

Sensitivity analysis comparing level of detail and the accuracy of building energy simulations.

Edwin Bosscha

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Title Page

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Author: Edwin Bosscha (e.bosscha@student.utwente.nl)

Institution: University of Twente, Enschede

Organization: IAA Architecten

Supervisors: ir. Timo Hartmann (University of Twente)
Wouter Zwerink (IAA Architecten)

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ABSTRACT

Whole building energy analysis is simulating a building's energy consumption based on building properties, function properties and weather data. This research is aimed at pinpointing the relationship between the level of detail of a building simulation and the accuracy of this simulation. This is done by running 72 simulations in EnergyPlus, varying level of detail over two axis. The geometry and material properties are varied, and the installation properties are varied. This was done with the Epi Drost building in Enschede as a reference building with benchmark data. Analyzing the results, an obvious relationship between level of detail and the accuracy of the building energy simulation could not be found, but insight was gained into the correlation between installation setup and building geometry in energy simulations. It can be concluded that the increase in accuracy gained by more detailed geometry and zoning is highly dependent on the type of HVAC simulation used to simulate the building.

1. INTRODUCTION

With the increasing computational power available and more research done into the energy behaviour of a building, it is now possible to simulate a building's energy behaviour based on weather information and certain building properties. While these simulations have their roots in proven equations stemming from thermodynamics and physics, the accuracy of these simulations is debatable. To use a whole building energy simulation as an approximation of reality, and to incorporate it into the design process as a design tool, insight has to be gained on how these simulations work.

To gain insight into the dependability of energy simulations in building design, this research was conducted with the following research question:

What is the correlation between level of development and the accuracy of an energy model?

To answer this question, a case study researching and simulating a reference building was conducted. This reference building is the "Epi Drost" building in Enschede. It is an educational building owned and used by Saxion Hogeschool. The building was designed by IAA Architecten in 2006 and was completed in 2009. The research was conducted by creating 72 simulations, combining 12 different geometry levels of detail and six different HVAC levels of detail. By comparing the gas-, electricity- and total energy consumption to the benchmark building, information was attained about the relationship between the level of detail and the accuracy of the whole building energy simulation.

In the thesis the theory behind energy simulations will be summarized. Hereafter the research method will be presented, as well as the assumptions done while simulating the Epi Drost building. Next the results gained from the research will be presented and the simulation results from the different levels of development will be compared. The thesis ends with the conclusions on the correlation between level of detail and the accuracy of an energy simulation, as well as recommendations regarding findings and further research.

2. PREVIOUS RESEARCHES

Numerous studies involving sensitivity analysis in building energy modeling have been done over the past few years. While much can be learnt from these studies, it's surprising that only a few of these studies use a real project as a benchmark energy consumption. Studies such as 'Multivariate regression as an energy assessment tool in early building design' by Janelle S. Hygh et. al. discuss the influence of 27 building parameters on the output of the model. [1] Spitz et. al. defined the local sensitivity indices for 139 building parameters for a modeled house, by running 140 simulations of the energy model for the house, using the mean air temperature as the output variable. [2]

While the previous two studies mainly focused on building properties, Azer and Menassa conducted a research to investigate an energy simulation's sensitivity for occupancy-related parameters. They concluded that building use and occupancy parameters are an significantly influential factor in whole building energy analysis. [3] In addition to this, Rodríguez et al conducted a research revolving around uncertainties in building energy simulations. They defined a set of macroparameters, such as occupancy and weather, and tested the sensitivity of the simulation for this macroparameter. This showed a strong dependency on weather and occupancy. [4]

Less studies focus on the actual accuracy of the energy model used. 'The Building Energy End-Use Study' (BEES) by Gates et. al. at the BRANZ research institution discusses the influence of level of detail on the accuracy of the energy model using a benchmark building from the '70's. By varying the level of detail in geometry between a calibrated EnergyPlus template and a more detailed self made model, and doing the same for the HVAC model, five simulation levels of detail were defined. They concluded that detailed geometry can improve a simulation's reliability by 5 to 15%. [5].

In contrast to the studies mentioned previously, other studies discuss the faults found in building energy simulation software. In 2011, Basarkar et. al presented that the inclusion of HVAC control faults can influence the total HVAC energy consumption by 22%. [6] They stated that current building simulation software assumes that the HVAC controls work as designed, while in practice problems are bound to show up during the life cycle of the HVAC installation. Two papers by Kim and park and by Zhang, Lam, Yao and Zhang present the downfalls of the building simulation software concerning ventilation modeling and double skin facades. Kim and Park discuss the limitations of double skin facade simulations in EnergyPlus, and present a solution by using external tools like Matlab to increase accuracy of double skin facade simulation. [7] Zhang, Lam, Yao and Zhang notice the same discrepancies in the nodal approach of the EnergyPlus natural ventilation module, and present an alternative by using computational fluid dynamics(CFD) coupled to the EnergyPlus simulation. They test every EnergyPlus algorithm, and conclude a high impact of the coupled simulation on the heat transfer coefficients. [8]

3. ENERGY SIMULATIONS

The demand for energy simulations stems from the demand to gain insight into a buildings energy behaviour. Whole building energy analysis is a method to simulate the energy balance in a building over a certain time. It calculates heat or energy transfer between certain volumes of air(thermal zones), and calculates the energy consumption needed before the thermal zone air conditions reach certain

setpoints(temperature/humidity/ventilation).

Figure 1 shows an example of these thermal zones as air volumes.

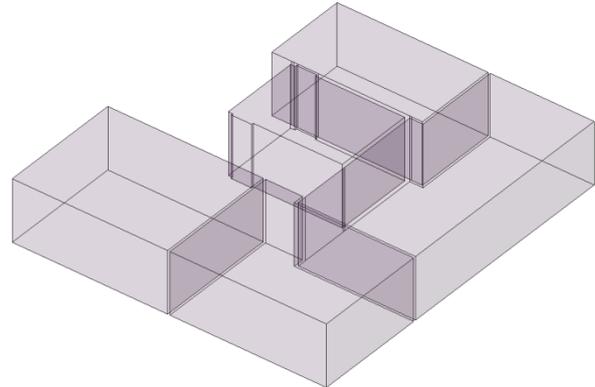


Figure 1: Example thermal zones

These calculations are based on the heat or energy transfer paths in a building. Figure 2

displays every energy path related to a thermal zone. It illustrates that a number of energy balance equations have to be solved simultaneously in the simulation to provide an accurate representation of the real building behaviour.

Figure 2 also provides a glimpse of which information is needed to create a whole building energy analysis. Every energy path requires some form of zone/outside air/construction information.

The information needed for a whole building simulation starts with defining thermal zones.

These thermal zones are volumes of air approximately have to the same properties or conditions. Therefore in a building a room might be a thermal zone, or a group of rooms can be defined as a thermal zone. For each zone, the setpoint conditions have to be stated, as well as internal conditions such as the amount of people in the zone and their activities, lighting and electric equipment.

Every thermal zone is bound by heat transfer surfaces. These are infinitesimally thin walls that have certain heat transfer and heat capacitance properties based on their construction. Openings such as doors or windows are simulated as child surfaces inside the wall surface.

To satisfy the heating and cooling loads of the model, an HVAC installation has to be defined. This installation is the module that consumes the energy to satisfy the zone setpoints.

Lastly, the weather data has to be specified. Hourly weather data from the location is required, because part of the building exchanges heat with the outside air, as well as it receives solar radiation and wind.

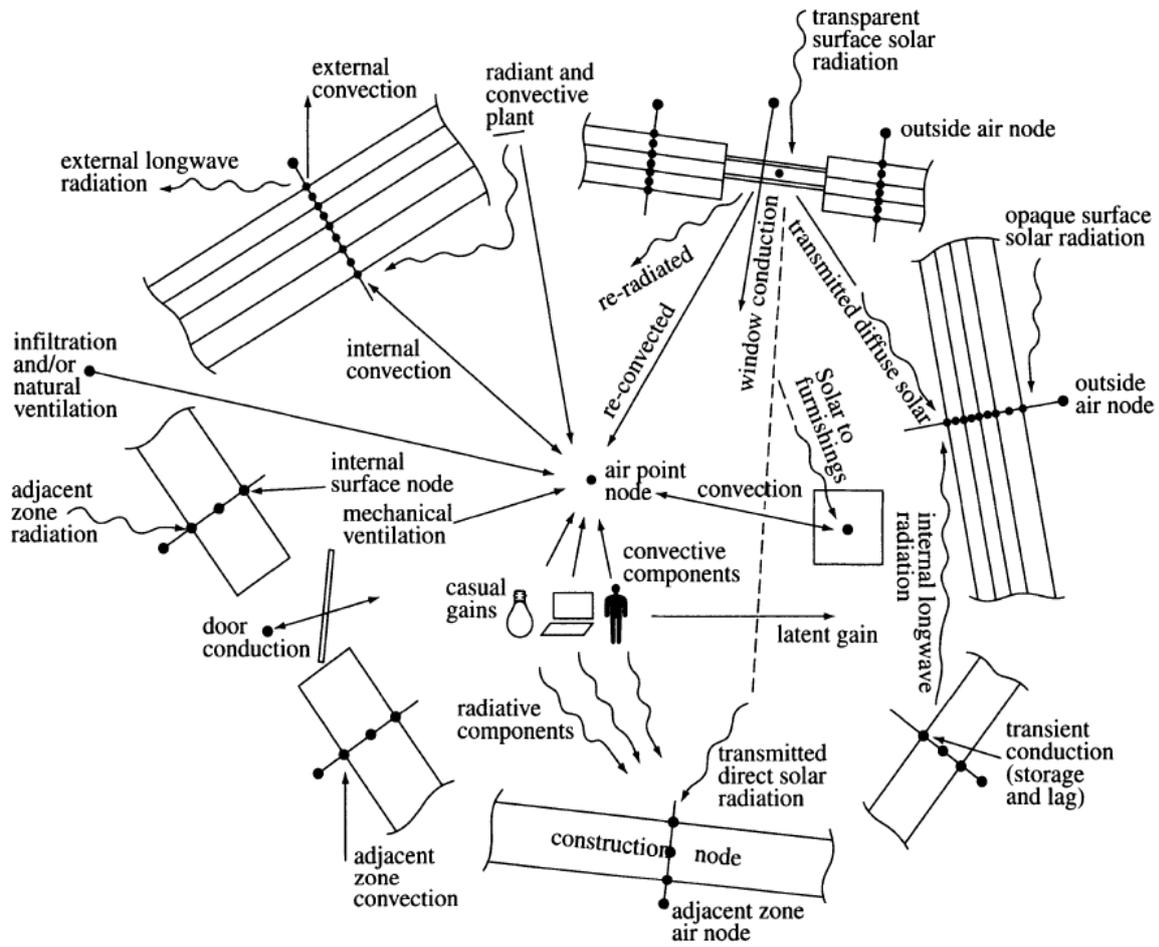


Figure 2: Schematic for the nodal energy model [9]

4. LEVELS OF DEVELOPMENT AND DESIGN PROCESS

To incorporate energy simulations into the design process, the information available during the design phase has to be matched to the information needed to make an energy simulation. To quantify the information available during the design process, the Level of Development (LOD) has been introduced by Jim Bedrick in 2008. This is based on the fact that during the building design process, one iteratively increases the detail of a design from an idea to a realized building. From simply a function and area to a structure that facilitates this function. While in this process, the level of development keeps increasing, and so does the amount of available information. These LOD's and the information available strongly relate to the information needed for an energy simulation. Figure 3 displays a summary of what energy related information is available at which LOD.

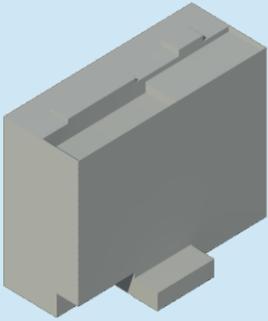
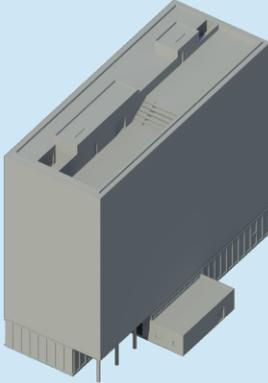
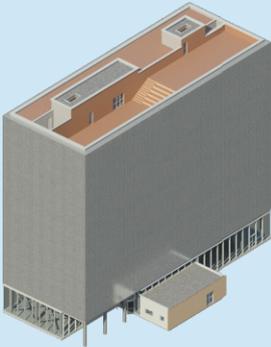
LOD100	LOD200	LOD300
		
Building Massing <ul style="list-style-type: none"> • Approximate shape • Area's by function 	Building interior geometry <ul style="list-style-type: none"> • Rooms • Specific room functions 	Detailed material properties <ul style="list-style-type: none"> • Constructions • Thermal capacities
Building use properties <ul style="list-style-type: none"> • Building functions • Internal loads 	Building glazing <ul style="list-style-type: none"> • Window size and placement • Doors and other openings 	Installation properties <ul style="list-style-type: none"> • HVAC type • HVAC capacities

Figure 3: Information available at certain LOD's

Regarding whole building energy simulations, related information consists of geometry, materials, thermal zones, HVAC information weather data and building use related parameters. When increasing the level of development, the amount and accuracy of information about geometry, materials, thermal zones and HVAC information increases. The weather data and building use parameters are mostly defined by initial building parameters such as location, function and user. Furthermore, the increase in detail about thermal zoning is a result of an increase in detail of geometry and vice versa.

