Determining energy relevant Information using the semantic 3D city model of Berlin for an energy Atlas

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Part I

Data Acquisition, Data Integration and Creation of LOD3 model

Extraction of energy relevant attributes from 3D city model

1 Introduction

The task for group 1 in phase 1 was to specify energy relevant attributes and try to calculate or extract them from the semantic city model.
First of all a connection to the database was necessary to establish, and the following three subtasks where reasonable to define. With the specification of the energy relevant attributes inside of the database, a data basis for the different algorithms was created. This algorithms can be differentiated into data analysis algorithms basing on the pure values stored in the database and geometry analysis dealing with the geometry information in the database.
Our work was restricted to the area of Berlin Moabit, a small subset of the full Berlin model. For the Java algorithms the database information where exported as .gml files and the obtained output was saved as .csv files, which were able to be re-uploaded to the database. All data kept their necessary identifier.
As important values for an energy atlas following parameter where determined:

- Airvolume of building to be able to calculate the Surface-to-Volume-Ratio
- Number of storeys which can be calculated by using the average storey-height of the specific building
- Orientation of the wallsurfaces of each building to get information about neighbourhood relations between buildings and inner- and outer walls

2 Data Analysis

Each building stored in the database contains at least one groundsurface, one roofsurface and three wallsurfaces. Based on these information, the volume of the buildings, the orientation of the walls (whether it is a outer or neighbouring wall), therewith also the surface-to-volume-ratio and the outer-wall orientation for sunlight-heating-effects can be calculated. Also necessary for the average storey height and important for the calculations is the buildings function as it is residential, public or industry.
Moreover, we identified some missing energy relevant data like the building's year of construction. With this it is possible to estimate the building's material, the mean size of windows, the type

of windows, and the mean story height. In addition, the topological relations between buildings are missing, as well as the number of people living in the building resp. number of flats, and the behaviour classes of the people living in the building (to estimate their energy consumption).

3 Geometry Analysis

In the geometry analysis we mainly focused on the surface area to volume ratio as well as the outer orientation of the walls. Carrion [**?**] defines the surface area to volume ratio as follows:

> "The S/V is the ratio of the aggregated area of all surfaces which transmit energy to the surrounding (wall surfaces touching other buildings are not considered) and the volume of the building."

To calculate the S/V ratio, we created two subtasks. One task is to calculate for each building the area which is touching neighbouring buildings as well as to calculate the sum of all surface areas of one building. The second task is to calculate the volume of each building.

3.1 Calculation of wall-surface intersection

Important to know is, that the S/V does not include wall surfaces touching other buildings, and therewith those wallsurfaces must be detected using the information which are stored in the database. For this issue the following workflow to calculate wall surfaces which are not touching other buildings was developed:

1. Calculate neighbouring buildings
2. Calculate area touching other buildings (for each building)
3. Calculate sum of surface areas (ground-, roof-, wallsurfaces)
4. Subtract intersecting area with neighbouring building from sum of surface areas

3.1.0.1 Calculate neighbouring buildings The calculation of neighbouring buildings is done, to minimize the candidate set for the calculation of the intersection of two buildings. Two buildings are neighboured if the wall surfaces of the two buildings are within a certain distance, and the angle between wall surfaces is smaller than a defined threshold (see figure **??**). Since we did the calculation in Java with the JTS Topology Suite (JTS), the problem was that JTS is not able to do calculations on 3D geometries. A workaround is to make the assumption, that the wall surfaces are vertical and parallel to each other. Then a projection of the walls into 2D can be done by ignoring the Z coordinates. This means, every wall surface becomes a linestring (see figure **??**). Then we

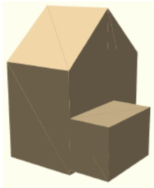

Figure 1: Neighboured buildings in 3D.

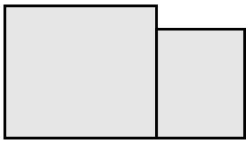

Figure 2: Neighboured buildings in 2D.

can test if two walls represented by linestrings are within a certain distance and the angle between the linestrings is smaller than a threshold using JTS.

3.1.0.2 Calculating area touching other buildings After determining if two buildings are neighboured, it is possible to calculate the intersection area of touching wall surfaces. Since JTS is not able to do calculations on 3D geometries, as mentioned above, the walls need to be transformed to 2D again. Therefore the coordinate system has to be transformed so that the wall surfaces are lying in the YZ-plane. Then, the X coordinate can be ignored and the intersection of the two walls can be calculated.

To rotate the coordinate system so that the wall surfaces are lying in the YZ-plane, the normal vector of one of the two walls has to be calculated. With this the rotation angle α can be calculated as the angle between the normal vector on the vector [1 0 0], which is the normal of the YZ-plane. Then both wall surfaces are rotated with this rotation angle α. Figure **??** shows the used rotation matrix. If these rotated surfaces are intersecting, the real world surfaces are intersecting, too.

$$\begin{bmatrix} cos(\alpha) & -sin(\alpha) & 0 \\ sin(\alpha) & cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Figure 3: Rotation matrix used for calculating intersection.

Thus, the intersection of the rotated surfaces can be calculated as in the following listing:

```
Geometry intersection=polygon.intersection(polygonNeighbour);
if (intersection instanceof com.vividsolutions.jts.geom.Polygon) {
  com.vividsolutions.jts.geom.Polygon intersectionPolygon
  = (com.vividsolutions.jts.geom.Polygon) intersection;
  // unit is m^2
  intersectingArea = intersectionPolygon.getArea();
}
```

3.1.0.3 Overall- and sharing wall area This is followed by the area calculation of the wall-, roof- and groundsurfaces for each building. These surface areas are summed up to get the overall surface area of each building. These results (the surface areas of each building (building id)) are written to a .csv file to be able to import it back into the 3D city model database. Table **??** shows some sample results.

3.2 Geometry Analysis - Building Volume

The building's volume can be calculated using several different approaches. The task is to have a volume which is a good approximation of the real existing air volume inside of the building, because it will be used afterwards for some energy-flow calculations. Necessary also for an operatively used approach is the automatisation of the algorithm and the potential for for its embedding into the other code.
The following approaches have been tested and checked whether they fulfil the requirements:

1. SQL algorithm/query
2. FME Software

building_id	surface_area	shared_wall_area
BLDG_0003000000432cd8	234.99638499102912	45.46462674214126
BLDG_0003000000432c80	1265.0716547126067	529.4226535306225
BLDG_0003000f000858d0	2201.2130139165056	975.798086083496
...		

