et al., 2018)
3. CityGML buildings (Mutani et al., 2018; Jin, 2022)
4. Terrain (Jin, 2022)
5. Shadowing objects (Mutani et al., 2018; Jin, 2022)
6. Building Physics Data (Jin, 2022)

Utilizing C. Leon-Sanchez's research (date: under review), the horizon file was produced. This needed a DSM covering the case study region in addition to the position of the nearest weather station in Wielewaal, Rotterdam, and the weather station itself. The 5 meter resolution AHN DSM was employed. The location data of weather stations was acquired in the .kml format from Lawrie and Crawley, 2022. The Wielewaal region and the site of the weather station are covered by the AHN DSM file, as shown by Figure 4.6. Given the lack of elevation in the Netherlands, the horizon file that resulted from applying C. Leon-Sanchez's technique produced a clear overview (see Figure 4.7 for the horizon file result).

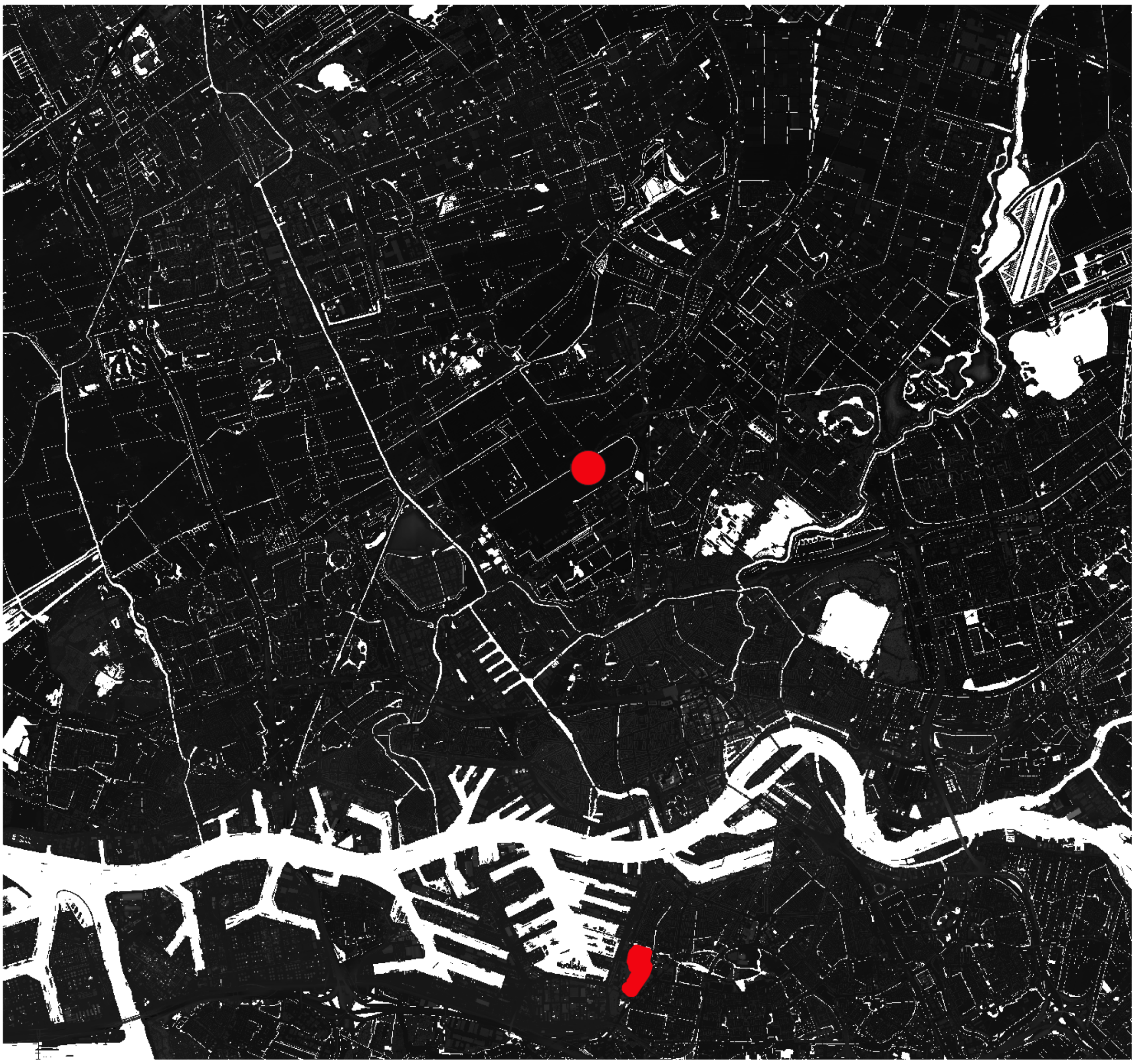


Figure 4.6: AHN DSM file displayed in QGIS with the weather station location indicated in red and Wielewaal area in red.

