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SOLAR ENERGY AND BUILDING PHYSICS LABORATORY

Evaluation and optimization of renewable energy in the Quartier Nord

MASTER THESIS of

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Abstract

The energy demand increases worldwide and due to the fact that fossil fuel is still dominating the energy mix, the corresponding CO_2 emission becomes a more serious problem that threatens the global environment. The building sector is the largest energy consumer and it is of vital significance to reduce the primary energy consumption thus the CO_2 emission in this sector.

Under this constraint, the standards were set up to design buildings with relatively low energy consumption. Following the standard, the proposal phase of the buildings can be well regulated. However, it is equally important to check the energy consumption of the building in operating condition.

In this project, a specific building was selected and its energy consumption condition was simulated both at building and neighbourhood level respectively. EnergyPlus was chosen to run the simulation at single building level and the results were compared with Minergie standard and the monitored data for the building. Another software, CitySim, working at a larger scale is also used. In order to validate the accuracy of the simulations, a benchmark was done based on the calculations of the ideal load of the building in EnergyPlus and CitySim. The sources of errors were analysed in detail.

At last, renewable resources were also integrated into the building to explore its potential of being a net-zero energy building.

Key words: *Minergie, energy consumption, EnergyPlus, CitySim, net-zero energy building*

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1. Introduction

1.1 Energy Demand and Global Warming

The global energy demand, which plays a vital role in the development of the world, is set to grow by 37% by 2040 according to the International Energy Agency. It also predicts a global energy supply mix comprised of four almost-equal parts: oil, gas, coal and low-carbon sources. However, decreasing the share of fossil fuels in primary energy demand to just below three-quarter is not enough to stem the rise in energy-related carbon dioxide emissions, which will grow by one-fifth by 2040. In this scenario, a long-term global average temperature increase of 3.6°C is predicted (IEA 2014).

It has been however internationally agreed that in order to avoid the most severe and widespread implications of climate change, this temperature increase has to be limited to 2°C ("Global Warming" 2015). As estimated by the Intergovernmental Panel on Climate Change (IPCC 2007), the world cannot emit more than around 1 000 gigatonnes of CO_2 from 2014 onwards to keep the 2°C objective. It is hence clear that urgent action is required to steer the energy system on to a safer path.

1.2 Energy Consumption in Buildings and Minergie Standard

As shown in Figure 1, buildings are the largest energy consuming sector in the world and it accounts for over one-third of total final energy consumption and an equally important source of carbon dioxide emissions (Pérez-Lombard, Ortiz, and Pout 2008). Thus reducing energy and carbon dioxide emission from the building sector is of vital significance on the path to sustainability. The building envelope can be largely improved to reduce the heating and cooling need of the building, which represents the largest building-sector energy end-use. Moreover, by integrating more renewable resources, the consumption of fossil fuels in buildings can be significantly reduced,

thereby contributing to the reduction of greenhouse gas emission.
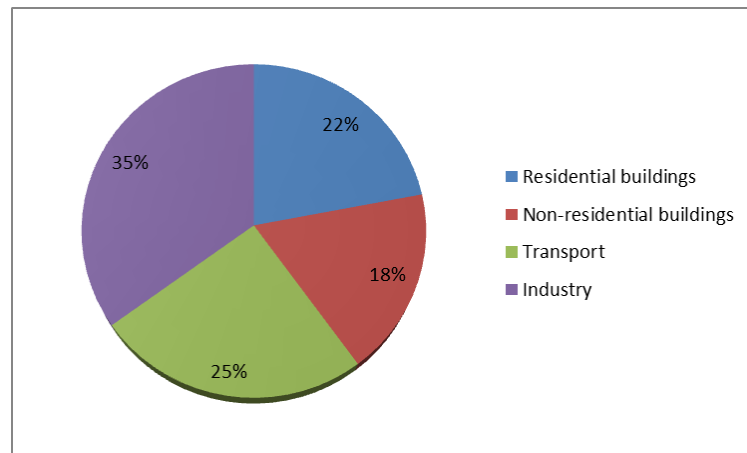
Figure 1: Global energy usage mix (IEA, 2011)

Developed in 1994, the idea of Minergie (Beyeler, Beglinger, and Roder 2009) was aimed for certificating new and refurbished low energy consumption buildings. In order to apply the Minergie standards, it is recommended to provide high-grade, air-tight building envelopes. A reliable assessment can be assured by using the specific energy consumption as the main indicator to quantify the required building quality.

It is a must to declare and verify the expected energy consumption per surface area. For new single-family homes and apartment blocks 38 kWh/m²/annum must not be exceeded. For refurbishment projects the limiting value is 60 kWh/m²/annum ("Minergie" 2015).

Since the Minergie standard does not focus on operational conditions, it is quite interesting to check the performance of the building in operation to validate the relative low energy consumption. In this project, a specific building, from the EPFL campus, is selected and its energy consumption condition is analysed under real condition. Geometrical models are built for simulation with different software and a comparison is done with the monitoring data.

1.3 Software Introduction

As the energy consumption in the building sector has drawn people's attention, varieties of mature building energy program have been developed and are now available on the market such as BSim (Sheu et al. 1987), Energy Express (Butera and Dempsey 1999), eQuest (Pérez et al. 1999), BLAST (Kent 2002), ECOTECT (Marsh 2003), EnergyPlus (Crawley et al. 2008), CitySim (Robinson et al. 2009a), etc. The basic function of building energy simulation programs is to provide users with key building performance indicators like energy demand and use. When selecting a simulation software, it is important to check its capabilities and features including general modelling features; zone loads; building envelope and daylighting and solar; infiltration, ventilation and multi-zone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; HVAC equipment; environmental emissions; economic evaluation; climate data availability, results reporting; validation; and user interface, links to other programs, and availability (Crawley et al. 2008).

The different tools that have been developed work at different scales. For example at the building scale, a much better description of the building can be given and hence the evaluation of the energy use is expected to be better. It is worth noticing, however, that the boundary condition of single building is always influenced by its surrounding environment, for instance, it can receive solar irradiation that is reflected by other buildings and also the wind speed can be changed by the urban environment (Mauree 2014) (Dorer et al. 2013). That is why it also makes sense to simulate the building's energy consumption both at building and neighbourhood levels respectively. In this project, EnergyPlus (Crawley, et al. 2001) is selected to run the simulation at building scale and CitySim (Robinson et al. 2009b) is selected to simulate on neighbourhood level.

Being an energy analysis and thermal load simulation program, EnergyPlus has been widely used. Although it is easy to define several buildings as separate zones, it is

hard to simulate the interactions between them and that is why it is mainly used for single building. Another point worth noticing is that EnergyPlus includes loop based configurable HVAC systems, which allow users to model typical systems and slightly modify systems without recompiling the program source code. However, it is difficult to model engineering customized HVAC systems based on the existing modules.

CitySim was selected for several reasons. First of all, being a simulation tool for modelling the energy fluxes from a small neighbourhood to an entire city, it has already been compared (Walter et al. 2014) to the Building Energy Simulation Test (BESTEST), a systematic procedure developed by the U.S. National Renewable Energy Laboratory (NREL) and the International Energy Agency (IEA) to validate the use of a program for a specific range of buildings and climate type (Judkoff and Neymark 1995). In addition to the simulation scale, it is a good match with EnergyPlus also thanks to the fact that several Energy Conversion System (ECS) models are implemented to represent the currently most widely used devices for supplying buildings' energy needs like solar panels, wind turbines, boilers, heat pumps and cogeneration systems, which make the integration of renewable resources quite easy.

Another highlight of CitySim is that it allows the users to develop a district resource centre to supply to potential resource exchanges between buildings locally.

1.4 Objectives

1.4.1 Problem statement

The Minergie standard is mainly focusing on designing and it does not guarantee that the low energy consumption will be realized in the operation. Thus it is very important to check and verify the condition after the buildings has been built for a period of time. By checking the differences between the ideal theory and practice, one

will be able to better understand the compatibility of the available technology with reality and also generate some advices on building's performance in order to fulfil the standards.