Table 1: Subset of result .csv file containing shared wall surfaces.

3. ArcMap Software - 3D Analyst

4. ArcMap Software - Buildings to DEM

3.2.0.4 Volume calculation 1. approach: SQL Using SQL (Structured Query Language) as a possibility to directly access the database and analyse the stored information is the first upcoming option. For the calculation several Oracle spatial functions have been used to get the building area. Multiplying this with the building's height which is already stored in the database leads to a good estimation of the building's volume.
But the differences between the building's roof structure leads to wrong estimations of a large percentage of the building's volume, because only one height can be taken from the database which is the distance between the ground up to the highest roof point. The figure **??** is showing a good example of a possible wrong estimation: The different building parts are stored using only one building identifier, and therewith only the height of the highest part is stored inside of the database.

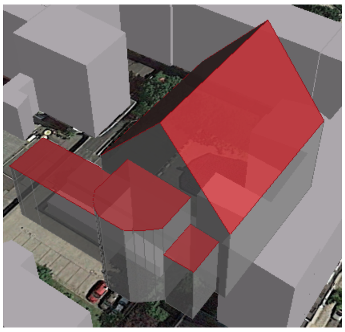

Figure 4: ..

3.2.0.5 Volume calculation 2. approach: FME The second approach was using the software FME (Feature Manipulating Engine). Its FME Data Inspector **??** shows the stored geometry and the buildings do not contain ground-, wall- and roofsurfaces. But the surfaces were represented as not connected so a building is not containing one closed geometry.
Since the FME workbench is very complex also a lot of errors occur, and therewith this approach is not really stable.

3.2.0.6 Volume calculation 3. approach: Arcmap The Software Arc Map offers an extension called 3D Analysed which can be used as an analysis tool for 3D objects.

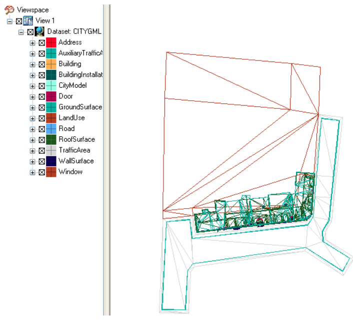

Figure 5: ..

In here it was possible to enclose the geometries of the buildings, but this procedure uses a shrinking of the building until every surface is completely touching its neighbours. Therewith the obtained volume of the building in systematically falsificated.

3.2.0.7 Volume calculation 4. approach: Arcmap again For the last approach another functionality of Arc Map can be used: The creation of a rasterlayer for ground- and roof- geometries with the extension: "Add Buildings to DEM".

A complex sequence of operations have to be applied to first create a difference raster which is showing ground level and roof level and secondly calculating the volume using this raster.

For the automatisation the Arc Map Modelbuilder can be used. With this every step can be defined as an output and input of others. Figure **??** is showing the process.

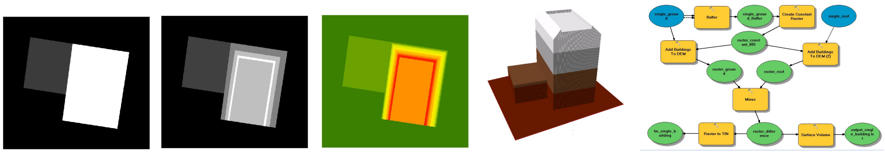

Figure 6: ..

3.2.0.8 Volume calculation - Comparison Since our knowledge about the buildings is only depending on our data, a valid number of volume cannot be calculated without any statistical analysis of the buildings and the different calculations.

The table **??** shows a comparison of the different obtained results which.

Heading group 2

Heading group 3

Part II

Estimation of Energy Consumption and Energy Demand

Approach	calculated volume
SQL	$10227m^3$
FME	no result
3D Analyst	$6000m^3$
Arc Map	$7400m^3$

Table 2: Comparison of the different volume calculation procedures.

Calculation of buildings energy demand

4 Introduction

The Task for the second phase was to calculate the building's energy demand using Java with the citygml4j library and the 3D city model. Necessary for that are the buildings volume and the attribution of walls as outer- or inner-/shared- wall surfaces which already was calculated by group one in phase one.

The most important information for this task are content of the so called IWU Report which is a report created by the IGG (Institute for Geodesy and Geoinformation Science) based on calculation methods of the "Institut Wohnen und Umwelt GmbH" [eng. Institute living and environment GmbH]. The IWU Report can be interpreted as a manual for the calculation of the building energy demand using the semantic citymodel of Berlin.

The document is structured into three parts: The determination of the input-values which are temperature, geometries and energy reference building-parameter, the calculation of the building's energy demand for space-heating using an accounting system and the calculation of the building's energy demand for warm-water.

5 Input values

For the calculation of energy flow of buildings, the surrounding climate is of an big importance. To take this into account some formulas contain a variable called "Gradstunden" which is representing the climate in a numerical value. For its calculation the summed up days per year have to be multiplied with the difference of the heated temperature inside and the actual temperature outside. To neglect the summer season in which buildings do not need any external heating energy, only the days with a switched on heater were considered.

The energy reference area is relevant for all calculations dealing with the building size. And due to the fact, that a precise indoor-model of the city is not available, the estimation of this value can be done with the formula (1). Important to know is that only heated storeys without roof and cellar are taken into account.

$$A_{EB} = 0.75 \times n_G x A_{FB} [m^2] \tag{1}$$

n_G**:** number of storeys

A_{FB}: building footprint

Necessary for air-volume calculations inside, either the precise storey height have to known, or the average storey height which is depending on type and age of the building. Figure ?? shows some average values of storey height depending on the building's age. Furthermore we took for our calculations additional 0.3m per storey in order to achieve (more or less) the same number of storeys as in real world. This number was found be supervising some samples of buildings which are part in our database-subset. The air-volume then can be calculated with the formula (2) which

