DATABASE DEVELOPMENT WITH "3D-CITYGML"-AND "ENERGYADE"- SCHEMA FOR CITY-DISTRICT-SIMULATION MODELLING

C. Fliegner, M. - A. Brüntjen, Dr. J. Frisch, Prof. Dr. C. van Treeck
Lehrstuhl für Energieeffizientes Bauen (E3d)-RWTH - Aachen, Germany

ABSTRACT

The paper details parts of the work within the Aachen EnEff:Campus RoadMap project aiming at developing a systematic road map towards a cost-effective reduction of the primary energy consumption of the campus. The project follows a systematic approach for deriving low-order dynamic building and distribution network energy performance models from a geoinformation data base. The building data aggregation process and the specific layout of the campus database is presented. The developed PostgreSQL data base comprises a 3D city model with application domain extensions (ADEs) for modeling the energy system, thermal networks, building physics, occupancy, material and time series descriptions.

KURZFASSUNG

In diesem Paper wird der Arbeitsstand des Forschungsprojektes „EnEff:Campus:RoadMap" vorgestellt. Ziel des Projektes ist einen Plan für minimalinvestive Sanierungsmaßnahmen zu entwickeln, die zu nutzflächenspezifischen Primärenergieeinsparung der Campus Liegenschaften führen. Die dynamische Gebäude- und Netzsimulation, die als Werkzeug Anwendung findet, benötigt dafür Modellparameter die in einer spezialisierten Datenbank abgelegt werden. Im Folgenden wird zum einen der Prozess der Erfassung bzw. Erzeugung von relevanten Daten, andererseits die Anpassung und Entwicklung der Datenbank beschrieben. Die entwickelte Struktur fußt auf einer PostgreSQL-Basis und umfasst die bestehenden Application Domain Extensions (ADEs) EnergyADE und UtilityNetworkADE [CityGML Energy ADE. 2016].

INTRODUCTION

The building sector has the largest single potential for reducing primary energy demands and, thus, for lowering energy-related greenhouse gas emissions [UNEP 2009]. Improving the energy efficiency of the thermal quality performance of the building envelope and the energy systems is a key element [IEA 2013]. Thereby, buildings cannot be treated as individual energy systems in an isolated manner. In order to make use of volatile renewable energy sources, future buildings need to store both thermal and electrical energy and need to interact with superordinated network(s) with respective demand-side management methods [Müller/Monti2015].

In order to find economically and ecologically viable solutions for energetic refurbishments and major savings in primary energy for a university-wide campus such as the RWTH Aachen campus, buildings cannot be treated in a passive and isolated manner. Furthermore, a campus typically comprises very different typologies of buildings in terms of age, size, topology, scope and usage. Huge energy demands for singular test facilities may come along with large potentials of waste heat and the like with individual differences in scheduling and availability. A campus is further subject to rapid changes due to new test facilities or conversions of buildings in terms of usage. For optimizing a campus in terms of a sustainable refurbishment strategy and roadmap, an integrated solution approach is needed taking into account both the demand and the suppy sides with respect to the individual buildings and their dynamics in terms of energy usage and waste heat potentials, the distribution networks and the power, heat and cooling generation side.

The central aim of the project "EnEff: Campus - RoadMap RWTH Aachen" is to develop a road map for the reduction of the specific primary energy consumption with respect to the effective area of buildings at RWTH Aachen University by 50% until 2025, based on the energy consumption of 2013/14. This goal will be achieved through an innovative global concept and will be determined by a newly developed and implemented comprehensive and transferable methodology for energy optimization of university campus buildings. Therefore, the current "in-situ" condition is systematically recorded in a database and presented using dynamic urban district simulation. Together with an integrated data management, a basis for the most efficient and economical optimization strategies and measure plans is created. For these plans of measures, three refurbishment alternatives for the three campus areas of the RWTH Aachen University will be developed as element of the road map for the reduction of primary energy consumption. All relevant data that is used to describe the thermal and energetic behavior of the campus areas was collected at the beginning of the project. This includes but is not limited to geographical data, geometrical and topological data, building physics data and occupancy. Furthermore, the energy performance of buildings and thermal networks are closely monitored. All collected data is stored in a common database.

