

Hochschule für Technik Stuttgart

University of Applied Sciences

Master Thesis

Master of Science Programme

Photogrammetry and Geoinformatics

Summer Semester 2019

Simulation of Cooling Energy Demand Using the 3D Citymodel of Singapore

by
Matthias Fitzky

Supervisors:

Prof. Dr. -Ing. Volker Coors, HFT Stuttgart
Dr. Viktor Khoo, Singapore Land Authority

Simulation of Cooling Energy Demand Using the 3D City model of Singapore

by

Matthias Fitzky

A Dissertation presented in Partial Fulfillment of the Requirement
for the Degree Master of Science in the Department of
Geomatics, Computer Science and Mathematics of the University
of Applied Sciences Stuttgart

1st Supervisor: Prof. Dr. -Ing. Volker Coors, HFT Stuttgart

2nd Supervisor: Dr. Viktor Khoo, Singapore Land Authority

I. Abstract

Using 3D city models for urban energy analyses requires certain semantic and geometrical information of each building. The quality of the resources for such information defines the quality of the outcome of energy simulations as previous research has shown.

In this thesis, it will be analyzed to which extent of quality and reliability a cooling energy demand simulation in Singapore is possible. This includes an investigation on analyzing the quality of available information and existing building geometries. Based on the outcome of the simulation, recommendations for improving the input datasets will be made. It will also be analyzed if the implemented cooling energy calculation method in Simstadt is suitable for the given data model and climate region. Additionally, a concept of visualizing the results in 3D is elaborated to enable an intuitive assessment of the energetical performance of buildings.

This thesis discovered as a result, that the simulation methodology as already applied in Germany is capable of calculating plausible results, but still has the potential to be improved in accuracy when having input parameters more oriented on the Singaporean building stock. It has also been found that the EnergyADE is a suitable data model for storing the needed input data. The 3D-visualization has been proven to consolidate information conveniently.

Keywords: Smart Cities, Smart Nation, 3D city models, CityGML, Energy Simulation, EnergyADE, 3D Web-based application, Singapore, Cooling energy demand

II. Acknowledgements

Foremost I want to express my sincere gratitude to the thesis committee of the Singapore Land Authority and the HFT Stuttgart. This work wouldn't be possible without the guidance of Prof. Dr. Volker Coors from the HFT Stuttgart and Dr. Viktor Khoo and Kean Huat Soon from the SLA. They provided me with valuable encouragement and insightful comments which enabled the finishing of this thesis.

Throughout the creation of this Master thesis I had the pleasure to get into contact with many smart people:

I would like to thank Dr. Adrian Chong from the Department of Building of the National University Singapore who gave me the understanding of many sources and important factual hints concerning the creation of a concept and collection of Singaporean Building-physics parameters.

I also want to thank Eric Duminil and Matthias Betz from the HFT Stuttgart for the good support for all questions I had concerning the software "Simstadt" and "CityDoctor".

Additionally, I'd like to thank Dr. Ji Zhang and his team from the Solar Energy Research Institute Singapore (SERIS) for the fruitful discussions we had about the use of 3D city models in energy analyses.

Also, I am grateful for the support in organizational issues that the members of the Survey and Geomatics Department of the SLA gave me, especially I want to thank Lee Wah, Evan Cheong, Sandy Teo, Kai Keng Low, Ai Hwee Leong, Richard Loo and many more.

Without the moral and financial support of my parents, namely Dr. Gerhard Fitzky and Dagmar Fitzky, the stay in Singapore would not have happened at all, which is why I want to show my gratitude to them as well.

Lastly, I want to mention the friends I met during the time in Singapore, providing a healthy work-life balance for which I'm appreciative.

III. Table of Contents

I.	Abstract.....	2
II.	Acknowledgements	3
III.	Table of Contents	4
IV.	List of Figures.....	6
V.	List of Tables	8
VI.	List of Abbreviations	9
1	Introduction.....	10
2	Research Questions.....	13
3	State of the Art	14
4	Background	17
4.1	CityGML.....	17
4.1.1	<i>Level of Detail.....</i>	<i>18</i>
4.1.2	<i>EnergyADE.....</i>	<i>18</i>
4.2	3D City Model Singapore	20
4.3	DIN V 18599	20
4.3.1	<i>Cooling-Energy Demand</i>	<i>20</i>
5	Concept	23
5.1	Usage of different Datasets	24
5.2	Preparation of the City Models	24
5.3	Testing the Simulation-Methodology	25
5.3.1	<i>Influence of faulty geometries.....</i>	<i>25</i>
5.3.2	<i>Research and prepare a Singaporean Buildingtypology.....</i>	<i>25</i>
5.3.3	<i>Influence of different Level of Details for the input dataset</i>	<i>26</i>
5.3.4	<i>Comparison simulation results to real consumption values.....</i>	<i>26</i>
5.4	Enable interoperability.....	26
5.5	Concept for 3D Visualization	27
5.6	Evaluation	27
6	Datasets used in this Thesis.....	28
7	Implementation	35
7.1	Used Software.....	35
7.1.1	<i>Simstadt.....</i>	<i>35</i>
7.1.2	<i>CityDoctor</i>	<i>40</i>
7.1.3	<i>FZKViewer.....</i>	<i>41</i>

7.1.4	<i>CesiumJS</i>	41
7.2	Prepare Singaporean City Models to enable Simulations.....	42
7.2.1	<i>Merge files together</i>	42
7.2.2	<i>Enrich the City Model with missing Attributes</i>	44
7.2.3	<i>Geometry Check and Schema validation</i>	51
7.3	Creating Singaporean Building Physics Libraries.....	67
7.3.1	<i>Evaluation on using Singaporean Parameters</i>	70
7.4	Influences of input data on the Simulation result.....	73
7.4.1	<i>Building-Physics Parameters</i>	73
7.4.2	<i>Geometry</i>	76
7.5	Creating EnergyADE datasets.....	79
7.5.1	<i>Setting up the EnergyADE Core-Module-Attributes</i>	81
7.5.2	<i>Setting up the Building-physics-Module Attributes</i>	82
7.5.3	<i>Setting up the Occupancy Module</i>	84
7.5.4	<i>Setting up the Construction Module</i>	86
7.6	Development of a Web Application for Visualization.....	88
7.6.1	<i>Evaluation of the Visualization</i>	92
8	Synthesis	93
8.1	Data availability.....	93
8.2	Geometrical Modelling.....	93
8.3	Plausibility of Simulation results.....	94
8.4	Recommended data model: EnergyADE.....	95
9	Conclusions	96
10	Future Work	97
VII.	Bibliography	98
VIII.	Annex	106
	Annex 1: Mapping of LOD1 Building names to ALKIS function Codes.....	106
	Annex 2: Preliminary Building Physics Library for Singapore.....	108
	Annex 3: Preliminary Usage Library for Singapore.....	110
	Annex 4: EnergyADE UML Diagrams.....	111
IX.	Statement of Authorship	117

IV. List of Figures

<i>Figure 1 Share of Energy-Uses in Residential and Commercial Buildings [9] [10].....</i>	<i>11</i>
<i>Figure 2 Relationship between energy consumption and energy performance of a building [11].....</i>	<i>12</i>
<i>Figure 3 Simplified UML-Model for the building-Module in CityGML [37].....</i>	<i>17</i>
<i>Figure 4 HFT Stuttgart building represented in 4 levels of detail in CityGML [38].....</i>	<i>18</i>
<i>Figure 5 Overview of the EnergyADE [24].....</i>	<i>19</i>
<i>Figure 6 Concept Diagram.....</i>	<i>23</i>
<i>Figure 7 Combined View of the LOD1 CityGML-Files describing the district Yishun, imported into FZKViewer,</i>	<i>28</i>
<i>Figure 8 Combined View of the LOD2 CityGML-Files, imported into FKZViewer</i>	<i>30</i>
<i>Figure 9 Excerpt of the LOD2 CityGML Dataset, Central Business District</i>	<i>33</i>
<i>Figure 10 Structure of the Usage Library</i>	<i>37</i>
<i>Figure 11 Structure of the Buildingphysics Library.....</i>	<i>38</i>
<i>Figure 12 Workflow for the preprocessing of the 3D city models.....</i>	<i>42</i>
<i>Figure 13 Steps creating a combined CityGML File.....</i>	<i>42</i>
<i>Figure 14 Excerpt of a CityGML-file (single building).....</i>	<i>43</i>
<i>Figure 15 Comparison between average values per variation of year of construction and real consumption values.....</i>	<i>45</i>
<i>Figure 16 Comparison of nearest simulated values to the BCA real consumption of 2016.....</i>	<i>46</i>
<i>Figure 17 LOD1 area Yishun, Walkway connecting to a building called “Yishun Gardens”.....</i>	<i>49</i>
<i>Figure 18 Walkway Yishun Gardens, Source: Google StreetView.....</i>	<i>50</i>
<i>Figure 19 Content of AlkisCodes.xml - Mapping between Singaporean and ALKIS Codes - Excerpt.....</i>	<i>50</i>
<i>Figure 20 Distribution of error types in LOD1 Dataset.....</i>	<i>52</i>
<i>Figure 21 “CS_CONCOMP” error: Two spatially separated buildings modeled as one - Source CityDoctor</i>	<i>53</i>
<i>Figure 22 Erroneous Linerring and Duplicate Point in LOD1 Model of Chong Pang Food Market.....</i>	<i>54</i>
<i>Figure 23 CityGML Code of a LinearRing with too few points (only 3 of 4) in LOD1 Model</i>	<i>55</i>
<i>Figure 24 CityGML Code of a Duplicate Point Error in LOD1 Model.....</i>	<i>55</i>
<i>Figure 25 Distribution of Errors in LOD 2, Modelling with Building-parts</i>	<i>56</i>
<i>Figure 26 Building with highlighted building-part – Source: CityDoctor V2.2.1</i>	<i>57</i>
<i>Figure 27 Not Closed building-part with highlighted edge - Source: CityDoctor V3 ...</i>	<i>57</i>
<i>Figure 28 Connection between Wall- and Roofsurfaces missing out additional points.</i>	<i>58</i>
<i>Figure 29 Variants of modeling a building with a Building-part in CityGML [35]</i>	<i>59</i>

<i>Figure 30 Structure of LOD2 Buildings with building parts (unmodified)</i>	<i>60</i>
<i>Figure 31 Structure of LOD2 Buildings without building parts (after modification)</i>	<i>60</i>
<i>Figure 32 Functionality of the Java Program - Connect building-parts to one closed solid.....</i>	<i>61</i>
<i>Figure 33 Amount of Errors with building-parts declared as Multisurfaces without Solids.....</i>	<i>62</i>
<i>Figure 34 Amount of Errors when assigning all Surfaces in building-parts to one solid per building.....</i>	<i>63</i>
<i>Figure 35 Comparison of Simulation Results for two ways of modelling the building-parts in LOD2 Yishun</i>	<i>64</i>
<i>Figure 36 Comparison of results using German and Singaporean Building-physics-, Usagelibraries.....</i>	<i>70</i>
<i>Figure 37 Comparison between Singaporean and German Libraries - Single Buildings</i>	<i>71</i>
<i>Figure 38 Influences of Building Physics Parameters</i>	<i>75</i>
<i>Figure 39 Comparison LOD1 to LOD2 of the Yishun 3D city model</i>	<i>77</i>
<i>Figure 40 Simplified schematic visualization of the input data needed for Simulations in Simstadt.....</i>	<i>80</i>
<i>Figure 41 Data sources and schema of the Workflow for setting up the Visualization .</i>	<i>88</i>
<i>Figure 42 FME Workflow to create 3D Tiles</i>	<i>89</i>
<i>Figure 43 Control Center of the Cesium Webapplication.....</i>	<i>90</i>
<i>Figure 44 Pane with Information about the selected building</i>	<i>91</i>
<i>Figure 45 Additional Information window showing the temporal distribution of the energy demand per month.....</i>	<i>91</i>
<i>Figure 46 Extension of the CityGML classes _AbstractBuilding and _CityObject [24]</i>	<i>111</i>
<i>Figure 47 UML diagram of the Building Physics module [24].....</i>	<i>112</i>
<i>Figure 48 UML diagram of the Material and Construction module [24].....</i>	<i>113</i>
<i>Figure 49 UML model of the Occupant Behavior module [24]</i>	<i>114</i>
<i>Figure 50 Simplified UML model of the Energy Systems module [24]</i>	<i>115</i>
<i>Figure 51 UML diagram of the time series classes [24]</i>	<i>116</i>

V. List of Tables

<i>Table 1 Differences between Heat Sinks and Heat Sources</i>	<i>21</i>
<i>Table 2 Available Attributes per Building in LOD1 area Yishun.....</i>	<i>29</i>
<i>Table 3 Available Attributes per Building LOD2 area Yishun.....</i>	<i>31</i>
<i>Table 4 Attributes in Energy Consumption dataset.....</i>	<i>34</i>
<i>Table 5 Mapping of Building names to ALKIS Codes (excerpt).....</i>	<i>48</i>
<i>Table 6 Volume Comparison for one sample building</i>	<i>66</i>
<i>Table 7 Buildingtype properties in IWU Library.....</i>	<i>67</i>
<i>Table 8 Overview of parameters changed for each simulation for assessing their influences</i>	<i>74</i>
<i>Table 9 Attributes of the AbstractBuilding Class in the EnergyADE.....</i>	<i>82</i>

VI. List of Abbreviations

ALKIS	Administrative cadastral property information system in Germany (In German: “Amtliches Liegenschaftskatasterinformationssystem”)
BCA	Building and Construction Authority
CBD	Central Business District
CSV	Comma Separated Values
DIN	Deutsches Institut für Normung (German Institute for Standards)
GFA	Gross Floor Area
GIS	Geo-Information System
GML	Geographic Markup Language
GUI	Guided User Interface
HDB	Housing Development Department
HFT	Hochschule für Technik (University of Applied Sciences)
HTML	Hypertext Markup Language LOD Level of Detail
OGC	Open Geospatial Consortium
SLA	Singapore Land Authority
UML	Unified Modelling Language
XML	Extensible Markup Language
YOC	Year of Construction

1 Introduction

Looking onto the resource consumption worldwide, it has been discovered that 75% of all resources are consumed by cities. That circumstance is even more dramatic looking onto the fact that urban areas only make up 3% of the whole earth's surface. Also, Cities have a share of up to 80% of the world's greenhouse gas emissions [1]. By the background of these facts, the search for new technologies and processes in order to reduce the environmental footprint of cities on the planet is pursued as never before.

Mainly driven by the ongoing climate change and social restructuring, cities more and more make use of thriving technological innovations and tend to describe themselves as "Smart Cities". Smart Cities nowadays are urban areas which implement many digital services, such as Monitoring and Management systems for traffic and transportation systems, water supply networks, but also for energy-related topics [2]. Based on these systems decisions can be taken, which include a comprehensive perspective on the given circumstances in a city and therefore give the chance to reduce costs, greenhouse gas emissions and resource consumption.

Singapore is one of the most developed smart cities in the world [3].

In its "Smart Nation"-Initiative, the government has already paved the way for many innovative technologies in the sectors of Transport, Startups and Businesses, Health, Urban living and Digital Government Services to be included in daily procedures [4].

Singapore has carried out multiple approaches to include 3D city models into the framework given by the Smart Nation project.

The dynamic 3D platform "Virtual Singapore" offers a highly detailed 3D city model provided under the collaboration of many Singaporean authorities. The comprehensive 3D Visualization allows the derivation of multiple use cases. One example is the display of the potential of Solar Energy production. Based on the height, the surface area and available sunlight irradiation, Urban planners can include the solar potential of buildings in their analysis [5].

Another functionality is the planning of escape routes for residents in the case of gas leaks or other incidents. Also, the 3D platform has been used to simulate the casting of shadows of buildings. [6]

The Singapore Land Authority has additionally to "Virtual Singapore" a project called "Singapore Advanced Map". This Mapping project is combining 2D and 3D Data into one Geo-Information System, which is currently used for the agencies internal operations, planning, and policy formulation [7].

In the background of planning Singapore's urban development, 3D Spatial data is important when it comes to building energy simulation. Being able to simulate the energy demand in buildings allows for environment-oriented urban planning. Based on simulation results, it is possible to take measures at an early stage and pave the way for reducing the energy requirements of buildings in the future.

Since Singapore is located in a tropical climate with an average temperature of 26 degrees throughout the year [8], the buildings are not required to be heated at all. In the figure below it can be seen that the biggest part of the building's energy consumption is taken by the cooling appliances, like air-conditioning. For the commercial sector, the Air Conditioning plays an even more important role since the energy-share goes up to more than half of the whole building's energy consumption.

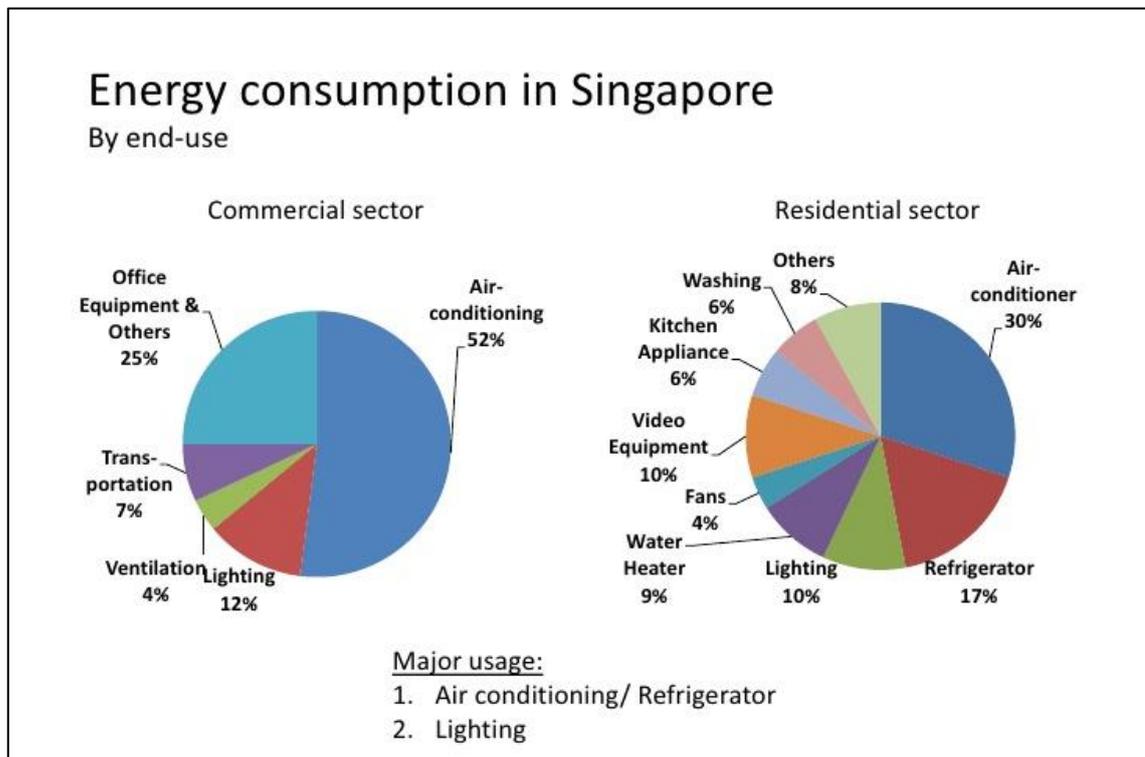


Figure 1 Share of Energy-Uses in Residential and Commercial Buildings [9] [10]

The large proportion of energy used for cooling, gives reason to orientate future urban planning on consumption values of this type of use. In order to be able to give a nationwide indication of approximate values, a method has to be developed to simulate the cooling energy demand.

The present thesis is intended to create a basis for a cooling energy demand simulation in Singapore using 3D city models.

Putting emphasis on the reachable accuracy of GIS-driven energy simulations when comparing calculated energy performance and actual consumption, it can be said that complete conformity is not to 100% possible. A huge part of a building's whole energy consumption is made up by the Physical parameters which already enable a high grade of accuracy of assessment methods. The factor which is uncalculatable is the occupant's behavior because only assumptions can be made in that case. This circumstance is also shown in Figure 2, where the relationship between Energy Performance (mostly meaning the energy derived by physical factors such as climate, and building fabric) and energy Consumption (meaning the consumption of buildings with respect to the occupancy schedules, etc.).

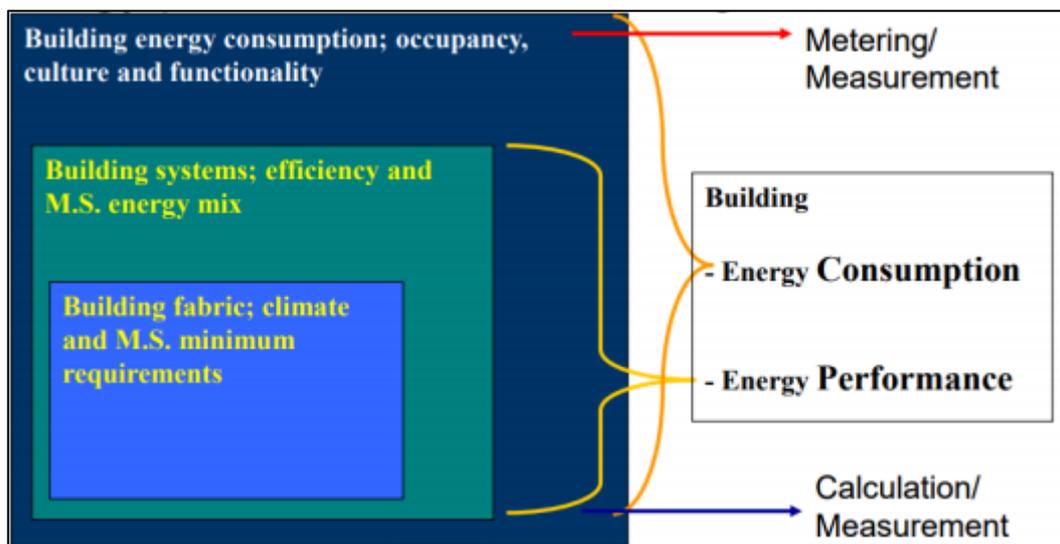


Figure 2 Relationship between energy consumption and energy performance of a building [11]

2 Research Questions

The overall goal of this research is to provide a concept for simulating Cooling energy demand using 3D city models of Singapore. Based on that, emphasis on several aspects can be set throughout the research.

Is the German Method for calculating cooling energy demand transferable to Singapore?

The question aims onto an analysis if the already established and approved German standard for assessing the energetical behavior of buildings is applicable in Singapore. This will be done by taking a GIS-based tool into account, which makes use of the German standard DIN V 18599 used for estimating building energy performance.

Are the modeling assumptions in the Simstadt methodology applicable to the Singaporean data model?

In order to retrieve plausible results for the energetical assessment using Simstadt, it will be analyzed how available information is applicable for cooling energy demand simulations. Based on that assessment, it can be said what structural prerequisites are still needed to be met, to enable the derivation of cooling energy demand assumptions in future.

How can energetical information on building level be consolidated and shared?

The question aims onto conglomerating and including the necessary information into a data model which is suitable for Energy Simulations using 3D city models. The thesis should give a recommendation on a suitable framework, for enabling the use of Singaporean 3D city models in future energy analysis platforms. Also, the thesis should provide a concept on how the information gathered during energetical assessments, can be accessed by using an interface.

3 State of the Art

There are several methods existing for the modeling of the energy demand of buildings. To show the state of the art of GIS-driven building energy simulation methods this section shows similar research as to this thesis which has been done before.

The software CitySIM enables energy simulations on urban-scale under the use of geometrical representations of buildings and has been developed in 2009 by the Solar Energy and Building Physics Laboratory of the EPFL¹. The fact that this method aims to enable energy simulations on large scale introduces the need for a building energy model with the aim of achieving a compromise between data availability and simulation accuracy [12]. Such a simplified model was developed with the aim to model heat flows in buildings considering multiple thermal zones [13]. This energy estimation methodology has been validated against a comparative testing approach for building energy simulation methods, called “BESTEST” which takes the results of multiple simulation software packages into account to provide a benchmark for new simulation environments [14]. The result of this test showed that CitySIM delivers results in heating and cooling energy demand simulations of 1% deviation of the expected result [15].

Another method of simulation has been investigated by A. Chong et. al.. This approach of simulating energy consumption is focusing on Singaporean office buildings and uses GIS as a connecting platform between data describing the surrounding morphology and the urban climatic assessment tool “ISV-VE” which is used to verify the assumptions done using several equations [16]. Morphology, in that case, stands for external conditions influencing the building energy performance and has been considered by introducing maximum, minimum and average temperature values transformed into hourly weather data in each building’s microclimate zone into the simulation process. The investigation found that the prediction method for the ambient temperature into a 24h scheme complies with performed measurements and that the resulting assessment of conduction gains through building enclosures and solar gains through windows delivered similar results as to the simulation using ISV-VE.

Kavgic et. al. described two approaches how a building energy model can be set up [17]. The “top-down” approach uses existing consumption data at urban level and compares it with climate variables, census results and statistical surveys so that the average energy consumption for buildings of a municipality or territory can be derived. The “bottom-up” approach takes building-specific data (such as year of construction, surface to volume ratio) into account to conclude on the energy consumption on a single building scale. The bottom-up approach can also be used for energy consumption predictions on urban scale under use of simplified building models. Based on the classification of different

¹ EPFL = Ecole Polytechnique Fédérale de Lausanne

approaches for building energy modeling as described by Kavgić et. al. [17] and Swan, Ugursal [18], Mutani et. al. [19] created a hybrid approach for building energy simulation. In this methodology, the bottom-up approach is used to determine the space heating demand of a spatial dataset describing the city of Turin. The Top-Down approach is used to validate and calibrate these results.

Bahu et. al. describe an agent-based model to simulate smart grids [20]. This includes an estimation of the heating energy demand of residential buildings using a 3D city model of the city Lyon (FR) in combination with a building typology containing thermal building properties as described by Pouget [21]. The results were calculated for two refurbishment scenarios and showed the influence of refurbishment measures by effecting a reduction of 70% of the simulated heating energy demand. A comparison to a validated energy simulation tool developed by the French company EDF showed a deviation of less than 5% to the applied method.

The in this thesis used energy simulation environment called Simstadt (further explained in chapter 7.1.1) was able to reach between 5% to 21 % of mean deviations in several case studies for heating energy demand simulations on urban scale in comparison to real energy consumption values [22], [23].

Focusing on the usage of 3D city models in building energy simulations, Agugiaro et. al. developed an extension for the OGC Standard CityGML, which is called EnergyADE [24]. It extends the CityGML UML model by feature-types and attributes which enable energy simulations using 3D city models.

Approaches using and producing EnergyADE-compliant data are the mentioned methodology “Simstadt” and a method developed by KIT [24]. This approach uses the Software GML-Toolbox [25] to semi-automatically create an EnergyADE-enriched CityGML dataset which is then imported into a 3D Viewer and data inspector called “IFCEXplorer”. This Software has been modified to access the Simulation Software “GebSim” [26]. GebSim then processes the actual information of the EnergyADE and is storing the resulting energy demand estimations inside a database that can be accessed by the IFCEXplorer, which in turn is again storing these results along with the 3D city model in an EnergyADE-enabled database called 3DCityDB [27].

A prerequisite for the use of 3D city models in energy simulations is the validity of the geometries which describe the buildings. As shown by Biljecki et. al. [28] city models are often shipped in poor quality, which is why multiple methods have been developed to analyze errors and ensure validity in these models. Ledoux shows a software called “val3dity” [29] capable of validating various 3D primitives, ArcGIS Pro contains functionalities to check if multiple surfaces add up to a volume [30], Kazar et. al. [31] and Colley et. al. [32] describe the validation rules of 3D Buildings stored in a database called “Oracle Spatial” and the software “FME” comes with a “GeometryValidator”-Transformer which also enables an automatic repair of solids [33]. A development team based at HFT Stuttgart created a software called “CityDoctor” which will also be used in this thesis, capable of analyzing errors in 3D models in CityGML by using a GUI [34], [35].

4 Background

4.1 CityGML

In this thesis 3D spatial data is used to calculate energy demand values. To be able to include geometrical properties and attributes of a feature into the simulation environment, a method for storing data in a logical and structured way is required. The OGC CityGML standard provides such a solution and also introduces the possibility of interoperable processing of 3D spatial data.

This format is an XML-based approach to store and exchange 3D Geospatial data with a focus on 3D city models. [36] It is implemented as a schema of GML, which is, in turn, a format to store geospatial data in general.

It is possible to store several kinds of feature types, such as water bodies, vegetation, terrain and for this work the most important, buildings. When looking onto the UML-diagrams of the different modules, it can be concluded that the building module is for the CityGML standard the most detailed described feature type.

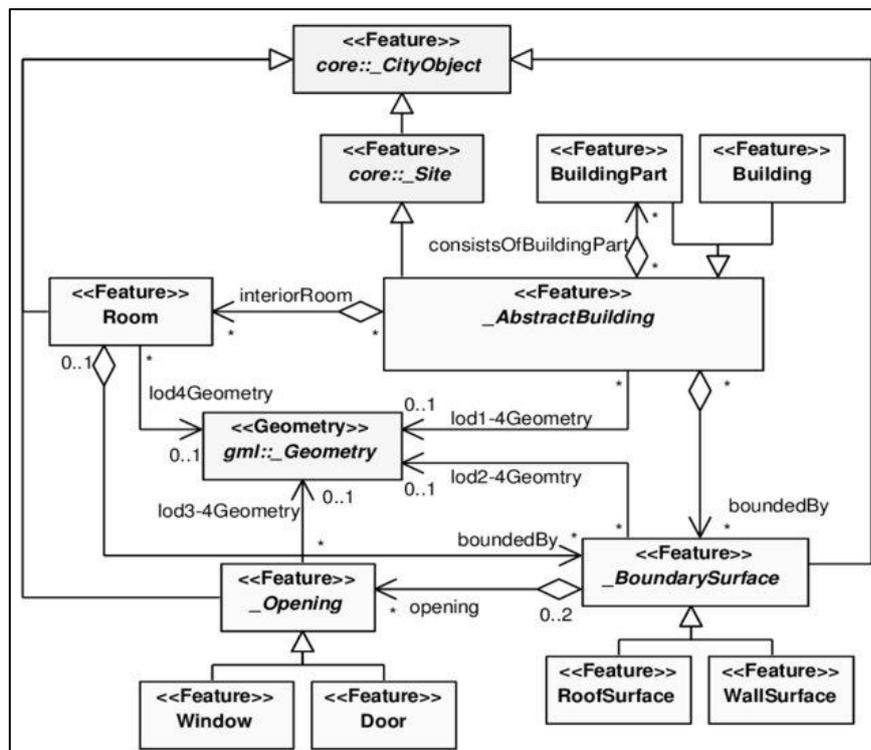


Figure 3 Simplified UML-Model for the building-Module in CityGML [37]

Figure 3 shows the simplified UML-Model for the building Module. A building is defined by several types of surfaces which connect together to a building-part or the whole building itself. Per surface, it is also possible to define openings just like windows or doors.

4.1.1 Level of Detail

Buildings can be modeled in various levels of detail. In general the LOD's are distinguishable in 4 categories:

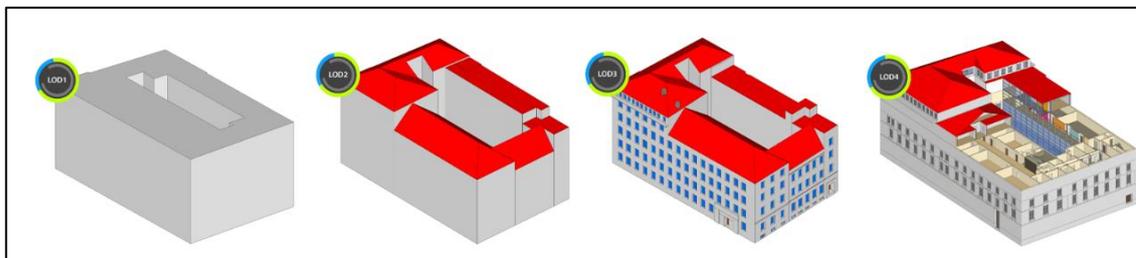


Figure 4 HFT Stuttgart building represented in 4 levels of detail in CityGML [38]

Buildings with Level of Detail 1 are represented as an extrusion of the surface on the ground, up to the average height of all roof surfaces of the building.

Level of Detail 2 adds roof surfaces to the building block and Level of Detail 3 includes wall and roof openings like windows and doors.

Level of Detail 4 includes the interior of a building, such as internal walls and furniture.

Additionally, there is the possibility to model buildings as footprints. This way of representing buildings is referred to as LOD 0.

Mainly in this thesis used is Level of Detail 1 and 2.

4.1.2 EnergyADE

Since the native CityGML schema doesn't support energy-related attributes per building, a so-called Application Domain Extension for that purpose has been introduced. The main idea behind this schema is to enable the calculation of energy flows and the storage of energy simulation results of buildings using CityGML [39]. In general, ADE's can be modeled using either the approach of extending already existing CityGML features or by defining new feature types [40]. For the EnergyADE mostly new feature types are introduced.