Durchschnittliche Geschoßhöhen nach Baualtersklassen (BAK) Stand 04.2013

BAK	Bauzeit		Geschosse	Geschoss-höhe	Gebäude-höhe	Quelle
			Anzahl	m	m	
1	1900	Jahrhundertwende	5	3,20	16,00	1
			Annahme	3,50	17,50	
2	1920-1935	Vorkriegsgebäude	5	3,00	15,00	1
3	1950er	Nachkriegsgebäude	6	2,70	16,20	1
4	1962 - 1974		6	2,70	16,20	
5	1973	Plattenbau	7	2,80	19,60	1
6	1994 - 2012		6	2,90	17,40	

Figure 7: Average storey height depending on building's age. Provided by Michael Prytula.

is the energy reference area multiplied with the assumed mean (lighted) storey height.

$$V_L = A_{EB} \times 2.5 \tag{2}$$

Since some energy flows through building parts, its physical behaviour has be taken into account when calculation the energy flow. For this issue the so called U-values (in the IWU-Report called "k-Werte") are needed. They are describing the amount of energy transmitting between different building parts as for example between building-roof and building-main-part. Due to the fact that energy will not flow between two parts having the same temperature, it is important to know which wall surfaces are shared with also heating neighboured buildings. Figure ?? shows possible directions of the energy transmission, and possible building parts differentiated by its mean temperature. The afterwards following figure ?? shows average U-values for specific building-ages and building-parts.

6 Demand of effective energy for heating

The following formulas are describing the sequence of calculating the effective energy demand for heating. Later on following formulas are partially depending on the previous ones.

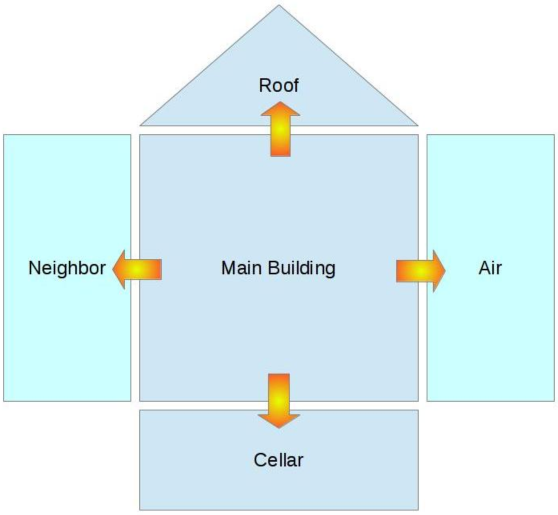

Figure 8: Possible energy flow directions of a building.

Durchschnittliche U-Werte zu den Berliner Baualtersklassen Stand 22.01.2013

BAK	Zeitraum	Durchschn. U-Wert Wand [W/m²K]	Durchschn. U-Wert Fenster * [W/m²K]	Durchschnittl. U-Wert Dach [W/m²K]	Durchschnittl. U-Wert Kellerdecke. [W/m²K]	Fenster-Wand-Flächen-ve Select table column	mittleres Fenster-Wan... nis
1	bis 1918	1,70	2,7	1,50	1,20	0,25 – 0,34	0,30
2	1919 – 1945	1,70	2,7	1,50	1,20	0,20 – 0,35	0,25
3	1946 – 1961	1,40	2,7	1,30	1,00	0,20 – 0,31	0,23
4	1962 – 1974	1,20	2,7	1,10	0,84	0,20 – 0,42	0,28
5	1975 – 1993	0,80**	2,7	0,45	0,60	0,20 – 0,40	0,33
6	1994 – 2012	0,40**	1,7	0,30	0,40	0,30 – 0,50	0,35

* detaillierte Ermittlung und g-Werte siehe gesonderte Tabelle
** Gebäudebestand nicht differenziert nach WschVO- (ab 1984) und EnEV-Standards (ab 2002) erfasst

Figure 9: Average U-Values for specific building-ages and building-parts. Provided by Michael Prytula.

The calculation of the energy demand for heating can be easily done with using an accounting system as follows (3):

$$Demand = Gain - Loss \tag{3}$$

The Energy loss in [kWh/a] can be calculated as follows (4).

$$Q_V = (Q_T + Q_L) \times f_{Abs} \tag{4}$$

Q_T: transmission loss [kWh/a]

Q_L: aeration loss [kWh/a]

f_{Abs}: reduction factor day-/night-setback

The values for the specific Day-nightsetback can be taken from a table with average values, depending on the building type (e.g. new-building).

The loss through transmission in [kWh/a] has to be taken from this formula (5):

$$Q_T = (\sum f_i \times k_I \times A_i) \times \Theta \tag{5}$$

f_i: reductionfactor [1.0 outer-walls; 0.5 inner-walls]

k_I: U-value [W/(m2K)]

A_i: building's area [m^2]

Θ: Gradstunden [kKh/a]

Summed up for every building part [i].

The loss through aeration in [kWh/a] can be calculated using the formula (6):

$$Q_L = 0.34 \times n \times V_L \times \Theta \tag{6}$$

n: frequency of aeration [1/h] (from table)

V_L: building's air volume [m^3]

For the energy gain following formulas have to be applied:

In general formula (7) is describing the utilisation of the available free heat inside of the building:

$$Q_G = \eta_F \times Q_F \tag{7}$$

η_F: utilisation

Q_F: free heat

The free heat is simply the solar irradiation plus the heat sources inside of the building (see formula (8)).

$$Q_F = Q_S + Q_I \tag{8}$$

Q_S: solar irradiation

Q_I: heat sources inside

And following formula (9) can be used for the utilisation:

$$\eta_F = 1 - 0.3 \times (\frac{Q_F}{Q_V}) \tag{9}$$

Q_V: (remember:) energy-loss

As important income the solar energy gain can be calculated with the precise formula (10) which needs precise knowledge about the window sizes.

$$Q_S = r \times g_{senkr} \times \sum G_i \times A_{F,i} \tag{10}$$

G_i: global radiation per orientation (e.g. south)

$A_{F,i}$: window area per orientation $[m^2]$

g_{senkr}: energy transmission through glass-area (from Kurzverfahren Energieprofil)

r: reduction factor due to windows (standard value: 0.36)

Taking an factor for the window sizes per wall, also the following simplified formula (11) can be used for the calculations.