5. RESEARCH METHOD

The goal of this research is to analyze the correlation between level of development and accuracy of an energy simulation. But to realize this, firstly level of development has to be defined and quantified. The LOD scale will be used as a guideline. Hereafter, the reference building will be presented, and the main simulation setup will be discussed.

5.1 DEFINING VARIABLES

Because the LOD scale discussed in chapter 4 contains a rather small number of steps between the conceptual phase and the as-built phase, a few other steps in detail were introduced. The level of development is increased per step by introducing one new specific detail into the model, such as windows or shading buildings. Figure 5 displays the resulting 12 levels of detail. The first level of detail is a simple cube matching dimensions of the reference building, in the upper left corner of figure 5. After adding glazing, shading surfaces and a facade model, the exterior geometry is increased to an LOD100 level, which is the global mass of the building. Eventually the model is detailed as a collection of around 350 thermal zones, representing every room in the building.

Considering that during the design process, the building function, and all function related properties such as internal gains are constant. But all geometry, material and installation related aspects keep increasing in detail during the design process. Therefore it was chosen to increase the level of development over two axis, as represented in figure 4. On one axis the level of development is being increased on the geometry, material and thermal zoning aspect. On the other axis, the level of development is being increased regarding the HVAC installation. A total of 6 different levels of development were defined and are discussed in chapter 5.4.

This biaxial analysis is one of the key aspects where this research differs from the research already done by BRANZ in 2012 [5]. By increasing the number of steps in level of detail and combining this with the use of a second axis, the total number of simulations is increased to 72, which seems to be adequate to analyze the effects of increasing certain details.

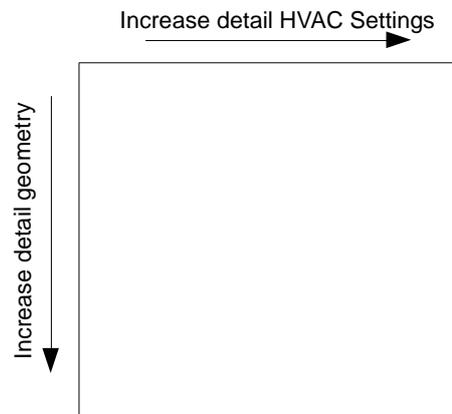


Figure 4: Increasing detail over two axis

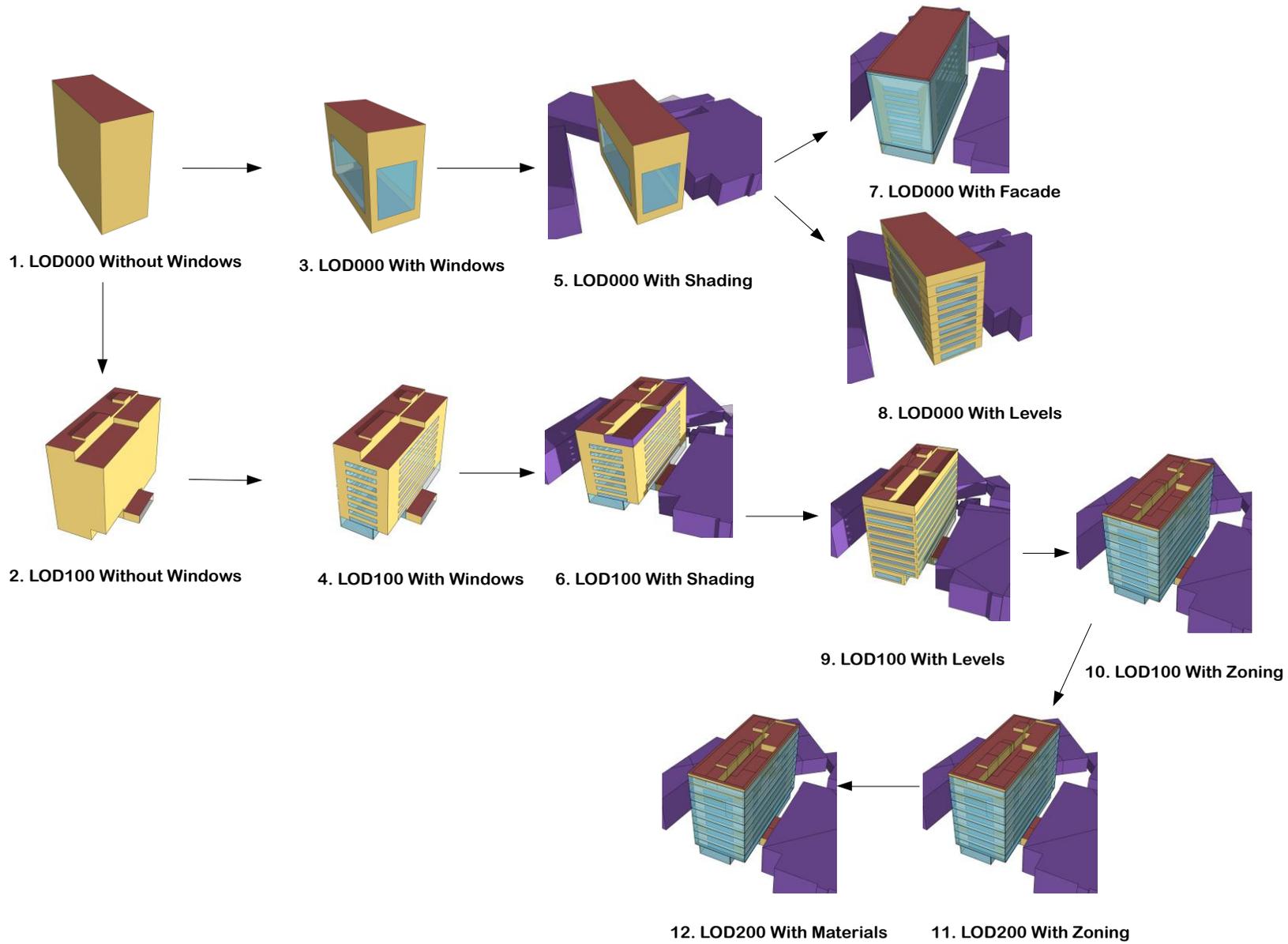


Figure 5: The 12 simulation levels of detail

5.2 REFERENCE BUILDING

The benchmark building used in this case study is the Epi Drost educational building part of the Saxion Hogeschool in Enschede. It's a building with roughly 8000 square meters of area, spread over 10 floors. The building is used mainly as an educational building, and partially as public space and offices. The façade is a ventilated double skin façade. Saxion and IAA Architects provided the necessary information needed to complete this research, such as drawings, technical information about the HVAC equipment and benchmark energy consumptions for 2011. The benchmark consumption consists of gas consumption, electricity consumption and total energy, which is the gas plus energy consumption.

To convert the amount of gas consumed from cubic meters to gigajoule, the amount of gas has to be multiplied by the energy density of gas, which is assumed to be $35,17 \text{ MJ}/\text{m}^3$ for natural gas.

For 2011, the following resources were consumed in the building:

Gas: 1879,06 GJ

Electricity: 2499,67 GJ

Total: 4278,73 GJ



Figure 6: The Epi Drost building

The case study will use the exact hourly weather data from Twenthe Airport, a location close to the reference building. [10] This will eliminate the high level of uncertainty that comes with averaged weather data as demonstrated by Rodríguez et. al. [4]

5.3 INSTALLATION SETUPS

To vary the models with different HVAC (Heating, Ventilation and Air Conditioning) setups in varying levels of development, four different HVAC setups were chosen. In addition to this, the floor area and volumes were manipulated for four setups to account for unconditioned spaces in the building. This totals up to six different HVAC settings to simulate. Figure 7 is a graphic representation of the components in each HVAC setting.

The first HVAC setup only requires assigning it to a thermal zone, whilst the most detailed HVAC setup requires defining the whole air loop and hot water loop.

1. Ideal Loads air System

The IdealLoads Template in EnergyPlus is an HVAC setup to calculate the building's heating and cooling loads. It solely calculates the energy needed to satisfy the thermal zone's temperature and ventilation requirements.

2. Ideal Loads air system with corrected areas

This setup is a duplicate of the first setup, with a correction in the models to match the area and volume of the total conditioned space in the building.

3. HVACTemplate VAV system

This setup uses the variable air volume system template in EnergyPlus. The installation capacities are all autosized by EnergyPlus, but it does offer more parameters to tweak. The setup simulates every conditioned zone being serviced by a packaged VAV system, and convective baseboard heating to simulate the radiators in the rooms

4. HVACTemplate VAV system with corrected areas

This setup is a duplicate of the previous setup, with a correction in the models to match the area and volume of the total conditioned space in the building.

5. VAV System with baseboard

This setup uses the expanded variant of the VAV template. The radiators are simulated using convective baseboard heating. The VAV system is set to cool air to 18 degrees or heat air to 20 degrees. All models are corrected to account for unconditioned spaces.

6. Detailed VAV System with baseboard

This setup is a duplicate of the previous setup, but uses the real cooling, boiler and heating capacities of the installation in the building. The autosize function is still used to calculate the air distribution between the zones.

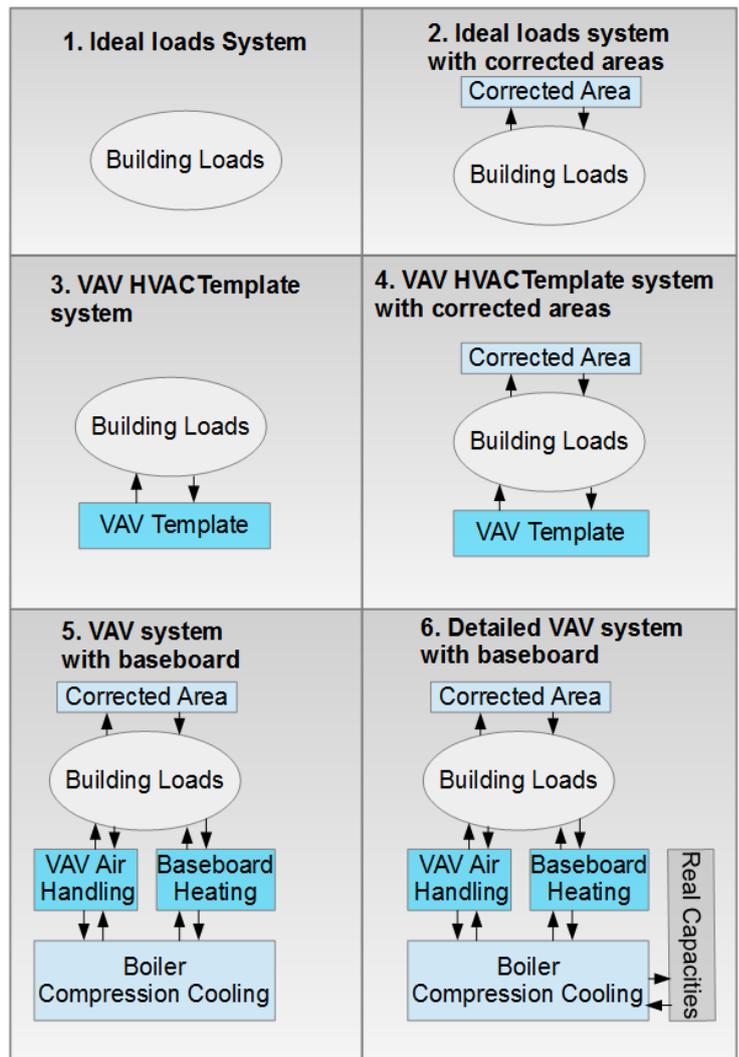


Figure 7: HVAC settings scheme

5.4 BUILDING SIMULATIONS

The energy simulations have been created with Autodesk Revit drawings as a basis. Using the geometry and materials from Revit, the building was exported to Autodesk Ecotect, where the model was manipulated, simplified and cleaned up. Through Ecotect, the model could be exported to EnergyPlus, the simulation engine. For every LOD, the same EnergyPlus file was used as a basis to keep a steady baseline, and as little difference between the models as possible. Appendix A provides an overview of the software flowpath, accompanied by the information added in each step of the process.