For effectively organizing the data and as basis for the transition to simulation, an appropriate and comprehensive database structure is necessary such as the GML-profile “CityGML” [Häfele 2013] and its Application Domain Extensions “CityGML EnergyADE” [Special Interest Group 3D 2015]. Based on the collected data and a structured database, it is possible to visualize the current state of all RWTH campus areas in a geographic information system (GIS). In the settings of this project, the specific software QGIS Vienna is used [QGIS 2015]. To build up the current state of the energy supply system, several thermal dynamic simulation models are created based on the collected dataset. The simulation models include the buildings with their building services systems, the distribution and generation systems. All of those previously mentioned systems have to be described by simplified models in order to capture the scale of the whole campus within a single simulation scenario. These buildings and system models are then coupled with thermal network models. Thus, the entire energy system can be detected and simulated with its dependent interactions. Consecutively, these coupled models will help to find an optimized solution for efficient measures and refurbishment options.

To ensure that the simulation results obtained by the simplified models correlate with the current energy consumption, important parameters, such as the consumption data of the buildings are recorded properly. Further monitored parameters represent produced and transmitted energy flows or energy quantities in the thermal network, for example. These are used for indicating irregularities in daily operation modes of energy systems and represent a potential for improvement.

Based on the analysis of monitoring data and simulation results, individual improvement measures are derived and verified iteratively, through which the primary energy demand and greenhouse gas emissions can be reduced. The measures consist of retrofitting the building stock, energy- and conversion system technology, the thermal network typology, or a combination of those. As well, savings resulting from conversion of existing buildings or strategic demolition and new construction of buildings can be considered in the model. For all these optimization approaches, a cost estimate is performed using the present value method, assessing their impact, feasibility and cost effectiveness, respectively. After the evaluation of individual measures conclusive refurbishment variants are developed. Various measures and packages of measures are combined, simulated and evaluated in the light of their respective interactions. By simulating several scenarios, refurbishment options can be tested under different conditions and checked according to their practical feasibility. This ensures that undesirable consequences are excluded and detrimental effects can be minimized. Hence, the simulated dynamic energy flows are represented by a three-dimensional GIS-based graphic model of the Aachen campus. In the following, the mentioned tools like QGIS, TEASER, and the developed PostgreSQL database structure are described in detail.

METHODOLOGY

In order to use the entire mentioned tools in an automated manner, the development of a central database is essential. Through this, relevant data is retrieved, which describes the current thermal energetic state of the campus buildings. As it is the aim of the project to develop a roadmap of measures towards reducing heating and cooling energy consumption, the data base necessarily needs to reflect the building geometry, thermal building properties (i.e., the building physics), usage, etc. in the database. A viable and existing database scheme is the "3D City Database for CityGML" [Kolbe et.al 2015]. It enables to store three-dimensional geometries with respect of predefined levels of geometric detailing (LOD) of a city in the database. Building up on this database, in the EnEff:Campus project the data base is extended by thermal and energy-related characteristics of the buildings. These characteristics become availabe in the CityGML Energy Application Domain Extensions (ADE). It is an extension of the CityGML standard and has the intention “to define a standard for exchanging information for energy simulation on urban level” [Energ ADE 2016]. This extension is currently under development; the currently available state is integrated within the 3D city database. With this extended database, an automated tool chain is created for district simulation. In the following, the tools are presented which are used for building performance simulation in the EnEff:Campus project.

3D City database and 3D City Database Importer-Exporter

The 3DCityDB is a PostgreSQL database based on the CityGML schema [Kolbe et.al 2015]. It allows for depicting roads, bridges or areas. Buildings can be mapped up to LOD4. In addition to the database, the ”3D City Database Importer / Exporter v1.6 - postgis“ tool [Kolbe et.al 2015] can be used to import CityGML data. Thus, for example, the campus buildings could be drawn as three-dimensional objects using a tool such as SketchUp Make [Sketchup 2016] and subsequently converted into a CityGML file. This file is then read by the Import/Export database tool.