The EnergyADE data model consists of 5 different main Modules, where the "EnergyADE Core" module marks the connection to the CityGML standard through the classes "AbstractBuilding", "BoundarySurface" and "Opening" [41].

The module "Occupancy" defines feature types related to the usage of the building, e.g. schedules for the usage of electrical appliances, occupancy schedules, number of occupants, etc.

The module “Construction and Materials” describes feature-types which contain parameters defining the physics of the materials used for the building model. This includes optical properties such as reflectance and physical properties like heat transfer coefficients of several components.

The module “Energy and Systems” describes the amount of energy demand accountable for several end-uses and also information about the setup of the building’s energy-system, meaning the building’s internal energy conversions and storages.

The last module “Building Physics” includes parameters enabling the simulation of thermal single- and multizone buildings.

An additional module (“Supporting Classes” in Figure 5) which inherits supporting classes represents, for example, the feature type “Time Series”, which is needed to include temporal sequences of certain types of physical parameters. Also, weather data is included in this module [24].

Figure 5 shows all modules along with their relationships to each other.

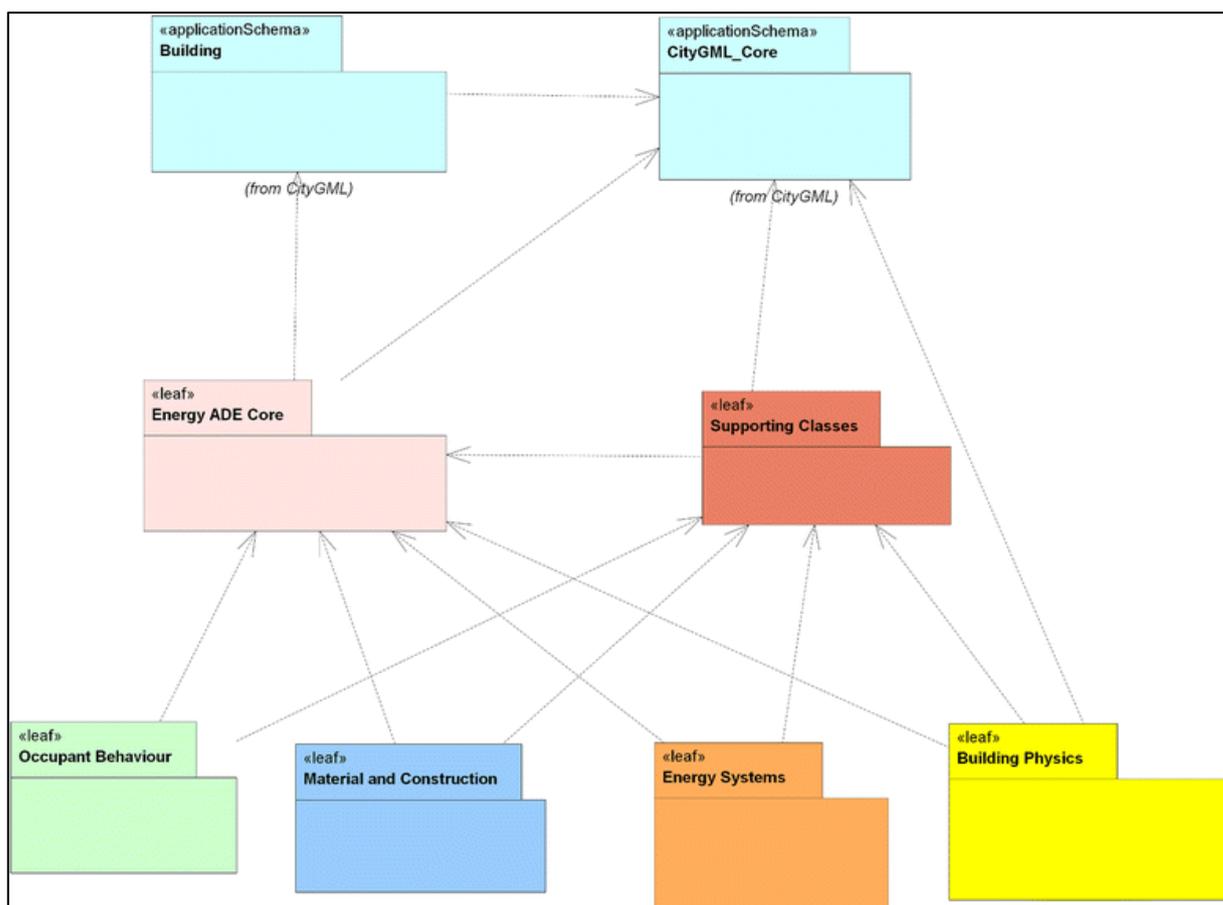


Figure 5 Overview of the EnergyADE [24]

4.2 3D City Model Singapore

The 3D city model in Singapore has been created by an external company (“AAM”) on request by the Singapore Land Authority. It should serve as the digital framework for the Smart Nation initiative.

For the creation of the city model, several imaging flights above Singapore have been made where oblique and Nadir Imagery has been captured. Using the aerial images, a semiautomatic way of modeling LOD1 and LOD2 buildings in the standard CityGML has been found.

In order to increase the accuracy of these models, 5500km of high-density mobile LiDAR Scans and spherical imagery has been harnessed by using mobile mapping systems. [42]

In the end, 45 TB of raw data has been processed and fabricated into 14 TB of deliverable data.

In total around 170000 buildings have been digitalized using this workflow. The storing of the 3D city model is organized using a GIS, where the area of Singapore is subdivided into several zones, each zone is then linked to a folder where the buildings are stored as single files.

4.3 DIN V 18599

In 2002, the European parliament initiated a directive requiring the member states to analyze and improve the energy efficiency of their building stock [43] [44].

Consequently, in 2005, the German Institute for Standards (“Deutsches Institut für Normung“) published a standard to assess the energy efficiency of buildings.

That standard, called DIN V 18599, defines the algorithms and formulas needed to calculate demands for several types of energy in buildings. [45]

It consists of calculation methods for the assessment of the energy demand of heating, cooling, ventilation, hot water and lighting. [46]

4.3.1 Cooling-Energy Demand

The focus in this thesis is put onto simulating the cooling demand. Inside the software used here, the cooling energy demand is calculated using the standard DIN V 18599.

The following sources for cooling energy are regarded in the calculation methods for cooling energy demand.

- Ventilation
- Solar gains and radiation losses via windows and opaque building components
- Internal thermal gains such as people, lighting, appliances

The formulas for calculating the cooling energy demand is regulated in part 7 of DIN V 18599. The main idea of the cooling energy calculation is to define so-called heat sinks and heat sources [47].

Table 1 Differences between Heat Sinks and Heat Sources

Heat Sinks Q_{sink}	Heat Sources Q_{source}
- Loss of heat because of Transmission (Q_{tSink})	- Gain of heat because of Transmission ($Q_{TSource}$)
- Heat loss through mechanical ventilation (Q_{VSink})	- Gain of heat through mechanical ventilation ($Q_{VSource}$)
- Internal Cooling (e.g. water pipes, frozen goods or material throughput, air vents, etc.)	- Solar heat gains through transparent and opaque surfaces ($Q_{STrSource}$, $Q_{SOpSource}$)
- Solar heat loss (Q_{SSink})	- Internal heat gains (e.g. pipes of the heating system, lighting appliances, Persons, machines, heated goods, etc.) ($Q_{iSource}$)
$Q_{Sink} [kWh] = Q_{tSink} + Q_{VSink} + Q_{SSink}$	$Q_{Source} [kWh] = Q_{TSource} + Q_{VSource} + Q_{STrSource} + Q_{SOpSource} + Q_{iSource}$

In energy simulations using a 3D city model, the calculation of heat-sinks and -sources is carried out by taking the orientation and size of the surfaces describing a building into account. Depending on the geometrical situation, different solar gains and other heat sources/losses per area are calculated.

The calculations made for Q_{sink} and Q_{source} lead up to the calculation of a “degree of utilization” (in German: “Ausnutzungsgrad”). This value indicates the ratio of energy used for heating.

Degree of utilization η :

$$\eta = f \left(\frac{Q_{\text{source}}}{Q_{\text{sink}}}, \tau \right)$$

Needed for η is the time constant τ . This value indicates how long a thermal zone needs to be cooled off:

$$\tau = f \left(\frac{C_{\text{eff}}}{H_{\text{T}}, H_{\text{V, Inf+Win}}, H_{\text{V, mech}}} \right)$$

C_{eff} = Effective Heat Capacity of the Thermal Zone [W/Kelvin]

Part of the formula for τ are two Transmission Heat Coefficients H_{T} and H_{V} :

$$H_{\text{T}} = U_{\text{mean}} * A$$

H_{T} = Transmission Heat Coefficient

U_{mean} = Mean Heat Transfer Coefficient [W/m²*Kelvin]

A = Area of Thermal Zone [m²]

$$H_{\text{V}} = \rho_{\text{Air}} * V_{\text{netto}} * \text{ACH}$$

H_{V} = Transmission Heat Coefficient for Ventilation

ρ_{Air} = Constant for Air Density

V_{netto} = Netto Building Volume [m³]

ACH = Air Change Rate [vol/m³]

For the above two formulas, the geometry of the buildings is considered. The area of the to be calculated thermal zone and the building volume can be derived by the 3D city model.

The calculation of η and the Heat-Sinks and -Gains leads up to the final formula for calculating the monthly cooling energy demand:

$$Q_{\text{c}} = (1-\eta) Q_{\text{source}}$$

Q_{c} = the Cooling energy demand [kWh]

This estimation of the energy, which is assigned to the end-use of cooling in buildings, is implemented into the software Simstadt which will be focused on in chapter 6.1.1.

5 Concept

The general questions to be answered in this thesis are referring to the way how 3D spatial data, as it has been created for Singapore, has to be processed, which additional data is needed and how a cooling energy demand simulation can be conducted in general. The proposed methodology should deliver an assessment of the workflow according to several aspects.

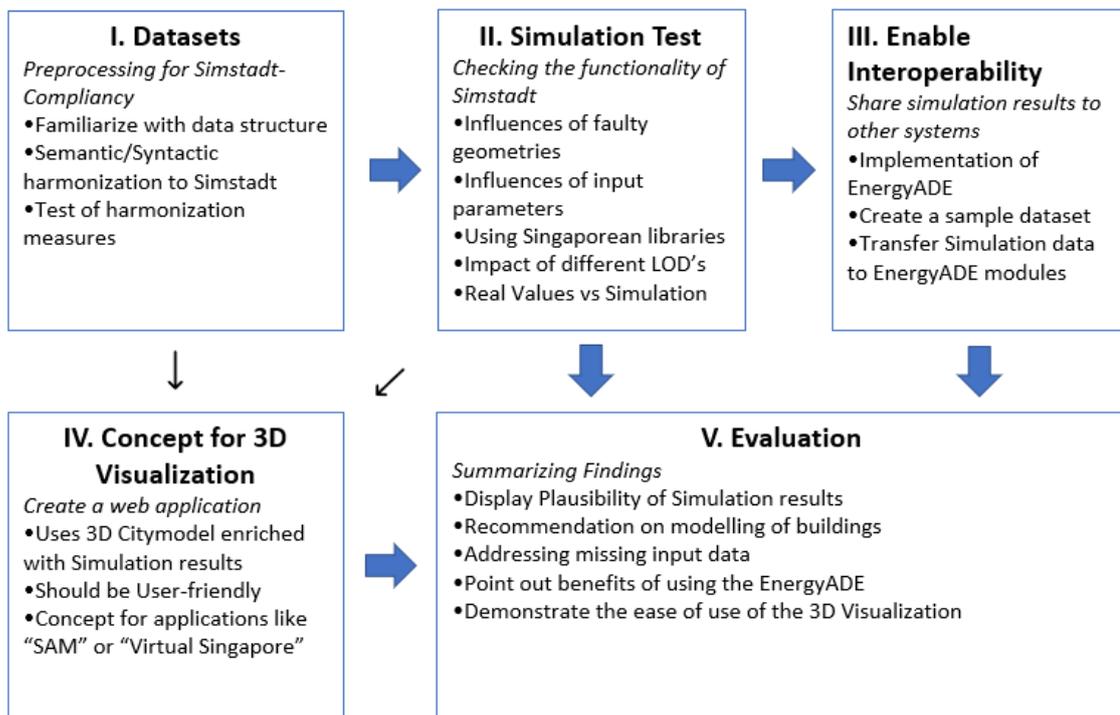


Figure 6 Concept Diagram

In Figure 6 the actions to be done and their connections to other steps are shown. The part "I. Datasets" delivers results, which are used again in the parts of the web visualization and the Simulation-tests. The results of the Simulation-tests are merged together with the input-datasets and -parameters in the setup of a 3D Visualization. The Implementation of the EnergyADE is driven by the results of the Simulation tests. The findings gathered for the Simulations, the set-up of the EnergyADE and the creation of the 3D Visualization are then put together in the final Evaluation part.

Important for the structure of this thesis is that for each part in the implementation, the findings are stated directly after each step is finished. The Evaluation part serves as a summary of the conclusions.

5.1 Usage of different Datasets

After the elaboration of a workflow it should be possible to do a cooling energy simulation for whole Singapore. To find out which additional data is required and what reliability can be expected, several datasets have been selected to stand as a placeholder for larger datasets. To be able to scale the simulation process to whole Singapore, the placeholder datasets are required to contain a wide variety of building types and usages which occur throughout the whole state.

For that purpose, it has been decided to use two datasets with different areas of interest.

The first dataset is representing a normal city district called Yishun. The dataset of the area of Yishun is available in LOD1 and LOD2 and mainly contains buildings administered by the Housing Development Board and therefore are mostly used for residential purposes. The Yishun dataset is introduced to familiarize with the structure in which the 3D city model was created. Several measures will be taken to apply the data model to the Simstadt-needs.

The other dataset is an excerpt of the Central Business District, where mainly office buildings and high-rise towers are located. The dataset has been introduced to test the measures taken for reaching Simstadt-compliance against for this region available real consumption values.

5.2 Preparation of the City Models

First, an analysis of the present datasets is done which concentrates mainly on the semantic part, i.e. the content of the available attributes is examined here. Should it be the case, that incisive information about the buildings is missing, a recommendation for the capturing of the dataset will be made. But in order to be able to carry out the further steps, it will be part of the workflow to find a way to replace missing information in the pilot datasets.

After processing the semantic part of the Yishun dataset, the syntactical part will be investigated. Since the standard CityGML is used to store the whole city model it will be checked if the way how the dataset is put together complies with the newest CityGML schema, more specifically the building module of CityGML.

It is also a goal in this step to find solutions if there is non-compliance of the present data model to the Simstadt simulation environment. This includes setting up software packages and creating programs which allow enabling the validity and syntactical correctness of the datasets.

The conglomerated methodologies and findings for the enablement of compliancy with the Simstadt data model will then be part of the evaluation where recommendations for the data storage and data preparation are made.

5.3 Testing the Simulation-Methodology

After analyzing and preparing the datasets, the simulations of these using the Simstadt-simulation approach are tested. As a first action, the overall functionality of the Simstadt workflow will be checked, meaning that it's going to be investigated if the software is capable of handling the location of the Singaporean CRS, the way how the buildings are modeled and if the declaration of attributes in the given datasets is Simstadt compliant. If that is not the case, ways to harmonize the Singaporean dataset to the needs of Simstadt are to be found, as mentioned in the previous step. For the harmonization, two aspects are looked at: The geometrical modeling and the available Metadata per building.

5.3.1 Influence of faulty geometries

Part of the preparation of the city model is the detection and assessment of modeling errors in the buildings. Should there be modeling errors in the input datasets, it will be investigated which influence these will have, by comparing the simulation outcomes of several buildings with and without faulty geometries against each other. This investigation is used for an assessment of how the simulation of the erroneous buildings is affecting the cooling energy demand assumption. What is made possible with such a review is a differentiation of the results which can help to eliminate the deviations coming from the simulation of buildings with certain error types in larger datasets.

5.3.2 Research and prepare a Singaporean Buildingtypology

In order to analyze the increase of the plausibility, an investigation on Singaporean parameters describing the physical properties of the present building stock is made. It is investigated from where such parameters can be taken during a literature research. It will also be tried to analyze the influence of several parameters on the simulation result for being able to set emphasis on specific input values during the creation of a Singaporean typology, containing all parameters per building type.

After setting up a Singaporean building typology in a Simstadt compliant way, the simulation results using that typology will again be tested against the real consumption values and against simulation results coming from the already existing, very comprehensive German building typology.

Based on that comparison it can be said if the Simstadt methodology changed its accuracy against the results under use of the German building typology or if further research for finding out the most fitting parameters should be done.

5.3.3 Influence of different Level of Details for the input dataset

Since the 3D city model of the district Yishun is given in LOD1 and LOD2, it is possible to analyze the outcome of the cooling energy demand simulation focusing on the influence of geometrical complexity in the input datasets. This gives the chance to assess possible benefits when conducting the simulation with higher detailed datasets.

It could be possible that a higher or lower complexity results in non-plausible simulation outcomes. It might also be the case that the amount of available metadata differs for each Level of Detail which has an influence onto the cooling energy demand calculation as well. In the case of high deviations between the simulation outcomes, an analysis on the dataset's integrity will be done, regarding the amount of available metadata and a recommendation on the use of a certain LOD can be given.

5.3.4 Comparison simulation results to real consumption values

Simstadt, as it is implemented now, includes two libraries describing building physics, as well as usage-specific parameters suiting to building types in Germany. It will be investigated if and to what extent these parameters can be applied to Singaporean building types.

This will be done by putting real consumption values of several buildings into comparison with simulated cooling energy demands of the same buildings. The real values are publicly available for a small selection of buildings in Singapore.

Not only to judge if the monthly energy balance method, as it is implemented in Simstadt, delivers dependable and realistic simulated values, but also to analyze to which extent the modification of Building-physics- and Usage-library can improve the accuracy of the simulation, real consumption values are introduced into the evaluation. Having the reference to real consumption values enables to evaluate how well the Singaporean Parameters are suiting to the buildings in the datasets. It can be the case that the results deviate drastically from the real consumption values and in this case recommendations on the setting up of the input parameters will be done.

5.4 Enable interoperability

Aiming onto the goal of sharing the results to other systems, it is recommended to investigate the possibilities of storing energy-related data along with simulation results in the same city model. Using the approach EnergyADE enables the inclusion into other systems

without depending on external libraries. For demonstrating how the city model can be extended to be used in other GIS-related simulation approaches, sample datasets including the data used for the simulation in Simstadt are created.

5.5 Concept for 3D Visualization

For being able to assess the simulation visually, a web-application showing the 3D city model in combination with the output of Simstadt is set up. The application should enable a user-friendly inspection of the data. The web-application not only serves the purpose of visualizing the pilot area along with the Simstadt-output, it should also provide a concept of how the data then can be used in projects like “Virtual Singapore” or the “Singapore Advanced Map”.

5.6 Evaluation

The evaluation part is aiming to summarize the findings done throughout the implementation of this research. Here the research questions will be revisited and answered based on the findings in the different steps.

Answers will be given on the suitability of the present 3D city models, which additional input data is needed for simulations, general plausibility of the results, as well as how a 3D visualization can be conceptualized. Additionally, the benefits of extending the 3D city model with the available information using the EnergyADE are shown.

6 Datasets used in this Thesis

The datasets used in this research are representative for the use of bigger, more comprehensive datasets. In the future, the concept of conducting cooling simulations should be applied to any dataset describing buildings inside Singapore.

The focus is put onto two different areas. The first dataset describes the area of ‘Yishun’, a district in the northern part of Singapore. All of the following datasets have coordinates given in the coordinate reference system with the EPSG-Code² 3414 which refers to the projected coordinate system SVY21. This coordinate reference system is based on the ellipsoid WGS 84.

Given for Yishun are two file directories containing buildings with two different levels of detail, which are LOD1 and LOD2.

In each directory, the buildings are stored as single files, meaning that one CityGML file contains exactly one building. In total 358 buildings are available in LOD1.

After the creation of a Software which combines all the single buildings to one city model the LOD1 dataset looks as can be seen below:

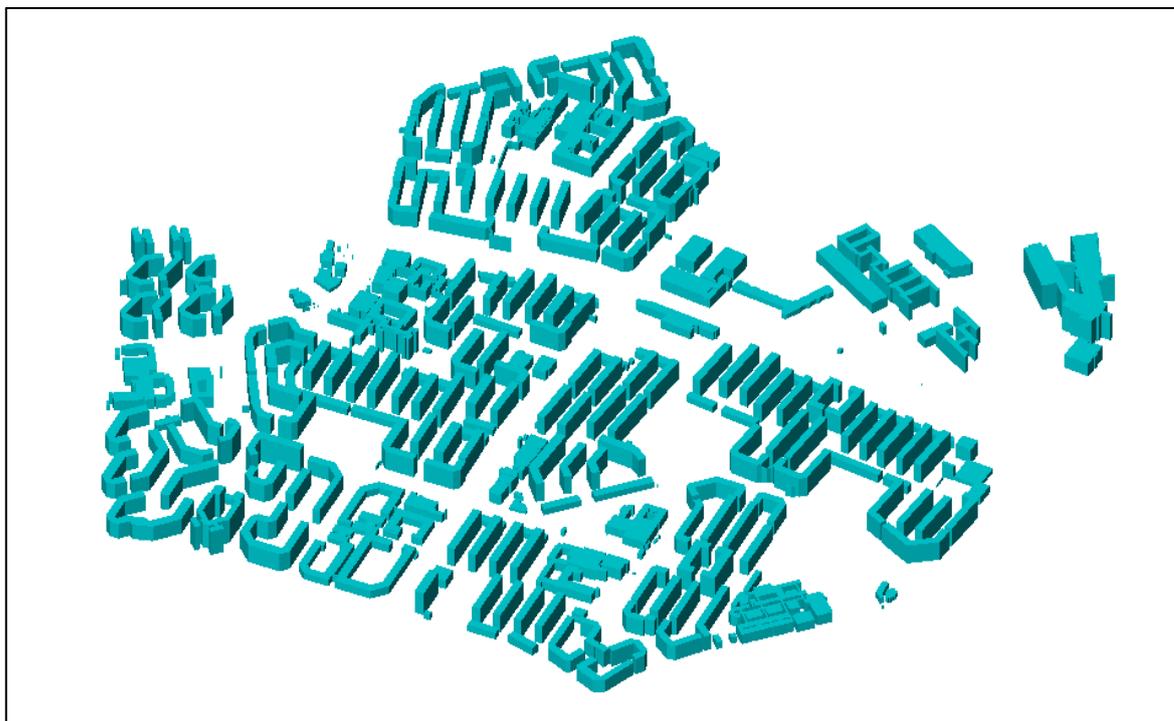


Figure 7 Combined View of the LOD1 CityGML-Files describing the district Yishun, imported into FZKViewer,

² EPSG: European Petroleum Survey Group Geodesy, they developed codes for uniform spatial reference identifiers. Each Coordinate system has a unique number with 4-5 digits.

The program which combines all single files to one coherent city model will be described in chapter 7.2.1.

Since the Software “Simstadt” is used for the simulation of energy-relevant results, a check of available attributes has to be made to ensure the linkage to the libraries enriching the city model with simulation-relevant parameters.

For LOD1 the following attributes are existent for each building:

Table 2 Available Attributes per Building in LOD1 area Yishun

Available Attributes per Building in LOD1 Yishun	
gml:name	Name of the Building (e.g. “AHMAD IB-RAHIM PRIMARY SCHOOL”)
creationDate	For all buildings in the dataset the same: 08.09.2014
bldg:measuredHeight	Measured height between lowest terrain intersection and the highest point on the roof. Since no terrain is given it is simply the height of the whole solid.

As can be seen in the table the attributes `bldg:function` and `bldg:yearOfConstruction` are missing inside the dataset. For the Simulation of cooling energy demand based on the DIN V18599 inside Simstadt, there is no alternative than adding these attributes to the already available ones of each building.

In this thesis, a preliminary method for the enrichment of the needed information has been found. This method will be described in chapter 7.2.2.

Also, for this research available is a dataset describing the same buildings as in LOD1, now in LOD2. In total there are 348 buildings stored in the LOD2 directory. After merging all the CityGML files together, the LOD2 Dataset looks like this:

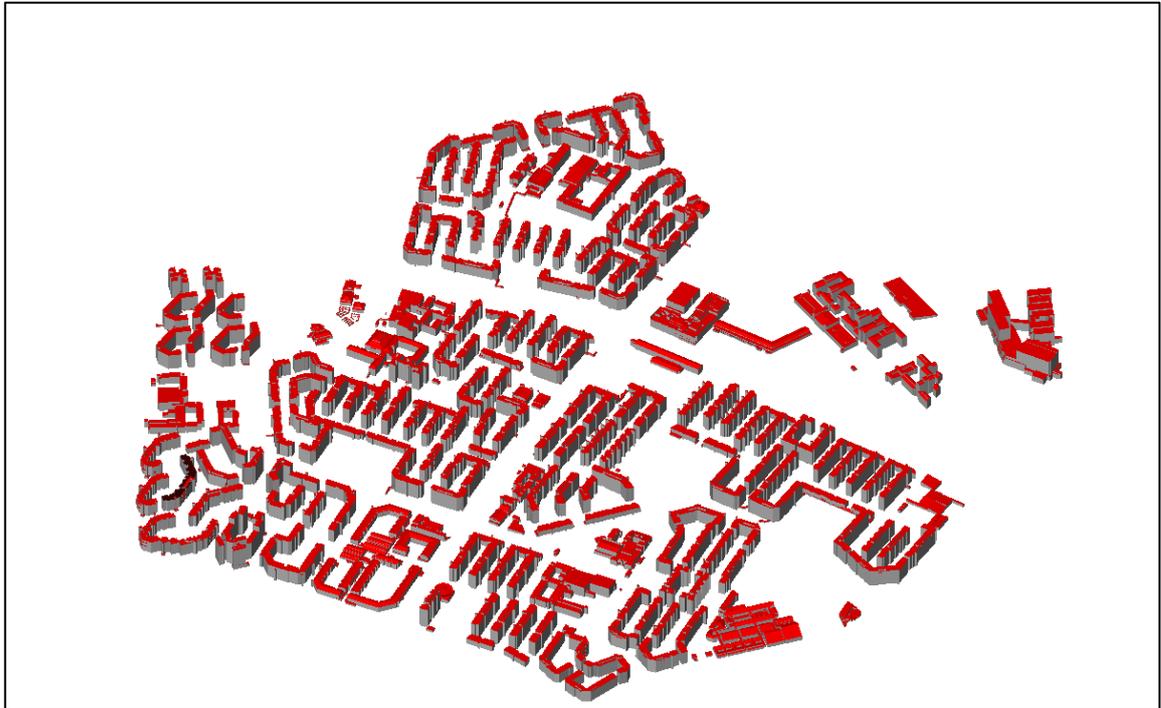


Figure 8 Combined View of the LOD2 CityGML-Files, imported into FKZViewer

Not only geometry-wise but also on the semantic level, this dataset is created with more comprehensive information available per building than LOD1.

The geometry gives information about the shape of the roof, which is a crucial part of the method inside Simstadt. Depending on the roof shape it will be automatically decided if the attic of each building will be accounted to the area to be cooled.

In the LOD2 dataset the following attributes per building are available:

Table 3 Available Attributes per Building LOD2 area Yishun

Available Attributes per Building in LOD2 area Yishun	
gml:name	Name of the building
creationDate	For all buildings the same: 05.01.2016
bldg:class	Contains codes referring to the Usage class of a building (e.g. Code 1050 -> refers to recreational buildings)
bldg:function	Contains codes for the exact use of a building (e.g. Code 3190 -> Chinese Temple)
bldg:usage	Basically refers to the same Codes as in function, but has been left empty for each building
bldg:measuredHeight	Measured height between lowest terrain intersection and highest point on the roof. Since no terrain is given it is simply the height of the whole solid.
bldg:storeysAboveGround	Number of floors above ground.

In above table it can be seen, that there is still missing the year of construction per building.

Since this attribute is a key-information to enable the simulation, it has to be manually introduced. During the research for the enrichment of missing attributes for the datasets, it has been found that this specific attribute can also not be derived by cadastral data, since the cadastral system in Singapore as it is now, is only enlisting the parcels and not the buildings itself. This is a minor difference to the German cadastral system, where the parcel and the building on it are separately modeled and kept with information just like the year of construction and function of each building.

But the Singapore Land Authority is planning to introduce a 3D Cadastral system, where that information is made available per apartment.

To be able to define a preliminary uniform year of construction for a whole dataset, an analysis on the most suitable date has been made. More on that analysis in chapter 7.2.2.1.

The first two datasets are used to investigate methods to harmonize the existing data model to the needs of the software Simstadt.

These methods and findings will then be used to test the derived simulated cooling energy demand and reachable reliability.

For that purpose, real consumption data has been found, but only for a selection of buildings. Since these buildings are mostly located in the Central business district of Singapore, the 3D city model for the test has been put together with a selection of 232 buildings. It has been decided to use the buildings modeled in LOD2 since the capturing of these are more up to date than the LOD1 model.

The reason for this is that the LOD1 model as it is existing for whole Singapore now has been created based on an extrusion of building footprints using height information of a LiDAR Scan conducted in 2014. Those footprints used for that purpose have been put together a long time ago and might bear some data uncertainties since many sources were consulted for the creation of these.

In future, it is planned to use the more up to date LOD2 city model and derive LOD1 buildings from it, by using the LOD2 Footprints and the height of each building modeled in LOD2.

The image below shows an excerpt of the full LOD2 city model put together for the area of the Central Business District around Raffles Place.

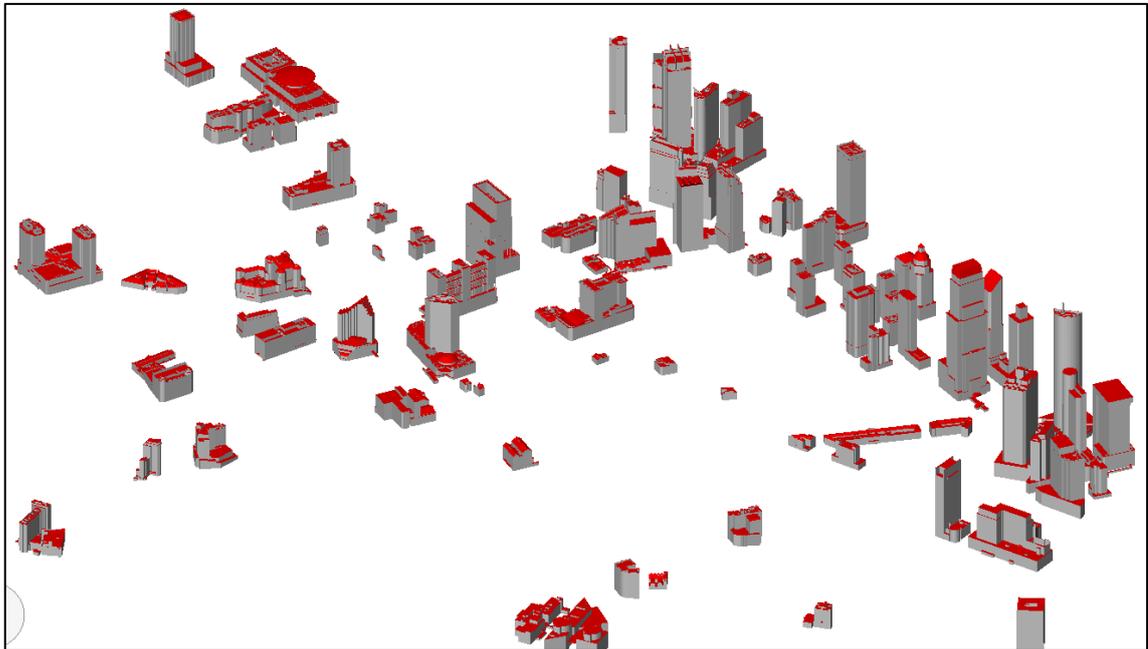


Figure 9 Excerpt of the LOD2 CityGML Dataset, Central Business District

The real consumption dataset has been derived from the open data portal “data.gov.sg” [48]. This portal contains datasets from 70 public agencies in Singapore. One of these agencies is the Building and Construction Authority (BCA). The BCA collects building information and energy consumption data on an annual basis. This collection is regulated by the Building Energy Submission system (BESS) which is in turn mandated by the building control act from 1990.

The dataset contains attributes referenced to the Green Mark Certificate. It is an assessment system, to rate the environmental impact and energy performance of a building.

Following table shows which attributes were captured per building.