$$Q_S = r \times g_{senkr} \times 240 \times A_{window} \tag{11}$$

A_{window}: estimated overall window area $[m^2]$

Inside of buildings there are more heat sources than only the heater. For example electric devices like the light bulb are producing a lot of heat energy, which is also a factor for the calculations. As a assumption, the next formula (12) is giving this factor a size.

$$Q_I = 0.024 \times q_i \times t_H \times A_{EB} \tag{12}$$

0.024: factor for conversation ([W] $\rightarrow$ [kW]; [d] $\rightarrow$ [h]

q_i: specific power of inside heat sources [W/m^2]

t_H: heating period [d/a]

A_{EB}: energy reference area

7 Demand of effective energy for warmwater

The demand of warm water [kWh/a] can more easily be calculated. It is simply the demand per person multiplied with the number of persons living in the building. The formula (13) shows how this can be calculated.

$$Q_W = \frac{Q_{W/P} \times A_{EB}}{A_{EB/P}} \tag{13}$$

$Q_{W/P}$: demand of warm water per year and person [kWh/(P a)] (standard: 600 kWh/(P a))

$A_{EB/P}$**:** living space per person [m^2/P] (standard: 35 m^2/P)

This formula calculates the number of persons living in the building by dividing the energy related area by the average space per person. When having a more precise estimation of inhabitants per building as group three was calculating, the formula can be changed into the formula (14):

$$Q_W = Q_{W/P} \times N_P \tag{14}$$

N_P**:** number of persons

8 Result

As results of the calculations, the Java algorithm produces a .csv file containing information about each building which has an own identifier. All values are calculated in [kWh/a]. The table shows a subset of the result file, with three buildings and the interesting attributes described in this report.

9 Discussion

The number of storeys is one central value of all calculation, because with a wrong estimated number of storeys the reference are can change rapidly. Figure **??** shows how the reference area is changing with the wrong estimated number of storeys. And therewith also the calculated energy parameters which are depending on the reference area are changing. Figure **??** shows how strong they are depending on a right estimated number of storeys.

building_id	heating_loss	heating_gain	...	..demand_heating	..demand_warmwater
BLDG_000300000026ed79	116670,763	15572,718	...	101098,045	4805,405
BLDG_000300000026f491	229314,037	32343,216	...	196970,821	16289,207
BLDG_000300000026f4a7	216882,225	31687,923	...	185194,302	15044,102
...					

Table 3: Results of the IWU-report-calculation [kWh/a].

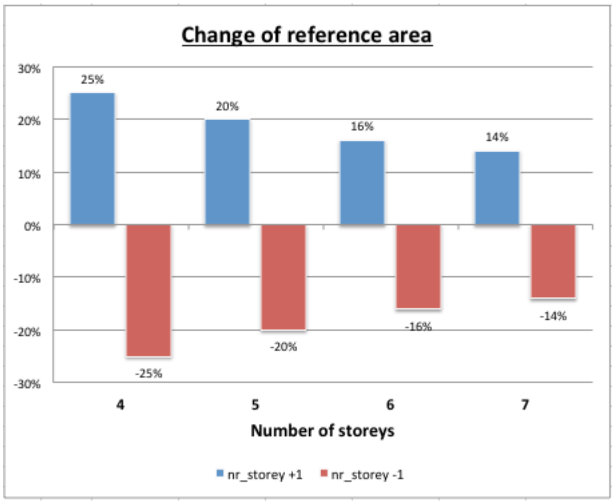

Figure 10: Changing area with wrong estimated number of storeys.

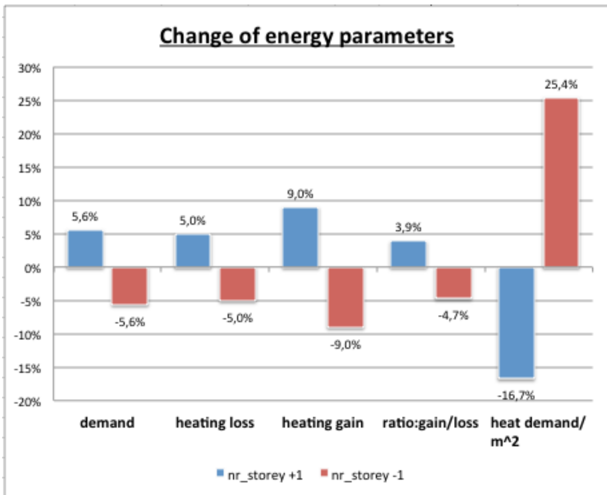

Figure 11: Changing energy parameters with wrong estimated number of storeys.

Following improvements could be helpful to obtain better results:

First as mentioned before we took additional 0.3m to obtain a better estimation, this is because in the calculations the average storey height was describing the inside storey height without ceiling thickness.

Maybe it would be useful to consider the building's usage for the estimation of the specific storey height.

In the IWU report 2.5m were assumed as the storey height for the air-volume, in our calculations we were using the previously calculated storey height.

10 Introduction

The Estimation of the solar potential of buildings or even entire cities has been done for several cities and comunes. One example is depicted in chapter 10.2. The research which should be done within the second phase of the GIS Project of the students at the "Institute for Geodesy and Geoinformation Science Berlin" is to estimate the potential using the 3D CityDB as data source. For each building the amount of energy in Mwh/a should be calculated which may be gained, if the roof is equipped with the maximal possible number of either photovoltaic or solar thermal modules while considering the orientation of the roof and the solar irradiance for the individual roof surfaces.For the implementation phase a cut of the 3D City DB of Berlin has been taken. In the test database approximately 1000 buildings in the district Moabit are included.

10.1 Work Flow

To estimate the solar potential of building, using the 3D CityDB as data source a Java program was implemented. Figure 12 shows the basic work flow of this program. First of all, the buildings in the database have to exported to a cityGML file, which may directly read by the program. In the beginning it is checked if the roof surface of the building is shadowed by another building. Therefore a simplified approach explained in chapter 15 will be used. If the building is not shadowed all roof surfaces are extracted and used for calculation individually. For each of the surface the tilt angle, the azimuth as well as the roof area is computed, hence these are the necessary input parameter for the calculation of the photovoltaic of solar thermal potential. Furthermore the roof area has to be reduced because of potential equipment located on the roof, such as chimneys, dormers and antennas. This is explained in chapter 14. After the solar potential is calculated for each of the individual surface, the values are summed up to get a global value for a building. The newly gained information are then added as generic attributes as well as some additional information to make the visualization possible. After this step all buildings are written in a cityGML file which may be re-imported to the database. Furthermore some file are written which contain statistical information about the result.