Moreover, two building simulation software, working at different scales, are used in the project. Some errors might be generated due to the differences of their working principles and models inside. Thus it is important to check and validate their output when the input is the same.

1.4.2 Aims

With the aim of reducing energy consumption in buildings and to validate the applications of the Minergie standards, a newly built building, was chosen for analysing its energy consumption. Additionally, the ideal load of the single building is computed using EnergyPlus and CitySim to give a quantitative analysis of the differences between these two models.

Furthermore, in order to decrease its dependency on fossil fuel and to further extend the Minergie standard, its potential for implementing more renewable resources and its functionality as an energy hub is also analysed.

1.4.3 Structure of the report

In Section 2, an overview of the study area is given. In Section 3, the Minergie building is simulated at a building level in EnergyPlus and the results is compared and validated with the monitoring data and with Minergie standard. In Section 4, the ideal load of the building is calculated by both EnergyPlus and CitySim to evaluate and quantify the differences between these two. Section 5 is about implementing more renewable resources into the building by using CitySim and to evaluate the possibility of making the neighbourhood autonomous in terms of an energy perspective.

2. Quartier Nord Overview

2.1 Introduction of the Neighbourhood

Quartier Nord is a whole new quarter on the École Polytechnique Fédérale de Lausanne (EPFL) campus and it is located at its northwest corner. This complex includes a Convention Centre with an auditorium with a maximum capacity of 3000 (seated) people, housing for 516 students, retail and service areas and a hotel. As a public space, this ensemble is organized around a main plaza (see Figure 2, Amato and Giambonini 2008).

With a particularly strong visual and formal identity, the SwissTech Convention Centre (STCC) is clearly the key protagonist. Applied with important functions for the region, the building has definitely become the new landmark of the region. Designed as a Minergie building, it already included certain energy conversion technology to reduce its energy consumption. It is very interesting for us to check and verify its energy consumption. As mentioned above, one can also analyse its potential to function as the energy centre for the region and apply the concept of energy hub.

Figure 2: Quartier Nord

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2.2 Data Collection

The information required in the simulation mainly comprises of two parts, geometrical information and operational data. The geometry information includes the building's shape, dimension, structure, material, etc. The operational data is mainly about the operational schedules of different systems in the building like daily occupancy, lighting and electrical equipment usage level, ventilation rate, etc.

The building was designed by Richter and Dal Rocha architects and built by HRS Real Estate SA. For the first part, we got most of the valuable information from DII, the Real Estate and Infrastructure Department of École Polytechnique Fédérale de Lausanne (EPFL), which was responsible for carrying out the project from call to tender to construction. A lot of useful information on the geometry was obtained from the document they provided. However, since the document is full of details and also conflicting with what has been installed as compared to the document before construction, it is a tedious task to abstract really useful information and some omissions might have occurred in this process.

Besides, it is more challenging to get the solid operational data as the building has been put into use in March 2014, the available measurements are quite limited. The regulation of the building is complex due to flexibility of spaces in STCC as there are about 20 different configurations of spaces. Engineers and technicians are still working on improving the regulation and the building now is not performing at its best and the measurements may have some discrepancies as compared to the standards set before the construction. The system was not initially designed to be controlled inside the building but from the main operational centre of EPFL.

Considering all the difficulties mentioned above, we decided to use the regulation standards applied in the designing phase from SIA norm for the missing information.

2.3 Structures of STCC

Figure 3 and Figure 4 show the exterior and interior structure of STCC respectively and both of them are provided by DII. As mentioned above, due to its functions and architectural choices, the building was designed with a special geometry and it is important to capture its main features in the model to build. A good compromise should be made between the detail level and the constraints of time. For the exterior geometry, it is important to capture the features of the roof and the windows since both of them will influence the solar gain of the building, which is of vital significance in our simulation.

Figure 3: Exterior structure of STCC

For the interior, it seems that the building can be mainly divided into 3 spaces including the left space on the ground, the right space on the ground and the one underground. However, in reality the structure between the two parts on the ground can be folded, so the whole building can be divided by two parts by the level of ground.
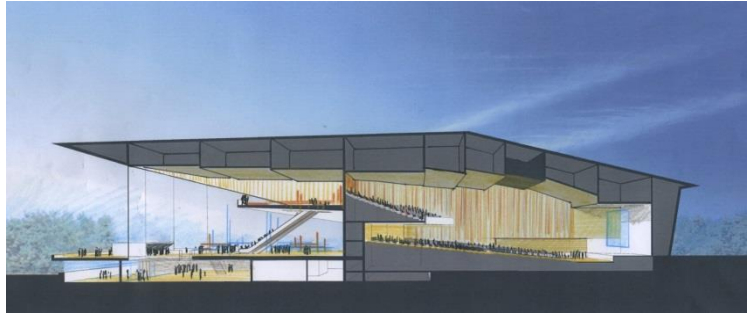
Figure <u>4</u>: Interior structure of STCC

2.4 HVAC system

The building mainly uses heat pumps to recover energy from the waste water of the EPFL campus to meet the heating and cooling need. For heating demand, as shown in Figure 5, the waste water flows out of EPFL at 12 °C, hotter than the lake water which is at 7 °C. The excess heat is recovered by a heat pump to raise the circulating water flow to about 45 °C to heat the room air. The water is then rejected back to the lake, via the Sorge River, with a temperature of 6 °C. The heat pump consumes electricity and is supplemented by an electric heater when the heating demand cannot be met. The working principle for cooling is the same except the operating temperature changes.
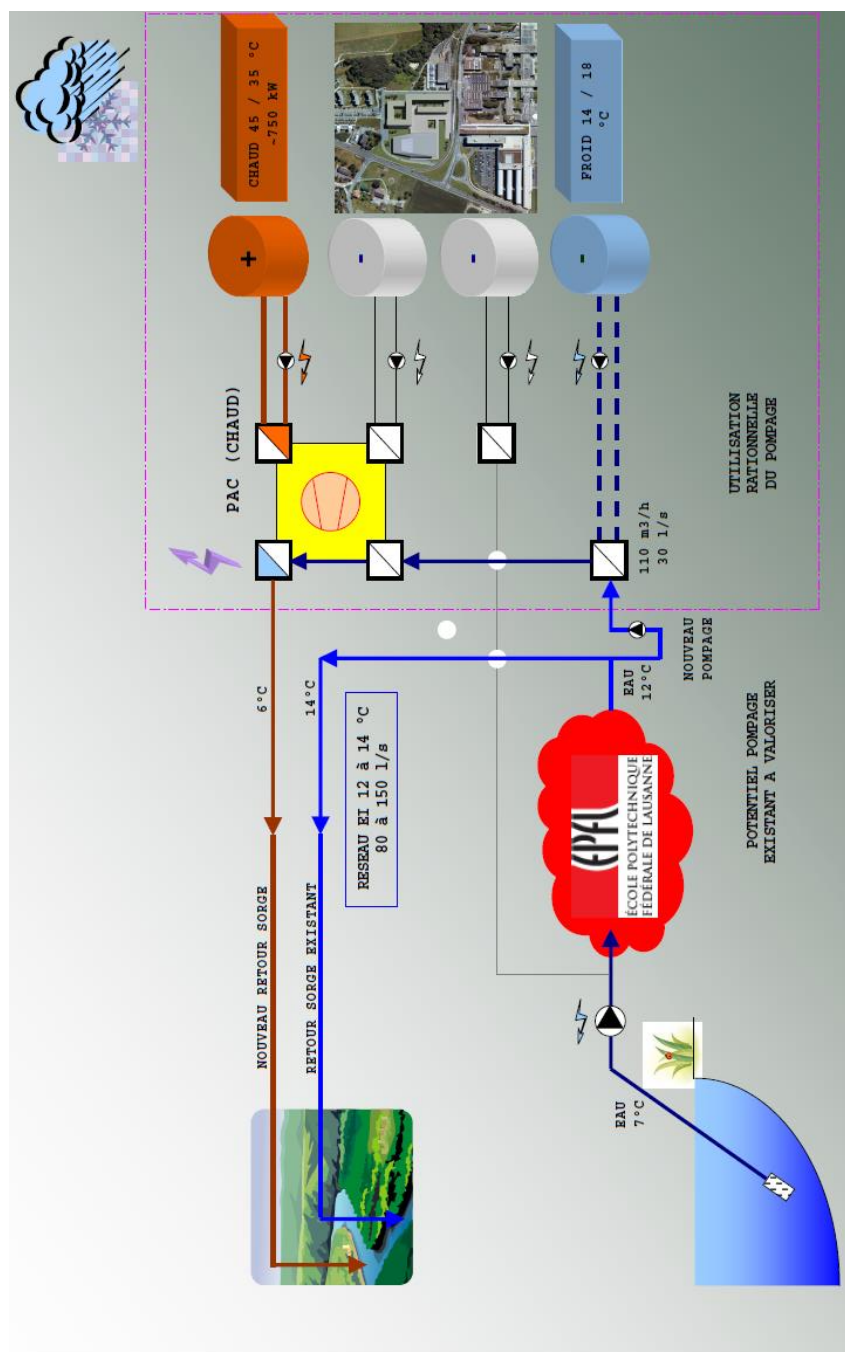
Figure 5: Heating scheme