TEASER

The "Tool for Energy Analysis and Simulation for Efficient Retrofit" (TEASER) is developed at RWTH Aachen University [Remmen 2016a]. It uses statistical analysis to set up a low-order building performance simulation model based on at least five heuristic parameters. These parameters are individual properties of buildings such as:

- net floor area
- building height
- number of stories/levels
- building type
- year of construction

The geometry of the building is generated by the parameters “net floor area”, “building type” and “number of stories/levels”, for instance. The parameter “year of construction” correlates with a typical heat transfer coefficient of the building envelope of this year of construction. The description “building type” is used for setting up zones [Remmen 2016b].
The 3D City database is, besides the Energy ADE, expanded by at least these five parameters. With these extensions, TEASER can be enabled to automatically query the required information from the database.

QGIS

QGIS (QGIS Wien) is a freely available geographical information system program [QGIS 2015] which can visualize geo-referenced geometrical contexts. QGIS is based on a client/server principle. The frontend client, containing the visualization kernel, establishes a connection to a PostgreSQL database acting as a server and displaying the status of the stored data within the selected database containing geometric datasets. In the campus project, QGIS is used to represent the current thermal and energy state of all campus buildings in a geographical-aware manner and to visually identify potential remediation objects. Furthermore, the thermal grid and the consumers of thermal energy – mainly the RWTH buildings – can be represented. Spatial relationships of significant heat sources and heat sinks can be identified accordingly. The integration of unused heat generator capacity or heat output from computing clusters can be an adaption of this method, for example. By uncovering spatial and temporal differences between energy production and energy requirements of different customers, concepts like energy shifting can be simulated and developed. Hence, QGIS facilitates the selection and analysis of potential remediation options and enables the subsequent presentation of results.

Data sources

Required data is subdivided into two different datasets: geometrical and thermal data. The facility management department of RWTH Aachen University provides a large share of production- and distribution-dependent information as well as measured data and operation parameters for all the technical installations. The local district government contributes additional geometrical data. These data consist of aerial laser scans to determine shape and height of the buildings. Additional data is taken from intensive on-site inspection. As the sources of data differ, different emphasis is placed on the details. Some of the datasets are taken from ongoing FM processes and are not primarily intended for simulation purposes. This is why it becomes necessary to find solutions to further merge different balance limited datasets. A parent-root data model is set up to align objects of deviating levels of detail into a singular class structure. If information about buildings as whole is available, as well as such data where buildings are subdivided into stretches, both levels of detail can be stored in a single directory. As data is hierarchically linked, information can be retrieved in any of the given levels of detail.

Figure 1 shows how data storage in the database reflects the data acquisition. Three different aspects of the database accompany the three sources of data. These parameters span a net of joints and connections as shown in Figure 1.

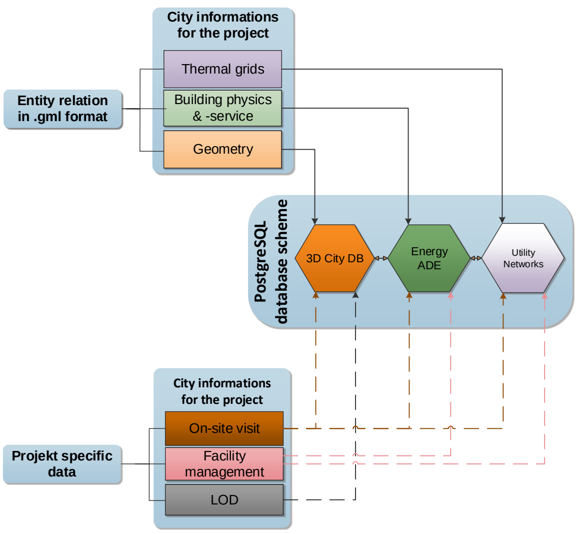

Figure 1. Developed PostgreSQL database schema with six add-on parts

DATABASE

The extedend PostgreSQL database for CityGML, which is used in an essential part of the tool chain in this project, relies on a database that provides a centralized storage of parameters for describing the campus buildings. The concept is based on an object-oriented PostgreSQL [PostgreSQL 2015] database system and uses a so-called PostGIS extension for enabling a direct connection to the QGIS frontend. Both tools are widely used and available as open source software, satisfying as well the projects claim to keep all developments and applied tools freely available.