The creation of every simulation started with a Revit drawing to outline the geometry and the rooms of the building. After creating the 12 different Revit drawings, they were exported to Ecotect as a gbXML file. In Ecotect, the material names were assigned to the heat transfer surfaces. The thermal properties were added after the export to EnergyPlus. Some higher detailed simulations were cleaned up in Ecotect by removing gaps or merging bounding surfaces together.

After exporting the Ecotect files to an EnergyPlus IDF file, the thermal properties for every material were added. These were derived from the NEN7120 norm for the first 11 simulations, and were derived from EnergyPlus template constructions and the LOD400 Revit drawing for the most detailed simulation.

When the geometry was fully translated to EnergyPlus, the thermal zone properties and HVAC setups could be implemented, as described in chapter 5.3 and 5.5. The higher level of detail simulations contain an approximation of the double skin facade, as described in chapter 5.6

All the simulations were entered and edited in EnergyPlus by following the EnergyPlus' engineering reference. This covers the basic algorithms used by EnergyPlus to calculate the energy consumption. [11]

5.5 BUILDING USE ASSUMPTIONS

Other than the building geometry and material properties, the energy model also requires building use information as well as internal equipment and lighting properties. These properties correlate heavily with the simulation output. As proven by Azar and Menassa and Rodríguez et al. the simulation output is highly dependent on the occupancy schedules of the building. [3] [4]

These building use properties are constant through every level of development in the energy simulations. This is because these properties are assumed not to change throughout the design process. To simplify the simulations severely, the zone properties are divided into occupied and unoccupied. The internal gains, schedules and other building use properties are equal for each occupied thermal zone.

Firstly, building use schedules have to be defined. These schedules are used to define time-based room temperature setpoints, room occupancy, lighting intensity and other time-based events in the simulation. In this research, the basis for these schedules was found in the EnergyPlus templates for educational buildings. These schedules were adapted to the specifications of the Epi Drost building and information from the Saxion technical services.

The internal loads in the building are assumed to be consisting of people, lighting and equipment. The amount of people in the building is assumed to be 562 at a maximum, which corresponds to roughly 0,08 person per square meter. This number is based on the initial requirements from the client. The amount of people is coupled to a building occupancy schedule. The amount of lighting in the building is assumed to be 10W per square meter, based on an initial energy analysis by an external contractor. This is coupled to a lighting intensity schedule.

The equipment intensity in the building is assumed to be 14W per square meter. This value is based on the NEN7120 norm and is also coupled to the occupancy schedule. The temperature is assumed to be kept around 21,7 degrees Celsius. This is based on information from the Saxion technical staff. While this might defer per zone in real life, the temperature was found to be around 21,7 degrees average in the rooms.

5.6 DOUBLE FAÇADE SIMULATION

To simulate the double façade of the building, several options were considered. The first problem with double façade simulation is simulation of the natural ventilation and convection simultaneously. The only EnergyPlus module capable of this is restricted to opaque materials, so it does not apply to glass double skin facades. To approximate the effects of the double skin façade to some degree, it was simulated using 4 convex zones on each outer wall of the building to model the cavity, with a zone on the bottom and top of the façade housing vertical outlet windows. The ventilation model is based on the big horizontal openings model, used to model the ventilation occurring due to stairways. This ventilation model requires the pressure coefficients $C_p = \frac{p-p_\infty}{\frac{1}{2}\rho V^2}$ depending on the wind

angle. For this case, the pressure coefficient was calculated at wind angle intervals of 30°. To calculate these pressure coefficients 12 CFD(Computational Fluid Dynamics) analysis were simulated using SolidWorks with 30° wind direction intervals. In this analysis, the ground and the buildings were all assumed to be made of rough materials with high friction coefficients to simulate the boundary layer effect. Figure 8 demonstrates the flow trajectories in one of these simulations, demonstrating a substantially lower air pressure on the downwind side of the building.

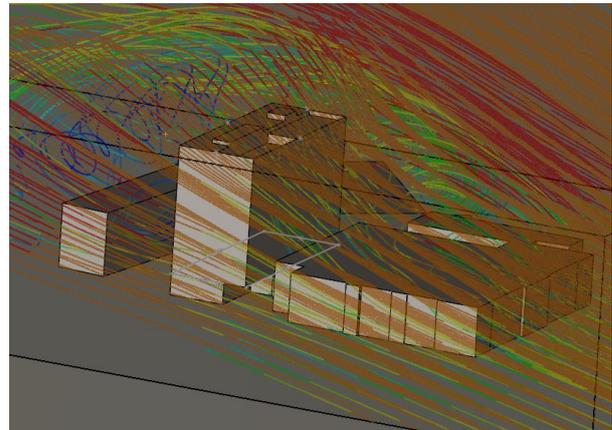


Figure 8: CFD Analysis

While Kim and Park(2011) prove that using a coupled method, using matlab or CFD analysis as well as EnergyPlus, instead of solely EnergyPlus for a double skin façade is more accurate, EnergyPlus is adequately accurate for this research purpose. [7]

6. RESULTS

The 6 series of 12 energy models for different levels of development all resulted in an interesting set of data. With these 72 energy simulations, level of development increased over two axis: Geometry/Zoning details and HVAC installation details. To analyze this data, the total energy consumption, the gas/electricity split, the deviation from the benchmark and the absolute deviation from the benchmark are considered. Every energy consumption value is in GigaJoule.

The benchmark energy consumptions for 2011 obtained from the Saxion Hogeschool are:

Gas: 1879,06 GJ

Electricity: 2499,67 GJ

Total: 4278,73 GJ

Total Energy Consumption

Total Consumption	1. IdealLoads	2. Idealloads Corrected Area	3. HVACTemplate VAV	4. HVACTemplate VAV Corrected Area	5. VAV With Baseboard	6. Detailed HVAC
LOD000 Without Windows	4290,67	3781,81	3067,9	2706,5	3587,28	3457,2
LOD100 Without Windows	4322,19	3794,04	3438,2	2700,5	3637,69	3507,6
LOD000 With Windows	4800,28	4271,57	3453,1	3114,11	4250,5	4132,5
LOD100 With Windows	4862,82	4235,17	3849,2	3074,37	4223,62	4105,42
LOD000 With Shading	4798,47	4270,63	3452,3	3113,32	4249,96	4132,1
LOD100 With Shading	4861,65	4234,27	3848,6	3073,83	4219,93	4103,5
LOD000 With Facade	4666,99	4141,85	3232,9	2898,89	4135,64	4026,7
LOD000 With Levels	4684,25	4242,13	4125,2	3495,21	4051,56	3832,0
LOD100 With Levels	5765,95	4350,32	4235,0	3700,66	3858,06	3704,0
LOD100 With Zoning	5112,48	4174,66	3988,7	3611,14	5465,61	5301,8
LOD200 With Zoning	4638,99	4540,85	3829,23	3829,23	4003,4	5400,2
LOD200 With Materials	4617,03	4680,55	3880,6	3881,73	3997,06	5485,1

Total Deviation	1. IdealLoads	2. Idealloads Corrected Area	3. HVACTemplate VAV	4. HVACTemplate VAV Corrected Area	5. VAV With Baseboard	6. Detailed HVAC
LOD000 Without Windows	11,9	-496,9	-1210,8	-1572,2	-691,5	-821,5
LOD100 Without Windows	43,5	-484,7	-840,6	-1578,2	-641,0	-771,2
LOD000 With Windows	521,5	-7,2	-825,6	-1164,6	-28,2	-146,2
LOD100 With Windows	584,1	-43,6	-429,6	-1204,4	-55,1	-173,3
LOD000 With Shading	519,7	-8,1	-826,5	-1165,4	-28,8	-146,7
LOD100 With Shading	582,9	-44,5	-430,1	-1204,9	-58,8	-175,2
LOD000 With Facade	388,3	-136,9	-1045,9	-1379,8	-143,1	-252,1
LOD000 With Levels	405,5	-36,6	-153,5	-783,5	-227,2	-446,8
LOD100 With Levels	1487,2	71,6	-43,7	-578,1	-420,7	-574,8
LOD100 With Zoning	833,7	-104,1	-290,1	-667,6	1186,9	1023,1
LOD200 With Zoning	360,3	262,1	-449,5	-449,5	-275,3	1121,5
LOD200 With Materials	338,3	401,8	-398,1	-397,0	-281,7	1206,3

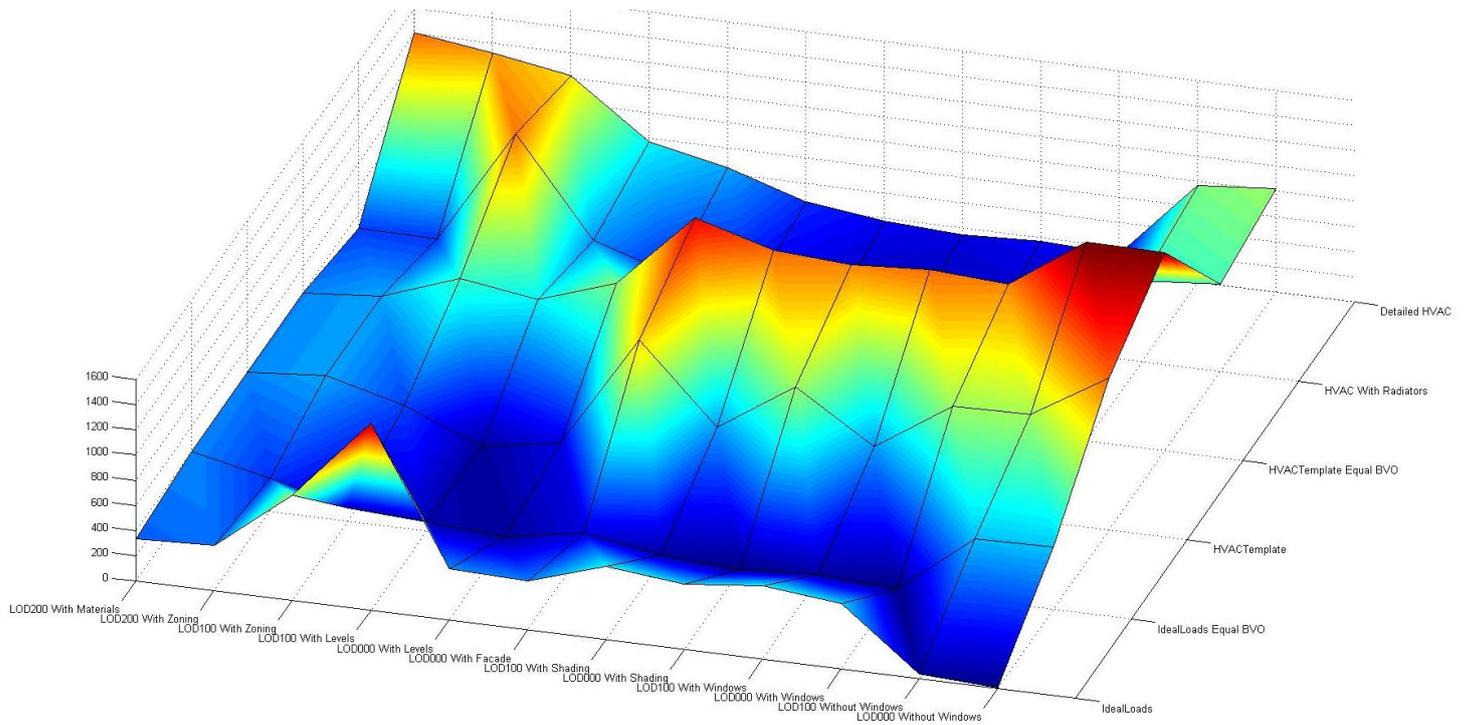


Figure 9: The absolute deviation in total energy consumption

The two tables and graph displayed above display the results in total energy consumption from the model, as well as the deviation from the benchmark energy consumption. The first notable relation is that the total energy consumption generally increases with the geometry level of development for every HVAC setup. Secondly, the output sensitivity for geometry level of detail seems to be highly dependent on the HVAC setup and vice versa.