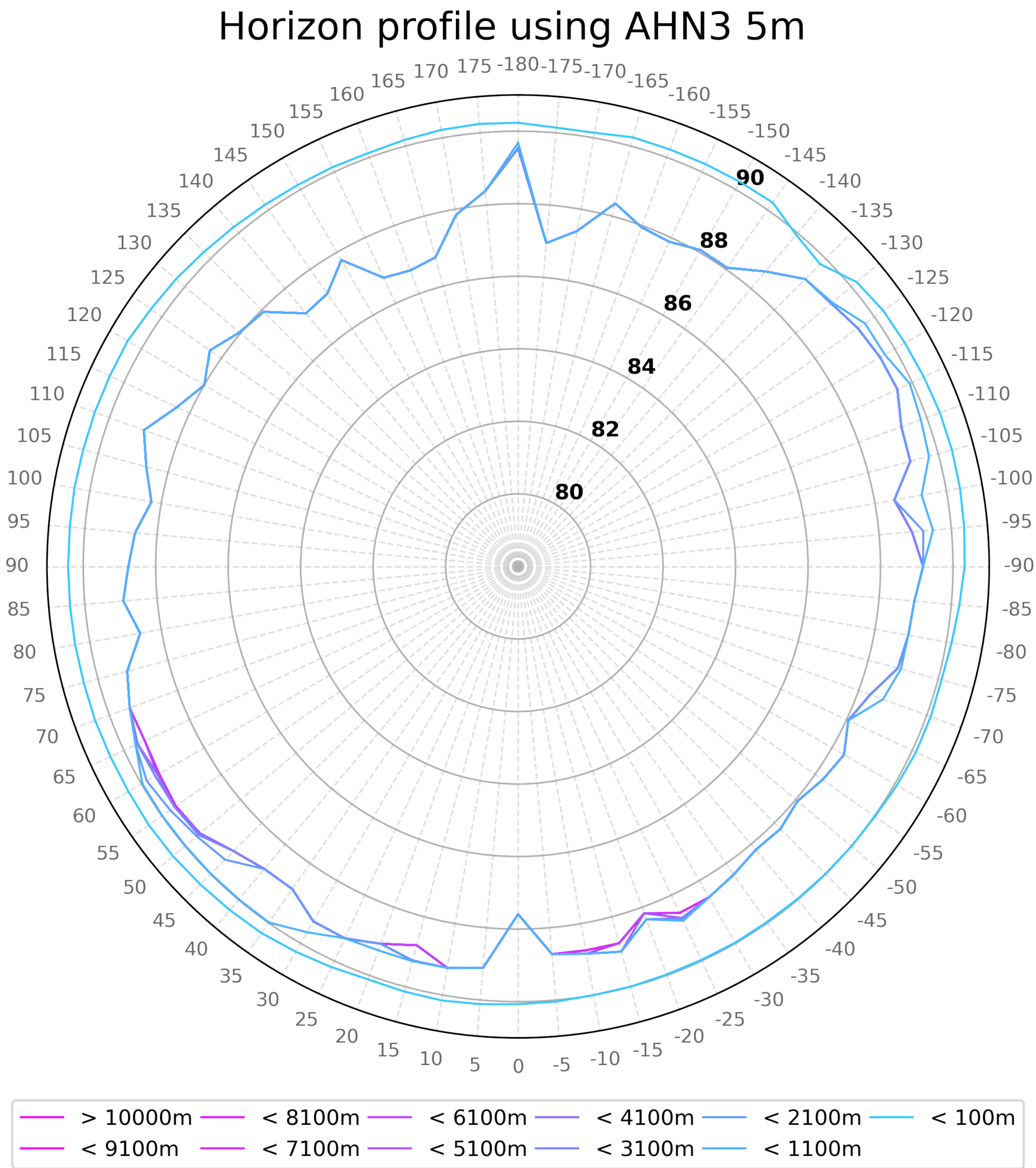


Figure 4.7: The horizon file.