The 3DCityDB scheme is derived from the CityGML model and currently available in the SQL languages PostgreSQL and Oracle. By combining the 3DCityDB tool and PostGIS, it is possible to display 3D rendered CityGML datasets. As the CityGML structure was originally developed for urban planning purposes, it is necessary to expand its capabilities for this project. In addition to geometrical and geographical data, building performance values and measured energetic values need to be processed. There are prefabricated expansions called ADE (Application Domain Extension) to meet certain additional requirements to CityGML. ”CityGML EnergyADE“, for example, contains information about the thermal energetic characteristics of buildings, and ”CityGML UtilityNetworksADE“ models the underground supply grids. These extensions contain necessary relationships that meet the specifications required by the project with respect to the thermal and energetic perspective of the campus properties. These relationships are captured in UML diagrams and are implemented into the relational database schema of 3DCityDB as depicted in Figure 2.

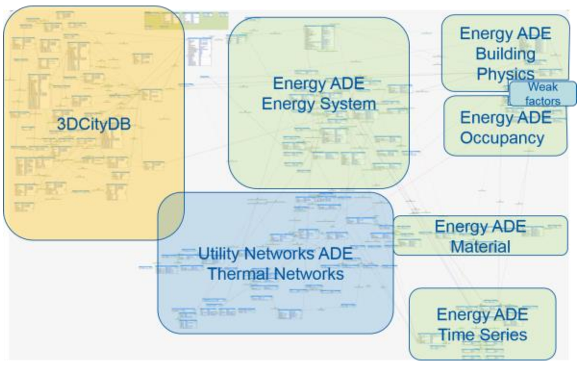

Figure 2.The developed PostgreSQL database schema

Figure 2 shows the combination of 3DCityDB and two of the ADE extensions. 3DCityDB and UtilityNetworksADE are kept coherent while aspects of the EnergyADE are fragmented into smaller subdivisions. This is done in order to utilize functions given by the EnergyADE in varying context as support for other components. Time series classes and material classes for example support both energy as well as network ADE components. Utilitynetwork classes can have time series elements now, although this feature has not been implemented in the UtilitynetworksADE in the first place. Apart from merging of functions there are a lot of additional classes and connections to make, as none of the ADE´s was intended to work combined with the other extensions. Some issues even needed to be implemented from scratch, as there were no equivalents in existing extensions. Architectural aspects, user-behavior, potential changes of usage or information on the building renovation/refurbishment status are just a few parameters to be mentioned here, which are summarized in a “soft factors” class.

In order to keep the core database in its original shape and to maintain the compatibility with the 3DCityDB-importer, both ADEs are decoupled from the 3DCityDatabase schema. Technically, this is realized via transfer classes, such as the “campus_building” table, which represent a unique interface between the basic structure and the newly added extensions. Hence, the developed database schema in this version meets all the project specific requirements and is well-suited for the necessary purposes and it is possible to store and retrieve the mandatory minimum required data for the city quarter simulation and, even more, all relevant parameters for a detailed building observation.

However, these extensions clearly show the need for revisions of the CityGML-related standards in order to better reflect energy-related issues.