Electricity consumption

Electricity Deviation	1. IdealLoads	2. Idealloads Corrected Area	3. HVACTemplate VAV	4. HVACTemplate VAV Corrected Area	5. VAV With Baseboard	6. Detailed HVAC
LOD000 Without Windows	-559	-806	62	-297	-255	-430
LOD100 Without Windows	-551	-809	79	-288	-268	-416
LOD000 With Windows	-586	-830	78	-247	-269	-416
LOD100 With Windows	-595	-836	64	-255	-271	-418
LOD000 With Shading	-269	-830	658	-248	-55	-217
LOD100 With Shading	-596	-838	108	-256	-284	-429
LOD000 With Facade	-590	-834	240	-258	-264	-412
LOD000 With Levels	-483	-839	239	6	-268	-416
LOD100 With Levels	-246	-842	577	25	-61	-213
LOD100 With Zoning	-378	-817	361	14	12	-162
LOD200 With Zoning	-766	-755	-32	-32	-125	-135
LOD200 With Materials	-831	-841	-217	-226	-208	-184

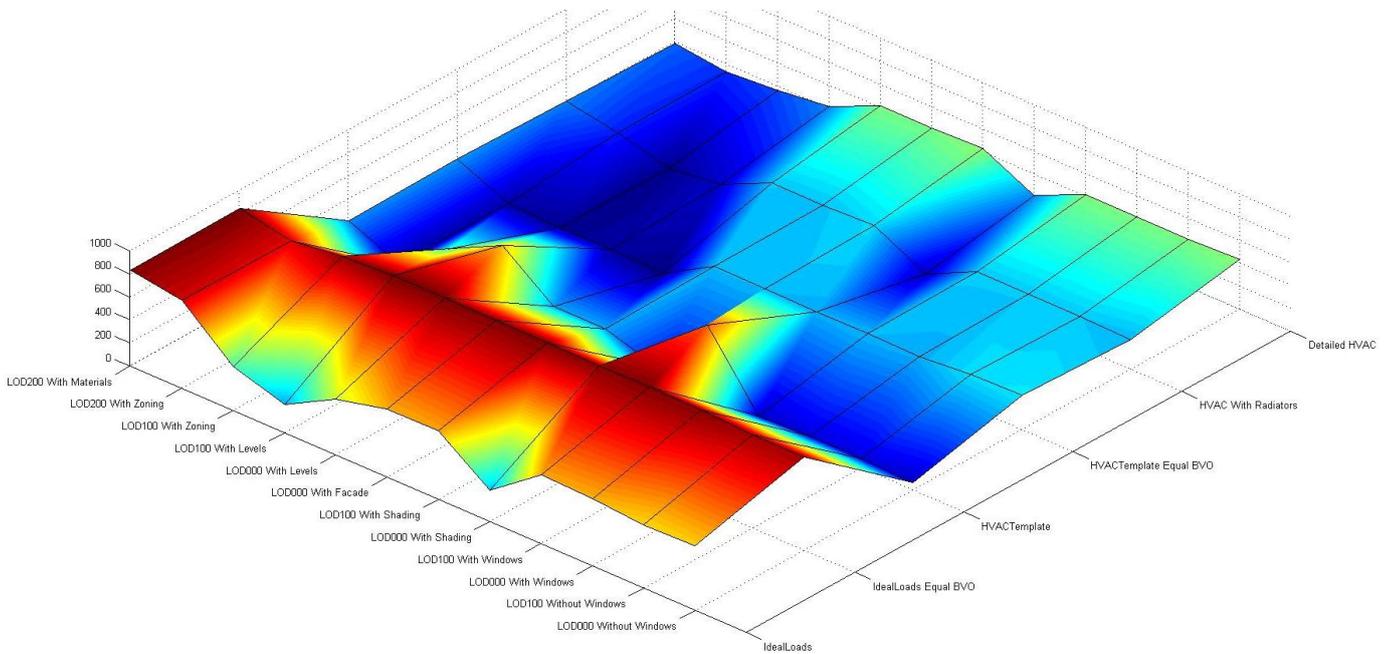


Figure 10: Absolute deviation in electricity consumption

The table and graph above illustrate the simulations deviation from the benchmark electricity consumption. This graph indicates a clear relationship between HVAC type and electricity consumption. This is due to the fact that the less detailed HVAC setups do not account for fan and cooling electricity consumption separately.

Gas consumption

Gas Deviation	1. IdealLoads	2. Idealloads Corrected Area	3. HVACTemplate VAV	4. HVACTemplate VAV Corrected Area	5. VAV With Baseboard	6. Detailed HVAC
LOD000 Without Windows	571	310	-1237	-1276	-406	-392
LOD100 Without Windows	1107	822	-1204	-1290	240	270
LOD000 With Windows	1107	822	-905	-917	240	270
LOD100 With Windows	978	698	-1110	-949	127	166
LOD000 With Shading	1570	808	-791	-917	-172	-230
LOD100 With Shading	595	324	-949	-949	-327	-342
LOD000 With Facade	1180	793	-670	-1121	209	238
LOD000 With Levels	1179	793	-669	-790	209	241
LOD100 With Levels	1733	913	-620	-603	-359	-361
LOD100 With Zoning	1212	713	-651	-632	1174	1185
LOD200 With Zoning	1126	1017	-418	-418	-151	1257
LOD200 With Materials	1170	1243	-181	-171	-74	1391

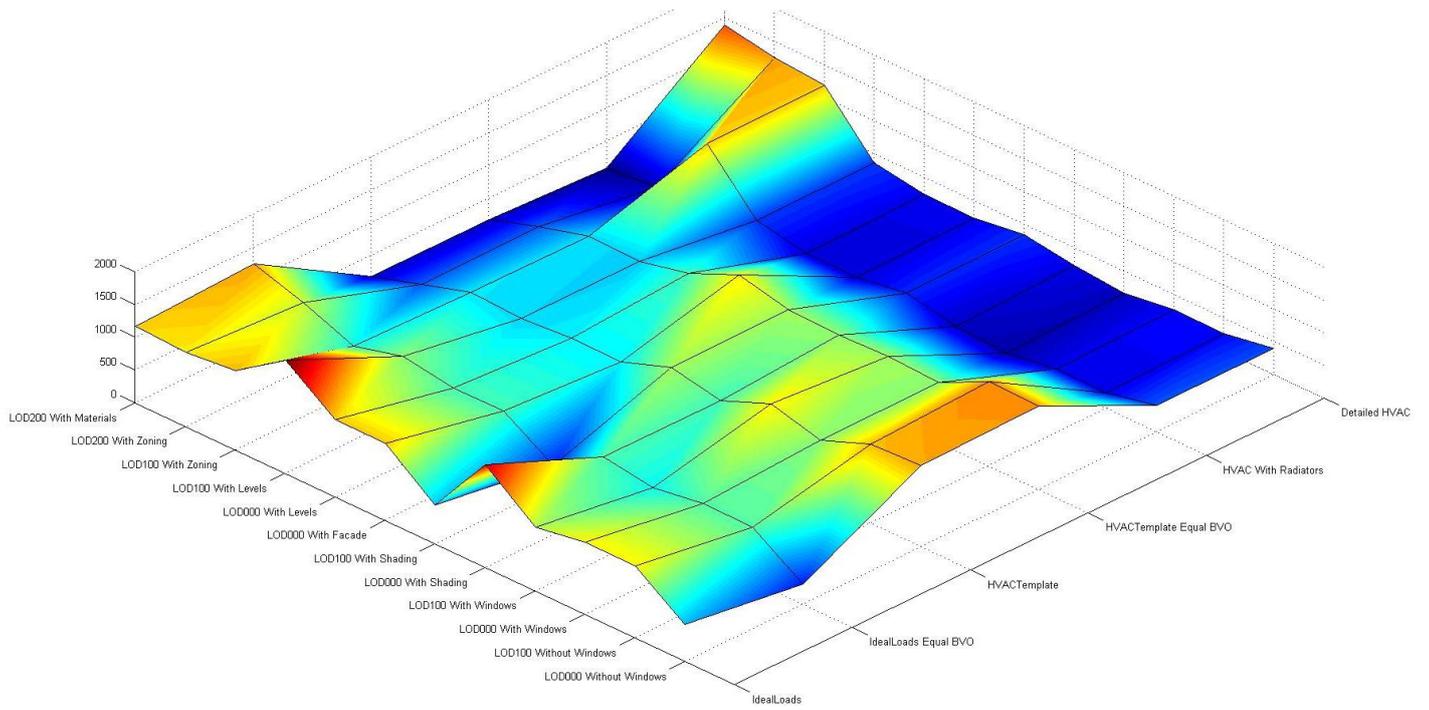


Figure 11: Absolute deviation in gas consumption

The table and figure above display the simulations deviation from the benchmark gas consumption. This shows an positive relation between accuracy and level of detail over both axis, with the exception of the peaks at the highest levels of detail.

Gas/Electricity split deviation

Gas/Electricity Split Deviation	1. IdealLoads	2. Idealloads Corrected Area	3. HVACTemplate VAV	4. HVACTemplate VAV Corrected Area	5. VAV With Baseboard	6. Detailed HVAC
LOD000 Without Windows	23,5%	24,9%	43,1%	38,5%	6,6%	1,6%
LOD100 Without Windows	23,7%	25,2%	28,5%	39,4%	4,5%	0,8%
LOD000 With Windows	32,6%	34,5%	27,9%	23,2%	10,6%	14,4%
LOD100 With Windows	33,8%	34,2%	14,1%	24,4%	10,1%	13,9%
LOD000 With Shading	20,8%	34,5%	57,9%	23,2%	1,6%	5,8%
LOD100 With Shading	33,9%	34,3%	16,2%	24,4%	10,6%	14,4%
LOD000 With Facade	30,8%	32,6%	45,6%	31,7%	7,9%	12,0%
LOD000 With Levels	27,0%	34,4%	14,1%	22,7%	6,2%	7,7%
LOD100 With Levels	33,4%	36,1%	25,3%	16,8%	8,1%	5,2%
LOD100 With Zoning	29,5%	32,4%	23,4%	19,2%	21,3%	24,7%
LOD200 With Zoning	37,2%	35,4%	10,2%	10,2%	1,3%	25,2%
LOD200 With Materials	39,4%	40,6%	0,3%	0,2%	2,2%	28,0%

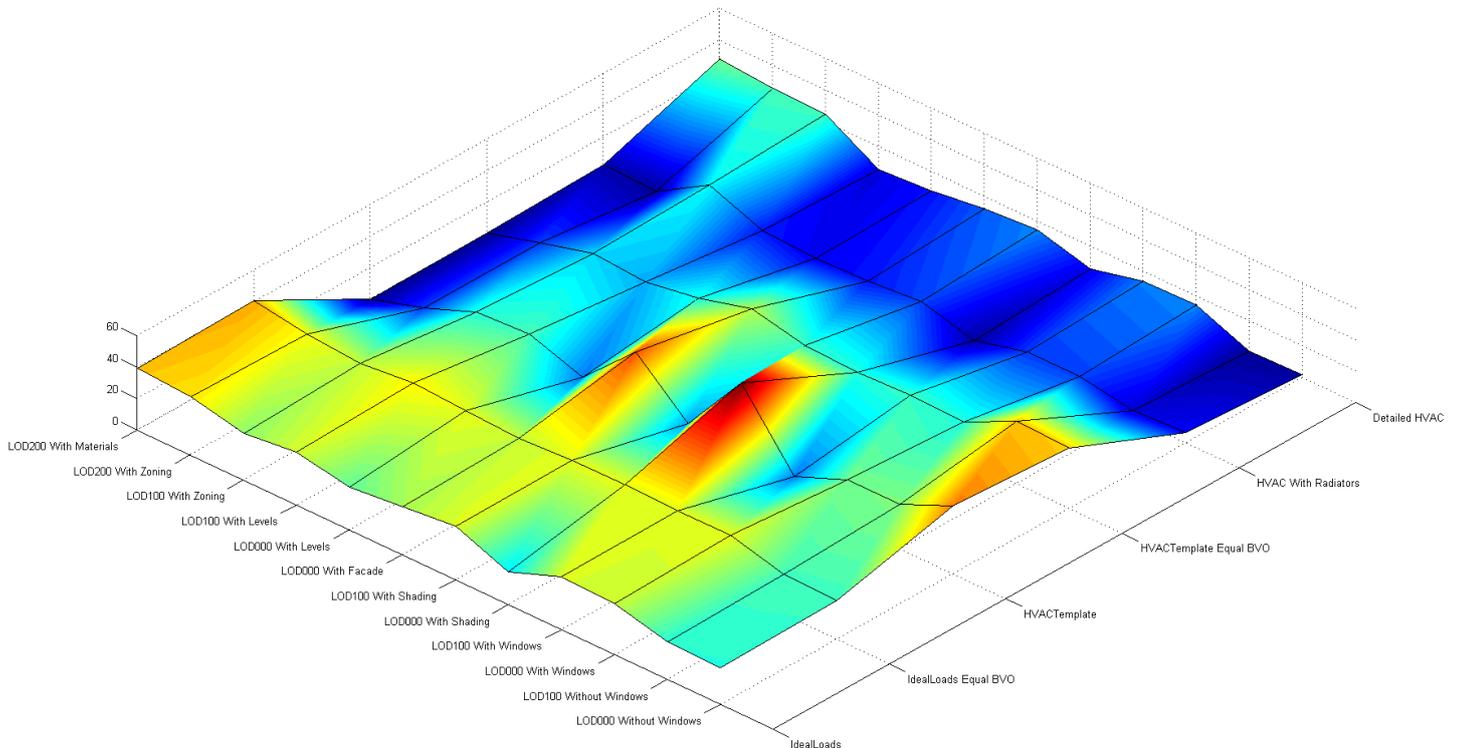


Figure 12: Relative deviation in gas/electricity split

The table and figure above display the relative deviation in gas/electricity split to the benchmark building data. This graph shows a positive relationship between level of detail and accuracy over both axis.