3. EnergyPlus Simulation

3.1 EnergyPlus

Combining the capabilities and features from BLAST and DOE-2 (Crawley et al. 2001) along with new capabilities, EnergyPlus is an energy analysis and thermal load simulation program. Based on the input of a building like physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points, conditions throughout secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would (Crawley et al. 2000).

3.2 Simulation description

3.2.1 Geometry model

EnergyPlus does not have a user interface for the geometrical drawing of the building and a third-party interface should be wrapped for drawing the geometry. In our case, we used the Legacy OpenStudio SketchUp Plug-in, a free plug-in developed for creating and editing the building geometry in the SketchUp 3D drawing program.
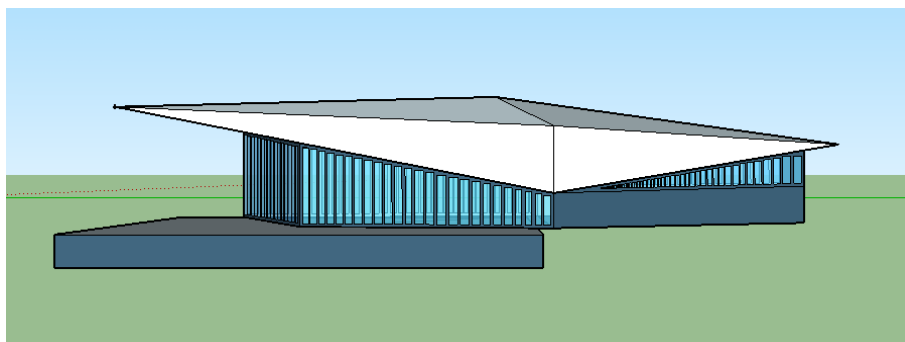
Figure 6: Geometrical model exterior structure

As shown in Figure 6, the geometrical model we built for the STCC has included the

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major geometrical features of the building. The main difficulty when building the geometry came from the roof due to its complex shape and structure. However, it is essential for simulating the shadowing effect from the roof and, will thus be important for the following simulations. Another important feature is the widely used glazing on the surface of the wall, which will play an important role in calculating the solar gain.
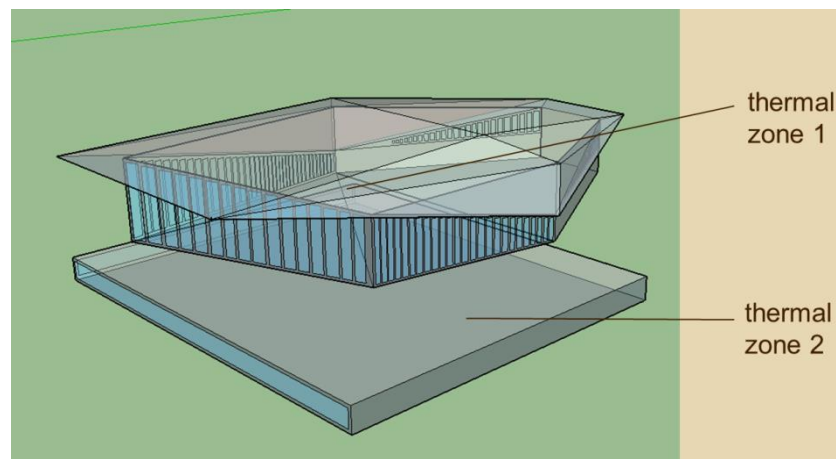
Figure 7: Geometrical model interior structure and thermal zones

As indicated in Figure 7, two thermal zones were defined based on their locations. The volume above the ground level that is connected to the roof was defined as thermal zone 1 and the one underground was defined as thermal zone 2. These two zones are actually connected and thermostat set points should be the same, so for simplicity, one can even define the whole building as a single zone. However, we considered that the two zones are applied with different functions and normally the activities are mainly held in zone 1, so by defining them as different zones, one can easily change their schedules separately in the future when more solid operational data is available.

3.2.2 Construction & material

Input information for different layers of the structure is required in EnergyPlus to calculate the thermal loss of the envelope as well as solar gain from the windows.

Classification of the structures of the building is illustrated in Figure 8 based on the information provided by DII. Since in EnergyPlus, the constructions have to be defined layer by layer instead of defining a general U value, information for different layers contained in the constructions are shown in Table 1.

As the required input in EnergyPlus is not exactly the same with the information provided by DII, errors are expected when calculating the U value of the whole structure and the calculated result will be compared with DII data.
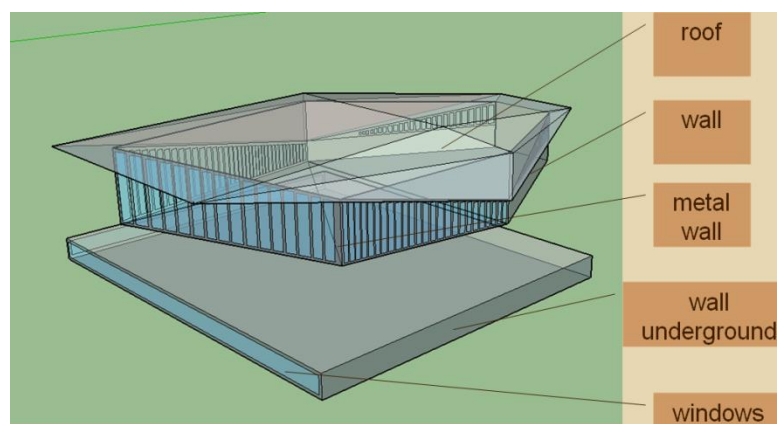
Figure 8: Different constructions of the building

As mentioned above, the windows are playing a quite important role in the simulations of STCC. However, there was no solid information about its structure which made it difficult to model in detail. So based on the U value provided by DII, we combined some commercial window solutions to define the structure of the window system. In our case, a double glazing window is defined with air between the layers, although these windows are not usually used anymore.