Jin's (2020) work, which is available at the following github link: https://github.com/tudelft3d/Dynamic-energy-simulations-based-on-the-3D-BAG-2.0, was utilized to create the climate file. The climate data for Rotterdam, Netherlands, Europe 2023 was obtained in the .epw file format from Lawrie and Crawley, 2022, and the CLifileCreator.py program was then used in order to generate the climate file.

CityGML buildings of Rotterdam were obtained through Rotterdam3D (GemeenteRotterdam, N.A.). Table A.1 in the appendix provides an overview of the attributes contained in the CityGML building file. The buildings had to be pre-processed further using FME. Figure B.1 shows the workflow used to process the buildings. Rotterdam3D building file had the geometries stored as LoD2Solids which needed to be converted to Lod2Multisurfaces to run Jin's CitySimXMLGenerator.py.

The terrain file also had to be created which was done using FME following the workflow depicted in

Figure B.2. Figure 4.8 conceptually summarizes the steps taken in the FME workbench for processing the terrain. Here, AHN DTM file had to be collected that covered the study area and the resolution was set to 10 m to speed up the processing time.

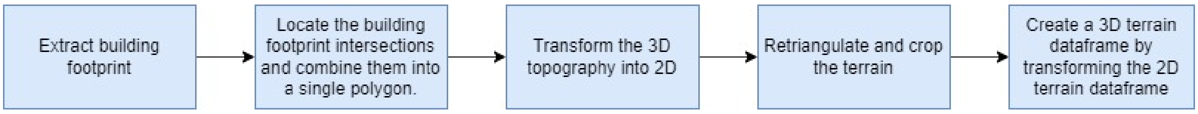


Figure 4.8: Overview of the terrain processing steps.

Building physics data were collected through the Voorbeeldwoningen 2022 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023).

4.5.2. With statistical consumption data

The estimates computed from the developed NTA 8800 energy balance heat demand model has to be compared with statistical consumption data to verify whether the theoretical heating demand calculated corresponds with reality. Comparing the theoretical estimates with actual consumption statistics allows for the model to be evaluated as a sanity check. The statistical dataset used for this study comes from the Centraal Bureau voor de Statistiek (CBS), using the dataset: "Energie postcode 6 2022", year 2022, downloaded on December 7, 2023 in CSV format from the website: https://www.cbs.nl/nl-nl/maatwerk/2023/46/energielevering-aan-woningen-en-bedrijven-naar-postcode (Centraal Bureau voor de Statistiek (CBS), 2023).

The data comes from network operators of individual buildings, which CBS linked through registries *Basisregistratie Adressen en Gebouwen* (BAG), Dataland and Locatus. CBS grouped the information into postal code 6 to preserve anonymity. A share of the energy supply is allocated to a residential buildings based on the building classification of residential or commercial through the registries. The remainder of the delivery is allocated to the commercial sector. Even if the supply to the home in question is higher than a statistically determined upper limit (the 99th percentile for that home type), the energy supply is imputed and the remaining consumption is considered commercial. Some of the homes do not have their own central heating boiler, but are heated by means of so-called "block heating". There is a central boiler in a building complex that provides connected homes with hot central heating water. In such a case, the total natural gas supply from the central boiler is distributed proportionally among the connected homes.

5 Preliminary Results

5.1. NTA 8800 Mind map

Figure 5.1 outlines how heat demand is modeled according to NTA 8800 standards. In essence, the NTA 8800 heat demand formulation consists of the components: recoverable energy losses, total heat transfer for heating, total heat gain for heating, and utilisation factor for heat gain. These components can be further broken down for total heat transfer into transmission and ventilation and for total heat gain into solar gain and internal gain. This mind map is not complete yet.