Table 4 Attributes in Energy Consumption dataset

Dataset Title: Voluntary Disclosed Energy Performance Data for Commercial Buildings	
Building Name	Name of each building
Building Address	Consisting of the name of the Street, House Number, and Postal Code. The Postal code in Singapore is unique for each building.
Building Type	Describes usages of the buildings: Office Building, Hotel, Retail Building, Mixed Development
Green Mark Status	Green Mark Rating is given, yes or no
Green Mark Rating	Rating in the Green Mark building energy test (good to bad: Platinum, GoldPlus, Gold, Certified)
Green Mark Year Award	Year of Green Mark certification
Building Size	<p>Large Size Commercial Buildings:</p> <p>i) Office Building, Retail Building, and Mixed Development - GFA $\geq 15000 \text{ m}^2$</p> <p>ii) Hotel - GFA $\geq 7000 \text{ m}^2$</p> <p>Small Size Commercial Buildings:</p> <p>i) Office Building, Retail Building, and Mixed Development - GFA $< 15000 \text{ m}^2$</p> <p>ii) Hotel - GFA $< 7000 \text{ m}^2$</p>
Gross Floor Area	The total floor area [m^2]
2015 Energy Use Intensity	Energy Consumption in [$\text{kWh}/\text{m}^2.\text{yr}$]
2016 Energy Use Intensity	Energy Consumption in [$\text{kWh}/\text{m}^2.\text{yr}$]
Voluntary Disclosure	Yes or No (in case of No, there is no data available for the respective building)

The dataset exists as CSV-file describing the details for 948 buildings. For some buildings, no address and names are given which reduces the amount of usable data to 585 entries.

7 Implementation

This chapter aims to describe the procedure, which has been carried out for testing and setting up a workflow for cooling energy simulations in Singapore.

7.1 Used Software

7.1.1 Simstadt

This software “Simstadt” has been developed in the frame of a project with the same name and has been published in the year 2015 [49]. The aim of this Java-based software is to include physical models of buildings, energy systems and distribution networks for the energetical analysis of buildings on an urban scale.

Simstadt can be described as an engine which performs energy-related analysis workflows based on 3D city models.

The workflows in Simstadt are made up of several processing steps which can be put together on a modular basis to create different outcomes.

Up to now, 6 different workflows are defined by using the different processing steps:

- Solar Potential Analysis
- PV Potential Analysis
- Environmental Analysis
- Environmental Analysis with Refurbishment Strategy
- Heating/Cooling Demand Analysis
- Heating/Cooling Demand Analysis with Refurbishment Strategy

The workflow Solar Potential Analysis is capable of calculating the radiation on each surface of the given 3D city model. The results strongly depend on the local weather data and the chosen radiation model, which can be chosen to include shadows and reflections, thus leading to longer processing time.

The Photovoltaic Analysis is estimating the power of solar panels placed on rooftops. It also includes a cost analysis, showing the to be expected price for installing the simulated solar panels.

The environmental Analysis is able to calculate the primary energy for each building. For that purpose, the workflow computes energy demand of the different end uses like space heating/cooling, domestic hot water, and electrical appliances. The calculated Primary energy which is the sum of the end-use, is then multiplied with a CO₂-emission-factor, which then results in the actual CO₂ emission per building.

The Heating/Cooling Demand Analysis is the workflow this thesis is focused on.

In the following, a description of how the workflow is concluding to results is stated.

An absolute requirement is a 3D city model in the format CityGML for the Software to work. This 3D city model has to include buildings with at least the attributes “Year of Construction” and “Function”. Having this information ready enables the connection to other libraries, which enriches the information per building even more. These libraries are the so-called Usage-Library and the Building-physics-library. The software-package Simstadt comes with editing-programs with a GUI for each library, enabling modification of the input-parameters, for the adaptation to the to be simulated building stock.

The fact that each building is assigned with a function attribute, enables the connection to the Usage-library. The library is structured into different Usage-types, such as residential, office, education, health care, etc. The distribution of the function attribute coming from the building itself, into the Usage-types is done according to a mapping which can also be specified in the Usage-Library-Editor software.

Per Usage-type several parameter-topics can be added. Distributed into the parameter-topics are the actual parameters which will be used for the calculation of the cooling energy demand according to the DIN V 18599.

Figure 10 shows which parameters are stored inside the Usage-library.

To also include Building-physics-related Parameters, which define the thermal characteristics of the fabric of the buildings, a Building-physics-library is also implemented into the Workflow. The Building-physics-library is structured into different building types. The library designed for a German building stock includes single family houses, multi-family houses, big multi-family houses, row houses, and skyscraper. Depending on the geometrical properties as described in chapter 7.2.3, a classification into each building type is done. For example, a building is classified as the German building type skyscraper, if it is taller than 23m.

Since the input dataset has to include a year of construction value, the building types are structured into year of construction epochs. Each epoch contains then the specified Building-physics-related parameters.

Figure 11 shows the structure and the parameters occurring in the Building-physics library.

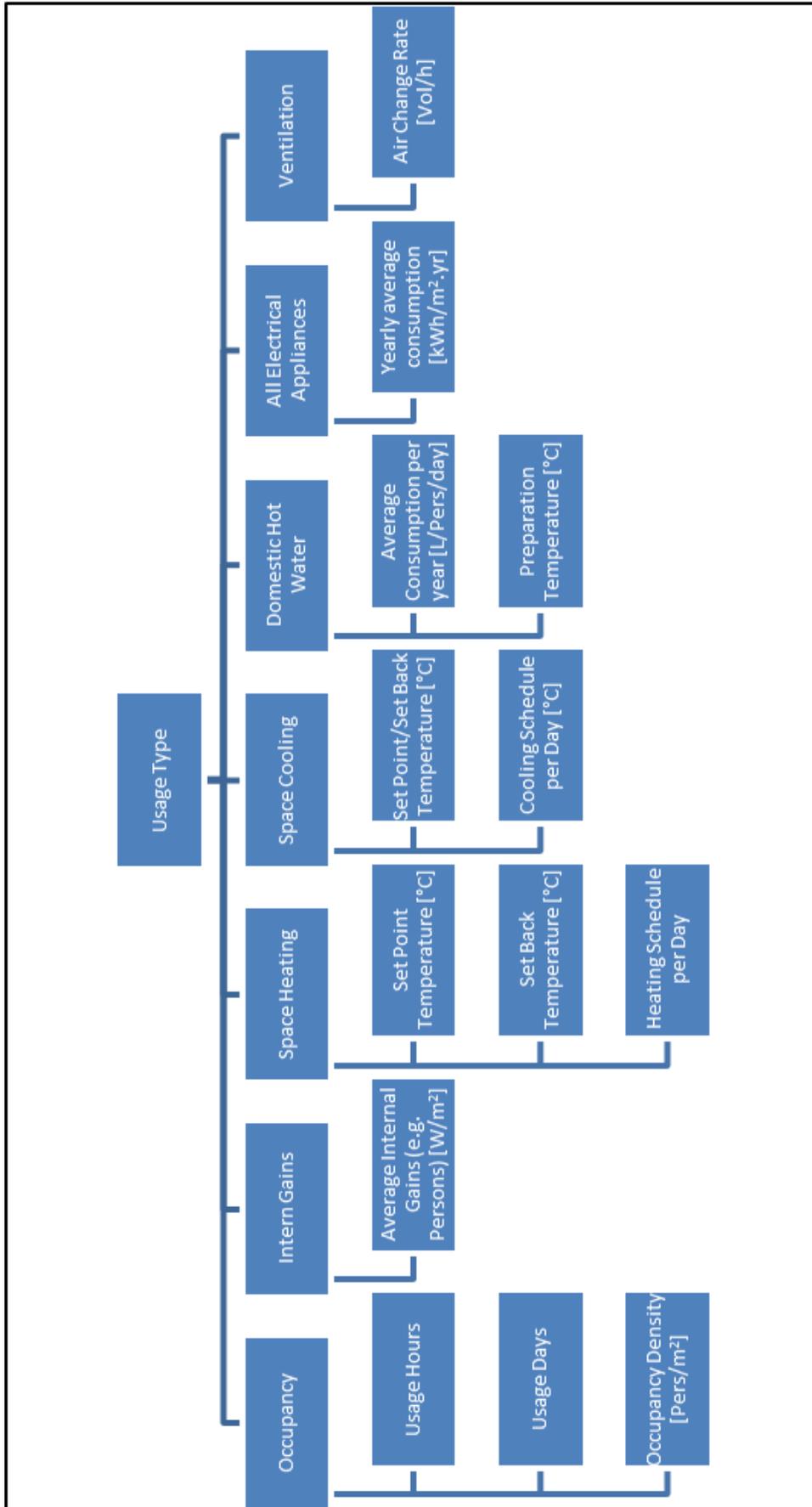


Figure 10 Structure of the Usage Library

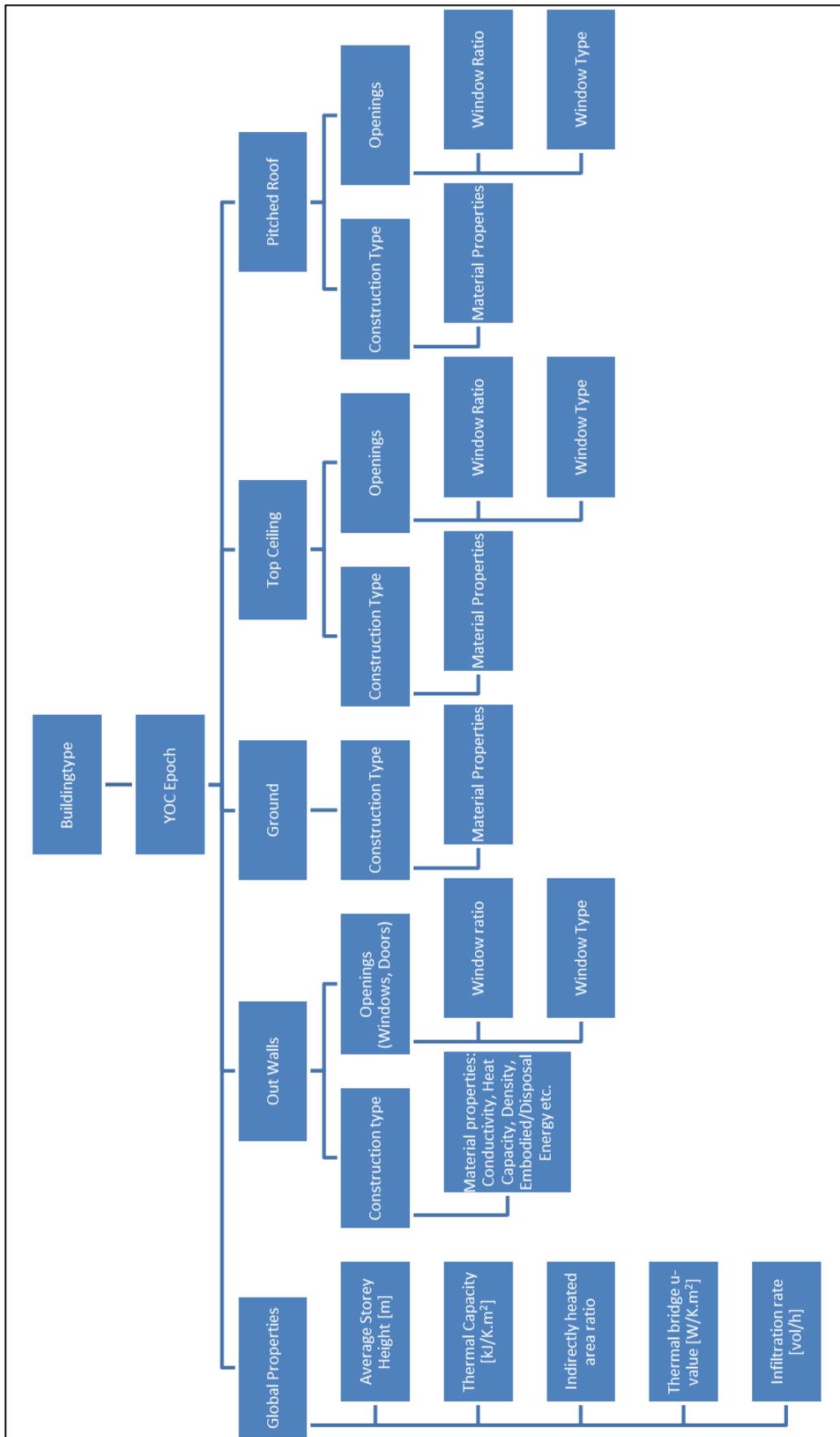


Figure 11 Structure of the Buildingphysics Library

After the preparation of the libraries, the workflow for estimating the heating/cooling energy demand is ready to be started. Having launched the GUI of Simstadt, a new project folder has to be created, and the “Heating Demand Analysis” workflow to be selected. A display of the several workflow steps is then shown. Each step is selectable and contains additional options to modify the workflow according to the user’s needs. The workflow steps are the following ones:

1. Import CityGML

This step imports the CityGML file into the workflow and optionally checks if the file is valid against its declared schema definitions. Also, the number of buildings for each level of detail is counted.

2. Create Simstadt Model

The city model is analyzed for available information per building. This includes a check of already existing EnergyADE-information in the input datasets. After that analysis, each attribute is extracted and stored in a so-called Simstadt-model which simply enables the software to use all attributes in further processing steps.

3. Geometry Preprocessor

Important geometrical attributes for the calculation of the final monthly energy balance are calculated. This includes the building’s volume, the amount of area covered by neighboring building’s, the height and other attributes.

4. Physics Preprocessor

In this step, the connection to the Building-physics-library is done. Depending on the geometric attributes, a classification into a building type is made, and the predefined parameter set per type is added to each building according to the compulsory included YOC-attribute in the input data set.

5. Usage Preprocessor

Here the assignment of usage-related parameters to the building is done based on the function-attribute of each building. It is possible to assume residential usages if the function attribute is left empty in the input dataset. These parameters enrich each building energy model to enable the calculation of the monthly energy balance.

6. Weather Processor

The database of the external software “Insel” is accessed to be able to include the local outside temperature into the calculation. More specifically the temperature in the sky, on the ground and the irradiance levels (Direct, Global, and Diffuse) in W/m^2 are specified by the information stored inside the database of Insel.

7. Radiation Processor

For this step, different radiation models are taken into account to make assumptions on the sun's radiation on each surface. Depending on the chosen radiation model, the software is capable to include shadows and reflections coming from the different surfaces in the 3D city model into the final calculation of the energy demand.

For each surface, the area, the tilt, and the azimuth are evaluated and an irradiance value allocated.

8. Monthly Energy Balance

Here the information of the previous steps is gathered for the final output of an energy demand value on buildings scale. Depending on the settings done before the simulation process is started, the output will be including heating or cooling energy demand or a combined output file, where both calculation results are listed per building. The exact calculation is done according to the workflow as described in chapter 4.3.1.

7.1.1.1 EnergyADE in Simstadt

Simstadt makes use of 3D city models which are described in the OGC standard CityGML version 2.0. This standard doesn't include attributes describing energetical properties of a building. To counterfeit this issue, the EnergyADE for CityGML has been developed. A short description of the EnergyADE can be seen in chapter 4.1.2.

Having a 3D city model which includes the objects and attributes as defined by the EnergyADE per building as input datasets, eases the processing of this data through Simstadt, since the parameters of the Usage- and Buildingphysics-library, which are basically assumptions on the characteristics of the building stock, won't be used for the estimation of the cooling energy demand. This delivers, in turn, the most plausible simulation results.

7.1.2 CityDoctor

CityDoctor is a software which enables to check and validate 3D Geometries written in CityGML. It has been developed at the HFT Stuttgart in cooperation with the Beuth University of applied Sciences. Using this Software enables the exact allocation of errors in the CityGML code and also as a visualization on the 3D Model itself.

The possible checks are subdivided into several categories. The first group of Checks are polygon checks, which mainly deal with the amount and sequence of points declaring a polygon and the assessment of the topological behavior to each other like invalid intersections. The category solid-checks is containing tests which prove the validity of solids. It is checked here if a solid is closed with the needed amount of faces and orientation of the surfaces. The category semantic-checks is checking if each surface is modeled as it is declared in the code. Other tests are located in the group of additional checks. The checks

which have triggered errors throughout the creation of this thesis are described in chapter 7.2.3.

7.1.3 FZKViewer

This software is used to do a quick inspection of the 3D city models in this thesis. FZKViewer allows analyzing if buildings have been successfully modeled in LOD2 or LOD1 [50]. Also, it is possible to check which attributes are existing per building, without opening the CityGML-code itself.

It has been developed at the “Karlsruhe Institut für Technik” (KIT).

7.1.4 CesiumJS

CesiumJS is not a standalone software, but a JavaScript library allowing to create browser-based 3D visualization applications. In this thesis, this framework will be used as the basis of a visualization showing the cooling energy demand in combination with the 3D city models.

7.2 Prepare Singaporean City Models to enable Simulations

Simstadt's simulation result reliability depends on two factors: the parameters with which the 3D city model is enriched and the structure of the city model dataset itself. In this section, it is described how the used city models are structurally processed in order to fit into the requirements of Simstadt. The following workflow has been applied:

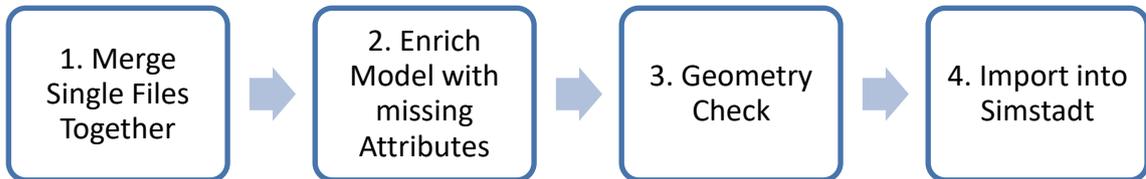


Figure 12 Workflow for the preprocessing of the 3D city models

7.2.1 Merge files together

Since the buildings for LOD1 and LOD2 of the district Yishun and CBD are stored as single files, a program has to be written in order to merge all the files together into one single CityGML file. Simstadt is designed to calculate the monthly energy demand by using one CityGML File, which contains multiple buildings in an area. Having the buildings combined into one 3D city model allows the software to calculate for example the amount of outward-facing walls since areas of surfaces touching another building are excluded from the calculation because there's no cooling energy absorption taking place.

The software for creating the coherent CityGML-Files for LOD1 and LOD2 has been written in Java, and is running through the following steps:

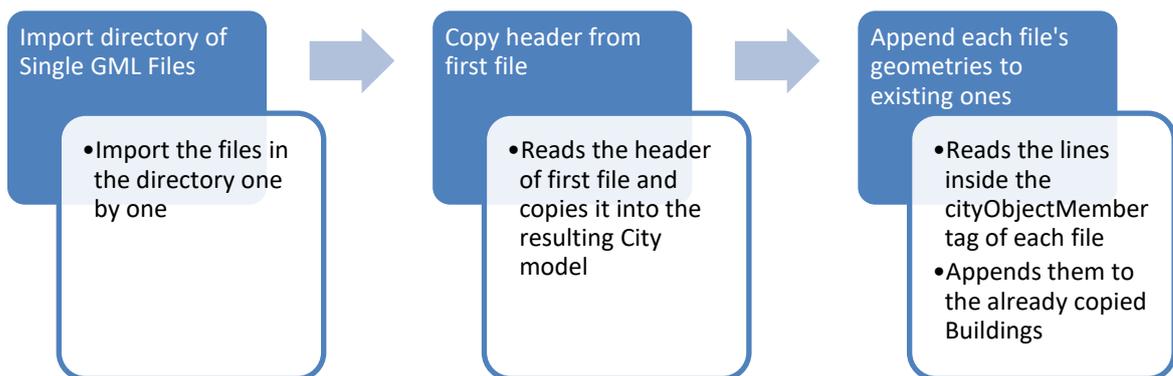


Figure 13 Steps creating a combined CityGML File

As import-path, the folder where all single GML- files are stored is selected. The software uses a for-loop to read file by file into the process which copies the lines of importance.

Each file is structured into a ‘header’, a bounding box and of course the “cityObjectMember”-tag which contains the attributive and geometrical information of a building. Along with the attributes shown in chapter 6, there comes information about the address of each building - represented by the ‘xAL’ namespace, and in the LOD2 case information about the textures of a building – represented by the Appearance - ‘app’-namespace.

Since Simstadt doesn’t make use of the textures a building has, the lines in the GML Files which have the appearance-identifier ‘app’ in it, are deleted during the import into the Java-program. The texture information also consumes unnecessary storage space which causes longer processing times in the software packages used in this thesis.

```

<?xml version="1.0" encoding="UTF-8"?>
<CityModel xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns="
http://www.opengis.net/citygml/2.0"
  xmlns:xAL="urn:oasis:names:tc:ciq:xdschema:xAL:2.0" xmlns:xlink="
http://www.w3.org/1999/xlink"
  xmlns:gml="http://www.opengis.net/gml"
  xmlns:bldg="http://www.opengis.net/citygml/building/2.0"
  xmlns:app="http://www.opengis.net/citygml/appearance/2.0"
  xsi:schemaLocation=" http://www.opengis.net/citygml/building/2.0
http://schemas.opengis.net/citygml/building/2.0/building.xsd
http://www.opengis.net/citygml/appearance/2.0
http://schemas.opengis.net/citygml/appearance/2.0/appearance.xsd">
  <gml:description>3D City Model of Singapore</gml:description>
  <gml:name>T12A0171</gml:name>
  <gml:boundedBy>
    <gml:Envelope srsDimension="3" srsName=
"urn:ogc:def:crs,crs:EPSG::3414,crs:EPSG::6916">
      <gml:lowerCorner>27406.610 46148.484 8.400</gml:lowerCorner>
      <gml:upperCorner>27424.651 46185.933 18.852</gml:upperCorner>
    </gml:Envelope>
  </gml:boundedBy>
  <cityObjectMember>
    <bldg:Building gml:id="SLA BLDG2 8e4488f9-e707-4c24-afe1-f7e552f711e4">
  </cityObjectMember>
</CityModel>

```

Figure 14 Excerpt of a CityGML-file (single building)

Above screenshot (Figure 3) shows the content of one GML-file representing a single building. The part which is copied from the first File in each folder is shown in sector A, the part which is copied from each file is simply the content inside the Tag “cityObjectMember” – here part B. A recalculation of the bounding box for the whole file can be included into future works but doesn’t throw errors in the to be explained validation of the 3D city models in chapter 5.3.1, nor produces errors in the calculation of cooling energy demand values.

In Figure 14, the tag “bldg:Building”, which contains the geometrical and attributive data for each building is collapsed. At the end of the combined file, the “city model” closing tag is appended.

The 3D city models in Figure 7, Figure 8 and Figure 9 have been created by first processing the single buildings with described Java-program.

7.2.2 Enrich the City Model with missing Attributes

To be able to test the cooling energy demand simulation, it is necessary to add the missing attributes per building. This will be done by including the information into the files representing the combined city model. To be able to derive an output of Simstadt, the software needs at least a year of construction and a function as attribute per building, with which a connection to the Usage-library and Building-physics-library is made possible.

In the LOD1 datasets, both information is missing, in LOD2 in most cases, only the year of construction is additionally needed.

7.2.2.1 Year of Construction

In chapter 6 it has already been mentioned that the year of construction hasn't been captured for all of the input datasets and it is not possible to derive this attribute from other official sources due to the fact that it is mostly classified as confidential information. It will also be mentioned in the synthesis that in a proper implementation of the here described concept, a way of including the real attribute values into the 3D city model has to be found.

For being able to still conclude on a successful analysis of the simulation methodology in this research, the YOC-values for each building will be filled with attribute values which fit the best in comparison to real consumption values. Using this approach displays the reachable accuracy of the workflow and serves not only the purpose of enabling the simulation but also as a test of sensitivity of the input dataset's YOC-parameter for the Simstadt methodology.

For these reasons, an analysis on a variation of the building years is made. As it has been explained in chapter 7.1.1, the German library, delivering parameters for the building physics of certain building types, is subdivided into several year-of-construction epochs. Looking onto the building type Skyscrapers, which simply describes buildings higher than 23m, the classification has been made into 4 different epochs:

- Before 1968
- Between 1969 to 1978
- Between 1979 to 2013
- After 2014

Comparing the geometrical properties of each building type in the German building typology to the actual building stock described in the given CityGML Files, it has been discovered that most of the buildings in Singapore are classified as skyscrapers. Therefore, for this test, the epochs of the building type skyscraper have been elected.

To address the parameters stored in each year of construction epoch, 4 different simulations are carried out, where the year of construction attribute has been set consecutively to 1960, 1970, 2000 and 2016 for all buildings.

The actual introduction of the year of Construction attribute is simply done by inserting the following text according to the schema of the building module of CityGML.

```
<bldg:yearOfConstruction>2000</bldg:yearOfConstruction>
```

It has to be inserted after the “gml:name” tag.

The different simulation results for several examples of year-of-construction epochs are set into comparison to real consumption values which in turn enables to define the most probable building year for the whole building stock, assuming that the Simstadt workflow delivers plausible values when having the real YOC-values available.

7.2.2.2 Evaluation on differing YOC-Values

In the following charts, the specific cooling demand simulated under the use of different years of construction has been compared to the real consumption values made available by the BCA. The 3D city model which is mainly describing buildings in the Central Business District area has been used because of being related to the same buildings as in the real consumption values dataset. Important to state is that the building’s area already is processed in order to have a valid geometry. A way how to do that is described in chapter 5.3.1.

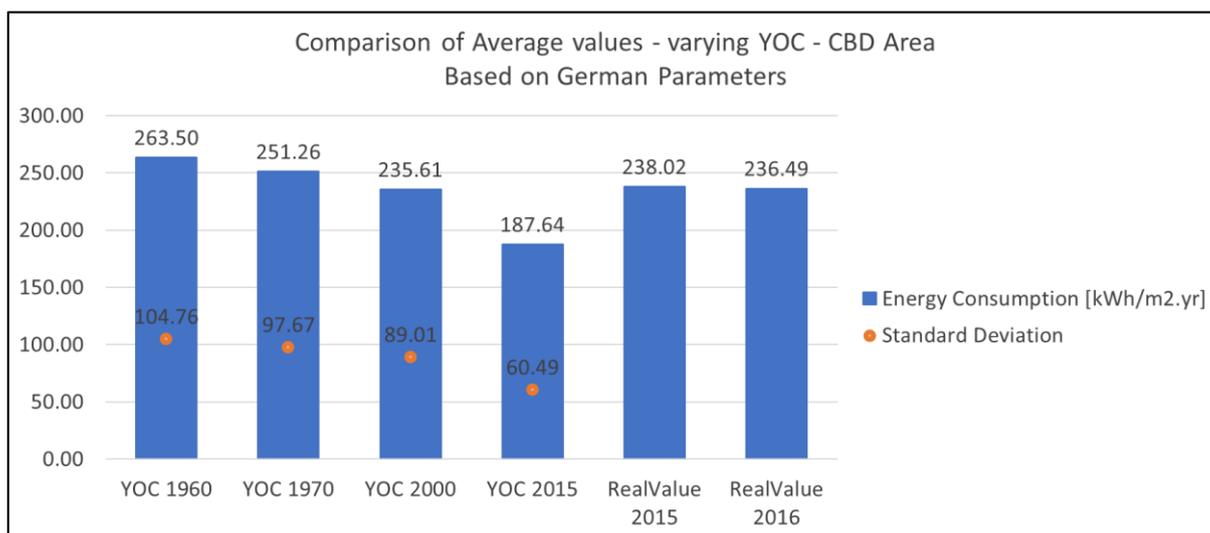


Figure 15 Comparison between average values per variation of year of construction and real consumption values

Having simulated each dataset under the use of the German libraries in Simstadt with a varying year of construction value allows creating the diagram seen in Figure 15. The average of the simulated specific cooling energy demand of all buildings is taken here and set into comparison to simulations of datasets with other building years and the real

consumption values. According to this diagram, it can be said that the average of all building's cooling energy demand is the closest to real consumption values when all buildings are set to the year of construction 2000. Including the standard deviation, it can be said that the values for a theoretical YOC of 2015 deliver the results with the least scattering. The problem with the result as seen above is that the average value doesn't represent how good the simulation of the buildings in a certain range of the simulated energy demand fits the real consumption value.

This why another visualization is introduced to show the accuracy of the simulations focused onto the result per building:

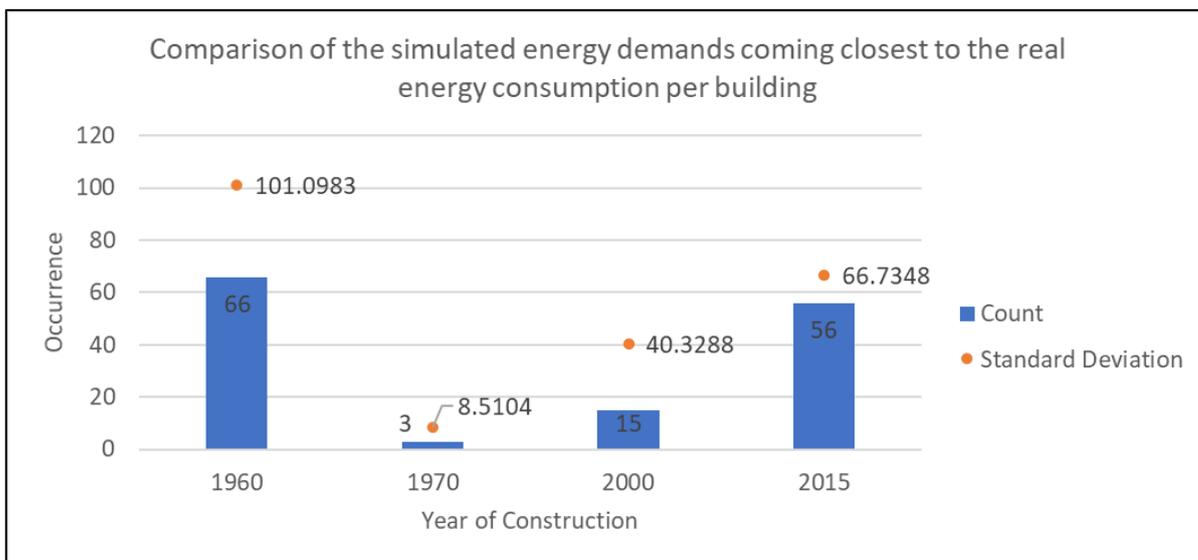


Figure 16 Comparison of nearest simulated values to the BCA real consumption of 2016

Figure 16 has been created taking a comparison of the specific cooling energy demand throughout all simulated YOC epochs per building into account. For example, if the simulated specific cooling energy demand for the YOC 2000 is the closest to the real consumption value of the year 2016, the building will be assigned to the bar in the diagram for buildings with the YOC 2000.

This diagram shows a completely different distribution of the simulated energy consumption of the buildings. Here it can be said, that for the most part, the real consumption value fits most to the simulation where all buildings are put to the YOC 1960 and older. But in both diagrams, the data uncertainty of the real consumption values plays a significant role. There is no information given to which end-use the energy consumption value in 2015 and 2016 is assigned. Most likely these values are describing the overall energy consumption of a building and not like in the simulated values, only the energy for the end-use cooling.

Looking onto the standard deviation, it can be said that the biggest scattering of results has been discovered for the buildings which have a simulated value the closest to real consumption using the YOC 1960.

Based on the standard deviations it is decided to assume the YOC 2000 for all buildings. This epoch delivers values located in the middle of the whole spectrum of standard deviations. Having a medium grade of scattering assures that the amount of energy demand estimation blunders³ after a simulation is decreased to an acceptable quantity. Assuming to have a building stock built in 1960 and older delivers a wide range of different results and is bearing mostly overestimated energy demand assumptions. Assuming a YOC of 2015 delivers also a very wide range of different values and the simulation for the energy mostly underestimates the demand in comparison to the real consumption. The YOC of 1970 hasn't been chosen because the standard deviation in Figure 16 is based on too few values in order to be significant and the small total number indicates that the least amount of buildings really fits real consumption values.

In terms of assessing the influence the Parameter YOC has, it can be said that this attribute is having a very high influence onto the workflow which rises the importance of capturing this attribute correctly. Also, this test has shown, that Simstadt is capable of calculating values which seem to be plausible. This circumstance will be picked up again in chapter 7.3.1.

7.2.2.3 Function-Attribute

After manually inserting the YOC using the replacement-function of Notepad++ [51], the function attribute has to be added.

In all of the LOD1 CityGML datasets no function attributes are given, but for a part of the building are descriptive names existent. These are stored inside the "gml:name" element.

The name of each building is looked up in internet research, where the description of the building can be interpreted and assigned to a building function which is also existent in Germany. The function then can be mapped to a certain ALKIS Code. The mapping to German functions has to be done in a first simulation since no library referring to a Singaporean function code list is existing in the first place. Also, the existing library consists of already very comprehensive parametrical descriptions for each usage type.

In Table 5 an excerpt of the mapping between the building names and their derived function can be seen. Most of the time the building name inherits several keywords which gives already hints on the usage (e.g. Primary School – Kindergarten).