To calculate the deviation in the electricity/gas consumption split, the relative deviation is defined as: The deviation of the electric consumption divided by the total consumption compared to the benchmark building. This information, combined with the deviation of total energy consumption, is useful to define if the simulation's inaccuracy is caused by a deviation in total heating/cooling load or the deviation has another cause.

The accuracy of the simulation results can be expressed as a combination of the deviation of the total consumption and the deviation in gas/electricity split. The accuracy a can be defined as

$$a = \frac{|R_{total} - B_{total}|}{B_{total}} + \frac{\left| \frac{R_e}{R_{total}} - \frac{B_e}{B_{total}} \right|}{\frac{B_e}{B_{total}}} * 100$$

R_{total} is the simulation total energy consumption, B_{total} is the benchmark total energy consumption, R_e is the simulation electricity consumption and B_e is the benchmark electricity consumption.

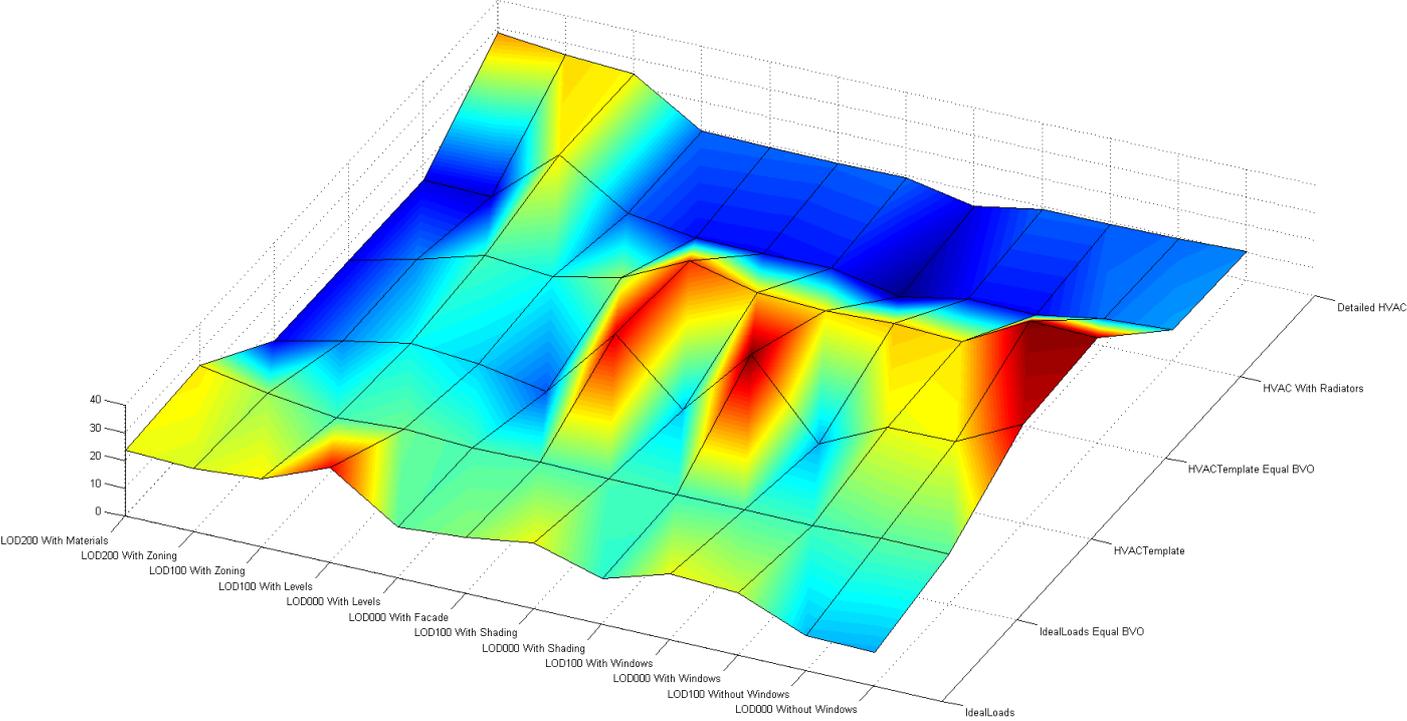


Figure 13: Accuracy of the simulation

Figure 13 shows the derived accuracy of the simulation. This figure indicates that certain combinations of level of detail are in fact more accurate, but that the simplest simulations are fairly accurate to begin with.

7. CONCLUSION

Considering the results of this research, it is quite hard to pinpoint an exact, if existent at all, correlation between level of development and accuracy of the energy model. The 3d plot displaying the absolute error of the model reveals that the most detailed models can quite easily produce a large error at certain HVAC settings, and be quite precise at other HVAC settings.

Regarding the consistency of the models with the different HVAC setups, one can see a clear trend that the less detailed IdealLoads HVAC Setups are more consistent throughout the different levels of development. The more detailed HVAC setups are quite inconsistent throughout the levels of development. This occurrence can most likely be attributed to the HVAC autosize function in EnergyPlus, which regulates HVAC airflow and capacity for the different zones.

The graph representing the relative deviation in gas/electricity split does display a positive effect for increasing level of development on both the HVAC and geometry axis. A higher level of development is in this case related to a more accurate gas/electricity split result. Another factor in this occurrence is that the IdealLoads models do not model fan electricity consumption and other HVAC electricity consumptions. This is a reason why the gas/electricity balance is far off for the IdealLoads simulations.

The LOD000 With Façade model seems to be most consistently predicting the total energy consumption throughout the different HVAC Setups. This is quite unexpected due to the inaccuracy of the EnergyPlus airflow network used to model the building's double skin façade, as explained in chapter 5.6.

Although the results of the research are quite inconclusive regarding the correlation between level of development and the accuracy of the energy model, it is reasonably safe to state that a model with a lower level of development can be adequately accurate regarding total building energy consumption. Although one has to keep in mind that with the increase in the model's level of development, the level of development of the results also increase. While the accuracy of the model does not necessarily increase, the available information about the building's energy behaviour does certainly increase with the level of development of the model.

So the recommended level of development to use for an whole building energy analysis largely depends on the information the user wants to obtain from the analysis. A lower level of development could be sufficient to get an indication for total energy consumption, while a higher level of development could be more suited to determine the effect of specific design options on the gas/electricity split or the overall energy consumption.

The level of development of the HVAC setup also works in the same manner. A simple IdealLoads model can be sufficient to calculate the total energy demand of the building, and can be used to determine the effect of design options on the total energy demand of the building. A more detailed HVAC model could be used to determine the actual yearly energy cost of the building.

8. RECOMMENDATIONS

While this research has provided some insight in the relation between level of development and the accuracy of an energy analysis, a lot can be done to continue research on this subject. For example the choice of reference building could be improved. If a generic building is used, without features as a double skin façade or a screen print used as shading in the façade, the initial accuracy of the energy simulation could be defined better. Because the more difficult the reference building is to simulate, the higher the chance on simulation deviations due to other causes than level of development. This is also applicable to the occupancy of the building. Because of the main educational function, the amount of people and equipment active in the building is highly fluctuating per hour. This makes it hard to make a reasonable approximation of the internal gains in the building.

The analysis could also be applied to a reference building with more available information. End-use analysis over multiple years and available building use schedules can be of great assistance to get more insight into the accuracy of whole building energy analysis methods.

Another possible research could be to increase the level of development of the energy model even more. By defining parameters such as lighting intensity, equipment intensity and schedules per zone, based on the building use, a more detailed model for building heating loads can be attained.

DESIGN RECOMMENDATIONS

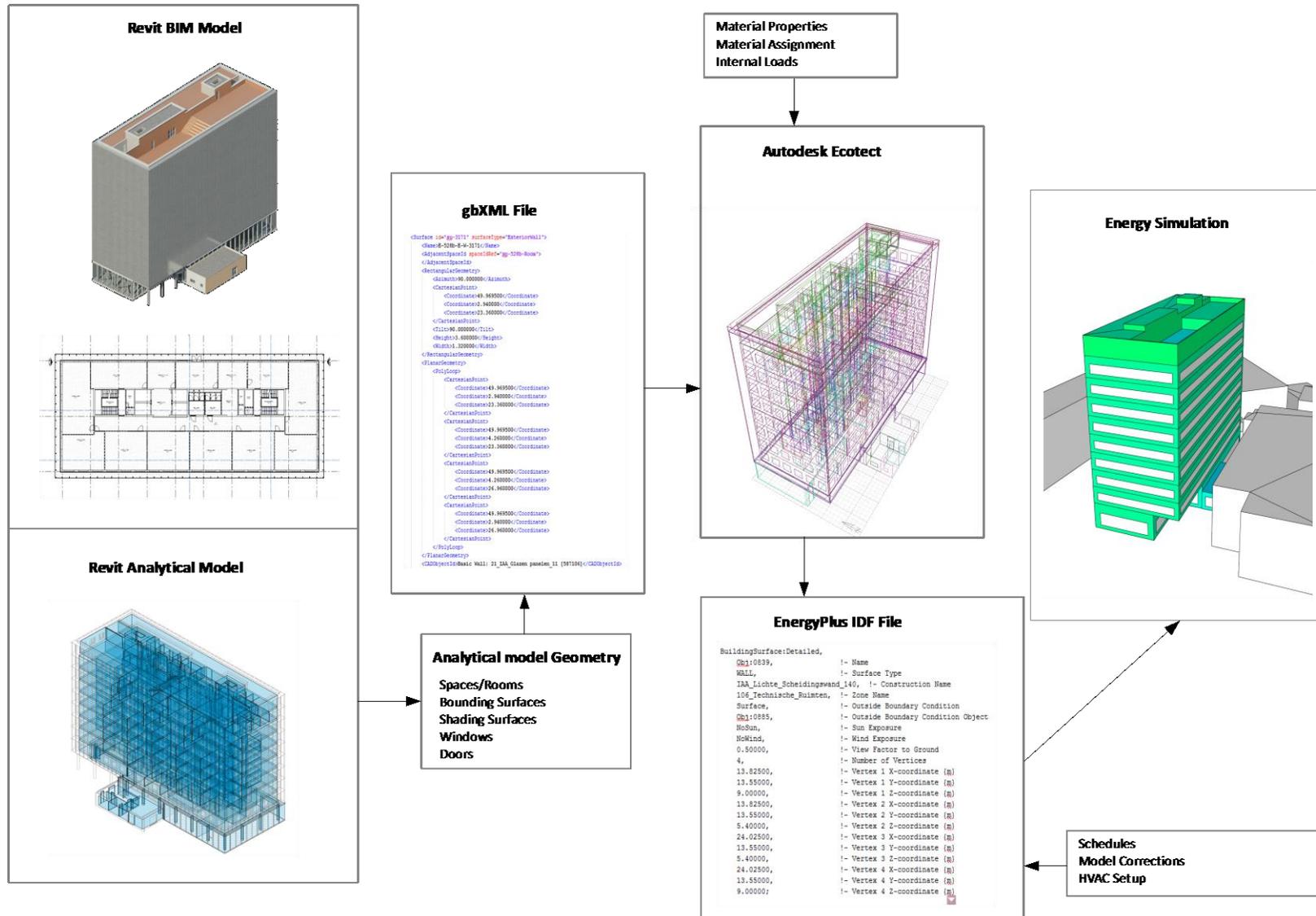
It is possible to incorporate whole building energy analysis into the design process. From an early conceptual phase, the analysis can be adequately accurate to test the design and different alternatives. And while the total amount of energy consumed in a year can be off by a significant percentage, the impact from different alternatives can be reviewed using whole building energy analysis. On a conceptual phase, the adjacencies of different functions can be tested and alternatives can be generated. In a later design stadium, the whole building energy analysis can be used to find possible spaces that can fall outside of the acceptable thermal conditions. This all contributes to finding a design that minimizes energy consumption.