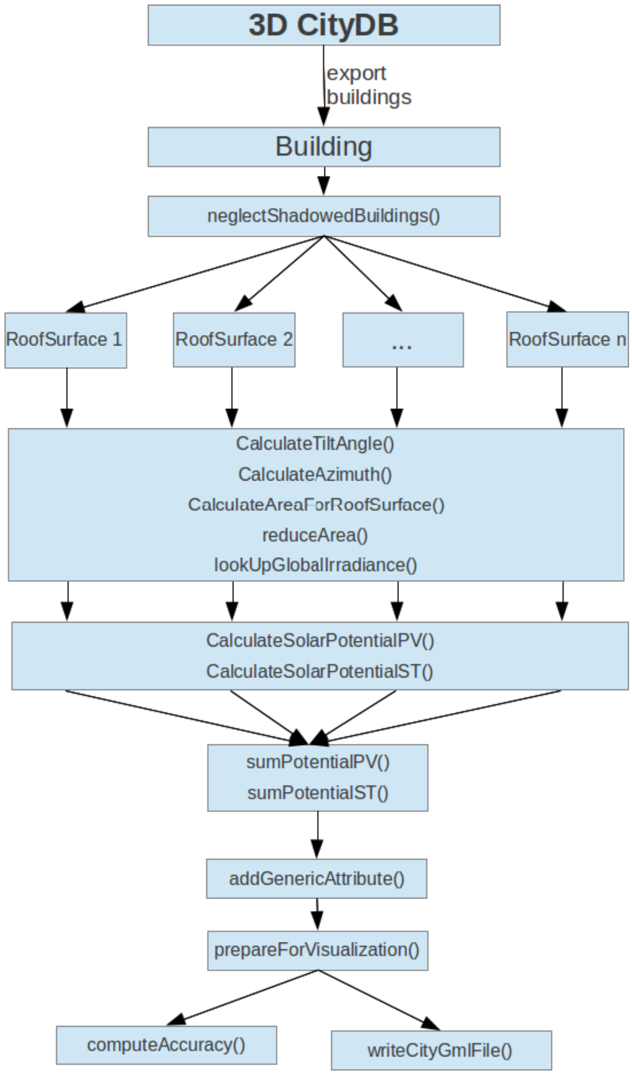

Figure 12: Work flow to estimate the solar potential from 3D CityDB

10.2 Related Work

The Solar Atlas Berlin is a project which was done by the engineering office simuPLAN to estimate the solar potential of the individual building of the City of Berlin. As data source a Digital terrain Model computed from laser scanning data was used. To estimate the solar potential the roof area applicable for solar panels, tilt and azimuth of the roof surface is used. In addition also the shadowing of other buildings is considered. After developing the program and obtaining own results, the results will be compared with this data. Since, laser scanning data has been used, the equipment on the roof surface in known in detail, therefore a it is assumed from the authors that the calculated potential from Solat Atlas Berlin is from higher reliability than the potential computed from an LOD 2 MOdel, where only the roof surface is known and information about roof equipment not included. **?**

11 Fundamentals of Photovoltaik systems

A Photovoltaic systems transduces solar radiation into electricity. The efficiency of a system depends on the properties of the used photovoltaic cells. Wagner (2010) **?**

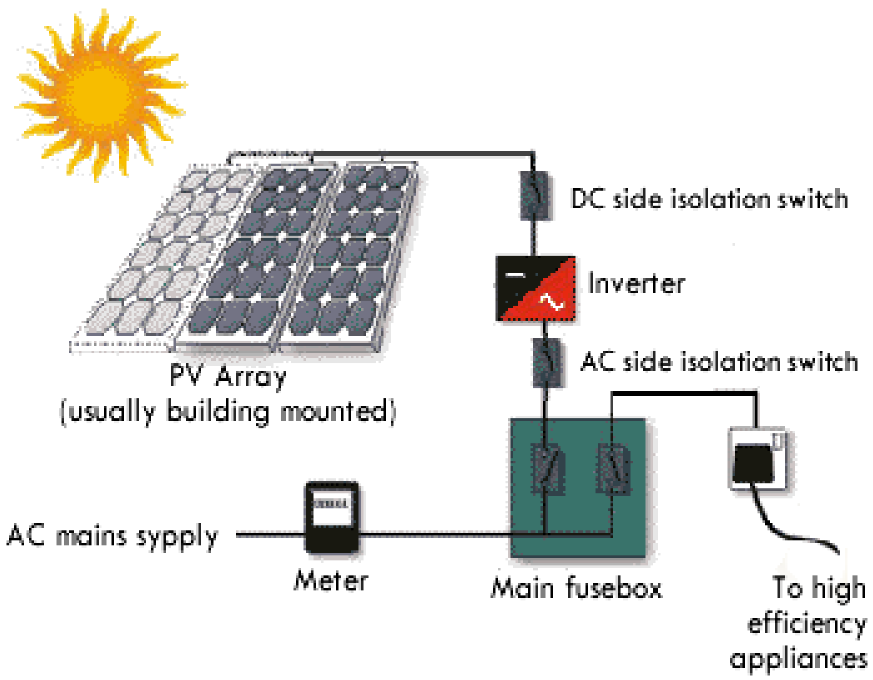

Figure 13: Architecture of Photovaltaic system

The nominal power of a cell is given in Watt and often denoted as W_p (Watt Peak). It is acquired under standard test condition (STC an international standard) from the manufacturer of the photovoltaic cell. STC means, that the cell temperatur is 25°C and the irradiance is 1000 W/m^2. The nominal power can be used to compare the power of photovoltiac cells of different manufactures.
The efficiency is given by the ratio between the produced energy and the energy radiated to the cell. It depends on the temperature of the photovoltaic cells. With increasing temperature the efficiency decreases. Often only one efficiency coefficient, including the efficiency of the power inverter, cable and accumulator, is given by the manufacturers.
In addition a performance ratio is given most times. It is the ratio of the actual and the desired gain of the photovoltaic cell. It depends not only on the cell itself but also on the weather conditions, respectivly on the location. The desired gain is the efficiency of the installation under STC, assuming that the efficiency of the power inverter is 100%. For a thin-layerd slicon cell, which is most common, the Performance ratio (PR) is 84% for Germany. Wagner (2010)

12 Fundamentals of Solar thermal systems

Solar thermal collectors are devices, which transform radiation emitted by sun into heat. Basically, a collector consists of a box with a black glazed cover, containing a pipe, which uses all the space in the box. The radiation is adsorbed by the black glazing and heats up a fluid, such as water or oil, which runs through the pipe equipped in the collector. The heated fluid can then be stored in insulated tanks, if it cannot be used directly. In general solar collectors are used for use water in a household or for heating.**?**

basically, the efficiency of a solar thermal collector depends on the absorption of the glazing, the input fluid temperature , the average air temperature as well as the solar radiation of the region.