³ "Blunders" in this case: very high differences between Real consumption and Simulated value

Table 5 Mapping of Building names to ALKIS Codes (excerpt)

Name	Function	SLA Code	Most Likely ALKIS Code
AHMAD IBRAHIM PRIMARY SCHOOL	Kindergarten	2380	3065
AHMAD IBRAHIM SECONDARY SCHOOL	School	3160	3021
CHONG PANG CITY	Mall	1170	2050
CHONG PANG COMBINED TEMPLE	Chinese Temple (Church)	3190	3041
CHONG PANG COMMUNITY CLUB	Communitybuilding	2250	3044
CHONG PANG FOOD CENTRE	Food Centre (Restaurant)	3120	2081
CHONG PANG GARDEN	Residential Building	1000	1010

The circumstance that the German usage library is used, is causing problems with the wide variety of building functions in Singapore. Because of the multiethnic character of Singapore, there are many different religions in the region. However, the German Usage library as it is implemented now has no other function codes for religious buildings than churches. In contrast to churches, most temples belonging to other religious believes are used almost daily. This makes it complicated to decide which function should be assigned to buildings since the occupancy schedules are different.

In the above table, the function codes as provided by the SLA are also shown. For the actual simulation of the LOD1 dataset in Simstadt, the German ALKIS Codes have been added in the CityGML Code. For the LOD2 case a mapping between SLA-Codes and ALKIS-Codes has been done, to enable the simulation using German parameters with SLA-Codes in the CityGML file. Further details on that can be seen on page 50.

A complete mapping of the name of buildings in LOD1 to its German counterpart and function code can be seen in Annex 1.

Important to state is that not for all of the buildings a descriptive name attribute is available, e.g. in the LOD1 dataset of Yishun there are 67 out of 352 buildings which have as name: "Building Name Unknown". In these cases, the box "Assume residential if unknown" is checked before the simulation process inside Simstadt. That function links buildings which have an empty function attribute to the Usage library where parameters for residential buildings are then used.

The now found function of a building is then simply inserted by using the Notepad++ replacement functionality. Following the sequence of the CityGML-schema files, the attributes have to be stated as can be seen in the Building Module-Schema. The text (e.g. for the Usage 'school') to be inserted looks like that:

```
<bldg:function>3021</bldg:function>
```

This tag has to be inserted after the “gml:name” and before the “bldg:yearOfConstruction”-tag, otherwise the validation according to the building module of the CityGML schema will fail.

What has been discovered in the LOD1 Dataset made available here, is that the walkways in front of each building are also included. These walkways are seen as separate buildings which has the cause that Simstadt delivers cooling energy demand estimations for these constructions as well. In reality, most walkways are just footpaths with a roof and therefore aren't cooled or heated, which is why a way to exclude these buildings from the simulation had to be found. It has been decided to give walkways the function 9999, which is causing them to be excluded from the simulation. In a future adaptation of this concept, it is hereby recommended to model the walkways according to the CityGML “Cityfurniture” module.



Figure 17 LOD1 area Yishun, Walkway connecting to a building called “Yishun Gardens”

Figure 17 shows an example of how walkways are included in the LOD1 3D city model. These have the same height as the building they are connected to.



Figure 18 Walkway Yishun Gardens, Source: Google StreetView

Figure 18 shows the same walkway as seen in Figure 17. Here it can be seen, that this part of the building is not cooled and doesn't have the same height as the connected building as it is depicted in the 3D city model.

In the LOD2-case the function-attribute is already existing. It is encoded using the official code list as issued by the SLA. For the simulation using the German parameter libraries, it is necessary to create a mapping file, which connects the Singaporean codes to the German ones. This file is named `AlkisCodes.xml` and has the following structure:

```
<?xml version="1.0" encoding="UTF-8"?>
<codes xmlns:buLib="http://www.simstadt.eu/BuildingUsageLibraries"
  xmlns="http://www.simstadt.eu/AlkisCodes">
  <codesForBuildingUsageLibraryNamed>
    Germany_DIN18599_with_SLA_Codes
  </codesForBuildingUsageLibraryNamed>
    <code from="1000" to="1010"/>
    <code from="1010" to="1020"/>
    <code from="1020" to="1010"/>
    <code from="1030" to="1121"/>
    <code from="1040" to="1122"/>
    <code from="1050" to="1123"/>
    <code from="1060" to="1131"/>
    <code from="1070" to="1220"/>
    <code from="1080" to="1222"/>
    <code from="1090" to="1223"/>
    <code from="1100" to="1312"/>
    <code from="1110" to="1313"/>
    <code from="1120" to="2020"/>
  </codes>
```

Figure 19 Content of `AlkisCodes.xml` - Mapping between Singaporean and ALKIS Codes - Excerpt

The content shown in Figure 19 is just an excerpt, the whole file contains a mapping for 193 different Singaporean codes.

In Simstadt it is now possible to set the option “Use AlkisCodes.xml” in the step Usage processor. Instead of searching for ALKIS codes directly in the “function” attribute in the GML file, Simstadt uses now the mapping to connect the Singaporean code list to the German “Usage Library” parameters. For the mapping, it has been considered that the Usage libraries, as they are implemented in Simstadt do not make use of every single ALKIS Code which exists, but only for a selection of them. This is why not all of the codes in the SLA-code list are assigned to an ALKIS code that matches to the exact translation.

The whole mapping as XLSX-file and as XML-file can be seen on the enclosed CD.

For a simulation with the use of an official Singaporean typology this interim solution of mapping between two different Code lists doesn't need to be used of course.

7.2.3 Geometry Check and Schema validation

The simulation environment Simstadt calculates in the process of the cooling energy demand simulation several properties based on the geometry of a building.

These properties are:

- footprint area [m²]
- total wall area above ground [m²]
- building's volume [m³]
- area of wall surfaces shared with another building [m²]
- area of walls facing to the outside [m²]
- area on the roof [m²]
- mean height of the building [m]
- heated area derived by the average storey height coming from the usage library and the building's height [m²]

Since Simstadt is using the calculated geometrical properties to apply formulas for simulating the cooling energy demand as shown in chapter 4.3.1, wrongly modeled 3D Buildings will either result in non-plausible values or in automatic exclusion of buildings which inherit errors.

In order to prevent Simstadt from excluding or miscalculating the cooling energy demand for erroneous buildings, a geometry check and measures for error correction are carried out beforehand.

For the purpose of detecting erroneous parts of buildings, the Software CityDoctor in the version 2.2.1 is used. Since CityDoctor is capable of checking the geometries of a whole city model – not just single buildings – the combined city models for LOD1 and LOD2

are imported into the software. A complete description of all errors is available in the software itself or in the modeling guide by SIG3D [52]. For the following tests of the geometrical quality, all possible checks in CityDoctor have been chosen.

7.2.3.1 Geometry Test for LOD1:

The checkup of the dataset of the area Yishun with LOD1 buildings and already inserted attributes for function and year of construction resulted in having 11 out of 383 buildings bearing errors. Of course, the attributes do not contribute to the geometrical errors, but during the import, the software checks if all the information per building is stored in sequence as described in the declared namespaces as seen in the header of each CityGML file.

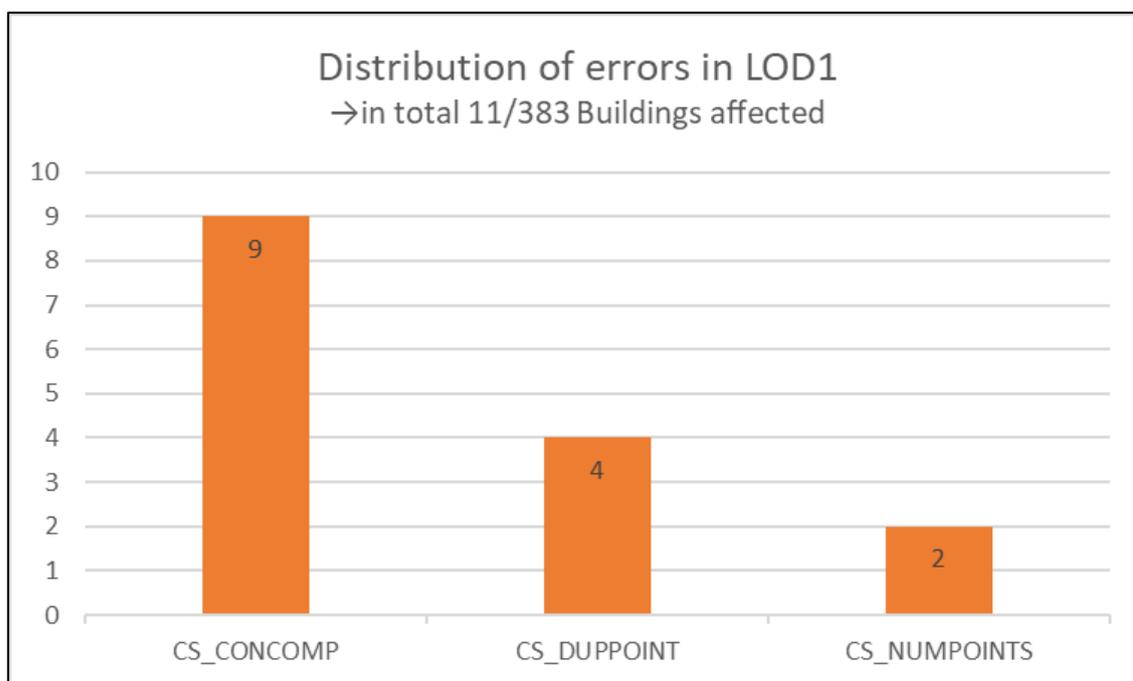


Figure 20 Distribution of error types in LOD1 Dataset

Figure 20 shows the frequency each error type occurred after the validation in CityDoctor. It can be seen that the most occurring error is of the type “CS_CONCOMP”, which appeared in 9 of the 11 erroneous buildings.

“CS_CONCOMP” is occurring when a building consists of spatially segregated components but is described as one solid.

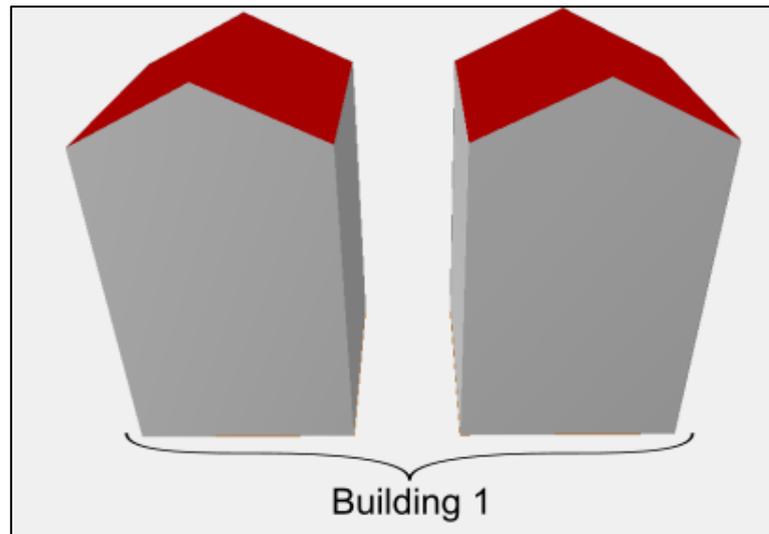


Figure 21 “CS_CONCOMP” error: Two spatially separated buildings modeled as one - Source CityDoctor

Looking onto the list of the geometrical properties derived by each building-model, this error doesn't have an impact on the simulation result itself. The surface calculations can still be conducted correctly even if the building is spatially segregated. Therefore, this error will not be considered to be corrected.

The errors “CS_DUPPOINT” and “CS_NUMPOINTS” are only existing for 2 buildings.

The “CS_DUPPOINT”-Error occurs when a polygon is defined by a set of points where one point is occurring more than two times.

The “CS_NUMPOINTS” occurs when a polygon, which is declared as a “LinearRing” has only 3 or fewer points in it.

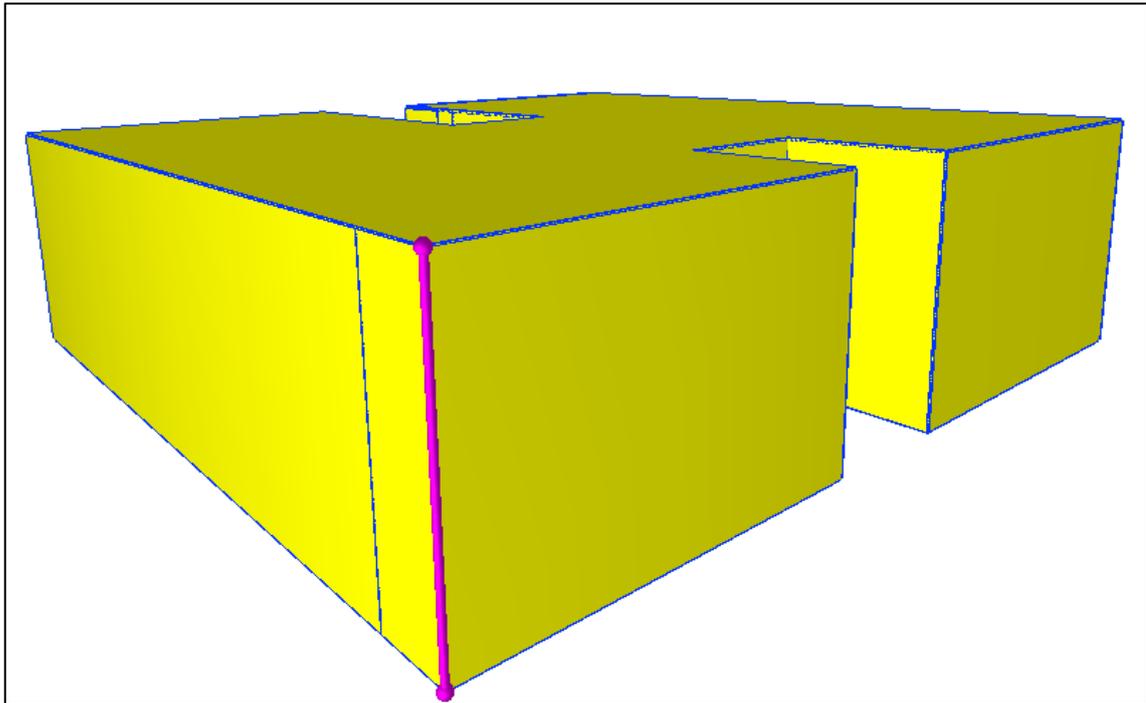


Figure 22 Erroneous Linearring and Duplicate Point in LOD1 Model of Chong Pang Food Market

In Figure 22 one of the two buildings which inherit the duplicate points is shown. The colored edge represents the erroneous linear ring, the two dots on both ends of the edge represents the points which occur double on the same position.

The upper duplicate point is part of the LinearRing which describes the polygon of the roof. The other duplicate point is part of the LinearRing describing the polygon for the ground.

In order to analyze if these two errors have an influence on the simulation result, a way to delete these errors is investigated.

```

<gml:exterior>
  <gml:LinearRing>
    <gml:posList>
      27438.51 45960.5 8.5
      27440.88 45924.29 8.5
      27424.84 45923.23 8.5
      27424.4 45929.99 8.5
      27418.66 45929.62 8.5
      27419.16 45922.86 8.5
      27403.16 45921.81 8.5
      27403.16 45921.81 8.5
      27402.98 45924.68 8.5
      27400.79 45958.03 8.5
      27416.75 45959.08 8.5
      27417.66 45945.35 8.5
      27423.6 45945.74 8.5
      27422.95 45954.24 8.5
      27422.83 45955.8 8.5
      27422.55 45959.46 8.5
      27438.51 45960.5 8.5
    </gml:posList>
  </gml:LinearRing>
</gml:exterior>

```

Figure 24 CityGML Code of a Duplicate Point Error in LOD1 Model

```

<gml:surfaceMember>
  <gml:Polygon>
    <gml:exterior>
      <gml:LinearRing>
        <gml:posList>
          27403.16 45921.81 8.5
          27403.16 45921.81 19.18
          27403.16 45921.81 8.5
        </gml:posList>
      </gml:LinearRing>
    </gml:exterior>
  </gml:Polygon>
</gml:surfaceMember>
<gml:surfaceMember>

```

Figure 23 CityGML Code of a LinearRing with too few points (only 3 of 4) in LOD1 Model

Looking into the CityGML-Code of the buildings inheriting the errors reveals that there are two LinearRings containing one Point which is occurring twice. In Figure 24 the coordinates for that duplicate point can be seen in the highlighted line. The duplicate point is simply deleted in both affected LinearRings.

In Figure 23 the CityGML Code of the erroneous LinearRing can be seen. It only consists of 3 Points, where one point is occurring twice as it is the start point for the polygon the LinearRing describes. A valid LinearRing is modeled using at least three different points which then can span up a polygon.

In this case, the geometry can be corrected by simply deleting the entire linear ring. The same correction method was applied to the other building, which also contains the errors CS_DUPPOINT and CS_NUMPOINT. The speed of this fix can be increased using the Sketchup software. With the extension "CityEditor" of "3DIS GmbH" it is possible to change building geometries in a user interface with 3D representation and a set of tools making it easy finding and repairing the faulty spot.

For analyzing the influence of these two errors on the simulation result, the affected two buildings are imported into Simstadt. The calculation of the cooling energy demand is started by using the standard Usage- and Building-physics-library. It turned out that the described errors have no influence at all on the simulation result. The geometrical properties like building volume, heated area, amount of wall area facing other buildings, etc. are still calculated with the same values as a result. Therefore, the estimated cooling energy demand is the same for building's inheriting duplicate points and linear rings with too few points, given the condition that these errors don't produce holes in the solid of the 3D models. Still, the correction of these errors is advisable since the increase of data integrity enables the use of the 3D city model in other applications and use cases.

After that procedure only the “CS_CONCOMP” errors are left which aren’t critical for the correct cooling energy demand calculation in Simstadt, since the building volume is still correctly calculated.

7.2.3.2 Geometry Check for LOD2:

The geometry check for the LOD2 city models of the area Yishun has been conducted similar to the LOD1 city model. After the successful import of the combined city model into CityDoctor (V2.2.1), the validation with all available tests is started. CityDoctor found that all buildings in the input dataset are faulty, which has its reasons in the way how the CityGML dataset has been created.

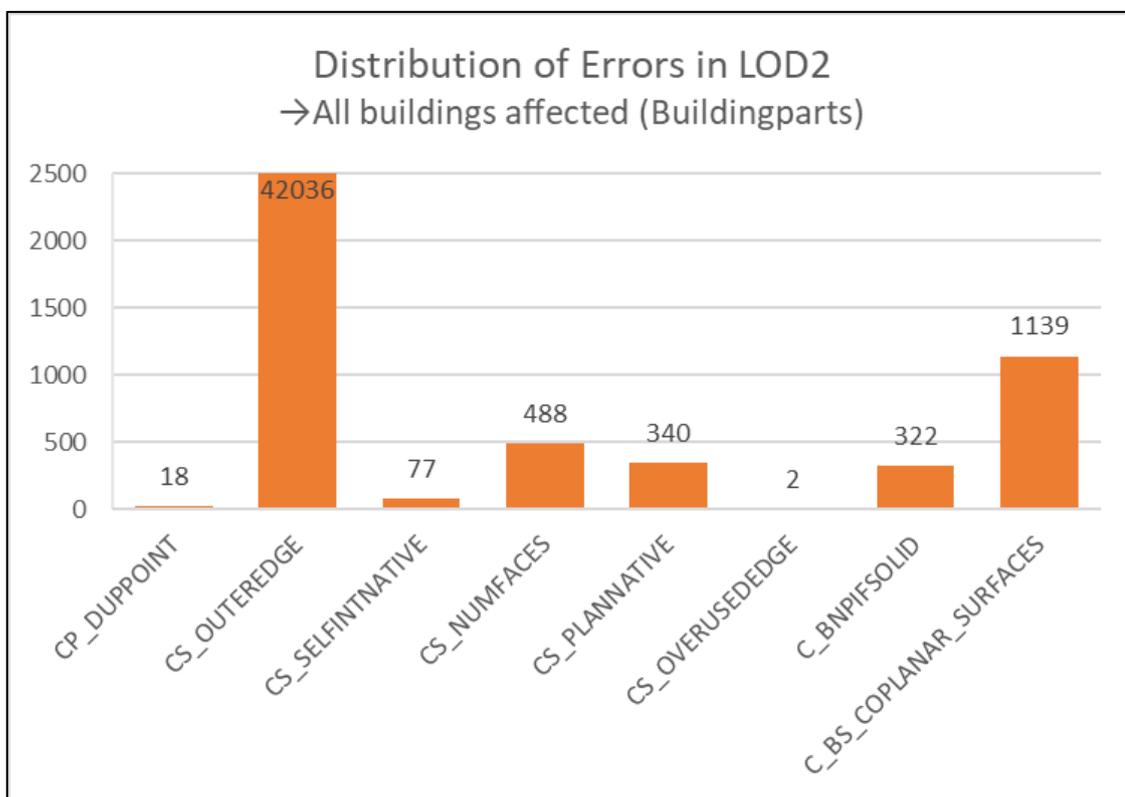


Figure 25 Distribution of Errors in LOD 2, Modelling with Building-parts

Figure 25 shows the distribution of errors in the CityGML-file where all the single buildings have been merged together.

The biggest group of buildings contains the error CS_OUTEREDGE.

This error is shown for each edge of a geometry which has only one adjacent polygon. In order to be correctly modeled, an edge should have a neighboring edge, belonging to another polygon.

In other words: This error occurs on edges where the geometry of a solid is left open.

An example of that can be seen in Figure 26 and Figure 27.

The building which can be seen here consists out of building-parts. In Figure 26, one of these building-parts has been colored purple. In CityDoctor V2.2.1 it has been discovered that for each building-part multiple missing adjacent Polygons are missing. Therefore, the geometry of the marked building-part is left open.

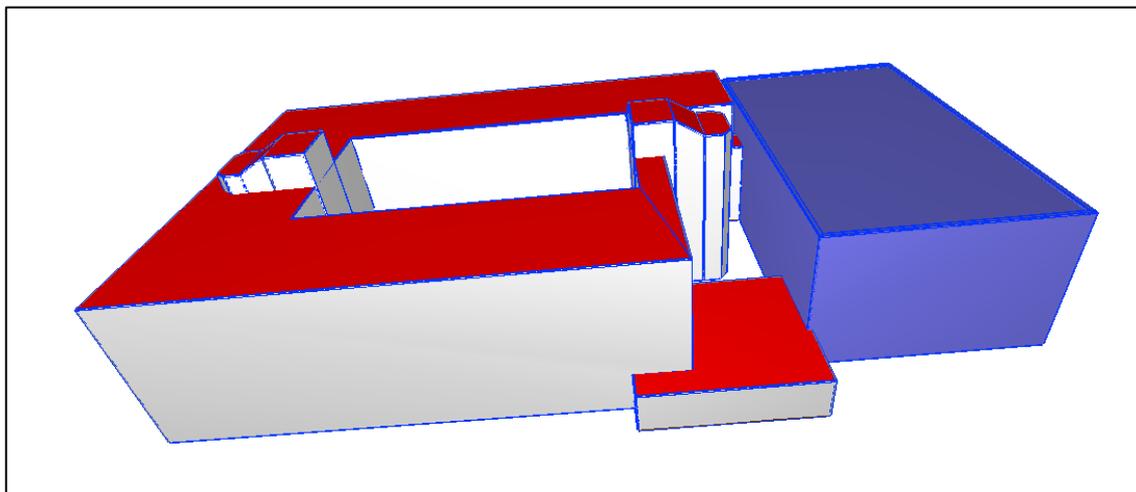


Figure 26 Building with highlighted building-part – Source: CityDoctor V2.2.1

In Figure 27 that circumstance can be clearly seen. CityDoctor V3 marks all edges where adjacent polygons are expected in orange. The endpoints of each edge are colored red. Each building-part of a building can be selected, and for all of these, the solids have been found to be not closed. This applies to every building in the LOD2 datasets.

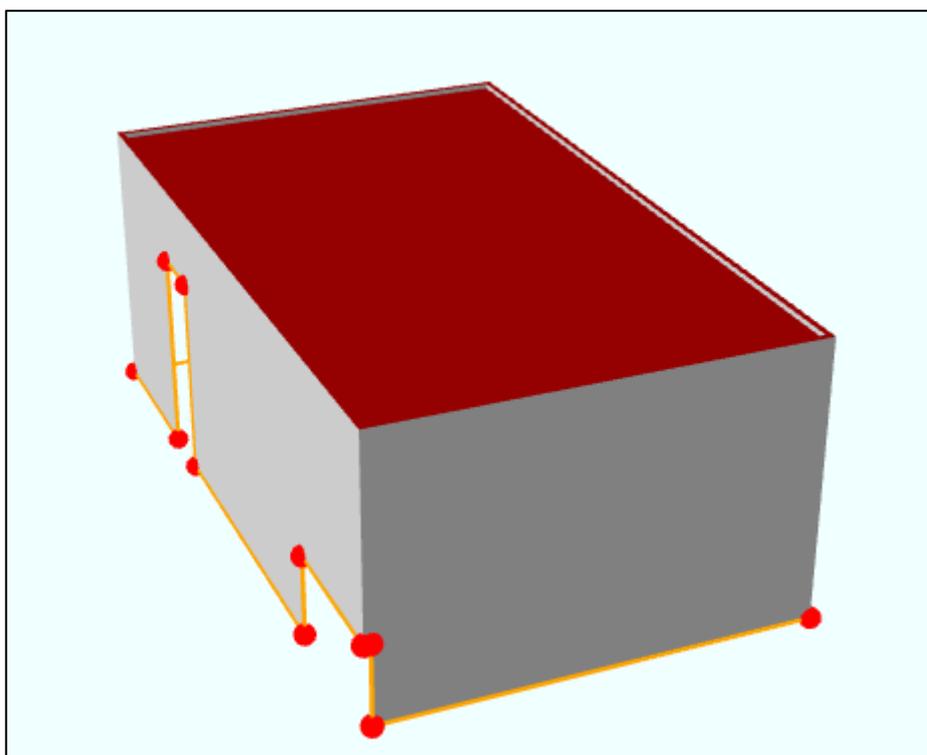


Figure 27 Not Closed building-part with highlighted edge - Source: CityDoctor V3

What has been discovered for some buildings that some of the edges of wall surfaces aren't connected properly to the neighboring Roofsurface.

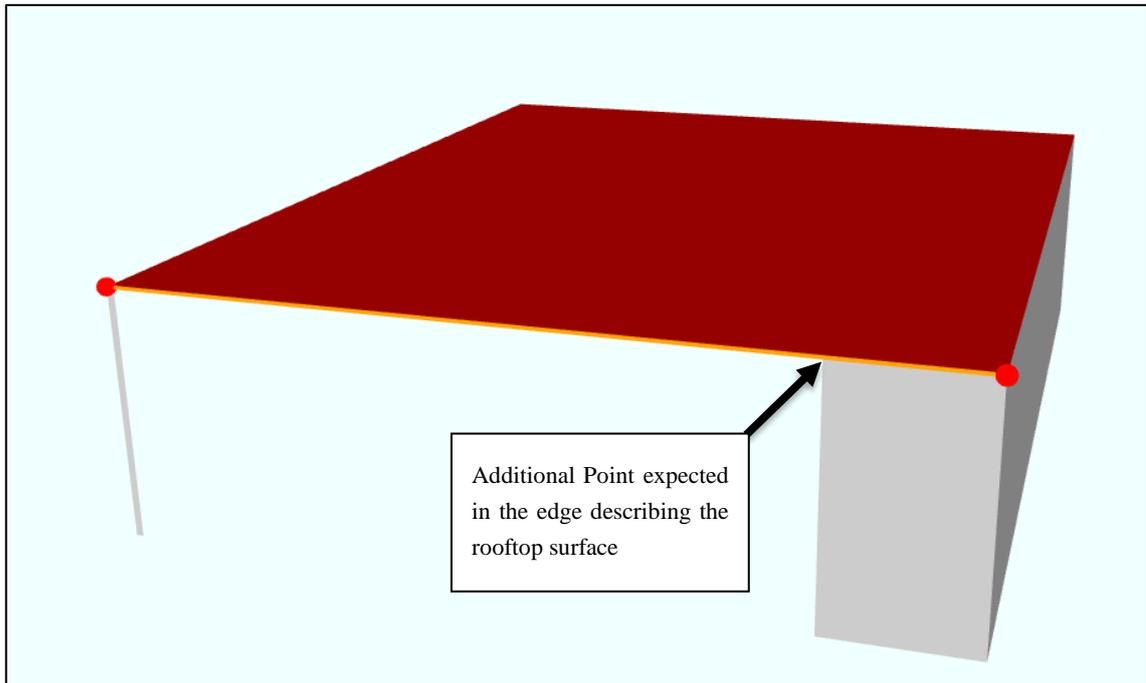


Figure 28 Connection between Wall- and Roofsurfaces missing out additional points

Figure 28 shows a building-part where the edge of a roof surface has been highlighted. The validation error is caused by the fact, that an additional polygon point in the roof surface is expected where the wall on the left ends. Missing out that point results in a portion of the CS_Outeredge errors causing a solid to be opened.

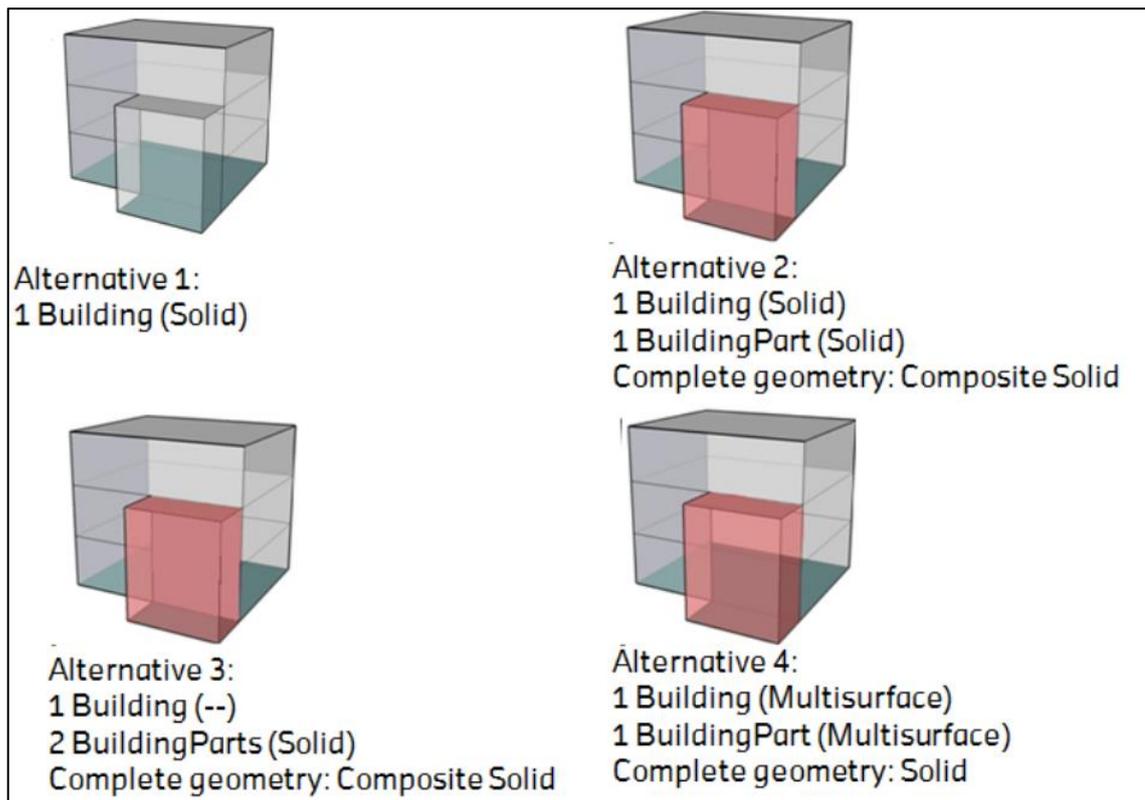


Figure 29 Variants of modeling a building with a Building-part in CityGML [35]

Figure 29 shows some of the possible modeling methods for buildings in CityGML.

The datasets for LOD 2 in Singapore are now modeled by using building-parts declared as solids. This way of modeling would be similar to the principle shown in alternative 2 of Figure 29 but without any geometries for the building itself. It is still a valid way of modeling [53], even though it's not shown in Figure 29. The solids are made up by several surfaces, like wall-, roof- and ground surfaces which have been declared as Multisurfaces. It is required that the solids for each building-part are closed watertight, otherwise, the CityGML building model wouldn't be valid [52]. Also, if a solid has holes in the boundary surfaces, Simstadt would calculate incorrect volumes for the buildings, which in turn would lead to an incorrect prediction of the cooling energy demand.

One way to reach the goal of closing the building-part solids would be to modify each building manually in the Sketchup Editor [54], which would take too long for a bigger dataset.

Also, the HFT Stuttgart does research on the automatic healing of 3D city models. A methodology has been developed to introduce so-called "closure-surfaces" for Solids which inherit holes.

The reason why this methodology can't be applied to the datasets of Singapore, is that building-parts are modelled to be a part of the whole building, which means that large

portions of the building-parts to be closed are missing. The “Closure-Surfaces” approach doesn’t have the capability to close huge groups of missing surfaces.