STCC Roof

	material	thickness (m)	conductivity (W/m-K)	density (kg/m3)	specific heat (J/kg-K)
Outside layer	Asphalt coule	0.002	0.7	1600	920
layer 2	Acier	0.002	60	413.782	490
layer 3	Panneaux de laine de pierre	0.22	0.036	90	840
layer 4	BIKUVAP	0.002	0.17	530	1880
layer 5	Acier	0.002	60	413.782	490

STCC Wall

	material	thickness (m)	conductivity (W/m-K)	density (kg/m3)	specific heat (J/kg-K)
Outside layer	Feuille de PVC	0.01	0.2	1300	900
layer 2	Panneaux de laine de pierre	0.08	0.036	90	840
layer 3	MONTANAWALL	0.14	0.09	90	850
layer 4	Acier	0.002	60	413.782	490

STCC Floor

	material	thickness (m)	conductivity (W/m-K)	density (kg/m3)	specific heat (J/kg-K)
Outside layer	Beton arme	0.3	1.8	2400	750
layer 2	Asphalt coule	0.01	0.7	1600	920
layer 3	Polystyrene expanse	0.13	0.036	30	1300
layer 4	Polystyrene expanse	0.02	0.036	30	1300
layer 5	BIKUVAP Alu	0.002	0.17	530	1880
Layer 6	Beton coule	0.08	0.9	1800	960

STCC Wall Basement

	material	thickness (m)	conductivity (W/m-K)	density (kg/m3)	specific heat (J/kg-K)
Outside layer	Polystyrene expanse	0.12	0.036	30	1300
layer 2	Asphalt coule	0.01	0.7	1600	920
layer 3	Beton arme	0.2	1.8	2400	750

STCC Windows

	material	thickness (m)	conductivity (W/m-K)	solar transmittance at normal indicence
Outside layer	glazing	0.0021	0.0133	0.7
layer 2	air	0.02		
layer 3	glazing	0.0021	0.0133	0.7

Table 1: Layers of the constructions

U Value (W/m²K)	DII	EP results	Error%
STCC Roof	0.16	0.16	1.88
STCC Wall	0.25	0.27	6.00
STCC Floor	0.22	0.23	2.27
STCC Wall Basement	0.33	0.29	-12.42
STCC Windows	1.48	1.49	0.81

Table 2: U-value benchmark

A benchmark of the U-value of the different constructions type between the results calculated by EnergyPlus and the data provided by DII is shown in Table 2. As it can be read from the table, the U values we used for simulation are not exactly the same with the ones given by DII but the errors are within an acceptable range.

3.2.3 Boundary condition

One needs to define the surface type of the building surfaces and the options include Roof, Ceiling, Wall and Floor. Based on that, EnergyPlus will define its outside boundary condition but user can also change this. Each surface is assigned with a construction type by the user and this property is independent with its other boundary conditions.

For standard buildings, normally the default setting is accurate enough. However, in our case, the special design of the roof increases the complexity and it is necessary to be more careful about the boundary conditions.

For example, we found in a first instance that the roof of the first zone is not casting shadows as it was supposed to. We realized that there was an issue since the solar gain of the windows was abnormally high and confirmed it by checking the sunlit fraction of the windows, which can be exported from EnergyPlus. The sunlit fraction is almost constant during the daytime and shows no sign of the shadows. After some investigation, we established that the problem is caused by a conflict between our model and EnergyPlus's method to deal with overhangs.

In EnergyPlus, roofs and walls only cast shadows in a hemisphere in the direction of the outward facing normal. Because roof surfaces generally face upward, a roof surface which extends beyond the walls of the building will not cast shadows on the walls below it (see Figure 9; Tips and Tricks Using EnergyPlus).
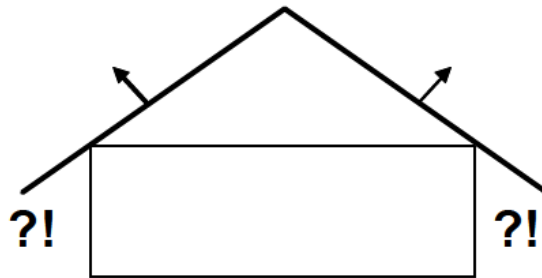
Figure <u>9</u>: Technical difficulties of designing overhang in EnergyPlus

Based on the EnergyPlus guide, we fixed the problem by defining soffits (coloured in purple in Figure 10) as floor surface in the attic and face downward. As mentioned above, the construction applied on the surface is independent with its surface type, thus here it is still applied with the construction of roof we defined before.
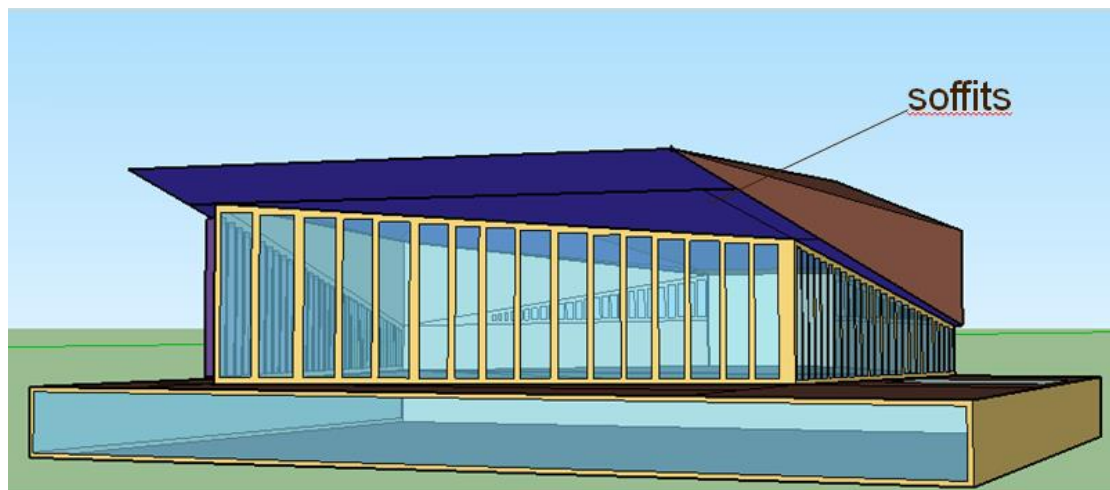
Figure <u>10</u>: Soffits (purple surface in the figure on the bottom side of the roof)

3.2.4 Ground temperature

The surfaces facing north and east in the zone 2 are actually underground and in contact with the soil. It is important to input the ground surface temperature as it can fluctuate from one season to another.

Along with the weather file for the simulation, our source of the ground surface temperature is Meteonorm.

Month	Ground surface temperature (°C)
1	-0.77
2	1.30
3	6.34
4	10.92
5	16.25
6	20.35
7	21.35
8	20.41
9	15.13
10	10.58
11	4.39
12	0.01

Table 3 Monthly ground surface temperature

The default setting of ground temperature is 18 °C for the whole year in EnergyPlus and as one can read from Table 3, there is a big difference in the winter, which can cause significant errors when calculating the heating load.

3.2.5 Internal mass

The interior of the building was not modelled for simplicity but the internal surfaces should have some effects on the heat transfer and storage. The major internal mass inside the building that might influence the simulation are the inside balcony, elevators with huge mass and construction and the structures that are holding the roof (see Table 4).

Internal mass	Surface Area (m^2)
Balcony	2600
Elevator	707
Roof Structure	4499

Table 4: Internal mass of STCC

3.2.6 Occupancy

People's presence and activities will have an important impact on the energy demand due to their heat emission which is usually considered as part of the internal gains. It will increase the cooling demand in the summer and decrease the heating demand in winter. Besides, it can also influence the ventilation system if the operating mode of ventilation is based on the number of people in the space.

We got some data from DII which tells us the monthly occupancy in the building which is listed in Table 5.

Since no more details are provided, some assumptions are made. First of all, since the meetings and activities are held there both in the week days and in the weekends, it is assumed that there are no special schedules designed for weekends and holidays. For the daily schedule, the default setting in EnergyPlus is corrected based on our observation as shown in Figure 11.

Since last year was the first year of operation for STCC, it might also have held more people than usual.