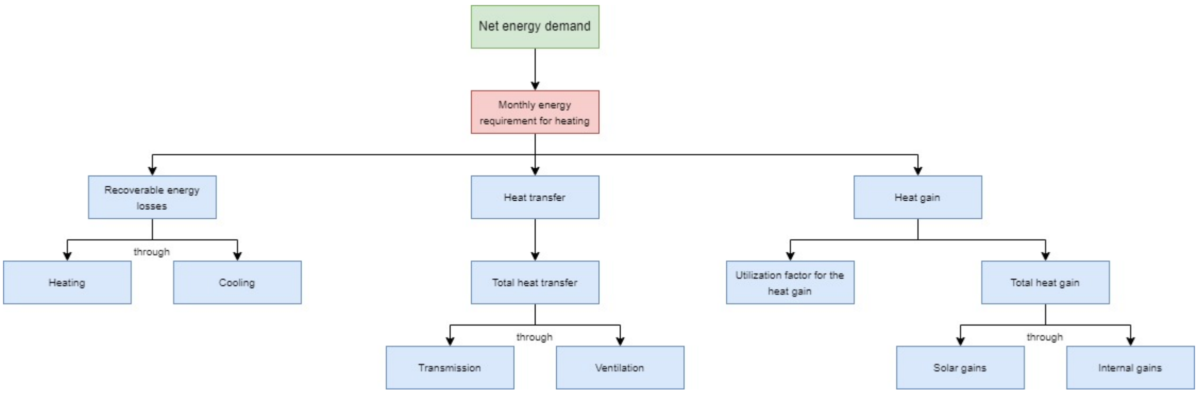


Figure 5.1: Overview of the preliminary mind map for heat demand modeling.

5.2. Heat demand modeling with semantic 3D city models

Figure 5.2 demonstrates how the Python-based model theoretically will be implemented to model heat demand that is compatible with CityGML 2.0 and Energy ADE V1. These results are not the final version used for the Python implementation.

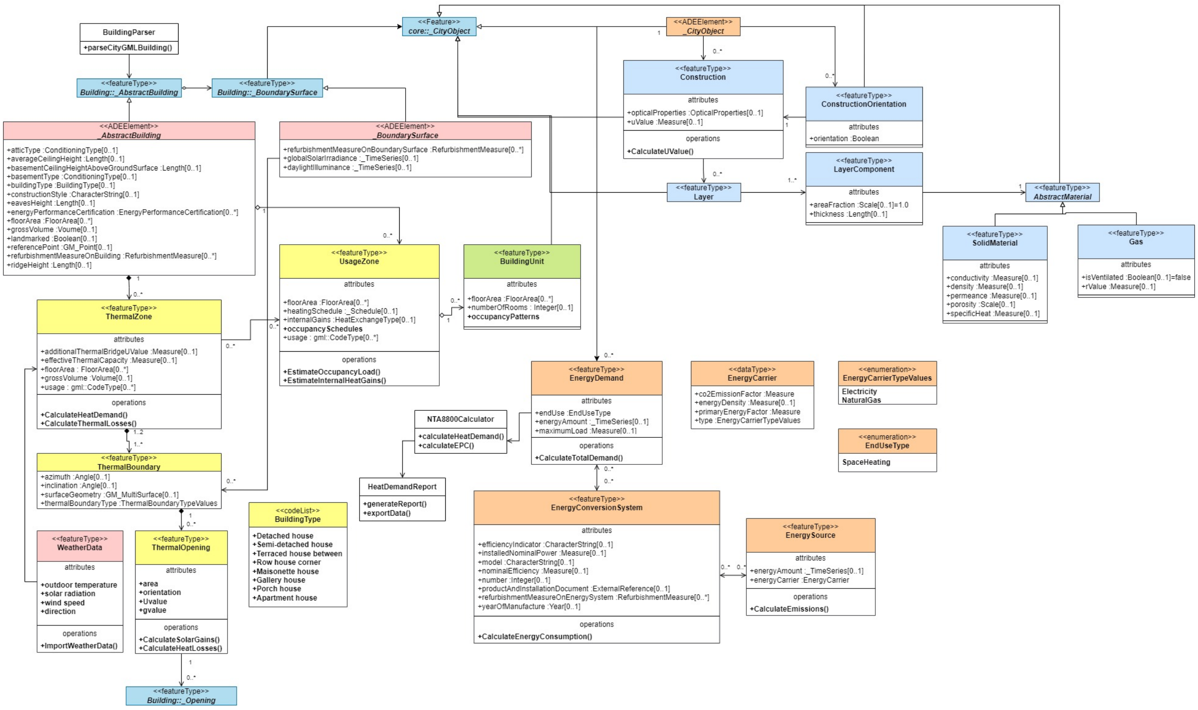


Figure 5.2: Overview of the preliminary heat demand modeling approach in UML.