Another method has been discovered by the fact that the openings of each building-part solid is connected to another building-part, which is also opened. Having a view on both building-parts combined, reveals that connecting the building-parts into the same geometry is causing the whole building to be one watertight solid for the most buildings.

In order to automate that process to save time on the geometrical validation of the city model, a Java software is written which automates the connection of the building-parts to one closed solid (See on enclosed CD).

The principle is the following: In Figure 30 the structure of each file can be seen before the modification of the program. One building is defined by multiple building-parts, which are put together by multiple surfaces which are declared as Multisurfaces.

To eliminate the error of opened solids an option would be to extract each Multisurface out of each building-part and directly assign these surfaces to the Solid-element of the building itself. This way of modelling would comply with Alternative 1 in Figure 29.

In Figure 31 the resulting structure using above described way of modelling. For visualization purposes the amount of wall surfaces has been reduced in this structural view.

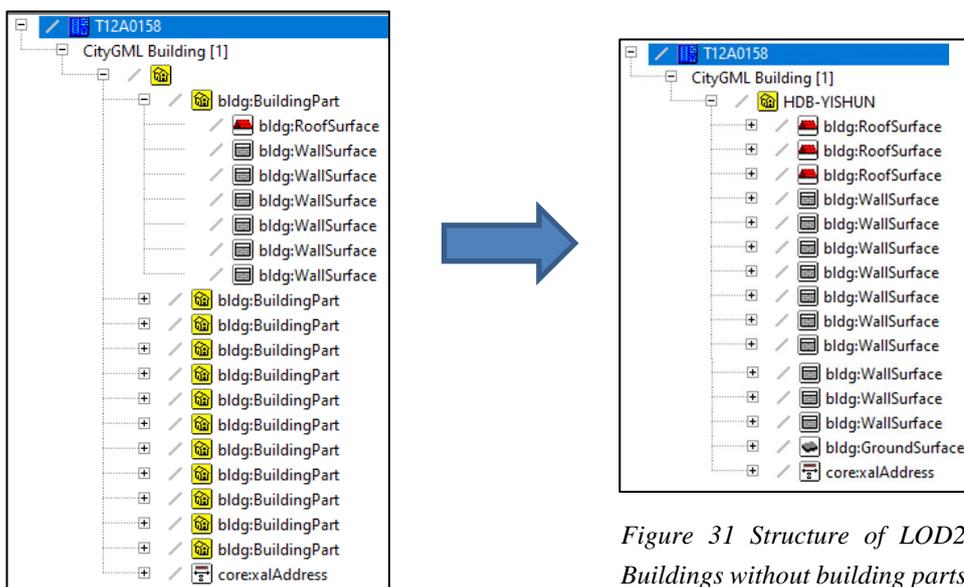


Figure 30 Structure of LOD2 Buildings with building parts (unmodified)

Figure 31 Structure of LOD2 Buildings without building parts (after modification)

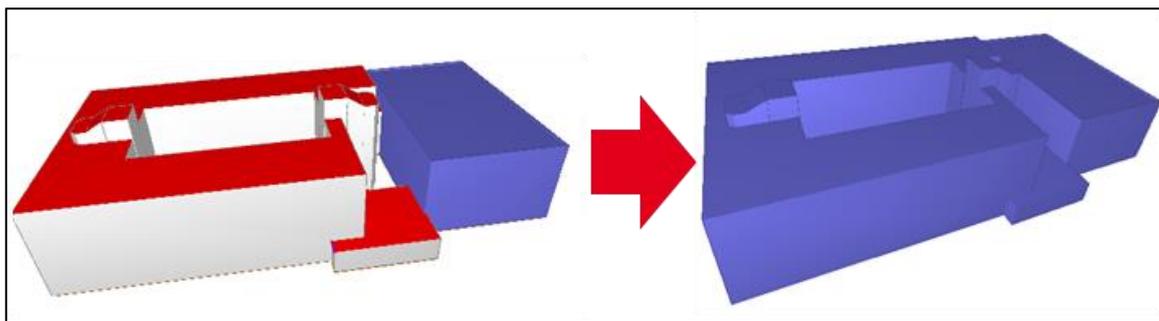


Figure 32 Functionality of the Java Program - Connect building-parts to one closed solid

In Figure 32, the purpose of the here created Java program is again visualized. On the left only one building-part is selected (here in purple). This building-part is opened on the locations where it is connecting to other building-parts. That circumstance is best visible in Figure 27, where the marked edge (orange) describes the shape of the adjacent building-parts. After the processing of the building in the Java program, all of the building-parts should be combined to one single solid, enabling to assess the cooling energy demand based on a correctly assigned volume for the whole building.

Another option for ensuring the validity of the buildings is to restructure the CityGML file in order to have building-parts put together by Multisurfaces without the declaration as a solid. This way of modelling would comply with alternative 4 in Figure 29. Again, no geometry for the building itself is given, only for the building-parts. What is also different from Alternative 4 in Figure 29 is that the combined geometry is not a solid but a combination of Multisurfaces. This variant of modelling is again proven to be valid [53].

Comparing the amount of geometrical errors found with CityDoctor 2.2.3 it has been discovered that the overall error count has been decreased by the applied options.

Using the option of having Multisurfaces without solids causes 26 Buildings out of 348 to be errorless. The other 322 building still have errors.

The option of merging the building-part-solids to one cause 32 buildings to be valid and 316 buildings bearing errors.

7.2.3.3 Evaluation of the Geometrical Modelling

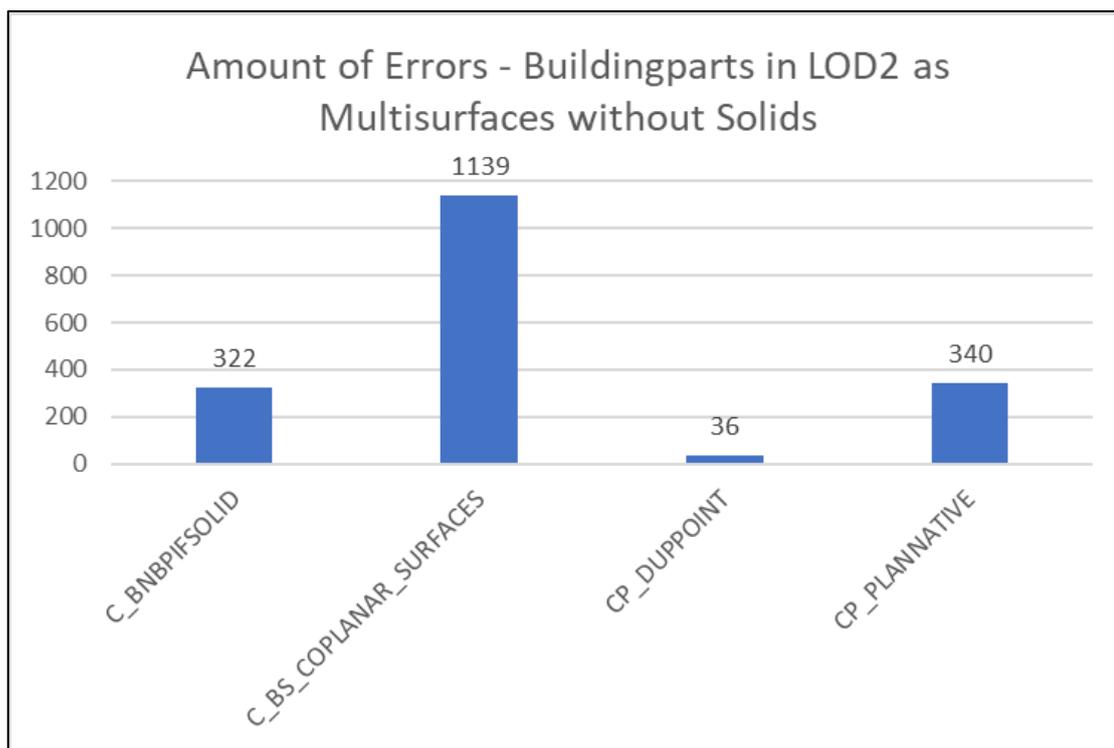


Figure 33 Amount of Errors with building-parts declared as Multisurfaces without Solids

Comparing the geometry validation result in Figure 33 to the result without any processing (Figure 25) it can be seen that the overall amount of errors has decreased a lot. Also, the variety of errors in the whole dataset is decreased from 8 to only 4. This has mainly its cause in the fact that using Multisurfaces is enabling opened geometries to be valid. This is why errors about solid geometries are not occurring anymore. The amount of errors for the checks CP_PLANNATIVE⁴ and C_BNPIFSOLID⁵ stayed the same, which is logical since the LinearRings or polygon geometries itself aren't touched by the restructuring of the CityGML file. A polygon which has been identified to describe a non-planar area is still bearing the same error after the modifications.

The error describing duplicate points slightly increased from 18 to 36. This may be because before the restructuring the building-parts were intended to be single solids, which are allowed to touch each other in certain spots. Describing these solids now as Multisurfaces results in having duplicate points and edges in the touching areas of these meant-to-be solids.

When analyzing the suitability for Simstadt of this modelling option, it is a problem that it can't be said if the buildings have closed volumes since the checks concerning solids

⁴ CP_PLANNATIVE: error occurs if a polygon is not describing a plane surface

⁵ C_BNPIFSOLID: occurs when the geometry of building-parts and Buildings are merged together, No critical error when calculating the volume of a building

won't be triggered by the fact that only Multisurfaces are used now. These solid-checks would've indicated if errors like holes in the geometries are existing. Watertight geometries of the buildings are a requirement for a plausible simulation inside Simstadt but won't be guaranteed by CityDoctor when using Multisurfaces.

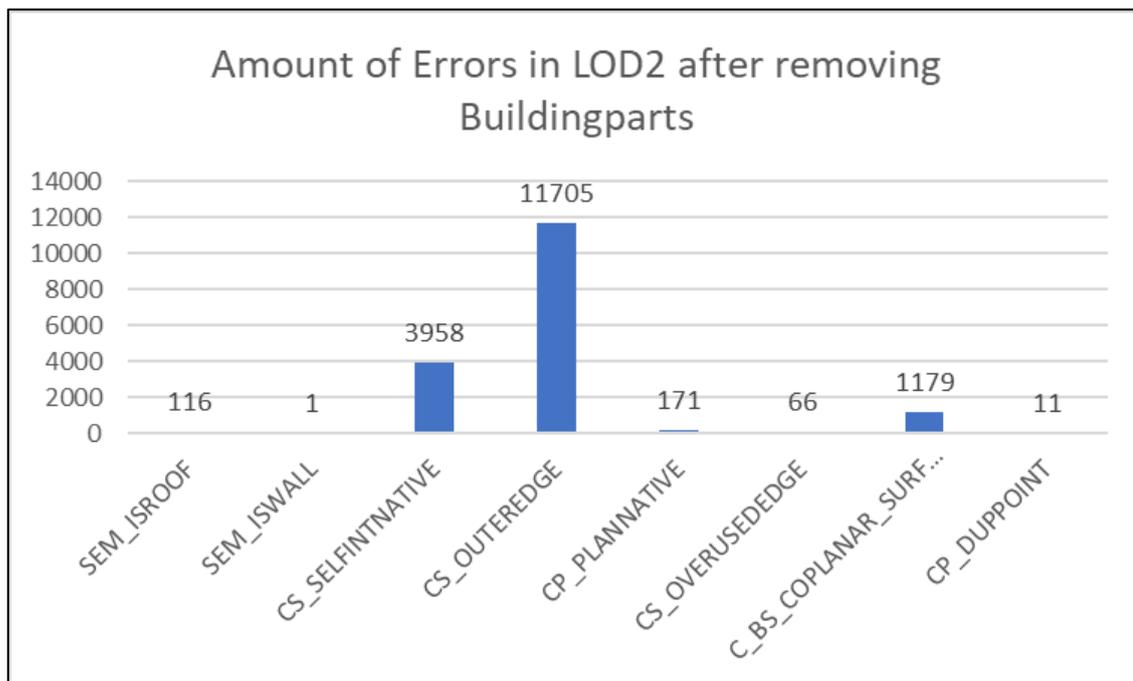


Figure 34 Amount of Errors when assigning all Surfaces in building-parts to one solid per building

Figure 34 shows the distribution of errors for the whole dataset of the area Yishun in LOD2, where building-parts have been modelled as part of one solid describing each building. As in the other building-parts modelling-approach it has been discovered that this option also decreases the amount of errors a lot.

The number of different types of errors has not increased, nevertheless there are new errors which are caused by the remodeling of the city model.

New error types are for example caused by the semantic checks. In this case the error SEM_ISROOF is indicating that 116 roof-surfaces of solids are not pointing upwards. 1 wall-surface in the whole dataset is declared as a wall but the normal of that wall-surface is not pointing in horizontal direction. This way of modeling a wall is invalid according to the guideline for modelling of 3D objects by SIG3D [55].

The errors for CS_SELFINTNATIVE increased since the building-part structures are not single solids anymore, but part of a solid for the whole building. This has its cause that some of the former building-part-solid geometries overlap other polygons, which is again not valid. That error occurred 3958 times, which is a lot more in contrast to the dataset with no modification where this error only occurred 77 times. An error which has been reduced drastically is the CS_OUTEREDGE error. Previously 42036 occurrences were

counted, now there's only 11705 occurrences of that error. This means there are far less edges where a neighboring polygon is expected, again because of the circumstance that the overall building-solid is inheriting the incomplete meant-to-be building-part-solids. Also, the reduction of this error is driven by the fact that each building-part geometry touches other building-parts mainly in places where these have been left opened.

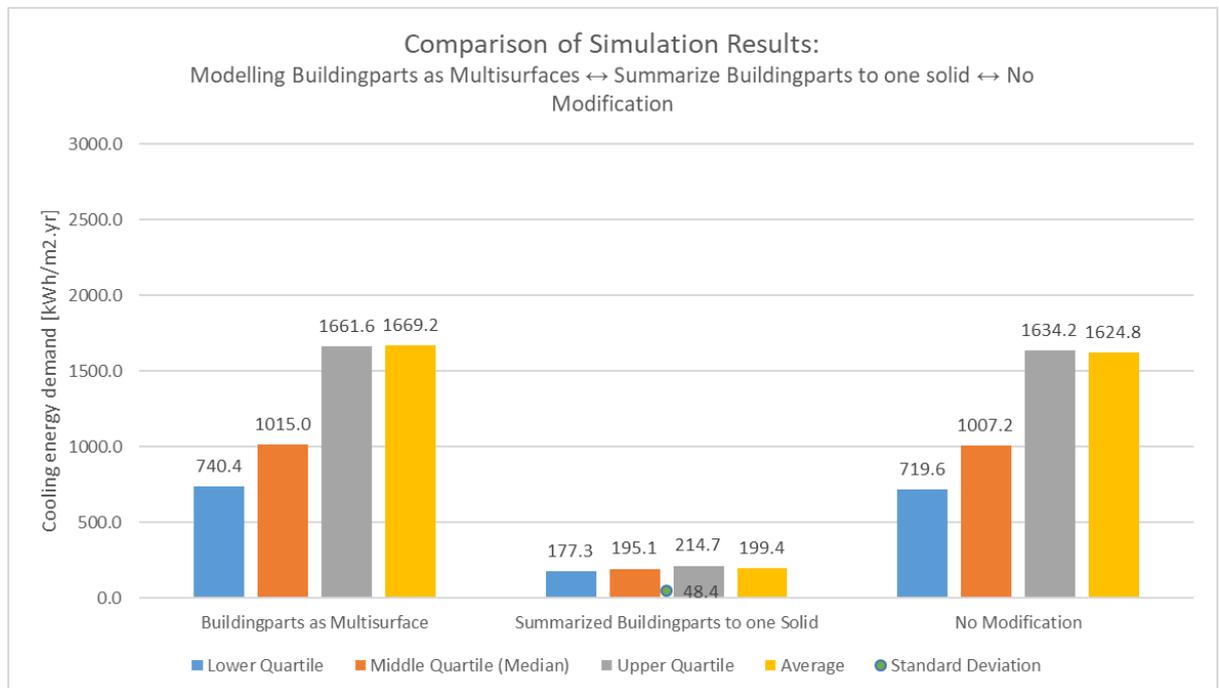


Figure 35 Comparison of Simulation Results for two ways of modelling the building-parts in LOD2 Yishun

Figure 35 has been created by importing the two modified CityGML files of the area Yishun along with the unmodified version of the same dataset into the simulation environment Simstadt. As has been decided earlier, the year of construction attribute per building has been set to the year 2000 for all testing procedures of the simulation workflow. Before the simulation, the German libraries for Usage-parameters and Building-physics-parameters as well as the mapping file for the ALKIS- to SLA-Codes have been selected. The option of assuming residential buildings if a building's function is unknown has been checked.

The method of modelling the building-parts as Multisurfaces delivers 1853 entries in the resulting CSV-file. For 287 building-parts the function attribute stored in the parent "building"-element is not identifiable as empty because it is not at all in the CityGML code. Otherwise the software Simstadt would've successfully assume a residential function for the building. The exclusion of 348 other building-parts was due to the fact that the calculated volume for these geometries is too small. The amount of entries in the simulation output-file is still very large compared to the amount of buildings the input dataset describes (348). This has its reason that Simstadt counts each building-part as one building in the first place and this has the effect that per building-part one entry is created

in the output-file. In this resulting CSV-file, the column “Parent GmlID” delivers the ID of the building each simulated building-part belongs to. This column has been used to sum up the simulation result for each building-part and to assign the summed-up value to one building.

The unmodified CityGML dataset contains buildings where the building-parts are meant to be solids, but the fact that the solids aren't closed and therefore aren't valid to the CityGML standard, causes the simulation to either assume the volume of the bounding box of a building, or to completely exclude several buildings automatically. Not only the argument of invalid geometries but also faulty volume calculations influence the exclusion of several buildings. In the output-file of the simulation of non-modified buildings, there are only 1954 entries occurring out of a total of 2487 existing building-parts in the input dataset. The exclusion of 285 buildings is due to the failed referencing of unknown building functions to residential buildings, which is caused by the lack of the function-tag in the affected buildings. For 348 building-parts the volume has been found to be too small for the inclusion into the simulation. Most of the excluded building-parts are the same as in the dataset with the Multisurface modelling variant. The summation and allocation of the results of the building-parts to its belonging building has been conducted the same way as for the dataset where each building-part has been modelled as Multisurface.

With that procedure it is now possible to compare these results to the other modelling option, which is the variant of merged building-parts - where the simulated value is already calculated summed up per building as can be seen in the column “specific cooling demand”. Again, an automatic exclusion of 96 buildings because of the complete lack of the function tag in the CityGML code has been done. For the comparison chart, the buildings where no calculation was possible due to erroneous volume calculation were left out. This delivers a collection of simulation results showing the specific space cooling energy demand calculations of the two modelling alternatives and the non-modified dataset describing the same 171 buildings.

With emphasis onto the values in Figure 35 it can be said that the modeling-variant where each building-part-solid of a building has been summarized to one, delivers the lowest and therefore most accurate ones. Having a look again onto real consumption values of Singaporean buildings, reveals that none of the specific energy demand values in 2015 and 2016 are higher than 1363 and 1412 kWh/m².yr where the average is located at 276.86 and 278.91 kWh/m².yr which comes closest to the calculated average of the option in the middle here (199.4 kWh/m².yr).

To further investigate the suitability of the two modelling methods for Simstadt, the calculated volume will be compared in the following.

If the building's volume can't be derived because of having a geometry which isn't watertight, the Simstadt methodology assumes the volume of the bounding box for the respective building. This results especially in the LOD2 dataset in mostly wrong estimations, since the building's geometrical detail richness isn't considered anymore.

In the modelling variant of merged building-parts the volume has been assumed by using the bounding box for 54 out of 219 buildings, in contrast using the Multisurface approach delivered 219 bounding box volume calculations out of 233 simulation results.

Having applied no modification on the modelling causes that the Boundingbox of a building is assumed as the volume in 209 out of 219 results.

In the following a comparison between the different volume calculations using the different modeling approaches is made.

Table 6 Volume Comparison for one sample building

Volume Comparison (all values in m³)		
ID: SLA_BLDG2_046342aa-8c3b-4a08-8317-26a979c101db		
Merged Building-Parts	Gross Volume	40978.2
Multisurfaces	Volumes of all Building-Parts	68862.1
No Modifications	Volumes of all Building-Parts	68862.1
Own Calculation	Using Measuring tool of FZKViewer	41100

Table 6 shows the different volume values for one building, which have been calculated by Simstadt and by hand.

Clearly to see is that the volume in the modelling option of using Multisurfaces and without any modifications are the same, whereas the merged building-parts-approach is very similar to the volume estimation which has been done manually. For the manual volume measurement, the measuring tool in FZK-Viewer has been used to extract the length of the needed edges.

Based on these observations it can be said that the modelling option of using merged building-parts is delivering the most plausible results when calculating the geometry related parameters.

7.3 Creating Singaporean Building Physics Libraries

Since Singapore is located in a very hot and humid climate, the German Building-physics and Usage library using parameters by the IWU⁶ doesn't fit completely to the present building stock. As an example, German buildings are more likely to be heated instead of cooled. This has an effect on the electricity consumption and the usage scheme in general.

The Software-package of "Simstadt" comes with two separate programs, which enable the user to create own Building-physics-, and Usage-libraries. In this chapter it is intended to create such libraries for archetypes of Singaporean buildings in order to get results which are more oriented on local Buildingtypes and -uses, construction materials and properties which come with different usages.

During a literature research it has been found out, that there is no official building typology prefabricated in Singapore like for many European countries as seen in the project "Tabula" [56]. It will be part of recommendations to use the interconnected agency network in Singapore to enable research projects which aim on setting up an official typology of buildings for energy assessment purposes.

For this work a preliminary typology has been set up by searching relevant parameters and classifications in research papers about typical south east asian building types. For some parameters no relatable information has been found which is why the most applicable value from an already existing Simstadt-compliant library related to Buildings either from New York or Germany is taken.

The Building-physics library has been set up by using the same classification properties as in Germany, since the variety of buildings depicted using these 5 different building types is already fitting well to the cityscape of Singapore where a multitude of different construction styles is present.

Table 7 Buildingtype properties in IWU Library

Skyscrapers	Buildings higher than 23m
Big Multi Family Houses	higher than 16m
Multi Family Houses	More than 3 floors and higher than 11m
Single Family Houses	Lower than 11 m and no shared wall surface
Row Houses	Long shaped/large footprint areas or >20% of the outwall surface is shared with other buildings

⁶ IWU = Institut für Wohnen und Umwelt

It has now been tried to find the most suiting parameter-sets per building type in south east asia in general, since in that region the climatic conditions are mostly the same and therefore the construction of buildings is carried out similar. In general, there is not much research for this topic done as to the date this thesis has been submitted.

Because an official comprehensive typology of south-east Asian buildings is still missing, large parts have been adapted from Germany's IWU library.

Adrian Chong et. al. published a paper where a list with materials used for skyscrapers in the CBD area is shown [16]. The described buildings were visually inspected by using current online mapping services like Google Maps and OneMap and found to resemble the same building type (Skyscraper) and assumed to be in the same YOC-Epoch (2000).

This is why the median of each component's U-value as seen in A. Chong [16] is calculated and compared to an already existing material in the German Buildingphysics library. The result of that mapping can be seen in Appendix 2. It has been decided to use prefabricated building materials from Germany because of the fact that the main influencing factor is the U-value each building's component is assigned to. The already existing material which has the closest U-value as compared to the median in A. Chong's paper is then used for the whole Buildingtype skyscraper.

After a visual investigation on the so-called HDB-buildings which are hereby meant to be represented by the building-types big multi family house and multi family house, it has been decided to adopt these completely from the German building typology in the YOC-epoch 2000.

Typical for south-east Asia is the construction style of "shophouses". This kind of building is a terrace house which inherits traditionally a shop in the first floor and a residential usage zone in the second floor. Shophouses are most comparable to row houses in Germany. Most shophouses are very old which is why it has been decided to use the global parameters of German row houses in the YOC-epoch of 1950.

Andarini et. al. published a paper where a thermal simulation of a shophouse has been done, for that purpose a list of U-values for each component has been established [57]. Again, the material with the most similar U-value in the German library is used per component.

The building type single-family house is put together by using the parameters from the single-family houses built in the YOC-Epoch 1995 to 2001 because of having a lack of dependable information on that certain building type in Singapore.

The full Building-physics library in the format XML can be seen on the enclosed CD. The global parameters for the building types row houses and skyscrapers can be seen in annex 2.

The paper by Andarini et. al. [57] also offers valuable data for filling a preliminary Usage library. Since a shophouse has traditionally two usage zones, the parameters for residential and retail use are extracted from that research. A complete list of the values used for retail and residential buildings can be seen in annex 3.

In lack of dependable information on the Usage related parameters for the building functions office and administration, education, event location, hall, health care, hotel, industry, restaurant and sport-location the German values have been adopted. For the office and administration usage, an occupancy schedule has been found - again in A. Chong et. al.'s paper [16] - which has been detected to be the same as in Germany.

7.3.1 Evaluation on using Singaporean Parameters

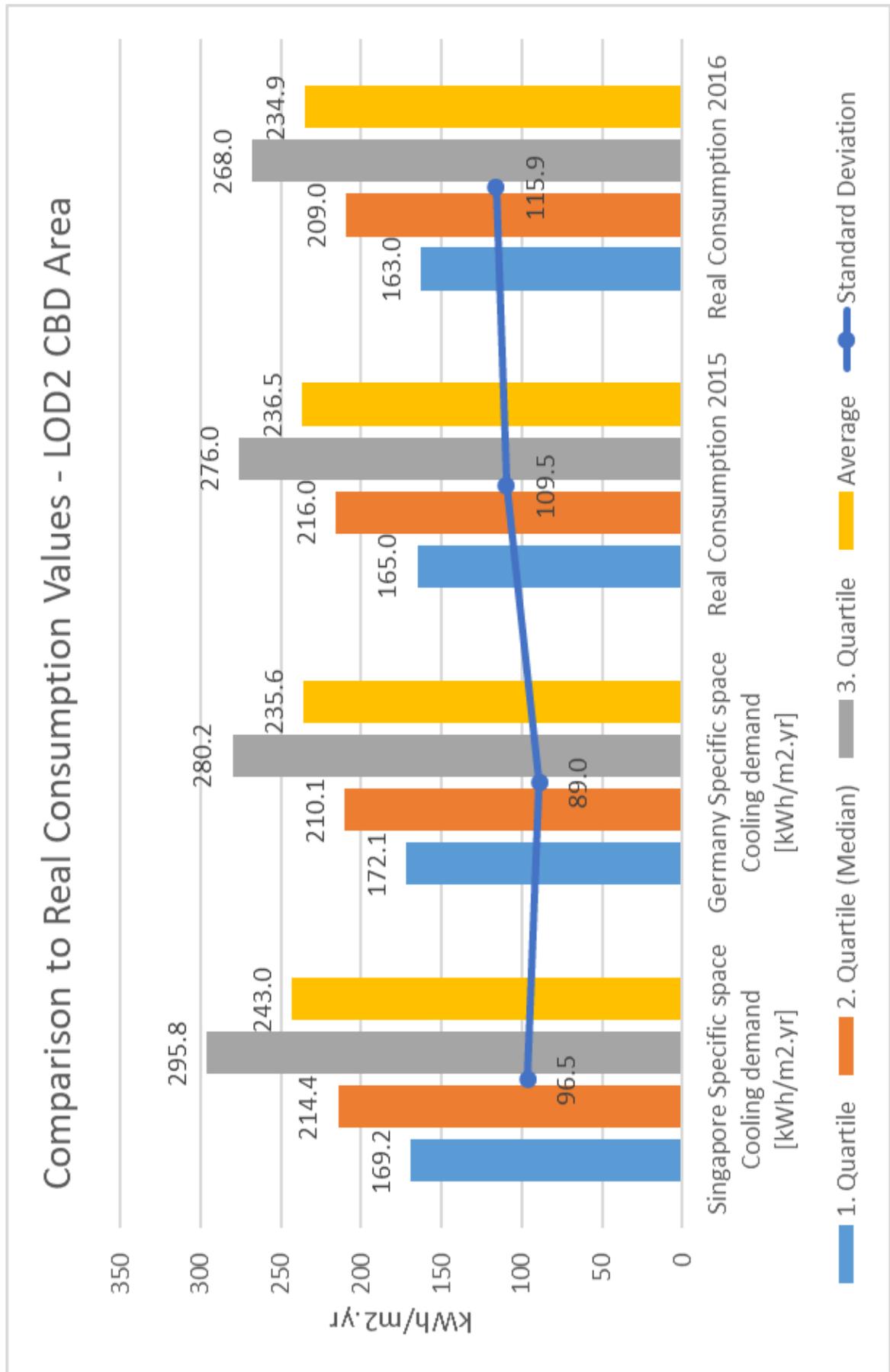


Figure 36 Comparison of results using German and Singaporean Building-physics-, Usagelibraries

Figure 36 shows the averages of each Simulation results in comparison to the average of real consumption data. The quartiles and average values, along with the standard deviation of each dataset deliver a perspective on the whole dataset.

The average of the results using the Singaporean libraries is higher than the values calculated using German parameters. The German parameters tend to fit better to the real consumption value.

This circumstance gets to be clearer when looking onto the actual values of several example buildings:

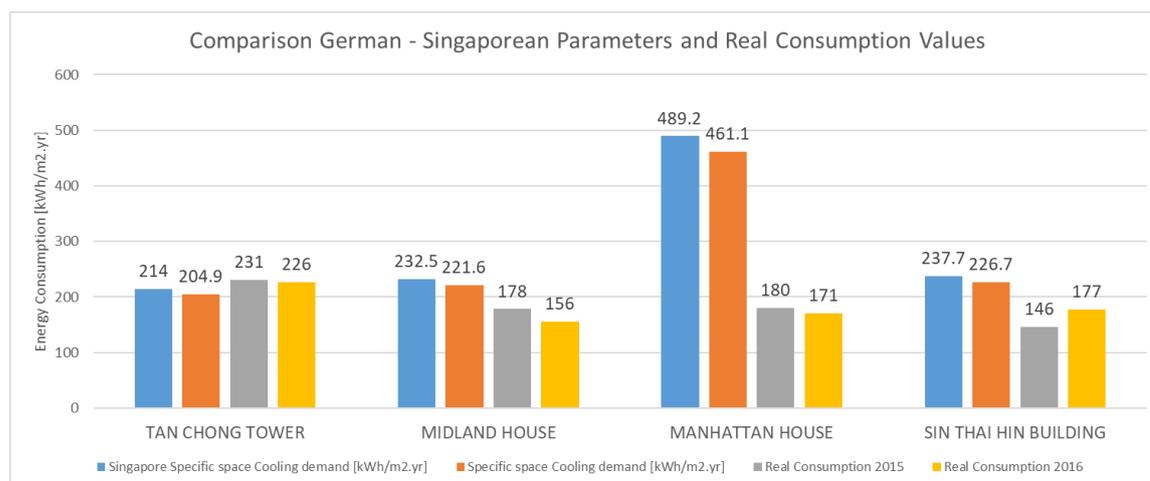


Figure 37 Comparison between Singaporean and German Libraries - Single Buildings

Figure 37 shows the cooling energy consumption calculated per m^2 . The calculation of the volume per building has been carried out by not assuming as volume the bounding box of the building, but the volume which has been calculated using the actual geometry of the building. It can be seen that the relation of the estimated cooling energy demand to the real consumption values is varying a lot. For the most buildings in the dataset, the bars look like the ones as can be seen for “Tan Chong Tower”. The Singaporean parameters cause the energy estimation to be a bit higher than the simulation using the German ones. The real values are close to the estimated values, but normally the Singaporean parameters tend to overestimate the results, where the German ones cause an underestimation. For this building it is the case that both values are underestimated but still are very close to the real consumption values. This circumstance certifies that the cooling energy simulation as implemented in Simstadt is able to calculate plausible values. Of course, the simulations result for these buildings are correct with some degree of uncertainty, since input parameters like the YOC are assumed. Still for most cases the linkage to the correct parameters in the libraries was successful.

The difference between the real consumption values for the Midland House shows that measures were taken to reduce the energy consumption between 2015 and 2016. The input dataset assumed the input building model to be built in 2000 and along with this model

there is no information given about refurbishment, which is why the simulation result is significantly higher than the real consumption values. For optimizing the captured 3D models of buildings for a cooling energy simulation it is therefore advised to not just capture the year of construction but also information about the improvement of the building's fabric by a refurbishment. Simstadt is capable of analyzing different refurbishment scenarios, if the information is given in the input dataset.

The second most occurring case is depicted in the values of the Manhattan House. Here the estimated cooling energy consumption is 2.5 times more than the real consumption values. It seems like the volume which has been calculated in Simstadt is causing a too high energy demand estimation in both parameter constellations. This is due to the fact that applying the procedure of correcting the building's geometries doesn't delete all occurring errors, but a major part of them. The persisting errors still can be a reason for the wrong estimation of the volume of each building.

This comparison shows that the applied methodology is capable of calculating values which do not deviate completely. A rather plausible estimated energy demand has been calculated when comparing the results to real consumption values.