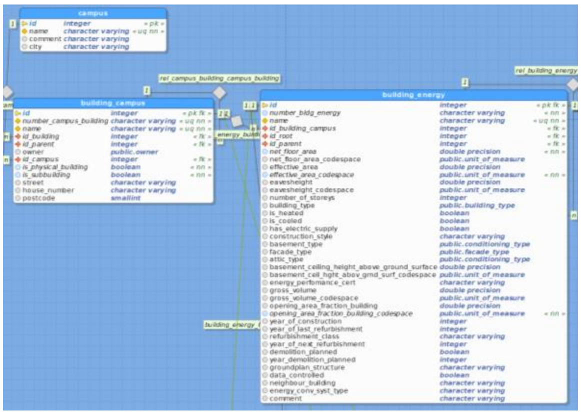

Figure 3. Three main tables of the developed PostgreSQL database schema

Figure 3 describes a small area of the database structure. The DB class “building energy” is used to store necessary minimal datasets for the teaser application in a singular table. This approach makes it simple to retrieve information for simulation by a standardized script such as Python. With automated interaction of database and simulation tools, building models can be created in an instance and hence more variations can be calculated in less time. As the

TEASER application can be used with varying depth of information, it is possible to import the best dataset for each appliance. For this purpose, there is room for all the detailed information in class tables as well. In the “energy building” table, for example, properties such as net floor area, year of construction, etc. are maintained. Furthermore, building-specific information like facade type or window-fraction-area is contained, which drastically improves the modeling accuracy of TEASER, if available. Even a combination of minimal and enriched datasets in one simulation cycle is possible. This flexible variation of the focus and detail enables an extended research in a city district environment taking into account restrictions in terms of limited available information and/or limitations in computing power or modeling constraints (e.g., in Modelica).

Another important factor are inheritance IDs that allow for coherent entities between different data sources. For instance, the root or parent IDs of a building allows linking different data from the campus facility management, the onsite-view and the CityGML for each individual building. Figure 4 illustrates this in detail. The examined building consists of four building parts and three structural entities. Energy consumption, however, is given for the building-complex in total. With hierarchical conjunctions as shown in Figure 4 it is possible to connect data of varying level of detail to one consistent dataset. In this example, the first four numbers represent the building-number given by the FM and the second column identifies the part of the building. In addition, the last set of numbers describe the LOD2-blocks the building consists of.

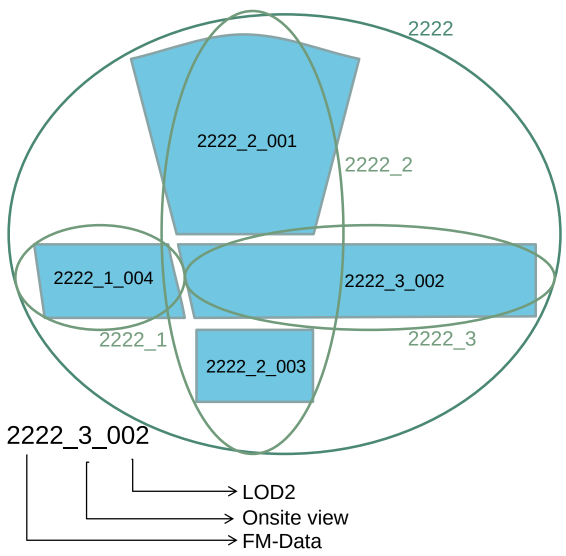

Figure 4.Example for one building complex (Facility Management data) consisting of three building wing s(determined by onsite views) and four sub-buildings (geometry information from CityGML data)

Table 1 illustrates the connections of identifiers between those different building parts and their corresponding datasets.

Every building, regardless of its data sources, has its own serial ID. The building complex is based on data from FM and has neither a root nor a parent ID but a unique ID, here 13493 in this example. The building wings have the same id_root and id_parent and refer to the ID of the building complex. The individual parts of the building relate with their id_root to the complex and with its id_parent to the wing of the building. Due to these circumstances, properties that are only available for the building complex can be inherited to other parts of buildings. This gives the advantage of linking CityGML geometry information to the record of the building characteristics based on the FM and thus for the visualization in GIS, for instance.