5.3. Heat demand estimate comparison

5.3.1. CitySim Pro

Figure 5.3 displays some preliminary results of the heat demand modeling using CitySim Pro for the buildings in Wielewaal, Rotterdam. These results are not the final version used for comparison.

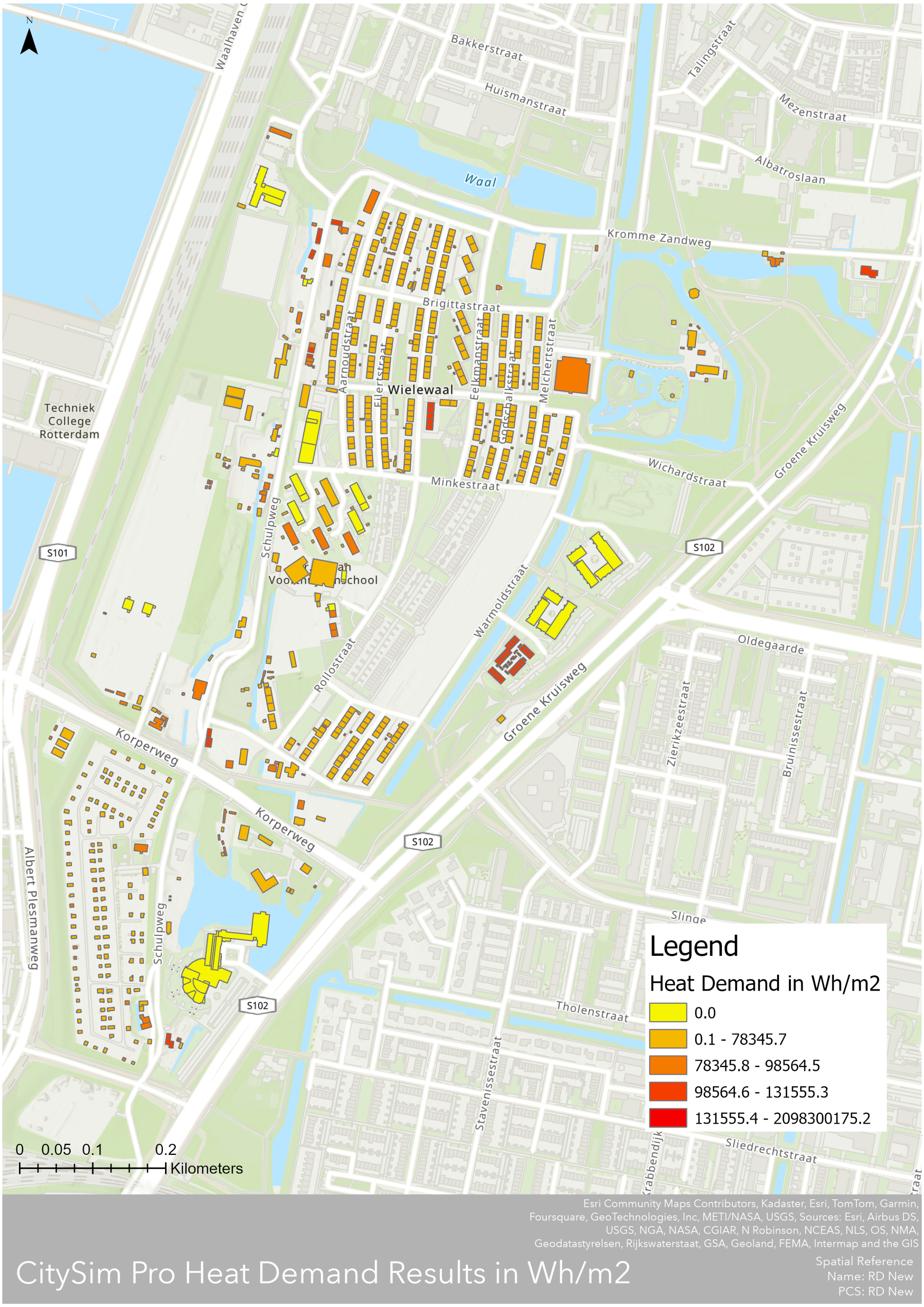


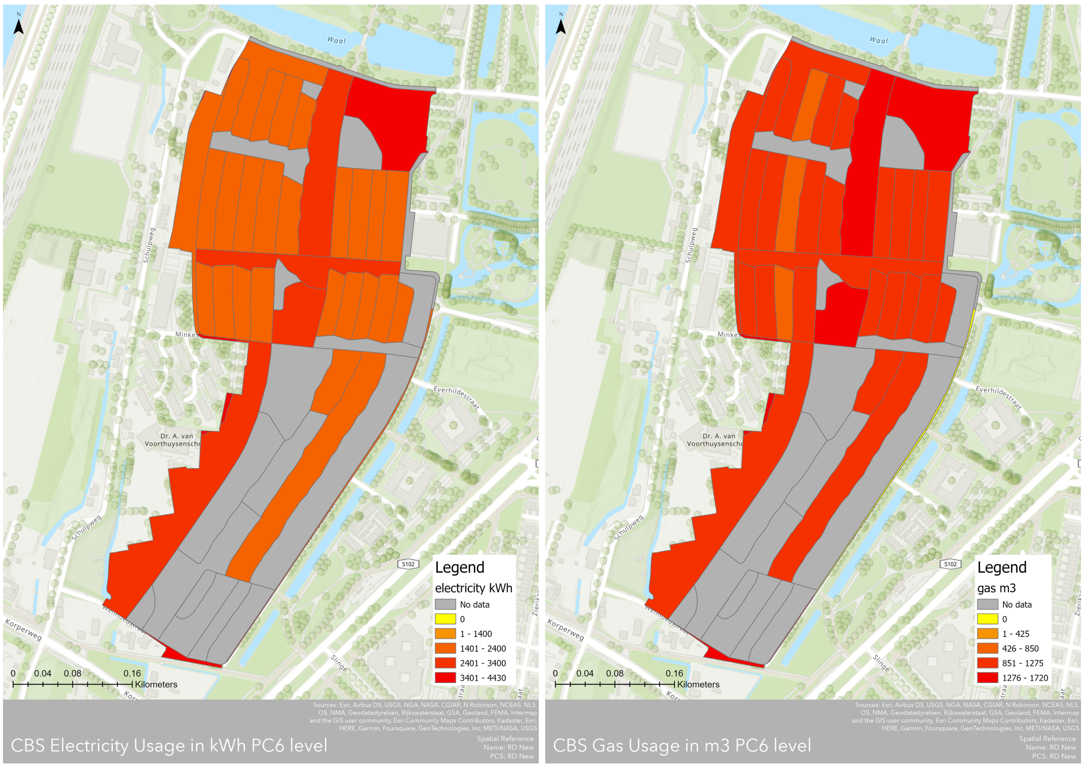
Figure 5.3: Overview of the preliminary results of heat demand modeling with CitySim Pro.

5.3.2. CBS gas and electricity consumption data

Figure 5.4 presents the statistical consumption values for electricity and gas, which can be used to compare the Python-based model results as a sanity check for program development. Both datasets were displayed as a choropleth map. Areas, where no information was available, are displayed in the grey of which the majority lies to the south side of Wielewaal.

As can be seen in Figure 5.4a, the electricity consumption data is displayed in the energy unit kWh using the spatial PC6 zones. In Wielewaal, it seems that the electricity consumption varies between 1401-4430 kWh.

As can be seen in Figure 5.4b, the gas consumption data is displayed in the energy unit m3 using the spatial PC6 zones. In Wielewaal, it seems that the majority of the gas consumption varies between 851-1720 m3.



(a) Overview of the electricity consumption estimates in kWh for Wielewaal PC6 level (Centraal Bureau voor de Statistiek (CBS), 2023).

(b) Overview of the gas consumption estimates in m3 for Wielewaal PC6 level (Centraal Bureau voor de Statistiek (CBS), 2023).

Figure 5.4: Overview of the energy consumption estimates from CBS (2022) to use as a comparison reference.

5.3.3. Comparison

The comparison will be visualized with a bar chart.