9. REFERENCES

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10. APPENDICES

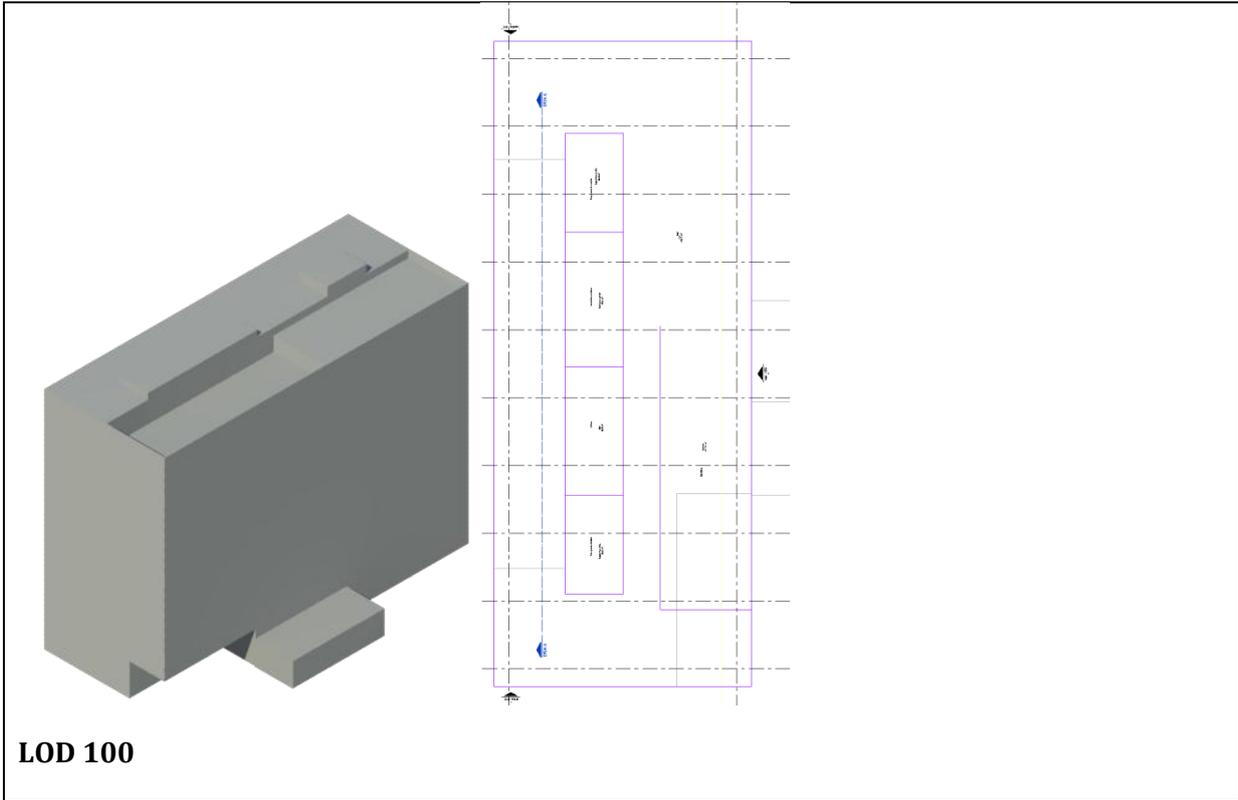
10.1 APPENDIX A: SOFTWARE FLOWPATH



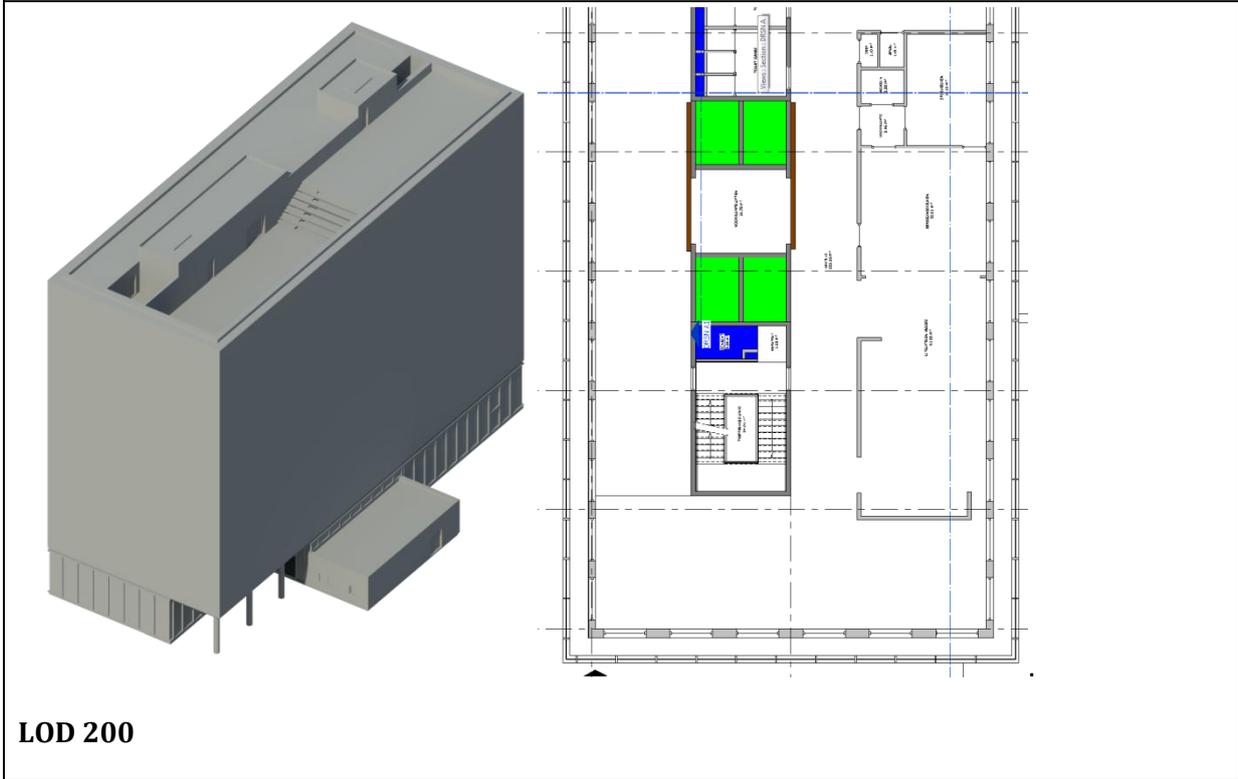
10.2 APPENDIX B: DIFFICULTY OF MAKING MODELS



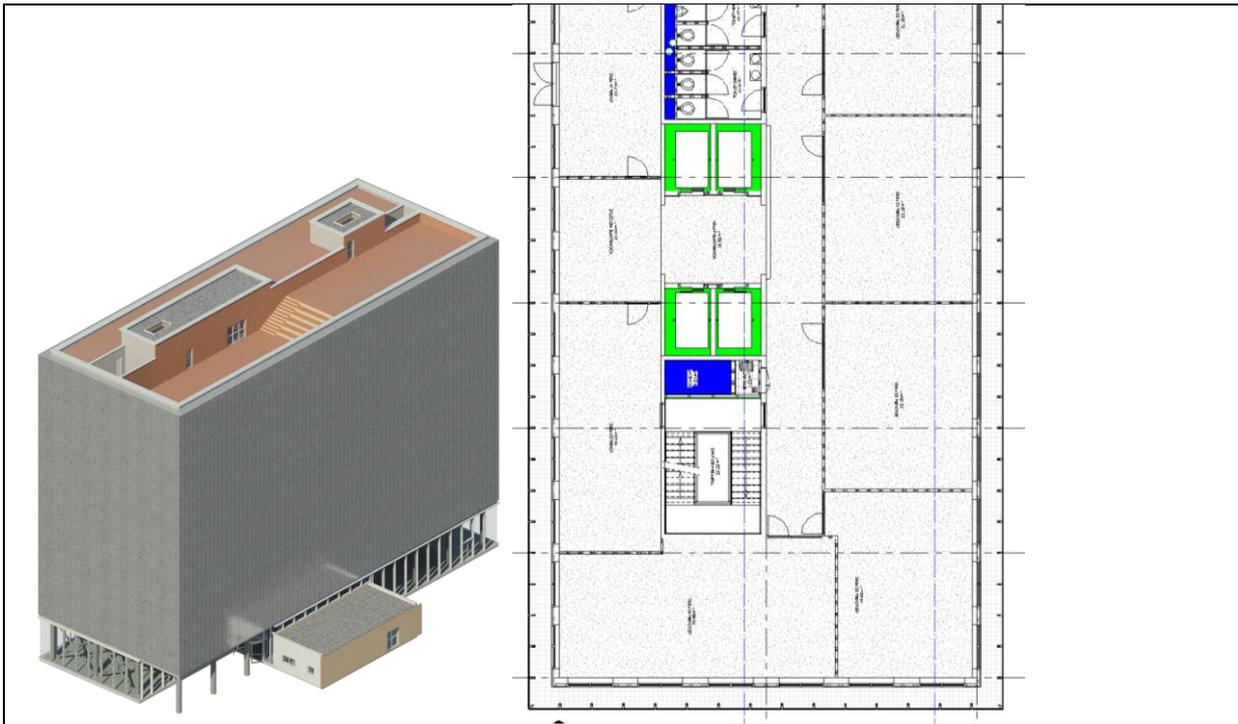
10.3 APPENDIX C: REVIT DRAWINGS



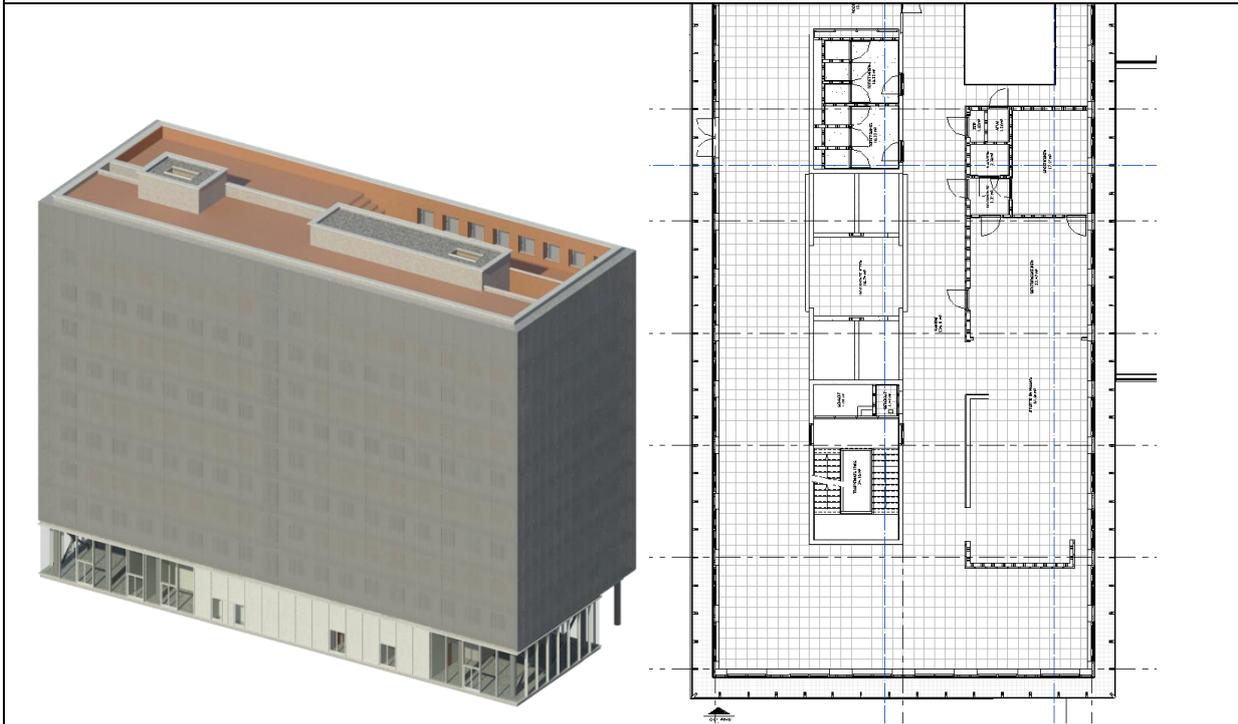
LOD 100



LOD 200



LOD 300



LOD 400

10.4 APPENDIX D: WORKGUIDE CREATING ENERGY SIMULATION

Een whole building energy simulation is een simulatie waarbij het energiegebruik van een gebouw gesimuleerd wordt gedurende een bepaalde tijd. Aan de hand van weergegevens, gebouwgegevens en gebruiksgegevens rekent de software het energiegebruik uit per uur over de gespecificeerde tijdsduur. In tegenstelling tot de EPC berekening is deze simulatie niet gebaseerd op hevige versimpelingen van de realiteit, maar is het doel om het energiegebruik zo nauwkeurig mogelijk te simuleren. Ook is tegenover de EPC de vrijheid om variabelen en detail te variëren veel groter, om het zo als een ontwerptool te gebruiken.