The results for building's like Tan Chong Tower show that the described trend in Figure 1 is also reachable, the more detailed the library used for input parameters is.

The relationship between the simulation results and the real consumption values for buildings like Tan Chong Tower is confirming the assumption that cooling energy is taking a share of between $1/3$ to $1/2$ of the whole energy budget of a building. For most of the buildings, the assumed energy demand values are a bit lower than the real consumption values. It is therefore assumed that having more precise input parameters describing the occupants behavior and the building fabric, will cause a more plausible prediction where assumed values are more trending towards a share of $1/3$ to $1/2$ of the whole building's energy budget.

7.4 Influences of input data on the Simulation result

In this section it will be investigated what influences several variations on the input datasets have. These findings will help in the creation of a typology which will serve as input additionally to the building's geometries.

A method for analyzing the influence of parameters has been developed by Morris [58].

The principle to apply this methodology to GIS driven energy simulations is to define a set of parameters which influences should be analyzed. Along with that ranges are specified, in which these parameters can vary. Then a huge set of simulations of a sample dataset are initialized where each parameter is changed one at a time. It is recommended to do around 200 simulations if the influence of 50 different parameters should be investigated. The differences in the results are then used to assign a sensitivity factor which can best be shown in a diagram. The parameters with the highest sensitivity factor are then the ones with the highest level of influence on the simulation result.

Since the realization of dependable simulation results in Singapore requires the setup of a comprehensive typology stating several building-physical- and usage-related-parameters, the influence of each of these parameters should be analyzed first when using the formulas of the DIN V 18599. This gives the chance to point out most important parameters, which in turn might reduce the effort which has to be invested for the setting up of a typology since the emphasis is put onto a certain set of values. The procedure can also be described as a what-if analysis, where the information about the influence of a certain parameter can be used to put focus on in the design- and retrofitting-process of buildings.

In this chapter a first assessment of main parameters of the Simstadt workflow is done under use of a simpler approach which provides a basis for the implementation of a proper sensitivity analysis using the Morris-method in the future.

7.4.1 Building-Physics Parameters

For the Building-physics-library, the most influencing parameters besides the U-Values are the global parameters which can be specified for each Buildingtype. These are modified slightly and put into comparison with the results using the standard Building-physics-library.

The Building-physics library consists of Buildingtypes allocated into building year epochs. Per epoch it can be stated with which materials the walls, roofs and ground components were built of. Also, per epoch the so-called global parameters per building type can be modified. These global parameters have been increased gradually as can be seen in Table 8. Important to state is that for the thermal-bridge-parameter a change from 10 to 30 percent causes too small changes in the actual value of the parameter to be inserted in the editor-software which is why a bigger stepsize for increasing these values has been applied. For each changed parameter a new Building-physics-library has been set up. The simulation is then carried out 16 times using the libraries set up for every single parameter-change. The results are then summarized into one diagram which can be seen in Figure 38.

Table 8 Overview of parameters changed for each simulation for assessing their influences

	Thermal Capac- ity	Average Storey Height	Infil- tration rate	Heated Area Ra- tio	Thermal Bridge U- Value
Standard Parameter Values Skyscrapers YOC 2014	90 KJ_k.m2	2.6m	0.3vol/h	0.15	0.04 W/K.m2
+10%	99	2.9	0.33	0.17	0.05
+20%	108	3.1	0.36	0.18	0.06
+30%	117	3.4	0.39	0.20	0.07

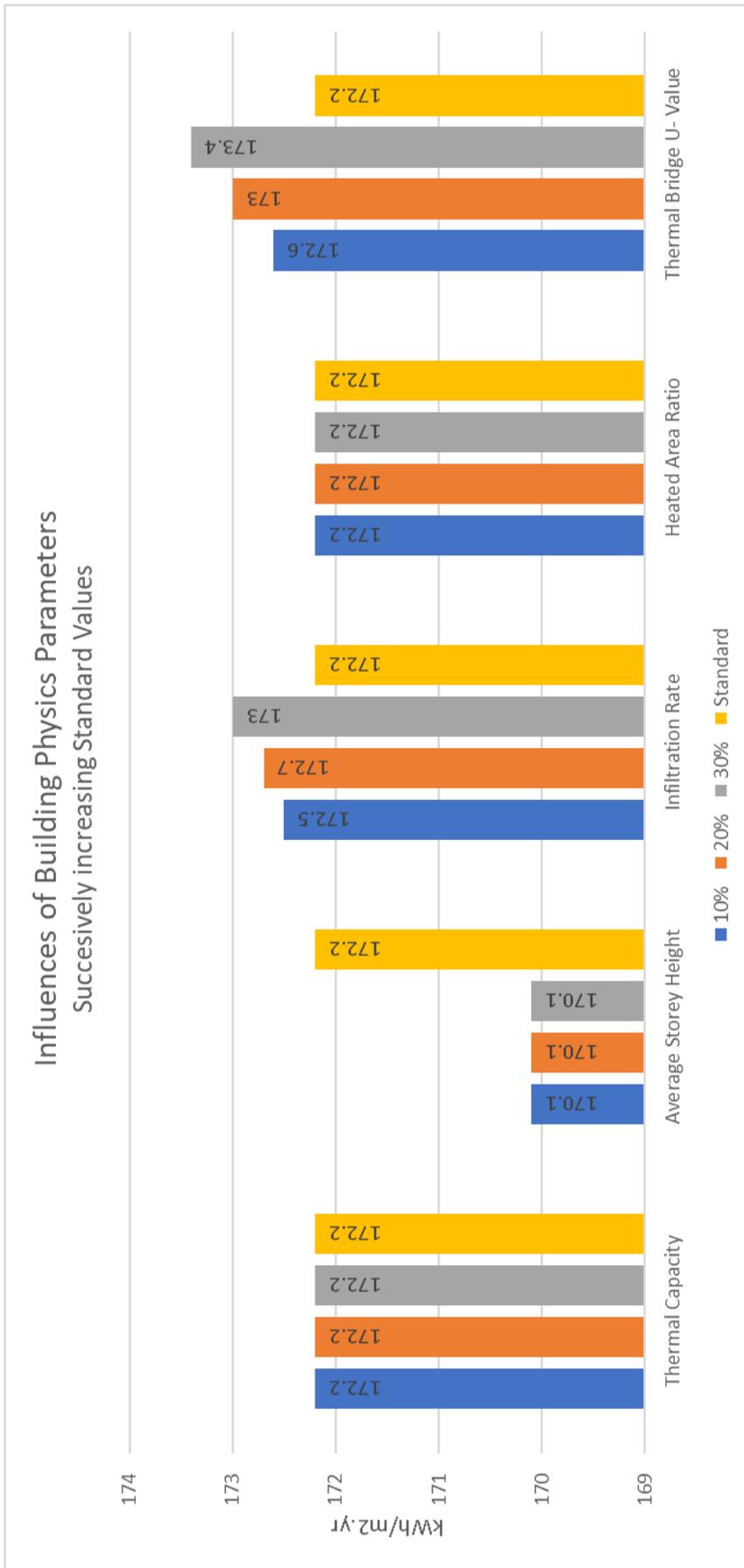


Figure 38 Influences of Building Physics Parameters

7.4.1.1 Conclusions on the Influence of Building-Physics Parameters

This analysis shows that a small change for the parameters “Inflation rate” and “Thermal Bridge U-value” causes a difference in the final output. For the thermal bridge U-value the change is not as meaningful since another scale of changing the parameter has been applied. Still with this investigation it is proven that this parameter is a minor influence on the simulation result.

The simulated outcomes for the average storey-height-parameter changed to the same level as soon as it has been altered from the standard value. This has its reason that Simstadt rounds the storey height in order to get integer values for the amount of storeys per building. In this case, the storey height has been set to 2.8 meters automatically to achieve an even storey number.

Having now pointed out several parameters allows to better understand the influence of building physical parameters on the simulation result. This information can be used when setting up a typology, showing parameters more oriented on the present building stock in Singapore.

7.4.2 Geometry

Wate et. al. published a paper where an analysis on the sensitivity of geometrical properties of buildings in a heating energy demand simulation using Simstadt is made. [59] For this a sensitivity analysis according to the Morris method is done which is focusing on two building models, which are buildings with a flat roof and buildings with a gabled roof-type. The result showed that for both cases the parameter which changes the simulated value the most, is the orientation of the building.

In this research the influence of geometries causing differences in the results is investigated by using two different levels of detail. An important factor is the surface to volume ratio, which regards the fact that a higher surface area allows a higher volume of cooled air to escape to the outside over the walls, which in turn leads to a higher cooling energy intensity used for reaching the internal set point temperature.

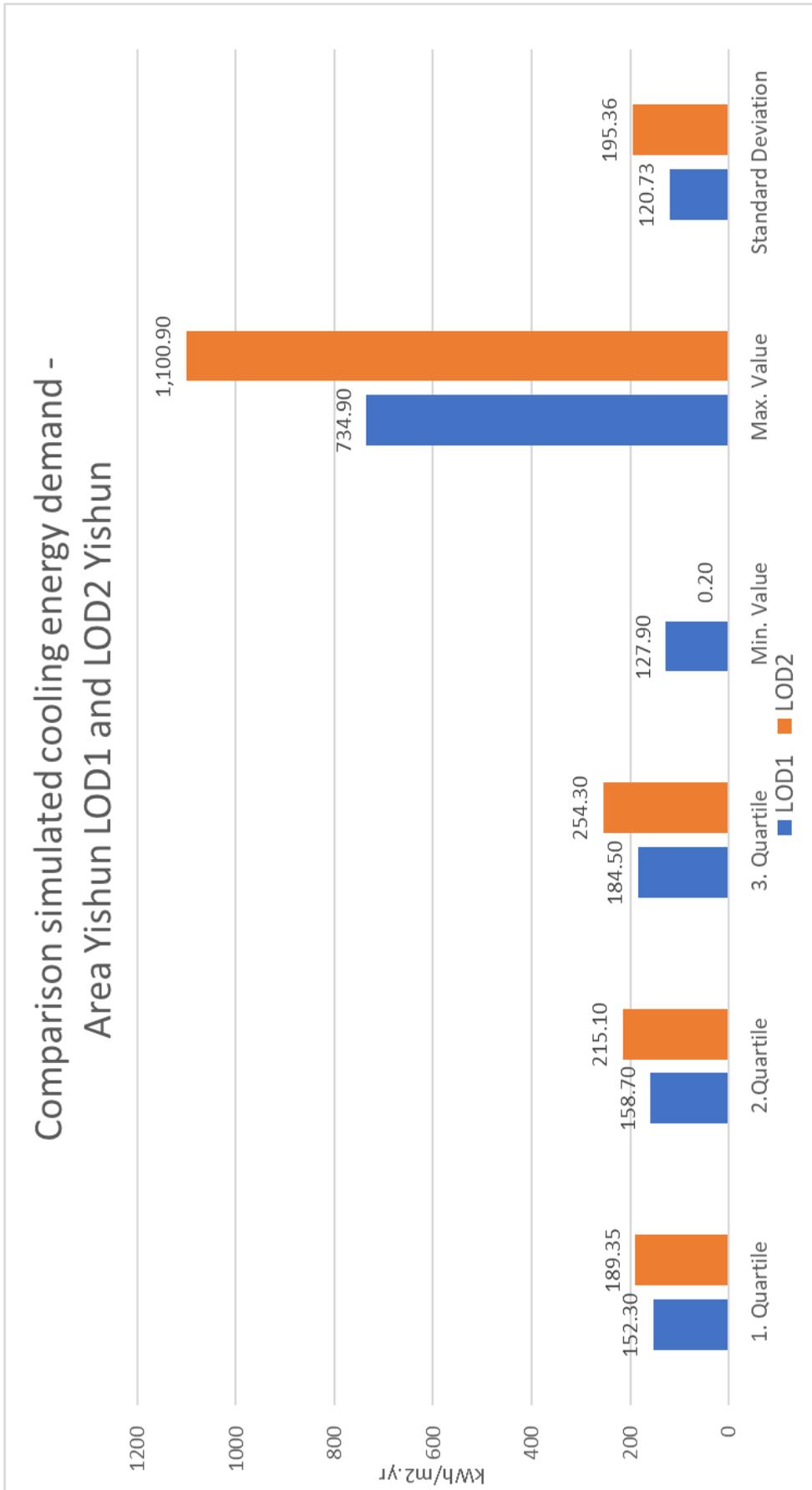


Figure 39 Comparison LOD1 to LOD2 of the Yishun 3D city model

7.4.2.1 Conclusions on Using Different Levels of Detail

Figure 39 shows the difference between different levels of detail quite clearly. In general, the higher LOD causes the structure to be more complex which results in higher surface areas and therefore an increased possibility of energy transfer through each building's structures. This in turn causes the estimated cooling energy demand for LOD2-buildings to be bigger than LOD1-buildings.

An estimation on the suitability of LOD1 and LOD2 can be done by focusing the amount of additional data available per building and the actuality of the 3D city model itself, where it can clearly be said, that for the LOD2 dataset more information is available and the creation date is later. For LOD2 the function of a building is mostly already included, and in general having a dataset available which is newer at least by a year compared to LOD1, is advisable for a cityscape as fast-changing as Singapore. Also, the increasing complexity allows for more realistic assumptions, of course given the condition that the geometries are errorless allowing a correct calculation of the volumes.

7.5 Creating EnergyADE datasets

The EnergyADE has been developed with the aim of being a general data model independently from a specific simulation system, which can be uniquely interpreted by any software without additional information. This fact serves as a motivation of including building energy model related parameters into the 3D city model of Singapore by using the EnergyADE which brings the aspect of data-interoperability to relevance. Also having 3D city models extended with the EnergyADE allows to store these into spatial databases like 3DCityDB which actually supports the attributes of the EnergyADE by using the extension authored by Zhihang Yao, Thomas H. Kolbe (Chair of Geoinformatics, Technical University of Munich) and Claus Nagel from virtualcitySYSTEMS GmbH, Berlin [60].

As described in chapter 7.1.1 Simstadt calculates the cooling energy demand using properties and attributes of buildings which account to what is understood as building energy model related information. The software is capable of interpreting information about the building's physics and usage related parameters which are already stored inside the input CityGML dataset by using the EnergyADE.

In general there are two ways including parameters about the energy model of a building: Either the libraries for Usage and Building-physics are set up in a way that it is representing the to be simulated building stock accordingly, or the relevant information is already included into the input datasets using the EnergyADE. The last option unlocks the possibility to define the parameters for each building separately, which in turn enables cooling energy simulation software to assume accurate energy consumptions based on more realistic building energy models.

In the following, a building from the LOD2 Yishun dataset has been used as an example of how the city model has to be modified to prepare the described buildings for simulations from a semantic point of view.

The data model of Simstadt, which simplified schema can be seen in Figure 40, is converted into the schema of the EnergyADE as defined by Agugiaro et. al. [24] and filled by values as they have been defined throughout the simulation process in Simstadt.

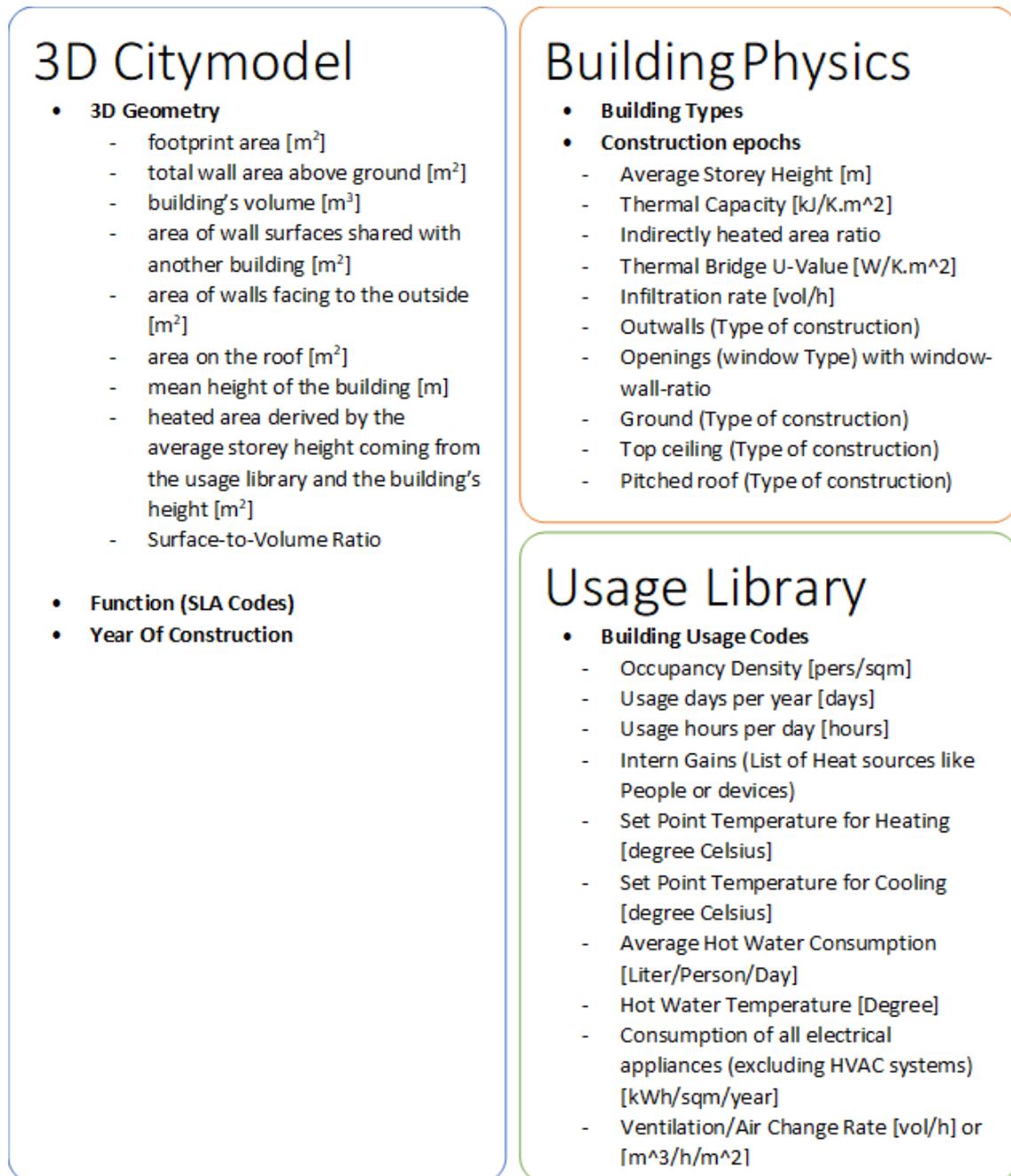


Figure 40 Simplified schematic visualization of the input data needed for Simulations in Simstadt

As first step the additional schema of the EnergyADE has to be stated in the header of each CityGML file. The namespace for that schema is then called “energy”. All attributes which are derived from the EnergyADE have to be declared with that namespace in front.

Then the elements which are accountable to the native CityGML standard are declared to be part of the “core”-namespace. This is again solved by adding the namespace in front of each attribute, an example for that would be: “<core:cityObjectMember>”

This has to be done to enable the linkage to the core-module in the EnergyADE and therefore to enable the inclusion of additional features and attributes.

The input parameters as they have been stated in the Simstadt Building-physics- and Usage-library are stored as attributes in the same CityGML file. This enables the use of the dataset in other simulation software with the benefit of not needing additional information.

To draw a comparison to the data model in Simstadt, it can be said that the attributes which define the “AbstractUsagezone” are basically parameters from the Usage-library and the attributes in the classes “AbstractThermalZone” and “AbstractConstruction” is mostly the content as described in the BuildingPhysics-library. This comparison can only be carried out partially since for example the key element for the Building-physics-library which are the Buildingtypes is stored inside the class “AbstractBuilding” and not in “AbstractThermalZone”.

In general, the structure according to the sequence of the schemas stated in the header inside the GML-file is the following:

1. GML – header with namespaces
2. BoundingBox for the to be described building feature
3. Building Opening Tag
4. CityGML Core-Attributes (e.g. CreationDate, externalReference)
5. Generic attributes (here the specific space cooling demand and the total yearly energy demand)
6. Energy demand values for heating and cooling on monthly scale
7. Building-module-attributes (e.g. class, function, usage, measuredHeight, storeysAboveGround)
8. Geometries
9. Address
10. Energy Attributes
 - a. AbstractBuilding ConstructionWeight
 - b. AbstractBuilding BuildingType
 - c. AbstractBuilding FloorArea
 - d. AbstractBuilding Volume
 - e. ThermalZone
 - f. UsageZone
11. Building Closing Tag
12. Construction Materials which will be linked in the Thermal Zone features

7.5.1 Setting up the EnergyADE Core-Module-Attributes

First the specific energy demand per square meter and the summed up total cooling energy demand for a whole year will be introduced by using the namespace “genobj”. These two

values are listed directly after the native CityGML attributes. The procedure of inserting these values in a namespace describing generic attributes is done according to the official sample files as issued by the KIT [61].

After that the energy demands on monthly scale are inserted. The class “EnergyDemand” is part of the EnergyADE Core module as shown in annex 4 Figure 46, and its attributes are inserted directly after the “genobj”-attributes per Building. This class is introduced by stating the monthly cooling energy demands by making use of a “regular time series” coming from the class “AbstractTimeSeries” as can be seen in annex 4 Figure 51. The calculated energy demand values from Simstadt for the months January to December are then written into the attribute “values”. In order to classify the stated values as simulated cooling energy demand, the attribute “endUse” of the class “EnergyDemand” is set on “spaceCooling”.

Next, the attributes stated in the “AbstractBuilding”-class in the “Core”-module are filled correctly. This includes the stating of a building type, the volume and the floor area. Also included is a classification of the building’s construction which has been set to medium.

The attributes in the following table are stated underneath the attributes of the address-module in the CityGML file.

Table 9 Attributes of the AbstractBuilding Class in the EnergyADE

Attribute	Value
Building Type	Apartment Block
Floor Area	3134.38
Volume	96103.9
Construction Weight	medium

For the attribute building type a UML-“Codelist” is used, which inherits certain archetypes of buildings which have been specified by the EnergyADE working group to be defined by the INSPIRE code register. These types are either apartment block, multi family house, single family house or terraced house [62]. Since the respective building has been classified as skyscraper in the German Building-physics-library the type apartment block as the most similar type is selected here.

7.5.2 Setting up the Building-physics-Module Attributes

The Buildingphycis module is aiming on introducing thermal zones in buildings. The elements defining the thermal zones are stated underneath the EnergyADE-“Core”-

module-attributes in the CityGML Code. Inside each thermal zone it is assumed to have one uniform set of parameters defining the thermal behavior of the respective zone. These parameters are then subject to be accounted for heating and cooling energy demand calculations.

Since we assume a monozonal building model, the ThermalZone will be set up for the whole building. The monozonal approach is used, since Simstadt isn't capable of calculating spatially divided usages/thermal zones for buildings. There is the possibility to state a mixed usage, but the energy demand will then be calculated by simply assuming 50% of the volume for each usage zone. The Building-physics-module can be seen in annex 4 Figure 47.

The structure of data to be inserted per ThermalZone looks like this:

1. Opening Tag ThermalZone
2. ThermalZone name
3. ThermalZone Bounding Box
4. Link to UsageZone
5. Thermal bridge U-Value and Thermal capacity
6. Floor area of ThermalZone
7. Volume of ThermalZone
8. Indirectly Heated area ratio and infiltration rate
9. Indicator if ThermalZone is cooled or heated
10. Volume Geometry (Solid Geometry – referencing the surfaces describing the solid)
 - a. Thermal Boundary – Each Thermal Boundary element describes an actual Surface, which – if all surfaces put together – are defining the Volume Geometry
 - i. Per Thermal Boundary stated: name, bounding box, boundary type (e.g. outerwall, etc.), surface geometry and the construction material which is linked from the features described in the construction module
11. Closing Tag Thermal Zone

In case a thermal zone is defined by a usage where occupants are assumed, like residential or office, then a usage zone must be referenced to the thermal zone by stating the attribute “energy:contains” with an “xref”-link to the respective GML-ID value of the usage zone. For this building the thermal zone describes simultaneously a usage zone with a residential use.

What can be discovered when looking onto the definition of the thermal boundaries is that the geometry of the whole building is listed again. The wall, roof and ground surfaces are used to be described as thermal boundary elements. Each element is then assigned to

a certain set of material which will influence energy simulation calculations by introducing heat-transfer- and shading-coefficients into each surface's information. The material is described by using classes and features in the construction module.

The attributes which have been incorporated in the building-physics module are listed in the following table:

Attribute	Value	Module
Thermal Bridge U-Value	0.05W/K.m2	ThermalZone
Thermal Capacity	90 KJ/K.m2	ThermalZone
Floor Area (Energy Reference Area)	3134.38 m2	ThermalZone
Cooled Volume (Energy Reference Volume)	92094.1 m3	ThermalZone
IndirectlyHeated Area Ratio	0.15	ThermalZone
Infiltration Rate	0.30 vol/h	ThermalZone

7.5.3 Setting up the Occupancy Module

The Occupancy Module's main element is the "UsageZone"-class which attributes are introduced after the closing tag of the ThermalZone. It inherits all the Usage related parameters such as occupant's presence, lighting-, heating-, cooling- and ventilation- schedules. The exact names of each attribute can be seen in the UML Diagram in the annex 4 Figure 49. Stating these schedules is referring to a selection of supporting classes, dealing with Daily Pattern Schedules, Yearly schedules, and other time related classes which can be seen in the annex 4 Figure 51.

The Usage zone is made up of the following structure:

1. Opening Tag UsageZone along with Identifier (GML ID) for referencing in ThermalZone
2. Cooling Schedule
 - a. Daily Pattern for a typical day
 - i. Set Point Temperatures in hourly resolution (constant at 25 degree Celsius in this case)
3. UsageZone Type (here: residential)
4. Normally VentilationSchedule, but for residential uses there is no ventilation indicated in the German Usage-Library
5. Occupants
 - a. Convective Fraction
 - b. Radiant Fraction
 - c. Total energy gain in Watt
 - d. Number of occupants
 - e. Occupancy Rate
 - i. Daily Pattern as ratio of present occupants (Value between 0 to 1)
6. Closing Tag UsageZone

The Occupancy module has been filled with the following attributes:

Attribute	Value	Class
Cooling Schedule	Hourly resolution; constantly on 25 degree	UsageZone
Usage Zone Type	Residential	UsageZone
Ventilation schedule	Hourly resolution; set constantly on 2.5 1/h	UsageZone
Average Internal Gains	Convective Fraction: 40% Radiant Fraction: 50% Latent Fraction: 10% Average Intern Gain: 2.1 W/m ²	UsageZone
Number of Occupants	104 Persons (estimated by the buildings floor area divided by the stated occupancy density of 0.03	Occupants
Occupancy rate	Hourly resolution; 17 hours per day	Occupants

The schedules for cooling, ventilation and occupancy rate are driven by a supporting class “Abstract Schedule”, where a daily pattern in hourly resolution can be defined. For the setting up of a daily pattern, first a period of the year where the following schedule is located in has to be set. Here it is chosen to reference a whole year. Then a daily schedule for the day type “typical day” is set up. The actual schedule in hourly resolution is then referring to the class “RegularTimeSeries” which is defined by a time period (here set from 0:00 to 23:00) and a time interval – set to hourly scale – followed by the actual values in the schedule.

The average internal gains are stated by using the HeatExchangeType which is declared by a datatype as specified in the Core module.

7.5.4 Setting up the Construction Module

The next part contributing to the contents in the building physics-library as modelled in Simstadt, is the Construction module, which UML-structure can be seen in annex 4 Figure 48.

This module mainly focusses on listing materials and their properties which are then incorporated into construction elements. These are then linked to thermal boundary elements using their respective GML-ID as a link. With that methodology the thermal behavior of the building’s hull can be modelled.

This way of assigning construction properties is a minor difference to the Simstadt data modelling approach. In the Building-physics library of Simstadt, the materials for all surfaces of a certain type are assigned together. The EnergyADE allows to describe different material properties per surface independently from its type (wall-, roof- or ground-surface). The material assignment in the EnergyADE can therefore vary from one thermal boundary element to another.

The main feature type of this module is the “Construction”-class. It allows to either define a construction of a surface just by stating the U-value and optical properties, or by additionally dissecting the construction feature into several layers, where per each layer a material is stated. For a layer the attributes thickness and areaFraction are given. Also per layer the used materials are linked via GML-ID’s. These materials are defined by the attributes conductivity, density, permeance, porosity, a specific heat coefficient and embodied heat and carbon amounts.

With focus onto the existent way of modelling in the Singaporean 3D city models, the inclusion of the EnergyADE gives the chance to indicate multiple thermal- and usage zones per building since a dissection into building-parts is already existent. For those buildings where different functions per building-parts are indicated, different parameter compositions can be realized since a thermal hull per building-part is already modelled. Of course, that approach would require the building-parts to be geometrically valid.

The structure for declaring a new construction element, to be linked in a thermal boundary is the following:

1. Opening tag Construction stating a GML-ID for the linkage in thermal boundaries
2. Specification of U-Value and optical properties like glazing ratio, indicating the amount of surface covered with windows.
 - a. Listing of Layers in a certain frequency
 - i. The most outside layer comes first, the layers located on the inside of a wall are listed lastly
 - ii. Layers can consist of Layer-components, where the “areaFraction” attribute indicates to which ratio the layer is made out of a certain material
 - iii. Per layer/layercomponent a material is linked using a GML-ID
3. Closing-tag Construction

Structure for Material-Elements:

1. Opening-tag featureMember
2. Specification of a “SolidMaterial” -feature provided with a unique GML-ID to be linked in layers of construction-element
 - a. Listing of attributes describing the materials thermal properties
3. Closing-tag featureMember

For the wall surfaces of this building, the construction type “Concrete sandwich wall 1980s” is stated inside the Building-physics library in Simstadt. This construction consists out of 5 different layers describing 5 different materials.

The Roof surfaces are made of the construction type “Timber rafters insulated 10cm” which inherits 3 different layers with 3 different materials.

Ground surfaces are described as “Concrete Slab insulated 4 cm” which has again 3 different layers each containing a certain material type.

The complete CityGML with the extension of the here described EnergyADE can be seen on the enclosed CD.

7.6 Development of a Web Application for Visualization

Part of the research goal is a visualization of the simulation done in this thesis. This chapter shows how a visualization has been conceptualized and set up. Developing a concept for a 3D Visualization is part of this research, because of having the possibility in mind, for including cooling energy simulation results into prestigious Smart City projects such as “Singapore Advanced Map” [7] and “Virtual Singapore” [63] in the near future. The goal for that is to show possible Users buildings along with information on cooling energy estimations per building. Along with the energy amount, additional information gained during the simulation should be made easy to access.

The research for possible 3D mapping platforms led to the decision to use the CesiumJS framework as a basis for the visualization. CesiumJS is an open-source Javascript Library which has a huge active Community [64], therefore tutorials for multiple concerns are well documented. Figure 41 shows the sources and workflow steps which have been applied to conclude onto the final web application which has been developed.

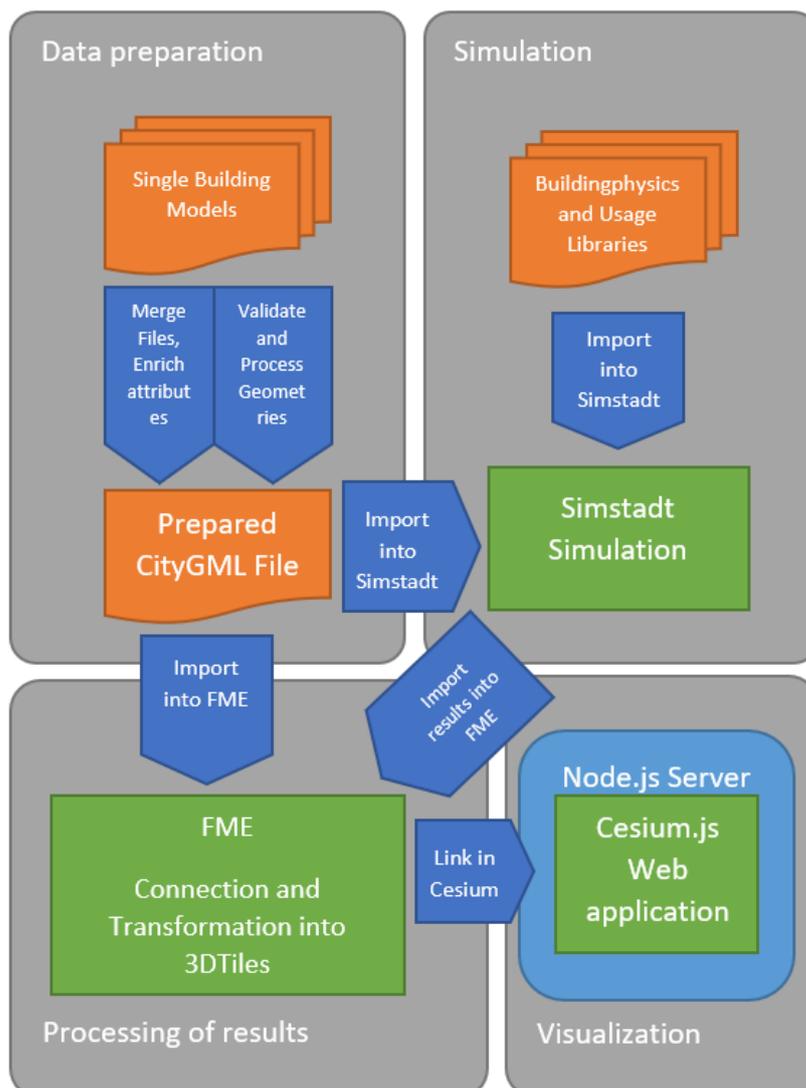


Figure 41 Data sources and schema of the Workflow for setting up the Visualization

For the 3D visualization in CesiumJS all available CityGML files have been preprocessed and simulated using the German libraries since these are by now delivering the most realistic results.