6 Planning

Figure 6.1 depicts the research project's scheduled activities, as well as the time allotted for each activity. The thesis's outline consists of the following components and is depicted in Table 6.1:

Section	Description
Title	Designing a Dutch building energy simulation tool using semantic 3D city models
Subtitle	Energy model testing for a case study area in Rotterdam
Abstract	Summary of thesis research
Table of contents	Overview of chapter's page number
Chapter 1	Introduction
Chapter 2	Literature Review: Overview of the current research state • Overview of urban building energy modeling • Overview of energy models and NTA 8800 • Overview of the building energy simulation tools • Overview of semantic 3D city models using CityGML • Overview of Energy ADE
Chapter 3	Research Design: • Research questions development • Research approach
Chapter 4	Methodology: • Research framework • Study area selection • Qualitative research: Literature review and concept mapping • Quantitative research: Heat demand modeling and testing • Sanity check: Comparing results with CitySim Pro and statistical data
Chapter 5	Research Outcomes: • Mind map on heat demand components based on NTA 8800 • Heat demand Python-based model and UML diagram of implementation • Bar chart of heat demands estimates from the Python-based model, CitySim Pro and statistical database

Section	Description
Chapter 6	Discussion: Overview of research implications, limitations, and future research
Chapter 7	Conclusion: Summary of the findings and answer to the research question
References	Overview of sources used
Appendices	Overview of supporting documents

Table 6.1: Overview of the thesis outline.

Figure 6.1: Thesis Research Gantt Chart.

7 Data and tools used

Table 7.1 provides an overview of the expected data collection and tools used for each research phase.

Research phase	Data	Tools
Concept mapping	NTA 8800 manual (NEN, 2023)	io.draw (method: mind map)
Heat demand modeling	• CityGML buildings geometries from Rotterdam3D (GemeenteRotterdam, N.A.) • Building physics from Voorbeeldwoningen 2022 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023) • Weather data from Lawrie and Crawley, 2022 • Terrain data from AHN DTM	• FME for data preparation • Python 3.11 for energy computation • 3DcityDB for data storage
CitySim Pro modeling	• Climate file and weather station position • Horizon file • CityGML buildings geometries from Rotterdam3D (GemeenteRotterdam, N.A.) • Building physics from Voorbeeldwoningen 2022 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023) • Terrain data from AHN DTM • Shadowing objects (e.g. trees) from Rotterdam3D (GemeenteRotterdam, N.A.)	• FME for data preparation • Python 3.11 for data preparation • 3DcityDB for data storage • CitySim Pro for energy computation

Research phase	Data	Tools
Statistical analysis	• NTA 8800 heat demand estimates • CitySim Pro heat demand estimates • CBS 2022 gas and electricity estimates (Centraal Bureau voor de Statistiek (CBS), 2023)	Excel (method: bar charts)

Table 7.1: Overview of the expected data collection and tools.

7.1. Hardware

The following are the specifications of the computer that was utilized to apply the methodology:

- Processor: Intel(R) Core(TM) i7-1065G7 CPU @ 1.30GHz 1.50 GHz
- RAM: 32.0 GB (31.6 GB usable)
- Operating System: Windows 11 Home

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A

Data attributes for building geometries

At the time of this thesis documentation, these were the attributes displayed on the dataset collected for building geometry. This can vary in future version downloads.

Attribute name	**Description**
Identification	This is a unique identifier for the building.
Construction year	The year in which the building was originally constructed.
Status	Classification of the building in use or not
Validity start date	The date when the information about the building became valid.
Number of storeys	The total number of floors in the building.
Highest floor	The highest floor number in the building.
Lowest floor	The lowest floor number in the building. A negative value indicate a below-ground level floor.
Building type	The type of building
District	The district or neighborhood in which the building is located.
Neighborhood	The specific neighborhood within the district.
Number of addresses	The total number of addresses associated with the building.
Address	The full address of the building

Table A.1: Overview of the attributes in the Rotterdam 3D dataset (GemeenteRotterdam, N.A.).

B

FME data preparation workbenches

Figure B.1 shows the FME workbench with all the transformers used to convert the Rotterdam3D building geometries from LoD2 Solid into LoD2 Multisurfaces. Figure B.2 displays the FME workbench with all the transformers used to create a terrain file with holes where the CityGML buildings are located, necessary to improve the accuracy of computations.