13 Global Irradiance

The most important input value to calculate the Solar potential is the global radiation. The global radiation comprises the direct solar radiation and the diffuse radiation resulting from reflected or scattered sunlight. It depends on the location, the orientation of the roof surface and the inclination of the roof surface. The location is the latitude $52°31'45.0''$ and longitude $13°19'42.6''$ of Moabit in Berlin. The orientation and the inclination are calculated from the CityGML Lod2 geometry. (European Database of Daylight and Solar Radiation)

13.1 Orientation of the roof

The azimuth angle α represents the orientation of the roof. It is given by the angle between the normal vector of the roof n_r surface and the normal vector of xz plane n_{xz}.

$$\alpha = cos^{-1}(\frac{\vec{n_r}\vec{n_{xz}}}{|n_r||n_{xz}|}) \tag{15}$$

The direction of the normal vector is defined by the order of the point sequence forming the polygon ring of the roof surface. To calculate the orientation the positive normal vector is needed. If n_r has a negative z component n_r is converted to the positive normal vector. The calculated angle α is always in a range between $0° - 180°$. Because the azimuth angle has a range of $0° - 360°$ we have to consider the sign of the x component of n_r. Is the x component negative the azimuth angle is calculate with

$$\alpha_o = 360^\circ - \alpha \tag{16}$$

else the azimuth angle α_o is equal to α.

13.2 Inclination of the roof

The inclination of the roof influences the input of solar radiation strongly and has to be considered. It is calculated as the angle between the normal vector of the roof surface n_r and the normal vector of the xy plane n_{xy}. To calculate this angle equation 15 is used. Again the calculated angle ranges between $0^\circ - 180^\circ$, although the maximal tilt angle is 90°. Therefore the tilt angle is

$$t = 180^\circ - \alpha \tag{17}$$

if $\alpha > 90^\circ$ else t is equal α. For further calculation all roof surfaces with an inclination $t < 8^\circ$ are considered to be flat roofs and the angle t is set to 0°.

13.3 Satel-Light Database

The estimation of the global irradiation for flat roof surfaces is simple, because no diffuse radiation effects the global radiation. For inclined surfaces the diffuse radiation resulting from reflected or scattered sunlight has to be considered. Because this is very complex we decided to use the European Database of Daylight and Solar Radiation (Satel-Light), which provides for every location within Europe the global radiation on tilted else well as flat roof surfaces with arbitrary orientation. We created a LookUp table for Berlin, which contains the global radiation for the inclination in 10° degree steps and the orientation in 45° steps. The resulting table is shown in figure 14.

14 Reduction of Roof Surface Area due to Roof Equipment

The main problem when using a LOD 2 model is that the suitable roof area is not known. Fact is, that not 100% of the roof can be used to install solar panels, since roofs may have dormers, antennas or chimneys which are not part of the LOD2 model. But the roof equipment is considered for the Solar Atlas Berlin and with use of this data source empirical reduction factors may be computed. Therefore group 2 implemented a program, which reads a cityGML file, containing all buildings of the test area (1000 buildings) and computes the reduction factor as in Equation 18.

	10	20	30	40	50	60	70	80	90
0	932.940	824.900	714.670	605.170	504.430	423.765	374.490	333.610	294.920
45	959.585	876.000	789.495	706.640	634.005	569.400	509.175	451.505	394.930
90	1021.270	998.640	966.520	926.005	876.730	817.965	750.075	674.885	593.855
135	1081.495	1111.790	1121.280	1109.235	1075.655	1021.270	947.540	856.655	752.265
180	1105.220	1155.590	1179.680	1177.125	1147.925	109.135	1012.875	792.780	792.780
225	1080.035	1108.870	1116.535	1102.665	1067.625	1011.780	937.320	846.435	743.140
270	1019.445	994.260	2629.000	917.245	866.510	808.110	741.315	667.950	588.380
315	958.125	873.080	784.385	700.800	628.530	565.750	507.350	451.140	396.390
355	932.940	825.265	715.400	606.265	505.525	425.955	377.045	335.800	296.745

Key	
Horizontal	degree
North	degree
Unit	Kwh/m^2

Figure 14: LookUp table for the global radiation for Berlin

$$r_E = \frac{A_{SAB}}{A_{LOD2}} \tag{18}$$

with:

r_E : empirical reduction factor

A_{SAB} : Roof Area according to solar atlas Berlin

A_{LOD2} : roof area calculated from LOD2 model in 3D CityDB

The Solar Atlas Berlin provides different areas for photovoltaic and solar thermal systems. Therefore also different reduction factors are computed. The reduction factors are also separated between exclusively flat roof and mixed roofs, contain flat as well as tilted surfaces. This is important because flat roofs are more likely equipped. Additionally, the age class of the building has been taken into account. Tables 4 and 5 show the result, including the number of surface and the variance of the value. It can be seen that, some reduction factors are not representative, because not enough roofs of this type are in the test area. With the use of a database of entire Berlin might fix the Problem.