Month	total	days	people per day
July	3375	31	109
Aug	3500	31	113
Sept	10500	30	350
Oct	10800	31	348
Nov	25400	30	847
Dec	6400	31	206
Jan	5200	31	168
Feb	4400	28	157
Mar	5300	31	171

Table 5: Occupancy
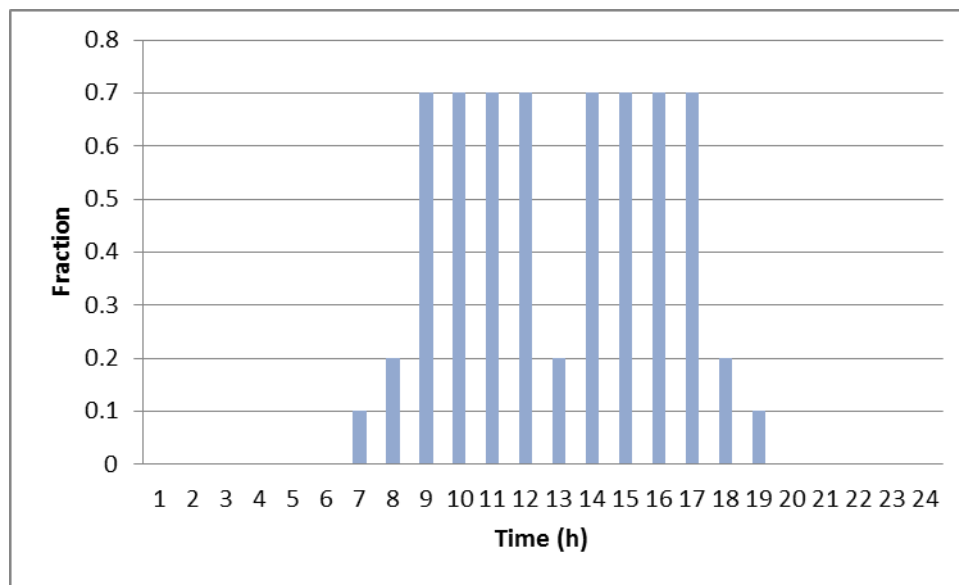
Figure 11: Daily occupancy fraction

3.2.7 Lights & Electric equipments

These two objects simulate the lights and other electric equipment used in the building. Being a major source of electricity consumption, they will also influence the heating and cooling load due to heat release.

According to DII, the lighting power density is about 12.6 W/m^2 and the design power for electric equipment is about 4W/m^2, which should also conform to the SIA standard ("Sia-Norm| Schweizerischer Ingenieur- Und Architektenverein" 2015).
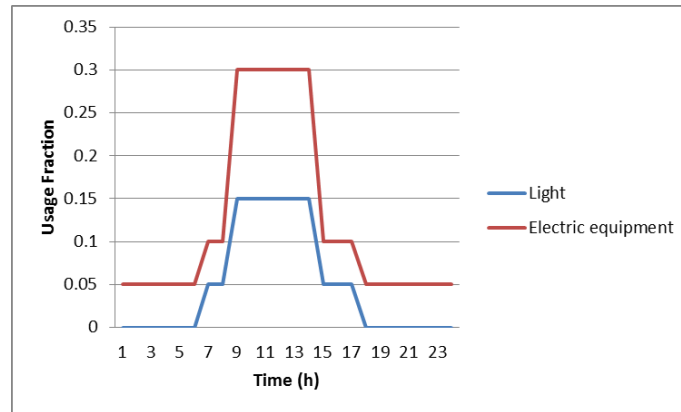
Figure <u>12</u>: Lights & electric equipment usage fraction

The daily usage fraction for lights and electric equipment is assumed as shown in Figure 12. It is also corrected from the EnergyPlus default setting. Since the surfaces of the building is widely covered by the windows and have good access to the daylight, also because the activities are mainly held during daytime, the usage level of the lights is set relatively low.

3.2.8 Infiltration rate & ventilation rate

Infiltration is the unintentional or accidental introduction of outside air into a building, typically through cracks in the building envelope and through use of doors for passage. Sometimes called air leakage, infiltration is caused by wind, negative pressurization of the building, and by air buoyancy forces known commonly as the stack effect (Philip 1957).

Because infiltration is uncontrolled, and admits unconditioned air, it is generally considered undesirable except for ventilation air purposes. Typically, infiltration is minimized to reduce dust, to increase thermal comfort, and to decrease energy consumption. Since STCC is well sealed and applied to the SIA standard, we took the regulated value from SIA for the simulation which is about $2.8*10^{-5}$ m^3/s.m^2.

Ventilation is defined as the process to replace air in the spaces to provide high indoor air quality. Ventilation is used to remove unpleasant smells and excessive moisture, introduce outside air, to keep interior building air circulating, and to prevent

stagnation of the interior air.

Ventilation includes both the exchange of an air to the outside as well as circulation of air within the building. It is one of the most important factors for maintaining acceptable indoor air quality in buildings. Methods for ventilating a building may be divided into mechanical/forced and natural types ("Ventilation (architecture)" 2015).

For a well-designed building, the ventilation rate is also regulated and the value is also taken from SIA standard and set to $0.01m^3/s*person$.

3.2.9 HVAC system

As mentioned before, it is not very convenient to customize HVAC systems in EnergyPlus. In order to do that, one has to break the system into its constituent loops which should then be separated into supply and demand sides. Moreover, these half loops are then defined by branches, connectors and components. In the end, it requires to set the controls for each loop. Because of that, in most cases, users will just use the HVAC templates which do not require defining the nodes in the system in detail. Besides, one can also combine several HVAC template objects to specify some standard HVAC systems and the node name will be generated automatically.

The main HVAC system has already been described in the Section 2. Following the guide of EnergyPlus, we modelled a water-air heat pump system with boiler and cooling tower. Heating and cooling set points are set to 20 °C and 22 °C respectively based on the information from DII.

Infiltration rate (m3/s.m2)	$2.8*10^{-5}$
Ventilation rate (m3/s*person)	0.01
Heating setpoint (°C)	20
Cooling setpoint (°C)	22
Heating schedule	October to March
Cooling schedule	April to September

Table 6: General setting of HVAC

3.2.10 Sanitary water system

Solar thermal collectors installed on the student houses next to STCC supply the hot sanitary water. Sanitary water system is modelled to supply hot water at 60 °C and cold water. The peak flow rate is set at 0.000435 m^3/s according to DII. Since no detailed schedule is provided for the flow rate, the default setting for offices in the EnergyPlus is used and shown in Figure 13.
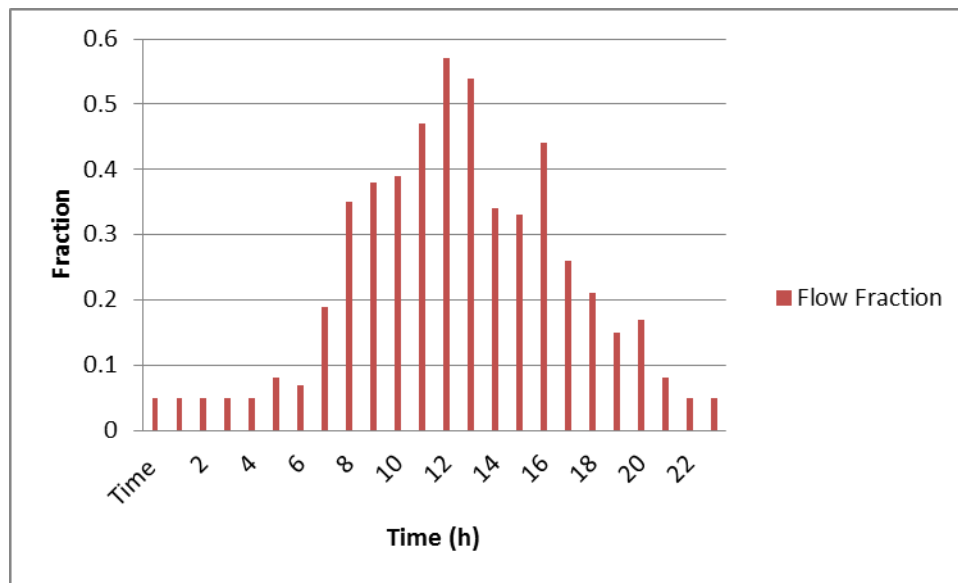
Figure 13: Flow fraction of sanitary water

3.3 Results and discussion

3.3.1 Comparison with DII data

The DII provided us the energy consumption data of STCC from July to December of 2014 and the comparison between their data and our simulation results is given in Table 7.