Tabelle 1:
Context between id, id_root and id_parent

id	name	id_ root	id_ parent
13493	2222		
13494	2222_1	13493	13493
13500	2222_1_004	13493	13494
13495	2222_2	13493	13493
13497	2222_2_001	13493	13495
13499	2222_2_003	13493	13495
13496	2222_3	13493	13493
13498	2222_3_002	13493	13496

APPLICATION

In addition to the queries in order to build thermal energy performance building models in an automated way, the 3D geometries stored in the EnEff:Campus database are of essential benefit for the visualization of the campus properties. For the visualization, both the geometric information from a laser scanning (in CityGML format) as well as the three-dimensional building geometries are available, the latter created by SketchUp Make. Due to the enlargement of the ”3D City database“ by the “Energy ADE” is it possible to assign for instance energy consumption data to building geometries and to visualize this content geographically. For example, by using the following SQL command:

```
SELECT
 time_series_regular_test.id,
 surface_geometry.geometry,
 surface_geometry.height,
 building.measured_height,
       ...
 building_energy.year_of_construction,
       ...
 time_series_regular.values,


FROM
public.building,
       ...
public.time_series,
public.time_series_regular,
public.surface_geometry
WHERE
       ...
building_energy.id_building_campus =
building_campus.campus_building_parent_id
AND
       ...
thematic_surface.building_id   =   building.id
AND
       ...
thematic_surface.lod2_multi_surface_id AND

thematic_surface.type = 'GroundSurface';
```

This code matches geometrical representations of the buildings to their particular properties, stored in the table ”building_energy“. Hence, a geographical distribution of year of construction of the campus buildings can be represented graphically in QGIS, as illustrated in Figure 5.

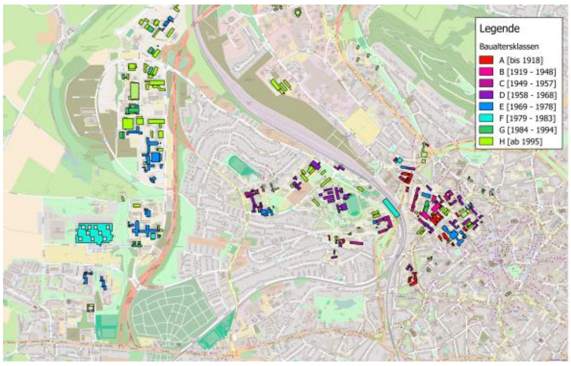

Figure 5. Distribution to the age of the campus buildings of the RWTH Aachen University

Through such a view, the scenario-based retrofitting potential of the building stock can be geographically identified. Another option is to view the geographical distribution of the heating energy consumption as shown in Figure 6, for example.

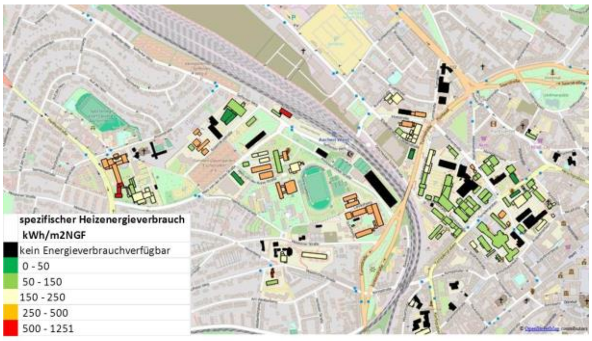

Figure 6. Specific energy consumption for heating of the RWTH Aachen campus properties

LIMITATIONS AND DISCUSSION

The challenge of minimizing potential sources of error comes along with the complexity of this project. As for all simulation approaches, the quality of the provided data determines the quality of the results. In this case there are a lot of unknowns and issues concerning data acquisition and data quality. Thus, it is very important to verify physical input parameters, design restrictions and environmental conditions. Hopfe and Hensen pointed out identification methods through sensitivity analysis and Monte Carlo simulations [Hopfe, Hensen 2011]. In this low-level approach, great emphasis is placed on appropriately modeling energy performance characteristics with a reasonable minimum of very few parameters, which comes along with uncertainties related to those parameters. Unrecognized relations such as user-behavior, usage of process heat or infiltration can greatly influence results . User-behavior in particular is difficult to estimate and to measure, although it impacts energy demand prediction.