Age Class	flat roof			mixed roof		
	r_E	count	σ^2	r_E	count	σ^2
1899	0.198	94	0.016	0.440	199	0.056
1918	0.152	56	0.019	0.435	233	0.059
1932	0.167	13	0.017	0.506	9	0.048
1945	0.304	2	0.0008	0.765	1	0.000
1961	0.221	74	0.013	0.581	56	0.049
1974	0.198	90	0.015	0.371	17	0.080
1993	0.219	66	0.006	0.293	5	0.016
2012	0.149	91	0.019	0.487	21	0.165

Table 4: empirical reduction factors for calculation of energy gain using solar thermal collectors

Age Class	flat roof			mixed roof		
	r_E	count	σ^2	r_E	count	σ^2
1899	0.127	94	0.019	0.349	199	0.050
1918	0.097	56	0.016	0.323	233	0.053
1932	0.056	13	0.008	0.403	9	0.076
1945	0.000	2	0.000	0.730	1	0.000
1961	0.147	74	0.015	0.498	56	0.050
1974	0.129	90	0.016	0.289	17	0.081
1993	0.128	66	0.011	0.146	5	0.013
2012	0.090	91	0.016	0.399	21	0.147

Table 5: empirical reduction factors for calculation of energy gain using photovoltaic modules

15 Shadowing

Roof surfaces may be shadowed by several object, such as other buildings, trees or even equipment on the roof itself. Since, the data source is a LOD 2 model only other buildings can be considered, because trees and roof equipment are not part of the model. The consideration of the shadowing may be done with a complicated illumination computation. Since this project is limited in time this is not possible. Therefore only a simple approach is applied, which completely ignore buildings which are shadowed, rather then adjusting the daily global irradiance on the specific surface. Within the simple approach a building is neglected, if there is a neighboured building which is x higher and is within a certain radius r. Only buildings between an azimuth of 90 to 270 are taken into account, as shown in Figure 15.

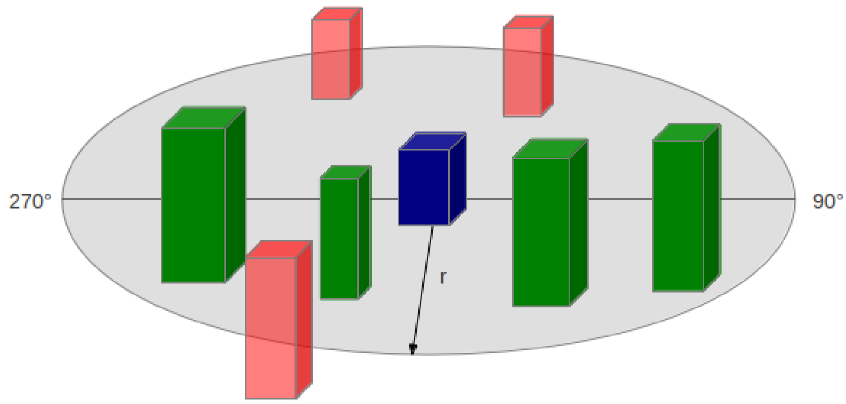

Figure 15: The green buildings are candidates, which may shadow the blue building

The implemented algorithm starts with iterating over all buildings and storing them in a spatial tree to make them easy queryable. After that before a potential of a building is calculated it will be checked if there are candidate buildings which are within the radius r. The list of candidates is checked for buildings which also meet the other conditions, such as an azimuth between 90° and 270° and if the building is x times higher. If both conditions are met, the building will be neglected for the potential calculation.

16 Calculation of the potential

The calculation begins with the reduction of the roof area according to the building age class as described in chapter 14. If the roof surface is a flat roof ($tilt < 8°$) the modules cannot directly mounted of the roof surface. To bring the modules in an optimal tilt angle they are mounted on a mounting system of the roof. Because they are tilted they might shadow the neighboring modules, therefore a certain distance between the modules is necessary as shown in Figure 16. The distance has to be $c = 2.75$ times longer then the width of the ground of the module w. Furthermore the

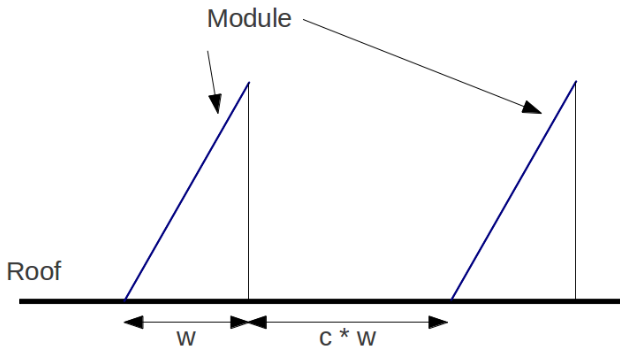

Figure 16: Solar Modules mounted on a mounting system of a flat roof

global irradiance has to be picked from the look-up table. According to Solar Atlas Berlin **?** areas with a global irradiance less than $905Wh/m^2$ have to be neglected. Also surface are neglected which have a smaller area then $5m^2$. It is assumed that it is economically not worth the mount modules on such a small roof. The actual calculation of the potential highly depends on the type of module. This will be explained in the following sub sections.

16.1 Potential of Photovoltiac systems

To calculate the potential of photovoltiac systems two approaches were applied. First the estimation as described by Wagner (2010) **?** was implemented. According to Wagner (2010) the energy gain of a photovoltiac system can be calculated with

$$E = M \cdot GA \cdot \frac{P}{E_0} \cdot PR \cdot \eta_{EUR} \cdot \eta_l \tag{19}$$

with:

E : total energy gain per year kWh/a

E_0 : 1000 W/m^2

M : Number of Modules

PR : Performance ratio

P : nominal power W

η_{EUR} : euro inverter efficiency

η_l : transmission efficiency

GA : Global Irradiation kWh/m^2a

The parameters P,η_{EUR},η_l and Mdepend on the photovoltaic cell and the inverter. Values for these parameters are taken from real photovoltiac cells. For the calculations the silicon cell BP 585F from BP Solar **?** combined with the inverter SP 2500-450 from the company Sun Power **?** has been used. The inverter efficiency is $\eta_{EUR} = 15\%$ and the transmission efficiency is set to $\eta_l = 9\%$. The nominal power of the cell is $P_0 = 85W$. This calculation method allows to use real data of photovoltiac cells and considers the inverter.