	Heating(GJ)	Cooling(GJ)	Sum(GJ)	Electricity(GJ)
DII	1395.14	907.87	2303.01	NA
EP	850.06	1268.51	2118.57	262.42
Error%	-39.07	39.72	-8.01	NA

Table 7: Comparison with DII

As one can read from the chart, although the sum of cooling and heating demand given by EnergyPlus is quite close to the data of DII, the comparisons for heating and cooling load respectively are not satisfying. When comparing with the recorded data, the heating demand is lower and the cooling demand is higher, it is quite possible that the heat gain in the EnergyPlus is higher than the reality.
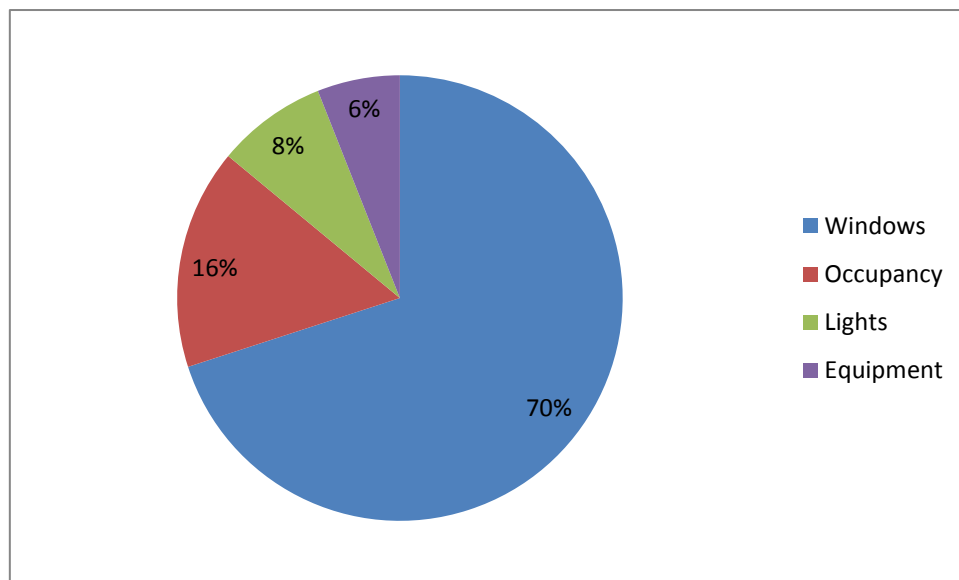
Figure 14: Sensible heat gain breakdown

The sources of heat gain include solar gain and internal gain, defined as the heat emitted by people, lights and electric equipment. As can be read from Figure 14, 70% of the sensible heat gain is solar gain. Considering that we are using the average weather data from 2000 to 2010, which is already the most recent data that is available, it might be quite different from 2014 and errors can hence be generated. As the data from DII is on a very short period, it will be more interesting to perform this

experiment again when there are data for one or two complete years. Furthermore, as have already mentioned, the detailed construction of the window system is not available, which definitely causes some error. Besides, the transparent shading installed on the west side of the building has not been implemented due to some technical difficulties in EnergyPlus and lack of necessary parameters. So considering the effect of those shadings, the solar gain should decrease which leads to a higher heating load and a lower cooling need, which should decrease our error.

For the internal loads which takes account 30% of the heat gain, on one hand, as already mentioned before, the operational information such as occupancy and schedules for equipment is not available and considering the many assumptions we made, this part maybe a major source of the error. And on the other hand, schedules like occupancy is always a big source of errors in building performance simulation as people's behaviour is quite hard to regulate and predict and hence a stochastic model is more proper. Obviously now the STCC is also not working at its optimized condition in the energy point of view, for instance, the ventilation system is working at its maximum rate for 20 hours a day regardless the occupancy which is different from our simulation.

Thus the benchmark with the recorded data cannot really give us a solid conclusion, it is necessary for us to validate the simulation results for now with the Minergie standard.

3.3.2 Benchmark with the Minergie standard

According to the Minergie standard, EPV, the sum of all weighted energy demand components, has to be compared to the limiting value which is 40kWh/m^2 in our case (Règlement d'utilisation de la marque de qualité MINERGIE). In order to calculate the value of EPV, first one needs to get the ideal demand of heating and cooling, and then divide it by the equipment efficiency to calculate the end use energy. Following that, one multiplies it by an energy-weighting factor to get the primary energy.

	Heating	Cooling	Hot water	Sum
Ideal load (GJ)	1119.41	1201.04	641.51	
Ideal load (kWh/m^2)	24.64	26.44	14.12	
Equipment efficiency	3.20	3.20	NA	
End use energy (kWh/m^2)	7.70	8.26	NA	
Energy weighting factor	2.00	2.00	0.00	
Primary energy (kWh/m^2)	15.40	16.53	0.00	31.93

Table 8: Primary energy usage

For heating and cooling, since a heat pump is used in our case, the equipment efficiency is calculated by multiplying the COP of the system by the efficiency of the system. The energy weighting factor for electricity is 2.

For sanitary hot water, since it is supplied by solar thermal collectors, the energy weighting factor is 0 and no primary energy is consumed in theory.

From the ideal load simulation given in Table 8, one can learn that the design of STCC indeed applies to the Minergie standard and has quite low energy consumption. However, by checking the data provided by DII, it is clear that the energy consumption is dramatically increased due to activities and operations. Without any doubt, there is huge potential for saving energy just by improving the behaviour and regulation.

3.4 Conclusions

Simulations are done in EnergyPlus to check the energy consumption of STCC and the results are compared with the monitored data and from DII the Minergie standard. The simulation results for the operational condition are quite different from the monitored data. Although the sum of heating and cooling energy is very close to the monitored data, heating is much lower (40%) and cooling is much higher (40%) in our simulation.

Based on these facts, it is very likely that the errors are mainly caused by the internal gains. Due to the fact that most of the operational data such as the daily occupancy profile is missing and the inputs are mainly our assumptions, it is hard to eliminate the errors. However, more case studies should be done in the future to improve the reasonability of the assumptions and inputs. Furthermore, this highlights the need for appropriate monitoring in the future in buildings to verify the compliance with the standards.

To check the reliability of the geometrical model we constructed, we compared the ideal load of the building with the Minergie standard. The results suggests that the load is 20% lower than the Minergie limit value which proves the well design and construction of the building as well as the accuracy of the model we used for our simulations.

For the next step in this study and to further increase our understanding of processes regulating the energy consumption of this building, we used the CitySim software, which is traditionally used at the neighbourhood scale.

4. CitySim Ideal Load Simulation

In this sector, simulation is designed to run on two scales, building level in EnergyPlus and neighbourhood level in CitySim, and a benchmark will be made to compare the differences of the results. However, since the major models implemented in the two software are quite different, it is important to make a compatibility analysis before. One needs to make sure the inputs of the two models are as similar as possible and check the differences in results. If the compatibility check is satisfying, one can start to run the simulation on two scales.

4.1 CitySim introduction

CitySim is designed for modelling the energy fluxes from a small neighbourhood to an entire city. It includes a radiation model based on Perez All Weather (Perez, Seals, and Michalsky 1993) and Simplified Radiosity Algorithm (Robinson and Stone 2004) to compute the hourly irradiation on the building surfaces. The thermal model planted in the software is based on an electrical analogy in order to fulfil the request for a good compromise between simplicity, data requirements and computational expense due to its working scale. Based upon the psychrometry of humid air, it also involves HVAC models and calculates the energy needs of the HVAC system to reach the comfort zone using the air enthalpy difference between specific points selected on the path of the air.