For the inclusion of the CityGML Files the first step of processing is to transform these into a format which is supported by CesiumJS. This Framework enables the Visualization of a format called “3D Tiles” which is suitable for the needs of the to be developed web application since it’s possible to store additional attributes per building inside of it and delivers a file-size for the respective 3D city models which still allows a relative fast speed of loading and rendering a whole dataset at once. For example, the Yishun area in LOD2 delivers a filesize of 4.65 Mb which is loaded completely in roughly 3 seconds by a rather old non-highend Hardware-architecture (5 years).

For enabling a visualization of the buildings, driven by the output information of Simstadt, the 3D city model has to be connected with the CSV-files of the cooling energy simulations. This has been done using the software FME [65]. In this software workflows for transforming and manipulating spatial data to other formats can be set up in order to reach compliancy between software systems.

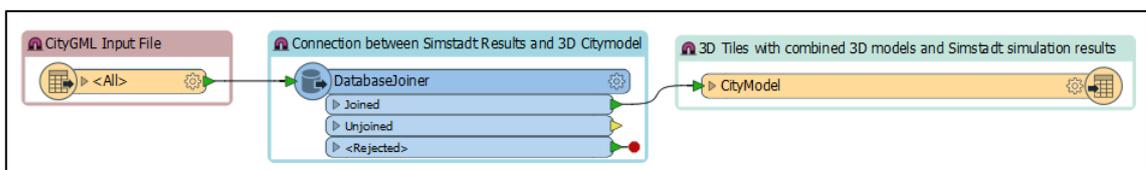


Figure 42 FME Workflow to create 3D Tiles

In Figure 42 the workflow for creating 3D Tiles in FME can be seen. First a so-called “Reader” has been created, which enables the import of the CityGML file into the software. In order to establish a connection of the existing important attributes in the input dataset, which are the year of construction and the function of each building, a transformer called “DatabaseJoiner” is connected to the CityGML-Reader.

This transformer uses the ID’s of each building to connect the geometries to the simulated results in the csv-file.

As last step a “Writer” is introduced which is creating the final 3D Tile-file based on the merged information coming from the “DatabaseJoiner” consisting of geometries and attributes from the output of the cooling energy demand simulation.

The now created 3D Tile-files for each of the 3 input datasets are then subject to be included into the Javascript code running on a server which is set up using node.js [66].

The Javascript code using the CesiumJS library is linked to an element in an HTML document which has been extended using several CSS modifications of implemented Bootstrap elements [67] and Fontawesome icons [68].

Since CesiumJS is taking 3D Coordinates of buildings into account to depict them, it has been discovered that all buildings are floating above the ground when visualizing them in Cesium. A solution would be including a terrain model into the web application, but this means that the scripts need longer to load for rather unimportant information when analyzing energy performance of buildings. It has been decided to use a software solution, created by Athanasios Koukofikis from the HFT Stuttgart, which clamps all buildings to the ground by assigning the footprints to height zero [69].

The complete Code of the 3D Visualization can be seen on the enclosed CD.

The guided user interface is segregated into the main window, which shows the actual 3D content and a control-pane hovering on the left as shown in Figure 43.

Here it can be switched between a visualization of either only LOD1 buildings or only LOD2 buildings. Also, it is possible to switch between the way of how buildings are colored, either these are colored in grey, or according to the legend which is shown underneath of the theme-switch. The coloring is done according to the specific cooling energy demand value each building received during the simulation in Simstadt.

The home button sets the camera back to the initial position the button “Monthly Chart” delivers the option of getting a visualization of the results calculated per building.

In the main window it is possible to hover over each building’s geometry which is then highlighted in yellow and the GML-ID of the respective building is indicated with an overlay appended to the pointer.

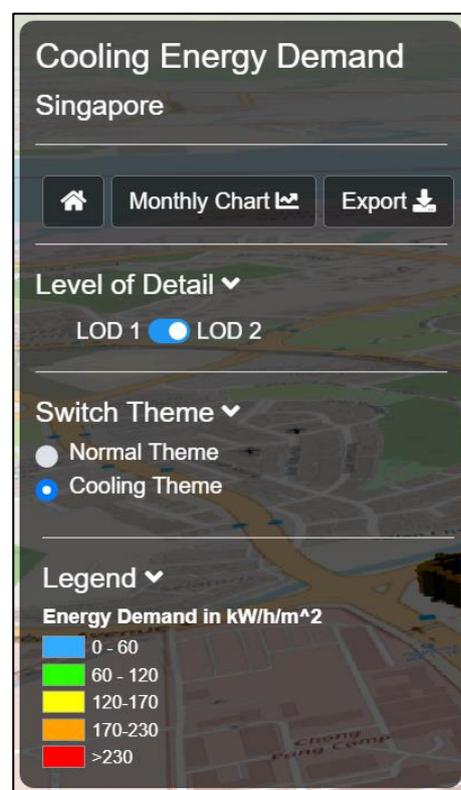
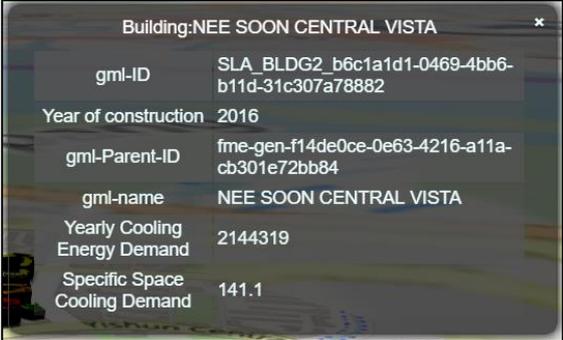


Figure 43 Control Center of the Cesium Webapplication

Clicking onto a building highlights it in bright blue and opens a pane on the right indicating the values as can be seen in Figure 44. As heading for this window it has been chosen to use the name as indicated in the input dataset as the attribute `gml:name`.



Building:NEE SOON CENTRAL VISTA	
gml-ID	SLA_BLDG2_b6c1a1d1-0469-4bb6-b11d-31c307a78882
Year of construction	2016
gml-Parent-ID	fme-gen-f14de0ce-0e63-4216-a11a-cb301e72bb84
gml-name	NEE SOON CENTRAL VISTA
Yearly Cooling Energy Demand	2144319
Specific Space Cooling Demand	141.1

Figure 44 Pane with Information about the selected building

Having a building selected and clicking onto the button “Monthly Chart” in the control center in Figure 43 opens another window showing extended information on the building (Figure 45).

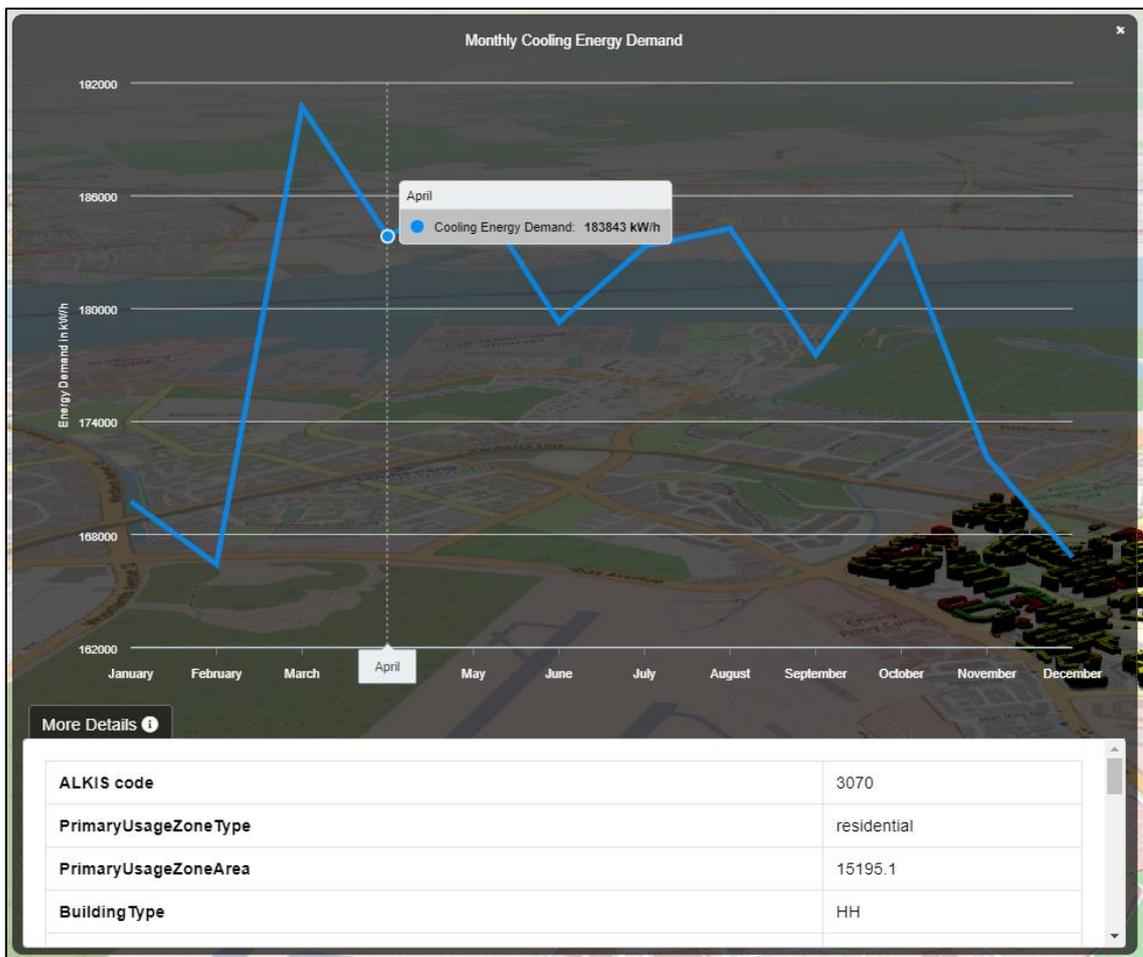


Figure 45 Additional Information window showing the temporal distribution of the energy demand per month

The main element is the graph which has been created using the Javascript library Apexcharts.js [70]. Hovering over the local peaks in the graph enables a popup indicating the Month and the calculated summed up cooling energy demand for the selected Month.

Clicking onto the button “More Details” extends the window with a scrollable list of all additional data of the building which has been written into the output file of Simstadt.

7.6.1 Evaluation of the Visualization

The proposed concept of visualizing the simulation results delivers the possibility to be able to investigate the cooling energy demand assumptions as a visual overview of a whole city quarter, but also provides with the capability to consolidate information on building scale. The provided web application delivers a concept how cooling energy demand can be included into ongoing 3D Mapping projects, which contribute to the Smart Nation Initiative of Singapore. The mixture of having a high density of information along with a non-complex intuitive User-Interface serves the need for planning Singapore in the future and allows to easily put the energetical performance of buildings into focus.

A video showing the features of the developed Web-Visualization can be found on the enclosed CD.

8 Synthesis

This chapter aims at summarizing the results obtained in the implementation-part of this thesis and gives recommendations on the structuring and preparation of the datasets used for cooling energy demand simulations.

8.1 Data availability

Throughout the implementation of the simulation-tests it has been discovered that key information about the buildings is still missing to enable a simulation using the data model of Simstadt.

In case a simulation should be carried out using the software Simstadt, the missing attribute “year of construction” must be available for assigning a set of building-physical parameters into each building’s energy model which then enables the conclusion onto an energy demand value.

Also, for the Simstadt methodology to work, the function of a building is required, which is missing for some of the buildings in LOD2 datasets and in LOD1 it is not mentioned at all. Still a preliminary method of deriving a function has been found by taking the building name into account and assign a function to each building depending on keywords occurring in the names using the code list established by the SLA. The function is then used to enable a linkage to Usage-related parameters.

The data for the two libraries, Usage- and Building-physics-library, still have to be set up for a Singaporean building stock. Throughout the thesis, not many data sources have been found, to create a typology which inherits parameters describing archetypes of Singaporean buildings. Based on that fact it is recommended to use the network of different authorities, mainly the Housing Development Board, the Building and Construction Authority and the Singapore Land Authority to start an initiative to collect needed information for simulations. A document which lists the needed information is appended on the CD.

8.2 Geometrical Modelling

Very important attributes influencing cooling energy demand predictions are the volume and the floor area of a thermal zone of a building. Based on the findings in chapter 7.2.3 it can be said that for the modelling of the 3D city model as it has been done now, some changes have to be applied in order to derive the volumetric affected influences onto the calculation of the monthly energy balance. The analysis of the status quo of the CityGML-modelling delivers that single building-parts are used to define a whole building-object. The check using CityDoctor as a tool of validation resulted in the discovery of the fact,

that building-parts in the LOD2 input datasets are not modelled in a valid way. For energy simulations, the best primitive object to be used for building geometries is a solid, since it's defining a watertight geometry resulting in an unequivocal volume calculation.

As a preliminary method for preparing the Singaporean 3D city model, the here described concept defines a way to summarize all building-parts to one solid. This method should be seen as preliminary, since the information about the segregation of a building into parts is lost after the procedure. Building-parts can be helpful when defining different thermal zones, which in turn increase the accuracy and realism of the definition of a whole building's energy model.

It is therefore recommended to analyze workflows which introduce the automatic healing of invalid building-parts before applying the here described concept of estimating cooling energy demand to a nation-wide scale. Important to state here is that the CityDoctor development Team at HFT Stuttgart is currently working on such an approach to be included into the next version of that software.

The Singapore Land Authority is currently (year 2019) conducting a campaign of recapturing the 3D models of buildings which have been changed or have been recently constructed. The models generated in that process have been found to be completely valid according to the modeling guidelines published by SIG3D [55].

8.3 Plausibility of Simulation results

The plausibility of the results has been investigated using the existing real consumption values. Of course, a certain uncertainty of the present values is given, since no highly detailed information on the capturing and end-use is stated.

What is also an impeding factor are the assumptions which have been made on the function and year of construction per building. Nevertheless, for the CBD-area, a visual inspection covers the assumed YOC of 2000 and usage classified as office buildings. A comparison between real consumption and simulated values, delivers promising results as can be seen in Figure 37, and confirms that Simstadt is capable of calculating plausible cooling energy demands using the DIN V 18599. The results tend to be conform with Figure 1, showing that energy accountable to cooling energy demand tends to consume between 1/3 to 1/2 of the whole energy consumption of a building. Implementing now a more detailed library which models Building-physics and occupants behavior of archetypes of buildings is assumed to cause an approximation to the hypothetical share of cooling energy demand.

8.4 Recommended data model: EnergyADE

By using the data model of the EnergyADE it can be shown what is needed to be able to conduct energy simulations using 3D city models.

In chapter 7.5 it has been demonstrated how the information, which is normally specified before a simulation in Simstadt, can be stored directly in the city model. This approach is recommended since the EnergyADE enables the interoperability of the used dataset. Also, a big benefit is that no additional information as input is needed, if such a 3D city model has been set up for uses in other energy analysis software.

Still it has to be said, that the actual transformation and enrichment of energy related information into the CityGML standard according to the EnergyADE has potential to be carried out more user-friendly by using e.g. UI's. Software like the GML-Toolbox by the KIT [25] are already a step towards the further establishment and spreading to a wider audience of users of the EnergyADE.

Still, using that data-concept doesn't prevent from capturing and collecting several information which is needed to be able to predict cooling energy consumptions using any reliable existing building energy modelling approach.

Based on Figure 5 the to be estimated data can be classified into several categories, which can be easily mapped to the data which is needed as input for the Simstadt methodology to work. By enabling the collection and inclusion of energy-relevant data per building, it is possible to combine the goal of using Simstadt as a cooling energy demand assessment tool with the creation of a multi-purpose dataset usable in other energy analysis frameworks and projects.

9 Conclusions

This research focused on developing a concept on how energy simulations can be done using Singaporean 3D city models. The implementation of a test of the cooling energy demand simulation has shown that a plausible cooling energy demand analysis is possible using Singaporean 3D city models while using the German methodology DIN V 18599.

There are currently several aspects which impede the workflow to result in plausible values on a large scale, namely a missing dependable source of building-physics parameters and a way of modeling the buildings which are not yet energy-simulation-compliant. For the geometrical modeling, a way of still being able to get dependable results has been shown.

The collection of parameters, which drives the establishment of a simulation-valid dataset can be oriented according to the data model of the EnergyADE which allows to efficiently store simulation relevant attributes in the same source as the geometries. This also introduces the ability to apply the dataset to other simulation platforms, since the interoperability of the energy-related attributes is granted by using a widely spread data model.

Another aspect of this thesis is to provide an approach to visualizing the Simulation results. Being able to do a simulation using the software Simstadt enables different ways of sharing the results in several Smart Nation projects. A way how to leverage the simulation results in urban planning projects was demonstrated with a concept for a 3D visualization of the provided city models in combination with their predicted energy value.

Using the 3D visualization in combination with interactive charts provides an efficient way to quickly investigate energy-performances of the analyzed buildings.

10 Future Work

This part should give an insight on a possible further implementation of the now described concept and its use cases.

As already shown in the chapter 7, the data availability for setting up a building typology is very limited. If it is intended to do a nation-wide cooling energy simulation, it is recommended to initiate the development of a building-typology. A basis for such a typology is already given when looking on certain data sources. For example, the platform “data.gov.sg” is containing a dataset showing the position of state-owned dwelling’s and per dwelling a Buildingtype is given. [71] That Buildingtype is also given as an attribute in a dataset showing the rental range for state-owned residential properties. [72] The BCA⁷ has an initiative called “Green Mark” which is intended to rate building’s according to their energy performance [73]. Using this already existing information as a basis, a Singaporean-oriented depiction of the existing building stock can be drawn.

Efforts are also being made to introduce a 3D cadaster where, compared to the current 2D cadastre data set, missing information per building will be available in apartment scaling.

Mentioning Green Mark, it would be possible under use of a cooling energy demand simulation to already classify buildings according their energy performance before they are built. This gives chance to further deepen the cooperation between the BCA and SLA, by developing strategies of rating not the built- but the to-be-built-environment which enables the developments of construction-plans that are even more oriented on the aspect of being sustainable and environment-friendly.

By including these results into already existing projects such as Virtual Singapore or Singapore Advanced Map a console for assessing relevant building information is already given.

⁷ Building & Construction Authority

VII. Bibliography

- [1] S. Murray, "How technology can reduce consumption in cities," 4 February 2015. [Online]. Available: <https://www.weforum.org/agenda/2015/02/how-technology-can-reduce-consumption-in-cities/>.
- [2] McKinsey Global Institute, "SMART CITIES: DIGITAL SOLUTIONS FOR A MORE LIVABLE FUTURE," June 2018. [Online]. Available: <https://www.mckinsey.com/~media/mckinsey/industries/capital%20projects%20and%20infrastructure/our%20insights/smart%20cities%20digital%20solutions%20for%20a%20more%20livable%20future/mgi-smart-cities-full-report.ashx>. [Accessed 12 July 2019].
- [3] B. Buntz, "The World's 5 Smartest Cities," IoT World Today, 18 May 2016. [Online]. Available: <https://www.iotworldtoday.com/2016/05/18/world-s-5-smartest-cities/>. [Accessed 12 July 2019].
- [4] Smart Nation and Digital Government Office, "Smart Nation - Initiatives," 2019. [Online]. Available: <https://www.smartnation.sg/what-is-smart-nation/initiatives>. [Accessed 12 July 2019].
- [5] National Research Foundation, "Virtual Singapore," National Research Foundation, 7 November 2018. [Online]. Available: <https://www.nrf.gov.sg/programmes/virtual-singapore>. [Accessed 3 July 2019].
- [6] National Research Foundation Singapore, "Uses of Virtual Singapore," Youtube, 11 10 2016. [Online]. Available: https://www.youtube.com/watch?time_continue=139&v=y8cXBSI6o44. [Accessed 3 July 2019].
- [7] esri Singapore, "SLA's new 'Singapore Advanced Map' to set new benchmark," esri Singapore, 18 July 2017. [Online]. Available: <http://esrisingapore.com.sg/news/slas-new-singapore-advanced-map-to-set-new-benchmark-nar-72>. [Accessed 3 July 2019].
- [8] Holiday Weather Ltd., "Singapore: Annual Weather Averages," Holiday-Weather.com, 2019. [Online]. Available: <https://www.holiday-weather.com/singapore/averages/#chart-head-temperature>. [Accessed 3 July 2019].

- [9] C. Qi, "Office Building Energy Saving Potential in Singapore," E2 Singapore, National Environment Agency, Singapore, 2006.
- [10] National Environment Agency, "Home Energy Audit," 18 October 2018. [Online]. Available: <https://www.e2singapore.gov.sg/households/saving-energy-at-home/HEA>.
- [11] J. J. Bloem, H. Madsen, J. Kloppenborg, J. Liisberg, J. Cipriano and G. Mor, "Dynamic Methodology for the Evaluation of Occupant Behaviour and Residential Energy Consumption," in *Proceedings of the 8th International Conference on Energy Efficiency in Domestic Appliances and Lighting*, Lucerne, 2015.
- [12] D. Robinson, J. Kämpf, P. Leroux, D. Perez, U. Wilke, A. Rasheed and F. Haldi, "CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning," in *Eleventh International IBPSA Conference*, Glasgow, 2009.
- [13] J. Kämpf and D. Robinson, "A simplified thermal model to support analysis of urban resource flows," *Energy and buildings*, vol. XXXIX, no. 4, pp. 445-453, 2007.
- [14] R. Judkoff and J. Neymark, "International Energy Agency building energy simulation test (BESTEST) and diagnostic method," National Renewable Energy Laboratories, Golden, 1995.
- [15] E. Walter and J. Kämpf, "A verification of CitySim results using the BESTEST and monitored consumption values," in *Proceedings of the 2nd Building Simulation Applications conference*, Bozen-Bolzano, 2015.
- [16] Z. M. A. Chong, N. H. Wong, M. Ignatius and S. K. Jusuf, "Predicting the envelope performance of commercial office buildings in Singapore," *Energy and Buildings*, vol. LXVI, no. 1, pp. 66-76, 2013.
- [17] M. Kavgic, A. Mavrogiann, D. Mumovic, A. Summerfield, Z. Stevanovic and M. Djurovic-Petrovic, "A review of bottom-up building stock models for energy consumption in the residential sector," *Building and Environment*, vol. XLV, no. 7, pp. 1683-1697, 2010.
- [18] L. G. Swan and I. V. Ugursal, "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques," *Renewable and sustainable energy reviews*, vol. 13, no. 8, pp. 1819-1835, 2009.

- [19] S. . T. Moghadam, G. Mutani and P. Lombardi, "GIS-Based Energy Consumption Model at the Urban Scale for the Building Stock," in *9th International Conference Improving Energy Efficiency in Commercial Buildings and Smart Communities*, Frankfurt, 2016.
- [20] J.-M. Bahu, E. Kremers, A. Koch and S. M. Murshed, "Towards a 3D spatial urban energy modelling approach," *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II, no. 2, pp. 33-41, 2013.
- [21] A. Pouget, "Amélioration thermique des bâtiments collectifs construits de 1850 à 1974. Le guide ABC," Les éditions parisiennes (EDIPA), Paris, 2011.
- [22] R. Nouvel, C. Schulte, U. Eicker, D. Pietruschka and V. Coors, "CITYGML-BASED 3D CITY MODEL FOR ENERGY DIAGNOSTICS," in *13th Conference of International Building Performance Simulation Association*, Chambéry, 2013.
- [23] U. Eicker, R. Nouvel, C. Schulte, J. Schumacher and V. Coors, "3D-STADTMODELLE FÜR DIE WÄRMEBEDARFBERECHNUNG," in *Fourth German-Austrian IBPSA Conference*, Berlin, 2012.
- [24] G. Agugiaro, J. Benner, C. Piergiorgio and R. Nouvel, "The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations," *Open Geospatial Data, Software and Standards*, vol. III, no. 1, pp. 1-30, 2018.
- [25] Institut für Automation und angewandte Informatik - KIT, "GML-Toolbox," Karlsruher Institut für Technologie, 07 June 2016. [Online]. Available: <https://www.iai.kit.edu/1650.php>. [Accessed 22 July 2019].
- [26] Hottgenroth Software GmbH & Co. KG, "Gebäude-Simulation 3D PLUS," Hottgenroth Software GmbH & Co. KG, 2019. [Online]. Available: <https://www.hottgenroth.de/M/SOFTWARE/SolarPVSimulation/Gebaeude-Simulation/Seite.html,73283,80430>. [Accessed 22 July 2019].
- [27] T. H. Kolbe and Y. Zhihang, "Dynamically extending spatial databases to support CityGML application domain extensions using graph transformations," in *Kulturelles Erbe erfassen und bewahren-Von der Dokumentation zum virtuellen Rundgang*, 37. Wissenschaftlich-Technische Jahrestagung der DGPF, Würzburg, 2017.

- [28] F. Biljecki, H. Ledoux, X. Du, J. Stoter, K. H. Soon and V. H. S. Khoo, "THE MOST COMMON GEOMETRIC AND SEMANTIC ERRORS IN CITYGML DATASETS," *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, vol. IV, no. 2, pp. 13-22, 2016.
- [29] H. Ledoux, "val3dity: validation of 3D GIS primitives according to the international standards," *Open Geospatial Data, Software and Standards*, vol. III, no. 1, pp. 1-12, 2018.
- [30] esri, "Is Closed 3D," esri, [Online]. Available: <https://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/is-closed-3d.htm>. [Accessed 12 July 2019].
- [31] B. M. Kazar, R. Kothuri, P. van Oosterom and S. Ravada, "On valid and invalid three-dimensional geometries," in *Advances in 3D geoinformation systems*, Heidelberg, Springer Berlin, 2008, pp. 19-46.
- [32] P. Colley, B. M. Kazar, R. Kothuri, P. van Oosterom and S. Ravada, "Validation of Three-Dimensional Geometries," in *Encyclopedia of GIS*, Cham, Springer International, 2017, pp. 2398-2405.
- [33] Safe Software, "GeometryValidator," 2019. [Online]. Available: <https://www.safe.com/transformers/geometry-validator/>. [Accessed 12 July 2019].
- [34] D. Wagner, N. Alam, M. Wewetzer, M. Pries and V. Coors, "METHODS FOR GEOMETRIC DATA VALIDATION OF 3D CITY MODELS," *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, vol. XL, no. 1, pp. 729-735, 2015.
- [35] N. Alam, D. Wagner, M. Wewetzer, J. v. Falkenhausen, V. Coors and M. Pries, "Towards Automatic Validation and Healing of CityGML Models for Geometric and Semantic Consistency," in *Innovations in 3D Geo-Information Sciences*, Cham, Springer, 2014, pp. 77-91.
- [36] Open Geospatial Consortium (OGC), "CityGML Standard," 2019. [Online]. Available: <http://www.opengeospatial.org/standards/citygml>. [Accessed 22 July 2019].
- [37] T. H. Kolbe, "Representing and exchanging 3D city models with CityGML," *3D Geo-Information Sciences*, vol. XVII, no. 436, pp. 15-31, 2009.

- [38] SemantiCity, "About Level of Details," 1 December 2016. [Online]. Available: <http://semanti.city/level-of-detail-lod/#prettyPhoto>. [Accessed 18 July 2019].
- [39] R. Nouvel, R. Kaden, J. M. Bahu, J. Kaempf, P. Cipriano, M. Lauster, J. Benner, E. Munoz, O. Tournaire and E. Casper, "Genesis of the citygml energy ADE," in *Proceedings of International Conference CISBAT 2015 on Future Buildings and Districts Sustainability from Nano to Urban Scale*, Lausanne, 2015.
- [40] J. Stoter, L. van den Brink and S. Zlatanova, "Modeling an application domain extension of CityGML in UML," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XXXVIII, no. 4, pp. 11-14, 2012.
- [41] Special Interest Group 3D (SIG3D), "Feature catalogue energy:Energy-ADE," [Online]. Available: <http://www.citygmlwiki.org/upload/EnergyADE%201.0/FeatureCatalogue/index.html>. [Accessed 11 July 2019].
- [42] B. Nicholls and V. Khoo, "Singapore 3D Map for a Smart Nation," 10 April 2017. [Online]. Available: <https://www.slideshare.net/AAMMarketing/singapore-3d-map-for-a-smart-nation>. [Accessed 6 August 2019].
- [43] European Commission, "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings," *Official Journal L 001*, pp. 65-71, 2002.
- [44] Institut für Energie-Effiziente Architektur, "Gegenstand - Neufassung EU Gebäuderichtlinie 2018," 2018. [Online]. Available: http://www.enev-online.de/epbd/2018/epbd_2018_01_gegenstand_eu_richtlinie.htm. [Accessed 26 July 2019].
- [45] Beuth, "DIN V 18599-1:2016-10," 2019. [Online]. Available: <https://www.beuth.de/de/vornorm/din-v-18599-1/257938824>.
- [46] Deutsches Institut für Normung, "DIN, V 18599: Energetische Bewertung von Gebäuden–Berechnung des Nutz-, End-und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung," Beuth Verlag, Berlin, 2007.

- [47] M. Rouvel and M. Wenning, "Nutzenergiebedarf für das Heizen und Kühlen einer Gebäudezone Bilanzierung nach DIN V18599 Teil 2," *Bauphysik*, vol. IV, no. 28, pp. 233-243, 2006.
- [48] Building and Construction Authority, "Voluntary Disclosed Energy Performance Data for Commercial Buildings," 13 June 2018. [Online]. Available: https://data.gov.sg/dataset/building-energy-performance-data?resource_id=17c5cf53-9b5c-428b-a5b7-d88b8071d4af. [Accessed 28 July 2019].
- [49] HFT Stuttgart, "Überblick & Projektziele SimStadt und SimStadt 2.0," 2018. [Online]. Available: <http://simstadt.eu/de/index.jsp>. [Accessed 12 July 2019].
- [50] Institut für Automation und angewandte Informatik (IAI) - KIT, "FZKViewer," [Online]. Available: <https://www.iai.kit.edu/1648.php>. [Accessed 12 July 2019].
- [51] D. Ho, "About Notepad++," 2019. [Online]. Available: <https://notepad-plus-plus.org/>. [Accessed 10 July 2019].
- [52] Special Interest Group 3D (SIG3D), "Handbuch für die Modellierung von 3D Objekten - Teil 1: Grundlagen (Regeln für valide GML Geometrie-Elemente in CityGML)," 9 April 2018. [Online]. Available: [http://wiki.quality.sig3d.org/index.php/Handbuch_f%C3%BCr_die_Modellierung_von_3D_Objekten_-_Teil_1:_Grundlagen_\(Regeln_f%C3%BCr_valide_GML_Geometrie-Elemente_in_CityGML\)#gml:Solid.%20\(retrieved%20June%202019\)](http://wiki.quality.sig3d.org/index.php/Handbuch_f%C3%BCr_die_Modellierung_von_3D_Objekten_-_Teil_1:_Grundlagen_(Regeln_f%C3%BCr_valide_GML_Geometrie-Elemente_in_CityGML)#gml:Solid.%20(retrieved%20June%202019)). [Accessed 8 July 2019].
- [53] D. Wagner, V. Coors and J. Benner, "Semantic Validation of GML-based geospatial data," in *9th 3D GeoInfo Conference*, Dubai, 2014.
- [54] Trimble Inc, "Sketchup - Modelling Software," 2019. [Online]. Available: <https://www.sketchup.com/>. [Accessed 18 July 2019].
- [55] Special Interest Group 3D (SIG3D), "Modeling Guide for 3D Objects - Part 2: Modeling of Buildings (LoD1, LoD2, LoD3)," 9 April 2018. [Online]. Available: [http://en.wiki.quality.sig3d.org/index.php/Modeling_Guide_for_3D_Objects_-_Part_2:_Modeling_of_Buildings_\(LoD1,_LoD2,_LoD3\)#Wall_Surfaces_.28bldg:WallSurface.29](http://en.wiki.quality.sig3d.org/index.php/Modeling_Guide_for_3D_Objects_-_Part_2:_Modeling_of_Buildings_(LoD1,_LoD2,_LoD3)#Wall_Surfaces_.28bldg:WallSurface.29). [Accessed 8 July 2019].