Because the the Solar Atlas Berlin is the only available reference, finally a second approach according to the Solar Atlas was used. The calculation of the photovoltaic energy is simplified and finally done with equation 20. Where the efficiency coefficient is set to $e = 15\%$ and the system area is the reduced roof surface area.

$$E = A \cdot GA \cdot PR \cdot e \tag{20}$$

with:

$$\begin{aligned} E &: \text{total energy gain per year } kWh/a \\ A &: \text{System Area } m^2 \\ e &: \text{efficiency coefficient} \\ GA &: \text{Global Irradiation } kWh/m^2a \end{aligned}$$

16.2 Solar Thermal

The calculation of the potential of solar thermal modules was done as described in Struckmann (2008) **?**. According to Struckmann (2008) the useful energy gain Q_U of a solar thermal module is calculated with the formula shown in Equation 21. Figure 17 shows a sketch of a typical solar thermal module and shows the parameter, which are necessary to compute Q_U

$$Q_U = F_R A \left(I\tau\alpha - U_L \left(T_i - T_a \right) \right) \tag{21}$$

with:

$$\begin{aligned} F_R &: \text{ Efficiency Coefficient of the module} \\ A &: \text{ module area, } m^2 \\ I &: \text{ Solar radiation, } W/m^2 \\ \tau &: \text{ transmission coefficient of glazing} \\ \alpha &: \text{ absorption coefficient of plate} \\ U_L &: \text{ collector overall heat loss coefficient, } W/m^2 \\ T_i &: \text{ input fluid temperature, } ^\circ C \\ T_a &: \text{ average outside air temperature, } ^\circ C \end{aligned}$$

For the calculation of the potential a standard solar thermal module has been taken, the TitanPower-AL2DH Flat Plate Collector from the company SunMaxxSolar **?**. The efficiency coefficient is assumed to be $F_R = 0.35$ since this value is also used by SimuPLAN for Solar Atlas Berlin. The

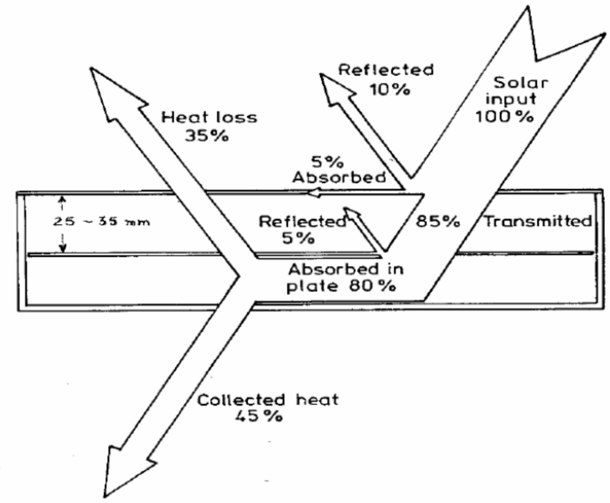

Figure 17: typical module with visualization of calculation parameters (Struckmann (2008))

input fluid temperature is assumed to be $T_i = 10°C$ which seems to be a realistic value for the region of Berlin. Also the average outside air temperature is taken as $T_a = 10°C$.

17 Validation of Result

The results are compared and validated against the values computed for the project "Solar Atlas Berlin". According to the roof area which is suitable for solar panels per building, the geometry data source of the Solar Atlas is expected to be of higher quality, because the data has been acquired using a laser scanning system. Therefore, the usable roof area may be exactly predicted for each building. Usable roof area is the area which is not used for any equipment on the roof, such as dormer, chimneys or antennas. The data source used within the GIS Project is an LOD2 Model of Berlin, which does not contain information about roof equipment. For this reason, we use the Solar Atlas Berlin to validate our results.

The value which is validated is calculated potential in MWh/a for photovoltaic systems as well as solar thermal systems. For each building in the test area the difference between the potential given from Solar Atlas Berlin and the potential calculate within the project in calculated. Note, that photovoltaic and solar thermal system are always considered separately.

Out of the differences, the standard deviation can be computed. Since the expectation is known ($e = 0$, no difference) the standard deviation is computed as in Equation 22.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(diff_i - e)^2} \tag{22}$$

For the test area a standard deviation of $\sigma_{pv} = 6.45Mwh/a$ for photovoltaic and $\sigma_{st} = 10.49Mwh/a$ for solar thermal systems has been reached. A weak spot of this approach is, that outliers influence the result. Although most of the differences are close to zero, the standard deviation is relatively high.

18 Conclusion

It can be concluded that the estimation of the photovoltaic potential as well as the solar thermal potential is only applicable to a limited extend. For single buildings the estimation is far to inaccurate, whereas the results for a statistical block become more reliable. The standard deviation for both potentials is too high, it is close to the mean of the potential, which means the result is for a high percentage of all buildings is totally wrong. But the standard deviation is calculated on the basis of the values given by the Solar Atlas Berlin. Therefore the values of the Solar Atlas Berlin are assumed to be correct. That this is not always the case was proved at least with on building. The potential was shifted by one decimal place. Also the geometry data is not sufficient. The used Lod2 (Level of detail 2) geometry only comprises simple polygons to describe the roof surfaces. No geometry of additional roof structures, as dormers, antennas or chimneys are available. Furthermore the roof surfaces representing one roof within the 3D City DB does not always correspond to the real roof surfaces. Some roof surfaces are represented by several small surfaces in the Database. This leads to errors for the estimation of the potentials, because horizontal roof surfaces smaller $40m^2$ and tilted roof surfaces smaller $15m^2$ are ignored during the calculation of the potential.

The solar potential of roofs depends strongly on the input of solar radiation, which in turn is strongly influenced by shadows. The used shadowing model is very simple. Only shadows due to very high neighboring buildings are considered. Shadows due to additional roof construction are neglected. Tests showed that only a few buildings were neglected due to the implemented shadow model.

Nevertheless the estimation of solar potential with existing CityGML data can be very fast and cheap, because no expansive Lidar data is necessary.

For the current implementation the disadvantages outbalance the advantages. The results are not accurate enough to use this approach

19 Future Work

Further investigations to improve the calculation model can lead to better results. Instead of an Lod 2 geometry a higher level of detail as Lod 3 can be used, which describes the geometry of the roofs in more detail. To avoid the neglection of too small roof surfaces due to wrong surface separations, neighboring roof surfaces with equal inclination and orientation should be merged in future.

In addition a high order shadow model, which considers partly shadowing of a roof surfaces due to other buildings and shadowing due to additional roof structures. Until now the shadow model is not capable of reducing the global irradiation, but neglects the whole building. The new model should be able to deal with this reduction due to partly shadowed roof surfaces.

Heading group 3