To determine systematic errors evoked especially by simplified models, detailed comparative simulations

are carried out. Physical parameters and environmental aspects are statistically tested and random samples are compared to empirical data taken from on-site visits.
Another issue is related to the level of detail of modelling and the total number of represented buildings. With the statistical approach on hand, a given number of buildings can be modeled while the overall accuracy is still acceptable. A comparison between detected U-values by on-site view and those put out by TEASER show that for ten selected facades, seven facades differ about 13 % and three facades differ between 20-50 % [Riedel2015]. This first comparison shows that if the number of buildings decreases, the accuracy may drop significantly. This makes it difficult to develop remediation plans for individual buildings, which is, on the other side not in the scope of this work and would require other modelling methods. Hence, the focus of this project lies on interdependencies of all involved sectors and this approach brings forth the potential of an integrated perception. Furthermore, a reduction of energy demand influences the production and distribution side as well, for example. In order to optimize not only certain aspects but the campus system as a whole, interdependencies and synergies need to be uncovered.
The development of this integrated database-driven approach enables researchers to gather and store information about the whole energy cycle in one place. With this comprehensive data, different viewpoints on energy efficiency and production demand balance can be obtained and optimized solutions can be proposed even in an ongoing process of adapting to ever-changing environmental and user-related restrictions.

ACKNOWLEDGEMENTS

We gratefully acknowledge the financial support of this work by the German Federal Ministry of Economics and Energy (BMWi) as per resolution of the German Parliament under the funding code 03ET1260A.

REFERENCES

CityGML Energy ADE. 2016. http://www.citygmlwiki.org/index.php/CityGML_Energy_ADE

Energy ADE. 2016. http://www.citygmlwiki.org/index.php/CityGML_Energy_ADE (downloaded .13/03/2016)

Häfele, K.H., 2013. - City Geography Markup Language, http://www.citygmlwiki.org/index.php/Main_Page (downloaded .11/12/2015)

Hopfe C., Hensen J., 2011. Uncertainty analysis in building performance simulation for design support, Energy and Building, Volume 43, 2789-2805

IEA, Technology Roadmap: Energy Efficient Building Envelopes, OECD/IEA 2013. https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf (downloaded 12.03.2016),

Kolbe, T. H., Yao Z., Nagel C., Kunde F., et. al. 2015. 3D City Database for CityGML Version 3.0.0 Documentation.

Lauster M., Teichmann J., et. al. 2014. Low order thermal network models for dynamic simulations of buildings on city district scale. Building and Environment, Volume 73, Pages 223-231. ISSN 0360-1323. http://dx.doi.org/10.1016/j.buildenv.2013.12.016

Müller D., Monti A, Stinner S, Schlösser T., et. al. 2015. Demand side management for city districts, Building and Environment, Volume 91, September 2015, Pages 283-293, ISSN 0360-1323, http://dx.doi.org/10.1016/j.buildenv.2015.03.026 (http://www.sciencedirect.com/science/article/pii/S0360132315001432)

PostgreSQL, 2015. PostgreSQL 9.3. http://www.postgresql.org/ (downloaded .13/03/2016)

QGIS. 2015. QGIS User Guide Release 2.8. http://qgis.org/en/docs/index.html (downloaded .26/11/2015)

Remmen P., Lauster M., et. al. 2016. CityGML Import and export for dynamic building performance 1 simulation in modelica

Riedel B., 2015. Datenbankgestützte Erfassung und Visualisierung ausgewählter Lehr- und Forschungseinrichtungen der RWTH-Aachen mithilfe eines Geoinformations-systems (GIS)

SketchUp. 2016. https://www.sketchup.com/de/products/sketchup-make (downloaded .02/02/2016)

Special Interest Group 3D. 2015. Energy ADE development. http://en.wiki.energy.sig3d.org/index.php/Main_Page (downloaded 11/12/2015)

UNEP, 2009. Sustainable Buildings & Construction Initiative, Buildings and Climate Change - Summary for Decision-Makers, http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf (downloaded 18/02/2016)