4.2 Intermodel Comparison

4.2.1 Simulation description

The geometrical model needs to be imported in CitySim either in the DXF format or in the XML format. After importing the model, an ID will be given to each of the surface in the model and its surface type as well as its construction should be defined

by the user. As opposed to EnergyPlus it is not possible to define specifically the windows. Hence the windows surfaces are defined by the surface area and glazing ratio.

As in EnergyPlus, the detail information for layers in the construction like thickness, density, conductivity and specific heat is required. It is worth noticing, in a single zone, one specific surface type must be applied with uniform construction. Additionally, the surfaces that are connecting two adjacent zones cannot be imported into CitySim since they are not exterior surfaces and users need to create them manually in the file.

On building level, the infiltration rate is defined by the fraction of the changed air in an hour of the overall building volume and we got the value from the SIA norm which is 0.1.

As discussed in the introduction, simulation is done in CitySim for getting the ideal load and we compared the result with the Minergie standard as well as EnergyPlus. In order to conduct the benchmark between the two software, the simulation condition in EnergyPlus is adjusted to be close with CitySim as much as possible.
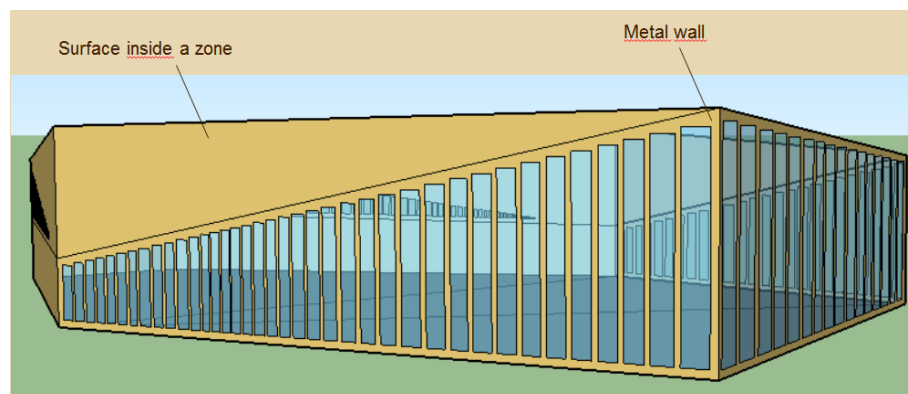
4.2.2 EnergyPlus simulation adjustment

Figure 15: Original model in EnergyPlus

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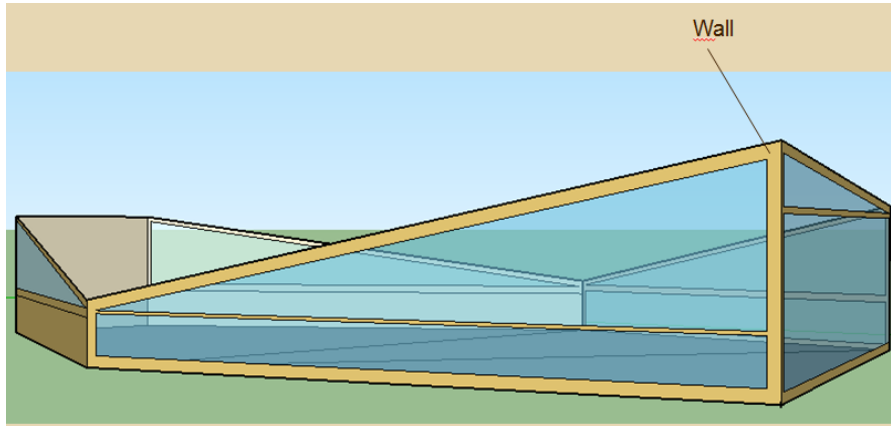
Figure <u>16</u>: Changed model in EnergyPlus

The major changes made in the geometry model are shown in Figure 15 and Figure 16. The other surfaces other than the walls of zone 1 are hidden to show the differences more clearly. As mentioned, the windows' shape and area are defined by the wall and glazing ratio in CitySim, thus the shape of the windows in EnergyPlus is also simplified and changed based on the shape of the walls behind. In addition, the same is done with the surfaces that are connecting adjacent zones since the surfaces within a single zone cannot be imported in CitySim and those are also deleted in EnergyPlus as shown. Finally, due to the fact that in CitySim, one specific type of surface within one zone should be applied with uniform construction, corresponding change is also made in EnergyPlus.

Moreover, the internal mass we defined in the EnergyPlus is also deleted since it is not supported in CitySim yet. The ventilation rate is set to 0 because of the same reason and the infiltration rate is set to the same value used in CitySim.

4.2.3 Results and discussion

The ideal load and the primary usage results in two software are shown in Table 9.

	Energyplus	CitySim	Error%	Minergie
Heating (GJ)	1602.45	1765.13		
Cooling (GJ)	1091.59	1301.78		
Heating (KWh/m2)	35.28	38.86	10.15	
Cooling (KWh/m2)	24.03	28.66	19.26	
Sum (KWh/m2)	59.31	67.52	13.84	
Primary energy (KWh/m2)	37.07	42.20	13.84	40.00
Differences with Minergie%	-7.33	5.50		

Table 9: Ideal load benchmark of EnergyPlus and CitySim

As shown, the overall error between EnergyPlus and CitySim is about 14% but there are more differences in cooling than heating. CitySim has a lower heating load than EnergyPlus and a higher cooling load. Compared with the Minergie standard, the primary energy consumptions in both models are lower than the limit value.

In the simulation, the system is in dynamic balance in order to control the room temperature at the defined thermostat setpoint, the ideal HVAC system is compensating the differences between the thermal gains and losses. To understand the differences in the ideal load, it is hence important to check the temperature in the room as well as the heat gains and losses.

The thermal gains include the solar gains through the windows and internal gains from people and electric equipment. Since in the ideal load simulation, there is no occupancy, the solar gain is thus the only input.

Thermal losses describe the heat transfer between the interior space and outside environment through the different surfaces. Although in summer, the environment temperature is higher than indoor, it is still regarded as a source of loss since it requires cooling load.

4.2.3.1 Temperature comparison
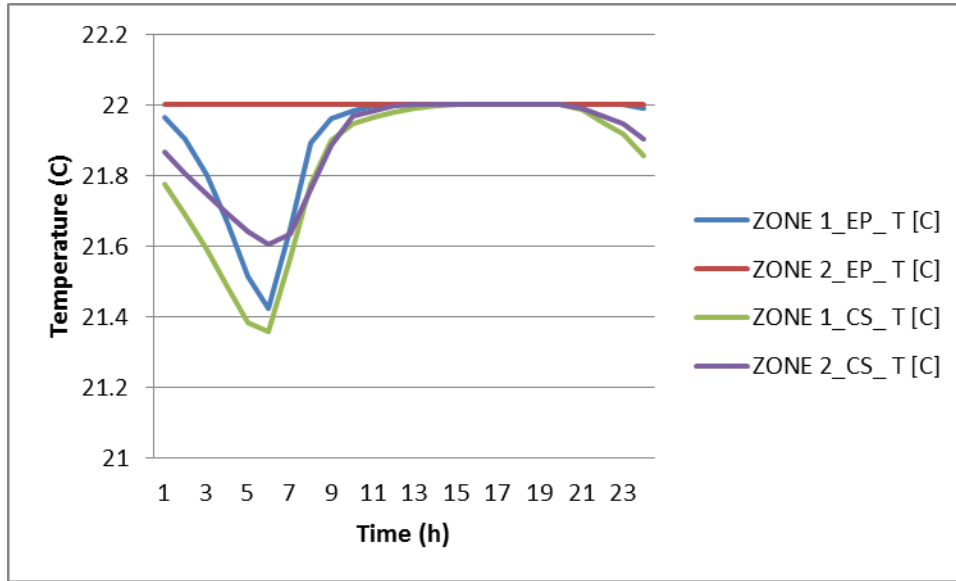
Figure 17: Average indoor temperature (°C) in July