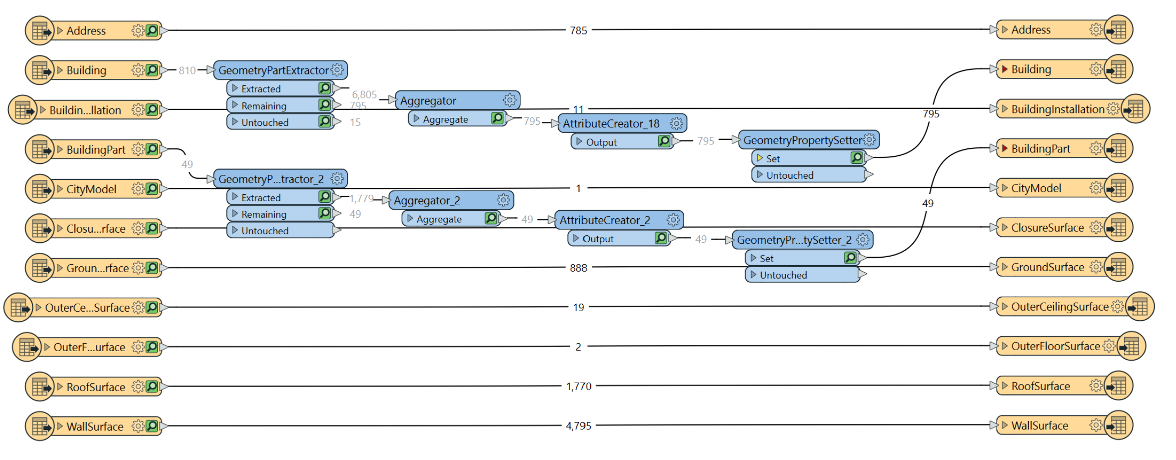

Figure B.1: FME workbench for CityGML building processing.

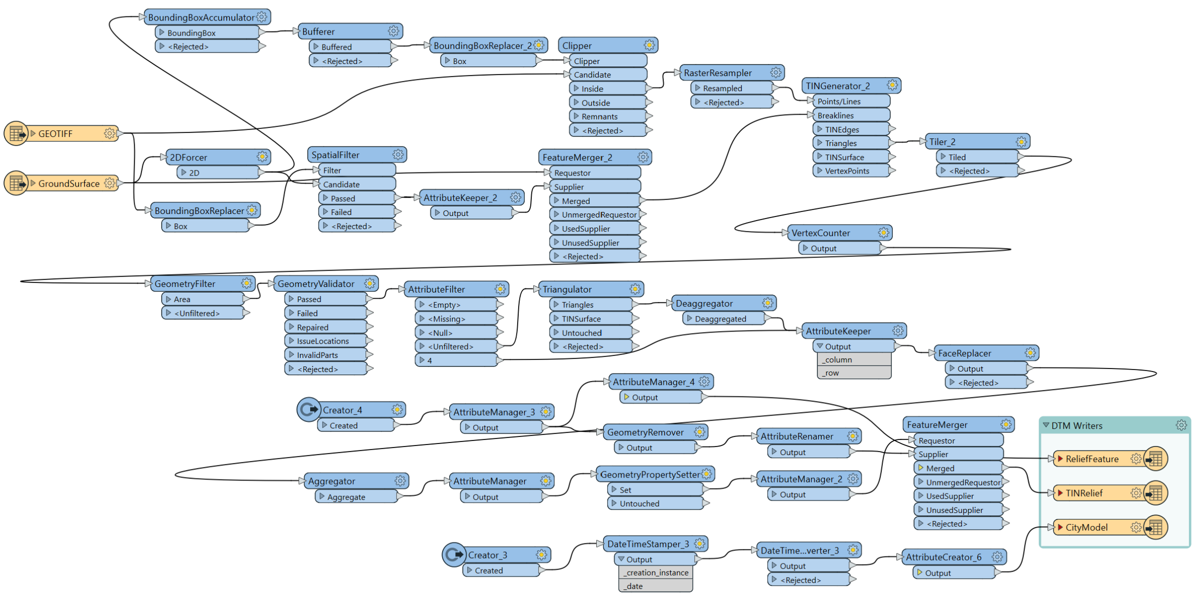

Figure B.2: FME workbench for DTM terrain processing.