- [56] T. Loga, B. Stein and N. Diefenbach, "TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable," *Energy and Buildings*, vol. 132, pp. 4-12, 2016.
- [57] R. Andarini, H. Schranzhofer, W. Streicher and A. K. Pratiwi, "Thermal simulation and cooling energy sensitivity analysis of a typical shophouse in Jakarta, Indonesia," in *Eleventh International IBPSA Conference*, Glasgow, Scotland, 2009.
- [58] M. D. Morris, "Factorial sampling plans for preliminary computational experiments," *Technometrics*, vol. XXXIII, no. 2, pp. 161-174, 1991.
- [59] P. Wate, V. Coors, D. Robinson and M. Iglesias, "Qualitative screening method for impact assessment of uncertain building geometry on thermal energy demand predictions," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII, no. 2, pp. 128-134, 2016.
- [60] Z. Yao, T. H. Kolbe and C. Nagel, "3DCityDB-Extensions-for-CityGML-ADEs," 28 October 2016. [Online]. Available: <https://github.com/yaozhihang/3DCityDB-Extensions-for-CityGML-ADEs>. [Accessed 23 July 2019].
- [61] Institute for Automation and Applied Computer Science (IAI) at KIT, "KIT Sample files Energy ADE," 29 June 2018. [Online]. Available: http://www.citygmlwiki.org/index.php?title=KIT_Sample_files_Energy_ADE. [Accessed 24 July 2019].
- [62] European Commission, "Geo Smart City - INSPIRE Registry - Buildingtype Codelist," 2010. [Online]. Available: <http://hub.geosmartcity.eu/registry/codelist/BuildingTypeValue/>. [Accessed 24 July 2019].
- [63] National Research Foundation Singapore, "Virtual Singapore," 7 November 2018. [Online]. Available: <https://www.nrf.gov.sg/programmes/virtual-singapore>. [Accessed 9 July 2019].
- [64] Cesium Consortium, "Cesium - An open-source JavaScript library for world-class 3D globes and maps," [Online]. Available: <https://cesiumjs.org/>. [Accessed 9 July 2019].

- [65] Safe Software, "FME — The Simple Solution for Complex Integration," Safe Software, 2019. [Online]. Available: <https://www.safe.com/>. [Accessed 23 July 2019].
- [66] Node.js Foundation, "About Node.js," Linux Foundation, [Online]. Available: <https://nodejs.org/en/about/>. [Accessed 7 July 2019].
- [67] Bootstrap, "Bootstrap - Examples," [Online]. Available: <https://getbootstrap.com/docs/4.3/examples/>. [Accessed 18 July 2019].
- [68] Fonticons, Inc., "Font Awesome," 2019. [Online]. Available: <https://fontawesome.com/icons?d=gallery>. [Accessed 18 July 2019].
- [69] V. Coors, "Web-basierte Visualisierung von 3D-Stadtmodellen Teil 2," 11 May 2018. [Online]. Available: <https://www.coors-online.de/web-basierte-visualisierung-von-3d-stadtmodellen-teil-2/>. [Accessed 23 July 2019].
- [70] ApexCharts, "APEXCHARTS.JS Modern & Interactive Open-source Charts," 2019. [Online]. Available: <https://apexcharts.com/>. [Accessed 18 July 2019].
- [71] Government of Singapore, "SLA Dwelling Information," 2017. [Online]. Available: <https://data.gov.sg/dataset/sla-dwelling-information>. [Accessed 26 July 2019].
- [72] Government of Singapore, "SLA Residential Property Rental Information," 2017. [Online]. Available: SLA Residential Property Rental Information. [Accessed 26 July 2019].
- [73] Building and Construction Authority, "About BCA Green Mark Scheme," 25 July 2019. [Online]. Available: https://www.bca.gov.sg/greenmark/green_mark_buildings.html. [Accessed 26 July 2019].
- [74] J. Benner, "CityGML Energy ADE V. 1.0 Specification," March 2018. [Online]. Available: http://www.citygmlwiki.org/images/3/38/Energy_ADE_specification_2018_03_25.pdf. [Accessed 24 July 2019].

VIII. Annex

Annex 1: Mapping of LOD1 Building names to ALKIS function Codes

Name	Function	Most Likely ALKIS Code
AHMAD IBRAHIM PRIMARY SCHOOL	Kindergarten	3065
AHMAD IBRAHIM SECONDARY SCHOOL	School	3021
CHONG PANG CITY	Mall	2050
CHONG PANG COMBINED TEMPLE	Church	3041
CHONG PANG COMMUNITY CLUB	Communitybuilding	3044
CHONG PANG FOOD CENTRE	Restaurant	2081
CHONG PANG GARDEN	Residential Building	1010
CHONG PANG GREEN	Residential Building	1010
CHONG PANG MARKET	Restaurant	2081
CHONG PANG VALE	Residential Building	1010
CHONG PANG VIEW	Residential Building	1010
CHU SIANG TONG TEMPLE	Church	3041
CHU SIANG WAH SUA TEMPLE	Church	3041
FAMILYLAND	Hotel	2071
GOLDEN PALMS	hospital	3051
GOLDEN VILLAGE	Recreation/ Entertainment Venue	2090
HDB-YISHUN	Residential Building	1010
JIEMIN PRIMARY SCHOOL	Kindergarten	3065
KHATIB SPRING	Residential Building	1010
KHOO TECK PUAT HOSPITAL	Hospital	3051
NAM HONG SIANG THEON TEMPLE	Church	3041
NEE SOON CENTRAL GREEN	Residential Building	1010
NEE SOON CENTRAL SPRING	Residential Building	1010

NEE SOON CENTRAL VISTA	Residential Building	1010
NEE SOON EAST COMMUNITY CLUB	Communitybuilding	3044
NORTHPOINT SHOPPING CENTRE	Shop	2050
SHELL YISHUN AVENUE 5	Gas Station	2130
SHELL YISHUN RING	Gas Station	2130
SMYRNA ASSEMBLY	Church	3041
SREE MAHA MARIAMMAN TEMPLE	Church	3041
SREE NARAYANA MISSION BUILDING	Nursing Home	1022
TEMPORARY YISHUN POLYCLINIC	Hospital	3051
XISHAN PRIMARY SCHOOL	Kindergarten	3065
YISHUN BUS INTERCHANGE	Garage	2463
YISHUN CHRISTIAN CHURCH	Church	3041
YISHUN COLUMBARIUM	Cemetry building	3080
YISHUN GARDENS	Residential Building	1010
YISHUN JUNIOR COLLEGE	School	3021
YISHUN MRT STATION	Garage	2463
YISHUN PALM SPRING	Residential Building	1010
YISHUN POLYCLINIC	Hospital	3051
YISHUN PRIMARY SCHOOL	Kindergarten	3065
YISHUN SECONDARY SCHOOL	School	3021
YISHUN SWIMMING COMPLEX	Swimming pool building	3220
YISHUN TOWN SECONDARY SCHOOL	School	3021

Annex 2: Preliminary Building Physics Library for Singapore

Skyscrapers:

Global Properties	
Average Storey Height	2.6 m
Thermal Capacity	90 (adapted from NYC and Germany)
Indirectly heated area ratio	0.15 (adapted from NYC and Germany)
Thermal bridge U-value	0.1 (adapted from NYC and Germany)
Infiltration Rate	0.3 (adapted from Germany)

Building Component	Material existing in Simstadt IWU Library - Shortwave reflectance (SR) values are taken from Germany	Material in A. Chong et. al. paper (closest to average U-Value)
Walls	Breeze block, Aged Rendering 1cm, Breeze block 27cm, Gypsum plastering 1cm, U-Value 1.22 (average U-Value of occurring bldgs. in A. Chong's Paper) SR=0.3	30 mm granite, 45 mm air gap, 125 mm RC wall, 50 mm wood wool slab, 12 mm gypsum board, U-value = 1.271
Windows	Low-E double glazed window, U-Value 1.60 (Most occurring U-Value and properties in Bldgs of Chongs paper)	Low E double glaze, U-Value 1.585, Shading Coefficient 0.34
Roofs	Timber rafters insul-6cm, U-Value 0.65 (closest to average U- Value in A. Chong's Paper) SR=0.2	12.5 mm roof gravel, 9.5 mm built up roofing, 50 mm polystyrene insulation, 150 mm concrete slab, 102 mm air layer, 13 mm acoustic tile, U-value = 0.637
Ceiling	Assumed: Concrete Ceiling insul-8cm Roofing Felt 2 cm, Expanded Polystyrene 8cm Reinforced Concrete 15 cm, U-Value 0.64 Based on High Towers YOC2000 SR=0.2	none

Walls- Window- Ratio	Total Average A. Chongs Paper: 0.48 (25 buildings classified as high towers taken into account)	none
Grounds	Assumed: Concrete slab insul- 4cm (german Library High towers YOC 2000)	none

Row Houses:

Global Parameters	Taken from German row houses YOC 1950
Average storey height	2.5
Thermal Capacity	90
Indirectly heated area ratio	0.15
Thermal bridge u-Value	0.1
Infiltration rate	0.3

Building-part	Material in Simstadt (closest to U-Value in Andarini et. al. Paper) SR-values taken from German library
Walls	Dense brickwork 32cm, U-value 1.67, SR=0.30
Grounds	Concrete Slab Insul 1cm, U-value 1.65
Roofs	Timber rafters closed, Hardboard Medium 1cm, Air Layer 10cm, Hardboard medium 1cm, U-Value 1.75, SR=0.2
Ceilings	Breeze block ceiling, Roofing felt 1cm, Breeze block 13 cm, U-Value 2.05, SR=0.2
Windows	Single Glazed Window, U-Value= 5
Window-Wall Ratio	0.31 (RowHouse YOC1950)

Annex 3: Preliminary Usage Library for Singapore

Retail Usage:

Parameter	Value	Source
Occupancy density	0.12 pers/sqm	Paper: Andarini et. al. [57]
Usage days per year	300 days	German Usage Library
Usage hours per day	12 h	German Usage Library
Intern Gains	19 W/m ² (4 W/m ² Electrical Appliances+15 W/m ² Lighting), Convective Fraction 100%	Paper: Andarini et. al. [57], German Usage Library
Space Heating	0 Because there's no heating in Singapore	
Space Cooling	8-18h Set Point Temp. 24 degree	Paper: Andarini et. al. [57], German usage library
Ventilation	3 vol/h	German Usage Library
Hot Water	24.6 L/pers/d Prep Temp 45°C	German Usage Library

Residential Usage:

Parameter	Value	Source
Occupancy density	0.12 pers/sqm	Paper: Andarini et. al. [57]
Usage days per year	365 days	German Usage Library
Usage Hours per day	17h	German Usage Library
Intern Gains	11.7 W/m ² (1.7 W/m ² Electrical Appliances+10 W/m ² Lighting), Convective Fraction 100%	Paper: Andarini et. al. [57], German Usage Library
Space Heating	0 Because there's no heating in Singapore	
Space Cooling	21-5 Set Point Temp. 25 degree	Paper: Andarini et. al. [57], German usage library
Ventilation	3 vol/h	German Usage Library
Hot Water	9.8 L/pers/d Prep Temp 45°C	German Usage Library

Annex 4: EnergyADE UML Diagrams

The following Diagrams have been created by Agugiaro et. al. [24] and Benner [74] and will be used in this thesis to give an overview on how the EnergyADE has been implemented in chapter 7.5.

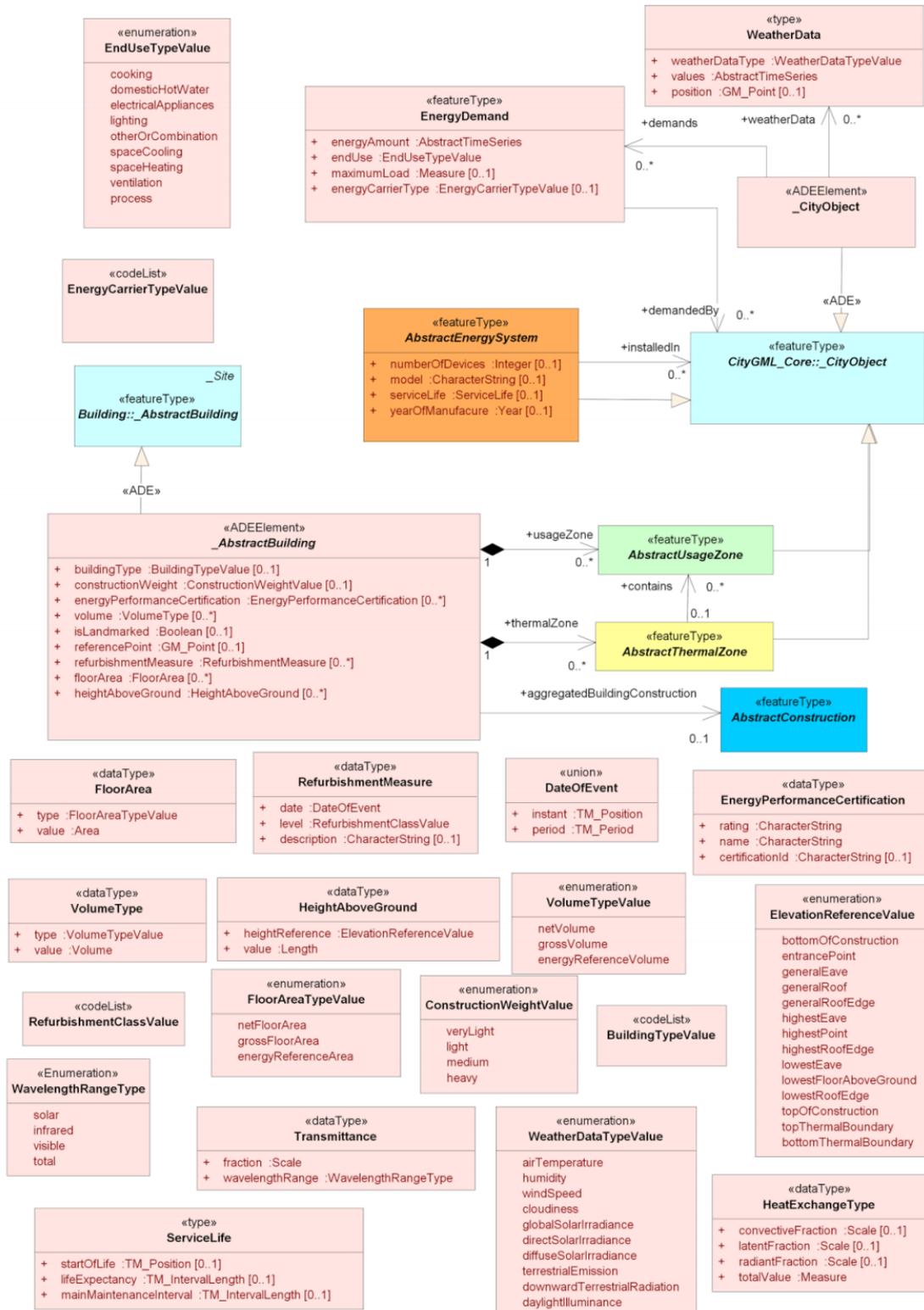


Figure 46 Extension of the CityGML classes *_AbstractBuilding* and *_CityObject* [24]

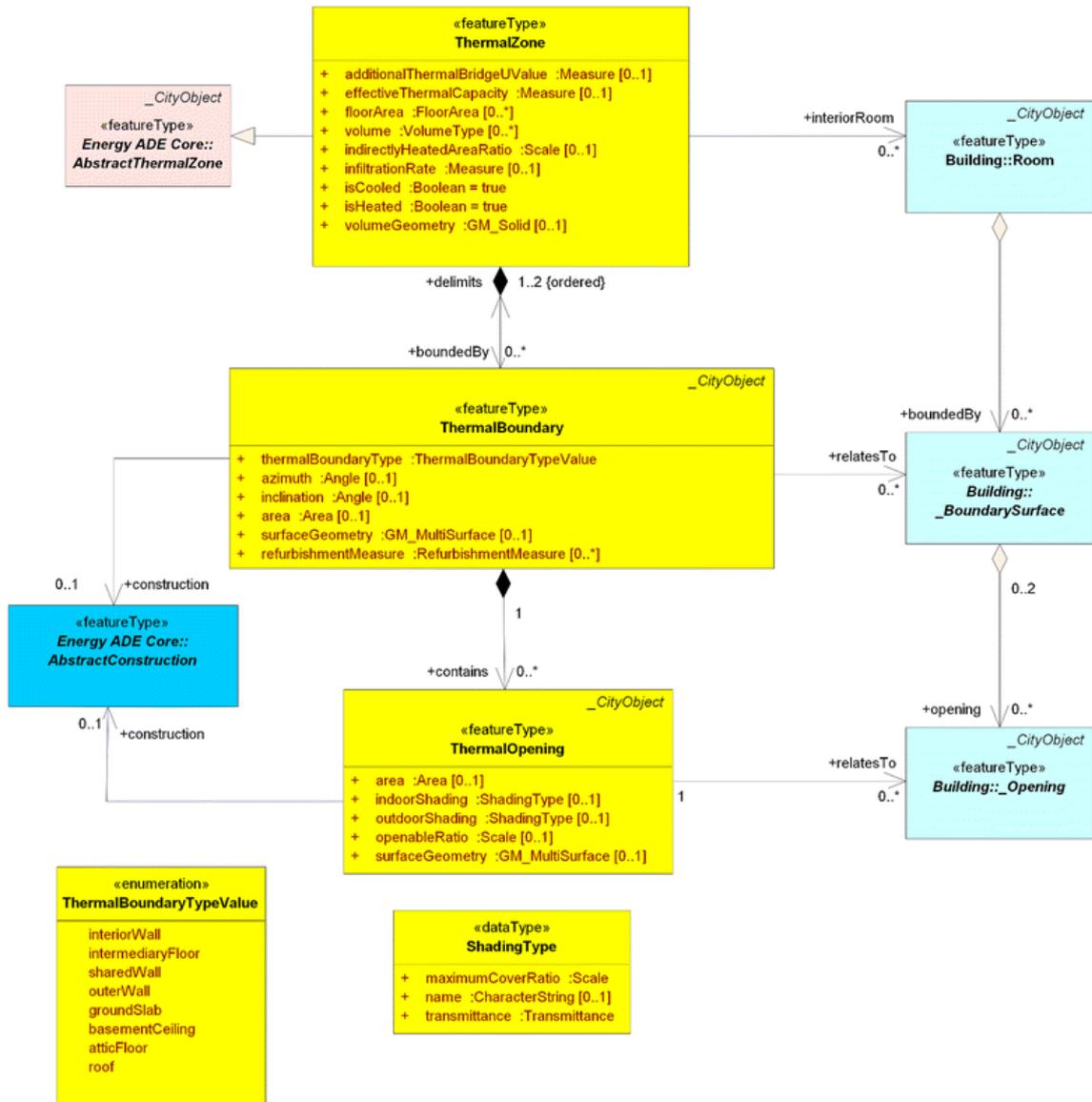


Figure 47 UML diagram of the Building Physics module [24]

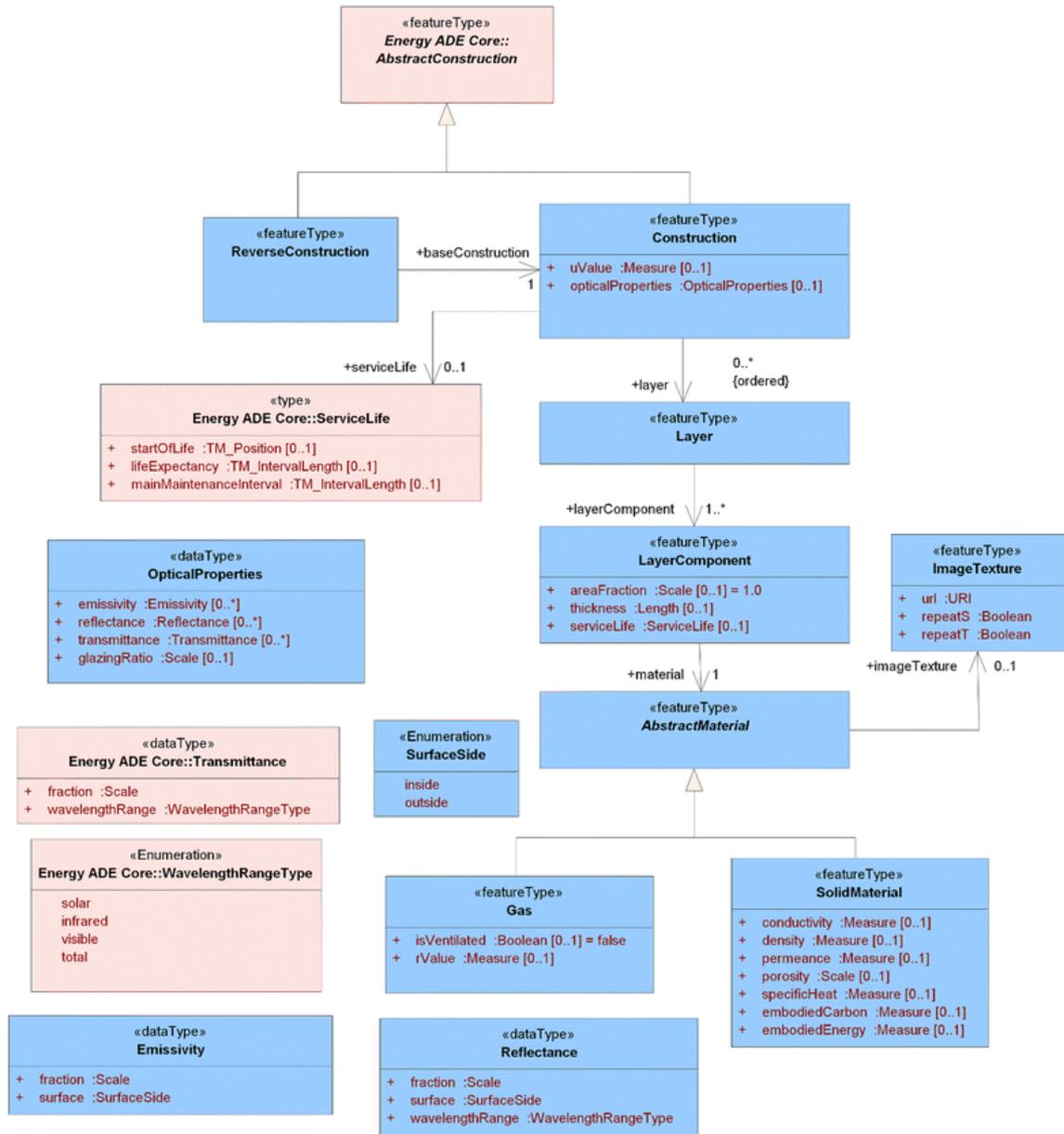


Figure 48 UML diagram of the Material and Construction module [24]

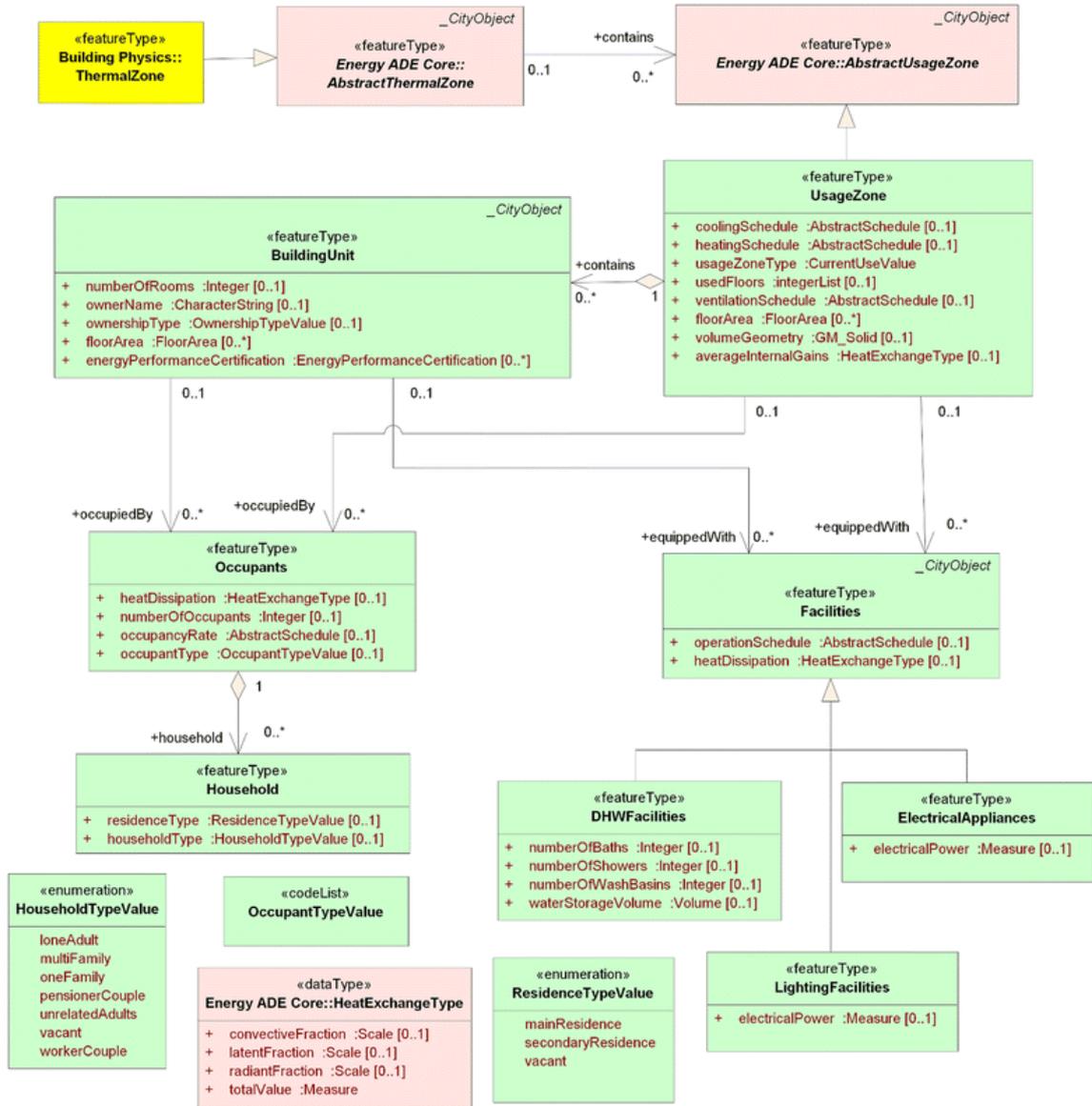


Figure 49 UML model of the Occupant Behavior module [24]

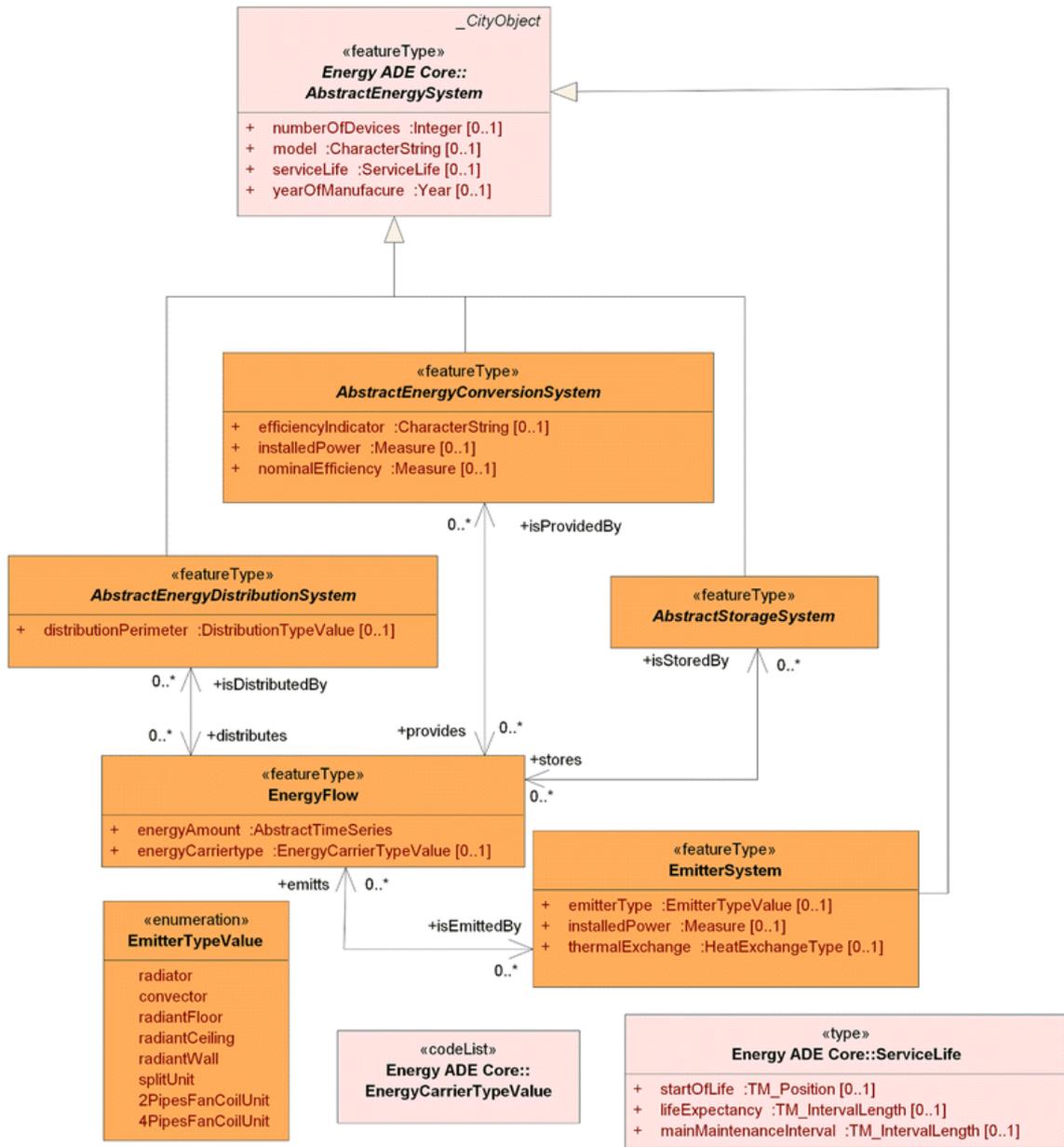


Figure 50 Simplified UML model of the Energy Systems module [24]

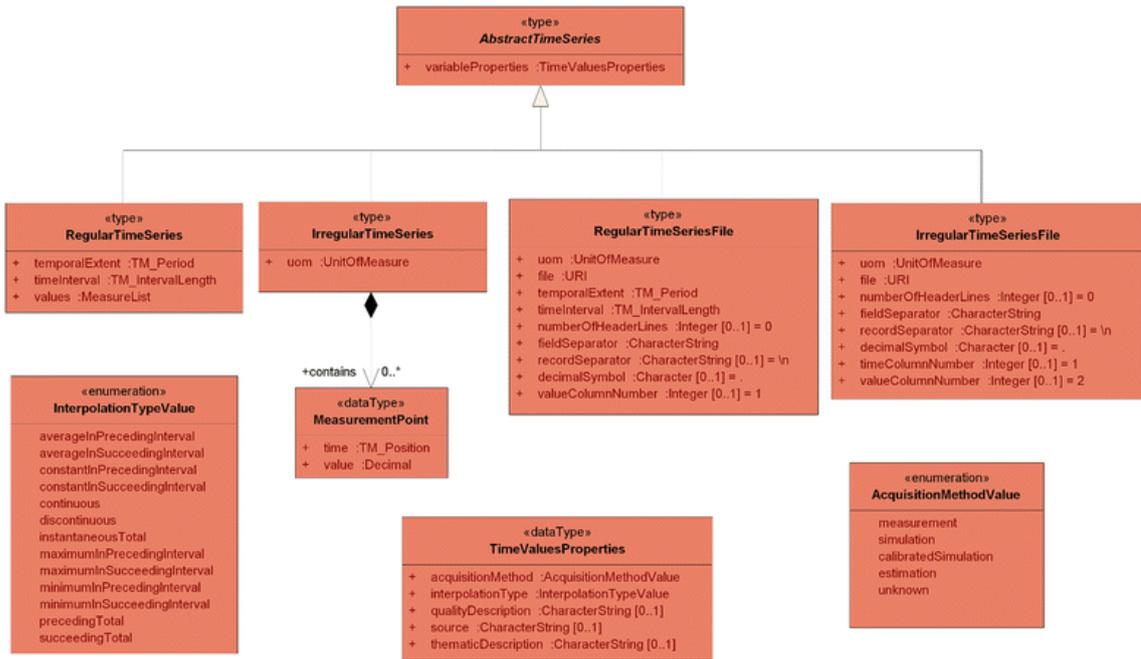


Figure 51 UML diagram of the time series classes [24]

IX. Statement of Authorship

I hereby declare that I am the sole author of this master thesis and that I have not used any sources other than those listed in the bibliography and identified as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree.

Place, Date

Signature