Het softwarepakket dat gebruikt wordt heet EnergyPlus. Dit is het energiesimulatiepakket ontwikkeld door de Amerikaanse overheid. Dit programma rekent aan de hand van de gespecificeerde thermische zones, oppervlakten, weerdata en gebruiksinformatie de uurlijkse hittebalans uit. Dit kan voor slechts de buitenschil van een gebouw, maar ook kan elke ruimte als thermische zone gespecificeerd worden om een gedetailleerder beeld van de energieloop binnen het gebouw te krijgen.

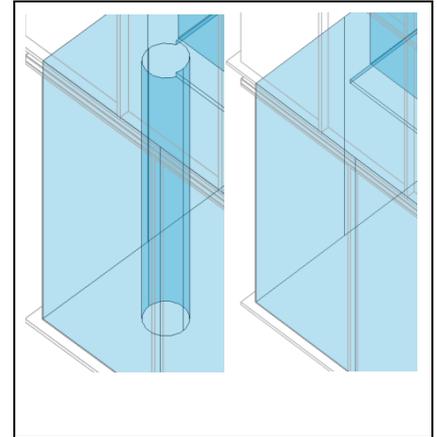
Elke thermische zone is een luchtvolume dat aan bepaalde condities moet voldoen. De temperatuur, luchtvochtigheid en ventilatie kunnen gespecificeerd worden. Deze thermische zones worden door oppervlakten ingebonden. Dit zijn oppervlakten tussen thermische zones of tussen een zone en de buitenlucht. Deze oppervlakten hebben bepaalde thermische eigenschappen afhankelijk van het materiaal en kunnen openingen zoals deuren en ramen hebben.

Om vanuit een Revit tekening naar een energiesimulatie te komen is een tool ontwikkeld die het bestandsformaat en de nodige informatie overzet. Maar hierbij is het belangrijk dat de Revit tekening aan bepaalde eisen voldoet, om een zo nauwkeurig mogelijke simulatie te krijgen.

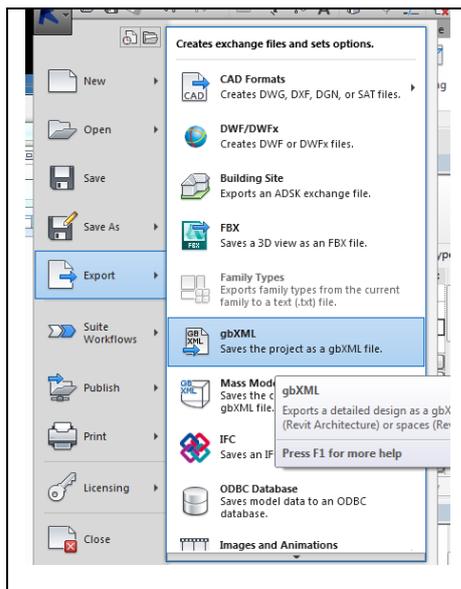
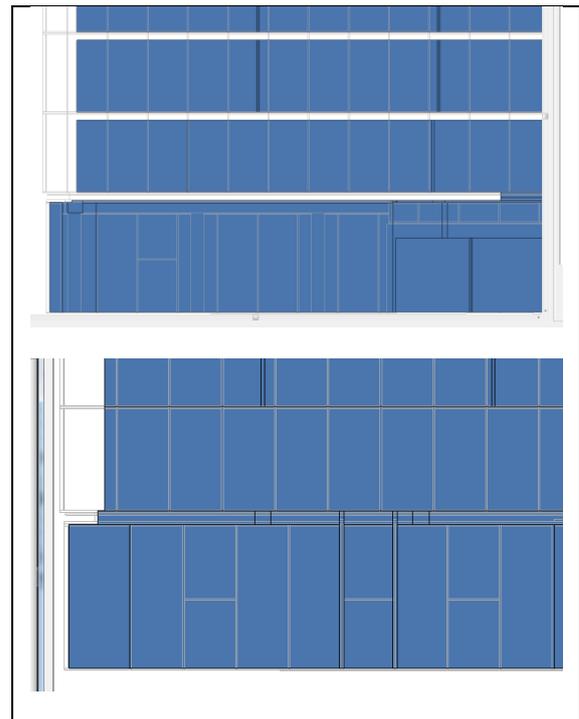
Tekenregels

- Thermische zones zijn gebaseerd op Rooms. Elke zone moet dus een Room bevatten.
Alle plekken die niet als buitenlucht beschouwd mogen worden vereisen een room te bevatten.
- Rooms moeten naadloos op elkaar aansluiten. Elke leegte tussen Rooms worden als buitenlucht gesimuleerd, en nemen dus ook de temperatuur van buiten over. Dit zorgt voor enorme afwijkingen.

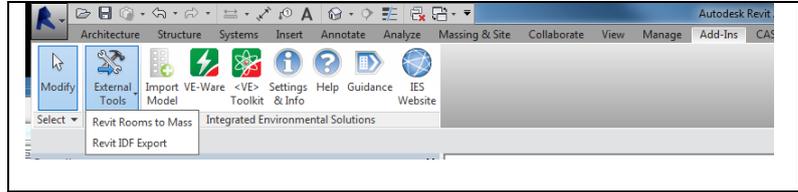
- Tussen Rooms mag maar een muur of vloer zijn. Dit betekent dat gelaagde structuren als enkele muur getekend moeten worden, ofwel dat voor bepaalde elementen de 'Room Bounding' instelling uitgezet moeten worden. Dit betekent dat deze elementen niet meer meedoen voor de ruimteberekening.
- Kolommen en andere elementen die niet direct een ruimte insluiten moeten niet room bounding zijn. Deze elementen zorgen voor onnodige onregelmatigheden in de thermische zones.
- Rooms moeten een ruimtenummer hebben. Dit moet een uniek nummer zijn. In het geval van twee de zelfde ruimtenummers in een project kan een toevoeging achter het ruimtenummer gedaan worden. Voorbeeld: 5.28 en 5.28a.
- Materialen moeten thermische eigenschappen bevatten. Dit kan door deze toe te voegen in de structure van het element. Als thermische eigenschappen niet bestaan wordt uitgegaan van een standaard Rc voor vloeren, muren of daken.



Met de functie Export gbXML in Revit kunnen de volumes gegenereerd door de rooms gecontroleerd worden. Hierin kunnen uitschieters en onregelmatigheden in het Revit model bekeken worden om daarna gecorrigeerd te worden.



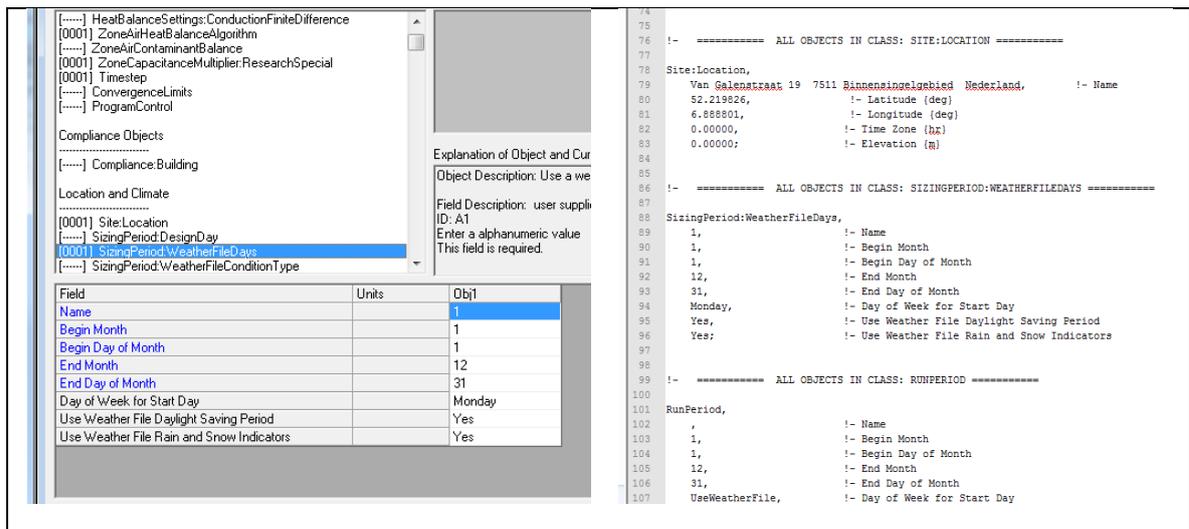
Als het model in Revit klopt en alle ruimtes en volumes kloppen, kan het model geëxporteerd worden naar EnergyPlus. Dit gebeurt via de plugin te vinden bij add-ins -> external tools -> Revit IDF Export. Een alternatieve route is een gbXML file te exporteren en deze via een ander programma (Autodesk Ecotect, DesignBuilder, OpenStudio, Simergy, etc...) naar een EnergyPlus IDF file te converteren. Echter bestond een directe koppeling van Revit naar Energyplus nog niet dus moet deze zelf geprogrammeerde plugin gebruikt worden.



EnergyPlus IDF file

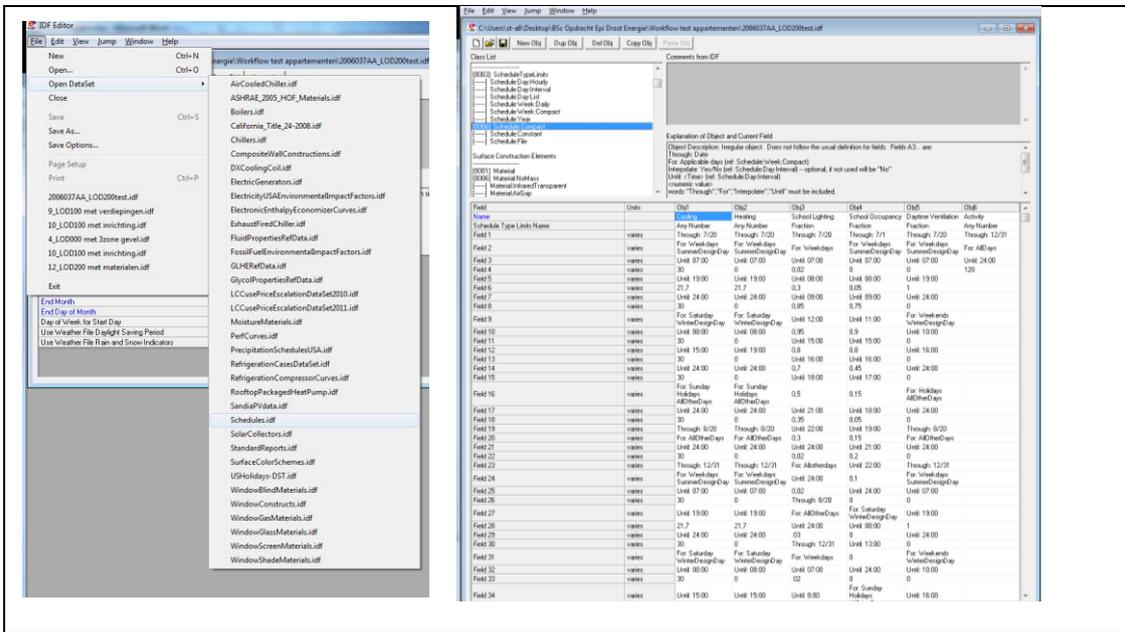
De simulatie wordt aangestuurd door een IDF file. Dit is een tekstbestand waarin alle parameters voor de simulatie in staan. Van simulatieduur tot oppervlakten en materialen staan in dit bestand.

Zo'n IDF file is te bewerken met het kladblok, Notepad++ en de bij EnergyPlus geleverde IDF Editor.



De informatie die nu uit de Revit tekening naar deze IDF file is overgezet bestaat uit: Thermische zones, muren, vloeren, daken, ramen, deuren, materialen en constructies. Maar nu moet de gebruiks- en installatiegerelateerde informatie toegevoegd worden. Dit bestaat uit tijdschema's, setpointtemperaturen, interne hittebronnen en de volledige installatie.

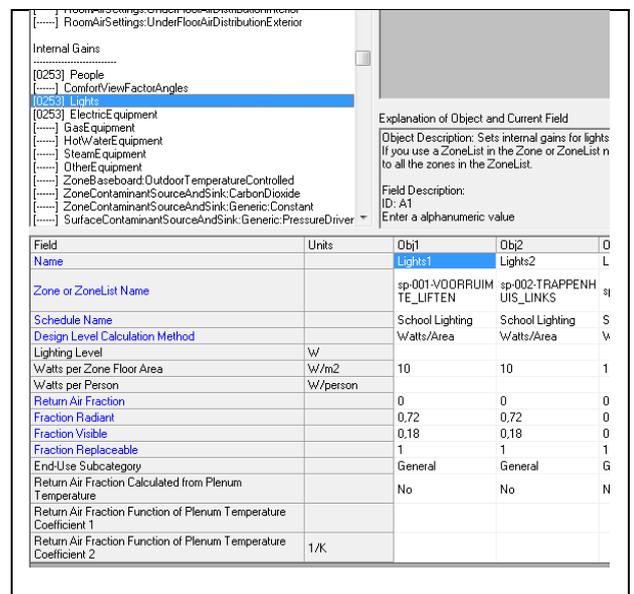
Voor de tijdsschema's kunnen de templates van EnergyPlus gebruikt worden:



Vervolgens moeten de interne hittebronnen opgegeven worden. Hierin zijn in de meeste gevallen mensen, verlichting en elektrische apparaten de maatgevende bronnen. Deze drie moeten per zone aangegeven worden. Voor referentiewaarden kan NEN 7120 geraadpleegd worden. De hoeveelheid mensen, verlichting en apparaten wordt gekoppeld aan een tijdsschema om de loop van een dag te simuleren.

Door een ZoneList in het EnergyPlus bestand aan te geven kunnen internal gains aan een volledige lijst zones tegelijk toegekend worden. Probeer daarom een ZoneList per gebruiksfunctie te maken. Laat hierbij ruimten die afwijken qua verlichting/bezetting achterwege.

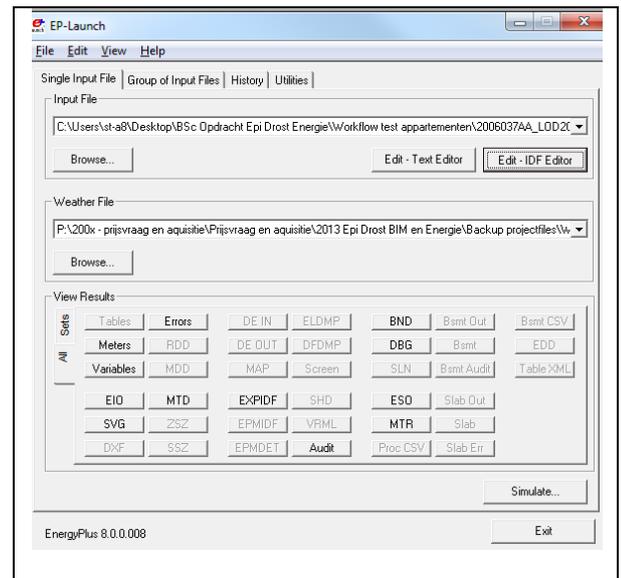
Als laatste moet de installatie toegekend worden per zone. Het uit Revit geëxporteerde bestand staat standaard ingesteld op een IdealLoadsAirSystem. Dit systeem berekend de absolute hitte- en koudevraag van het gebouw, als een ideale installatie aanwezig zou zijn. Dit is perfect voor het vergelijken van bouwkundige opties.



Vervolgens kunnen er modules aan de simulatie toegevoegd worden afhankelijk van het detailniveau waarop de simulatie gebeurt en wat voor aspecten informatie over vergaard worden. Zo kan bijvoorbeeld de natuurlijke ventilatie gesimuleerd worden, of het gebruik van bepaalde zonweringen.

Bij het gebruik van EnergyPlus zijn een aantal dingen belangrijk om te onthouden:

- Er is geen grafische interface. De geometrie moet klaar voor gebruik uit Revit komen.
- Het programma simuleert alleen de input. Als ergens geen oppervlakte staat gespecificeerd negeert het programma dit ook volledig.
- Hoewel de absolute waarde van energieverbruik misschien niet volledig accuraat is, kan het wel perfect gebruikt worden voor het vergelijken van alternatieven. Een tweede simulatie kan makkelijk gemaakt worden door iets in de IDF aan te passen en vervolgens op opslaan als te drukken. Zo maak je een duplicaat van de simulatie met alleen de laatste wijziging.
- Objecten in EnergyPlus verwijzen vaak naar andere objecten. Zo verwijst de installatie naar de thermostaat, de thermostaat naar een tijdschema en dit tijdschema op zijn beurt naar een schematype. Als hier iets niet in klopt geeft EnergyPlus een error aan.
- Meestal zijn warnings te negeren, maar severe errors niet. Kijk de warnings altijd wel even door naar iets ernstigs.

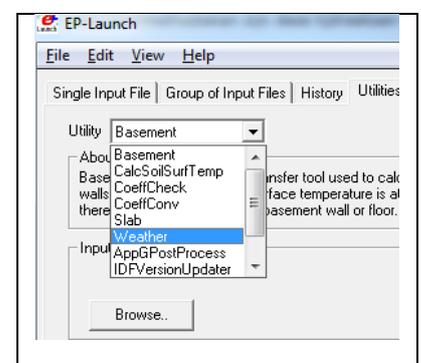


Weerdata

EnergyPlus geeft de mogelijkheid om ofwel gestandaardiseerde design days als weerdata te gebruiken, ofwel echte gemeten weerdata. Meestal zal dit uurlijkse weerdata van het KNMI zijn. Deze data is verkrijgbaar op:

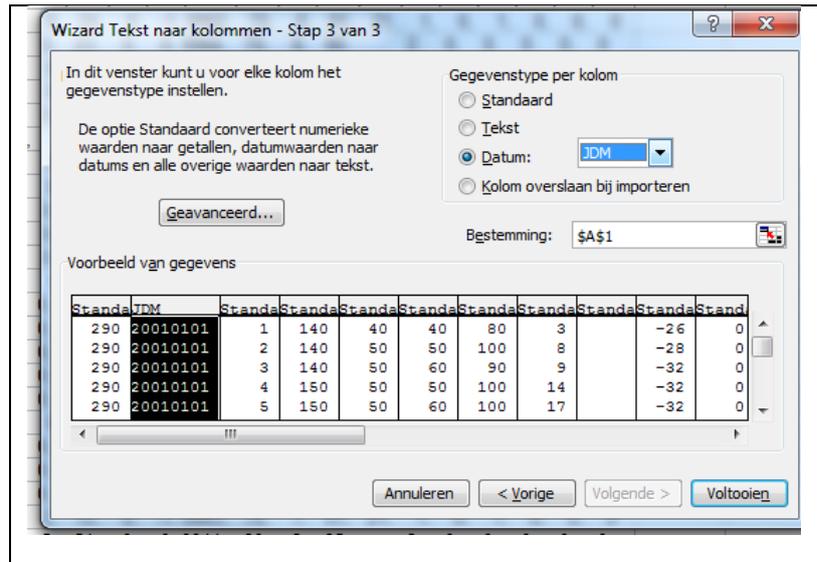
<http://www.knmi.nl/klimatologie/uurgegevens/#no>

Deze data wordt aangeleverd als tien jaren aan data in een tekstbestand, in een formaat waar EnergyPlus niks mee kan. Daarom moet eerst de Weather Converter gebruikt worden. Deze is te vinden in EnergyPlus onder Utilities.



De eerste stap is de data die niet gebruikt wordt uit het tekstbestand te verwijderen. Alle regels die geen pure data bevatten kunnen verwijderd worden, net als tekstregels uit andere jaren dan voor de simulatie vereist.

De volgende stap is het omzetten van het formaat van de datum in de data. Deze staat nu in YYYYMMDD formaat en moet in een DD-MM-YYYY formaat. Dit kan door de data te kopiëren en te plakken in Excel.



Gebruik de functie Data->Tekst naar kolommen om de tekst naar kolommen te verwerken. Stel hier een komma als scheidingsmiddel in. Verander vervolgens het gegevenstype van de kolom met de datum naar datum met JDM format, zoals in de figuur hiernaast. Sla vervolgens het Excel bestand op als .CSV bestand op.

Maak een .txt bestand met precies dezelfde naam met kladblok en plak daar de volgende code in:

```
&location
City='Enschede'
StateProv='Twente'
Country='NL'
InLat=52.16
InLong=06.53
InTime=1
InElev=42
InWMO=6290
/

&wthdata
NumInHour=1
InputFileType='CUSTOM'
InFormat='DELIMITED'
```

```

DataElements=Ignore,Date,Hour,Wind Direction,Wind Speed,Ignore,Ignore,Dry
Bulb Temperature,Ignore,Dew Point Temperature,Ignore,Global Horizontal
Radiation,Ignore,Liquid Precipitation Depth,Atmospheric Pressure,Ignore,Total
Sky Cover,Relative Humidity,Ignore,Ignore,Ignore,Ignore,Ignore,Ignore

DataUnits=x,dd-mm-
yyyy,x,'deg','m/s',x,x,'C',x,'C',x,'J/cm2',x,'mm','hPa',x,'%','% ',x,x,x,x,x,x

DataConversionFactors=1,1,1,1,0.1,1,1,0.1,1,0.1,1,0.36,1,10,10,1,1.25,1,1,1,1,1,1

DelimiterChar=';'

DateSeparator='- '

DecimalSymbolChar='.'

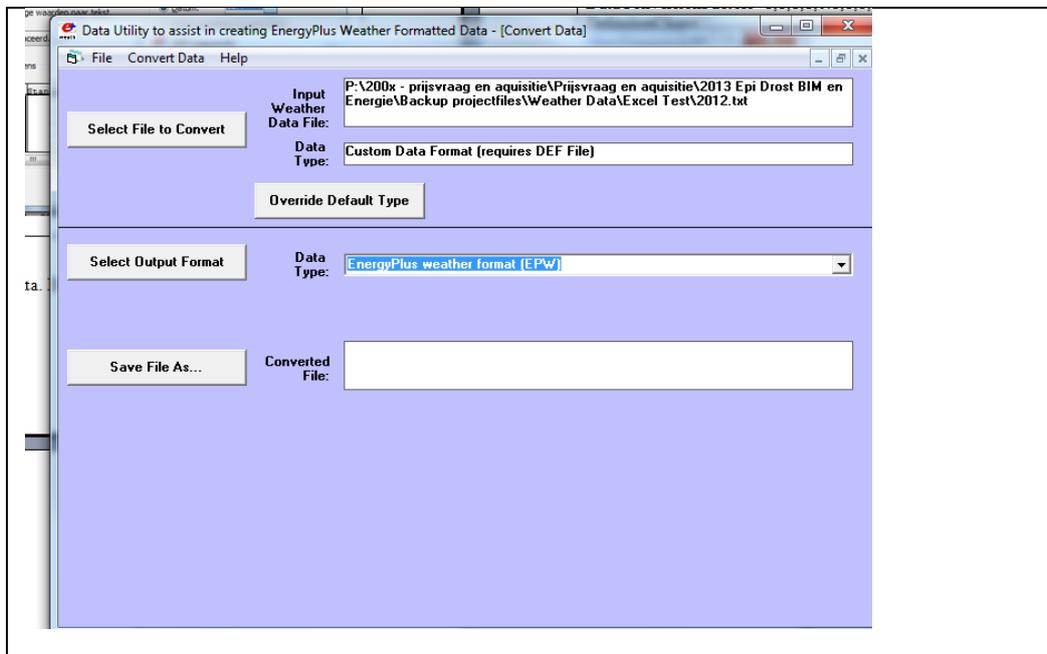
/

&datacontrol

/

```

Sla dit bestand op als .def bestand met dezelfde naam als het .csv bestand, en verander het bestandsformaat van het .csv bestand naar een .txt bestand. Open nu de Weather Converter in EnergyPlus. Selecteer het .txt bestand, en gebruik override default type om het data type naar custom data format te veranderen. Stel het output format in als EPW file, en sla het bestand op. Het bestand dat gemaakt wordt is een EPW file dat weerdata bevat voor EnergyPlus.



De output van de simulatie is samengevat in een HTML bestand. Hierin staan de end uses van het gebouw, gepaard met veel zone- en installatiegerelateerde data. Hierin wordt onderscheid gemaakt tussen Site energy en Source energy. Site energy is de hoeveelheid energie dat op de locatie verbruikt wordt. Source energy is de hoeveelheid energie die verbruikt wordt als de opwekking van de energie meegerekend wordt. Deze is dus zwaar afhankelijk van de hoofdbrandstoffen.

Meer informatie over het gebruik en de mogelijkheden van EnergyPlus is hier te vinden:
http://apps1.eere.energy.gov/buildings/energyplus/energyplus_documentation.cfm