(EP: EnergyPlus and CS: CitySim)
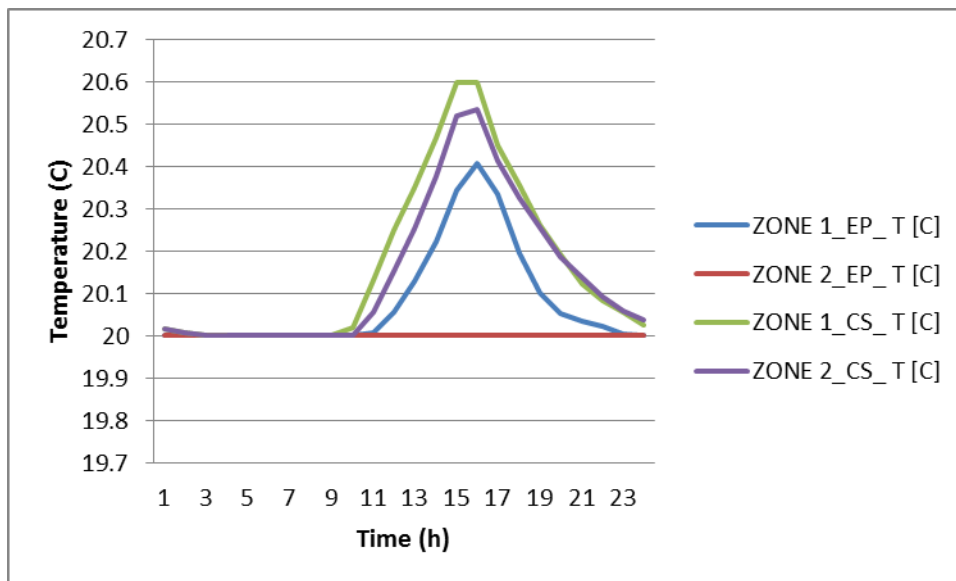
Figure 18: Average indoor temperature (°C) in December

Figure 17 and Figure 18 illustrate the average air temperature in the two zones in July and December, representing typical summer days and winter days respectively. The thermostat scale we set is 20 to 22 °C. As can be read in Figure 18, in July, the temperature of Zone1 has a variation less than 0.7°C in both models. The fluctuation

of Zone 2 is less, specifically in EnergyPlus where the temperature is constant. In December, the indoor temperature of Zone 1 has a variation of about 0.6°C from heating point in the afternoon, when the solar gain is the strongest. The Zone 2 still has a smaller variation and in EnergyPlus, it is also constant. The differences between the zones should be caused by the amount of solar incidence received.

4.2.3.2 Solar gain comparison

The solar gain in the models can be influenced by many factors. First of all, we confirmed that the direct irradiance and diffuse irradiance provided by the weather file is the same in two models. Then we need to check the relative position of the sun and the building which can be influenced by the algorithm as well as the site location information of the building, etc. We validated that by checking the shortwave irradiance falls on the surfaces and the differences between 2 models is quite limited and within 10%.

Following that one needs to check the transmitted solar irradiance through the windows which is mainly influenced by the sunlit area and the Solar Heat Gain Coefficient (SHGC) of the windows. The sunlit area of the windows is influenced by the shadowing over it and in EnergyPlus, as mentioned above, we changed the construction of the roof to make the shadowing work. However, to the best of our understanding, it is not easy to verify that the shadowing is working in the same way in both models.

SHGC is defined as the fraction of incident solar radiation that actually enters a building through the entire window assembly as heat gain ("Solar Gain" 2015). In CitySim, one only needs to input the SHGC value directly and in EnergyPlus, one can do the same or define the window system layer by layer in detail as we did. However, no matter which method is chosen, the SHGC one can input is always the normal value, which assumes that the incident irradiance is perpendicular to the surface of the window. However, during energy modelling, the solar incidence angles are usually

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quite high and thus the angular properties of windows are important. There are two methods in EnergyPlus to determine the angular performance of the windows and we chose the one that is similar to CitySim.

In order to check that, we selected the window face south in zone 2 and removed other windows in that zone to eliminate their influences as shown in Figure 19. We then calculated the corresponding SHGC value of the two models in EnergyPlus and compared it with CitySim by using the formula:

$$Q_i = SW * S * g$$

where Q_i (W) is the solar gain of the surface, SW (W/m^2) is the shortwave irradiance, S (m^2) is the surface of the glazing and g is the SHGC.
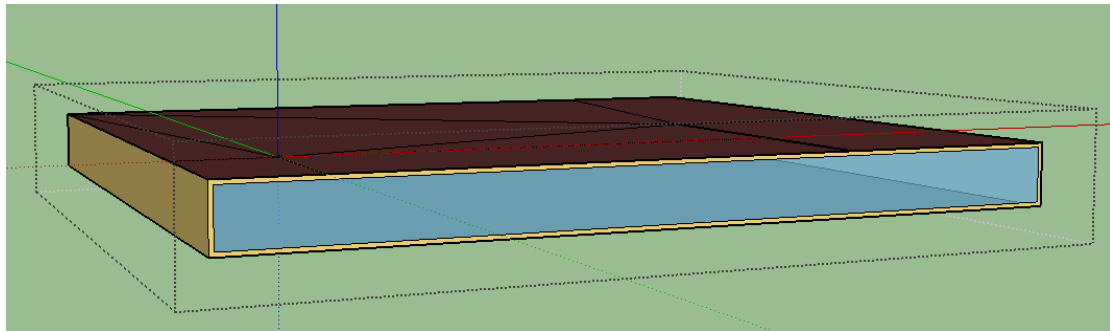

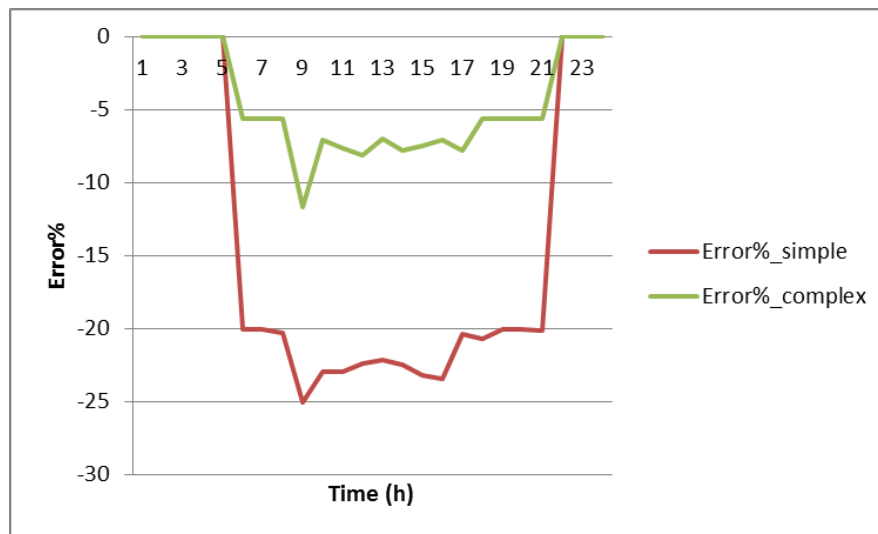**Figure 19: South window of zone 2**

Figure <u>20</u>: SHGC benchmark of EnergyPlus models (CitySim as reference)

From Figure 20, it can be seen that the detailed window model in EnergyPlus calculates a SHGC for this window which is in better agreement with that of CitySim and thus we decided to use that model.
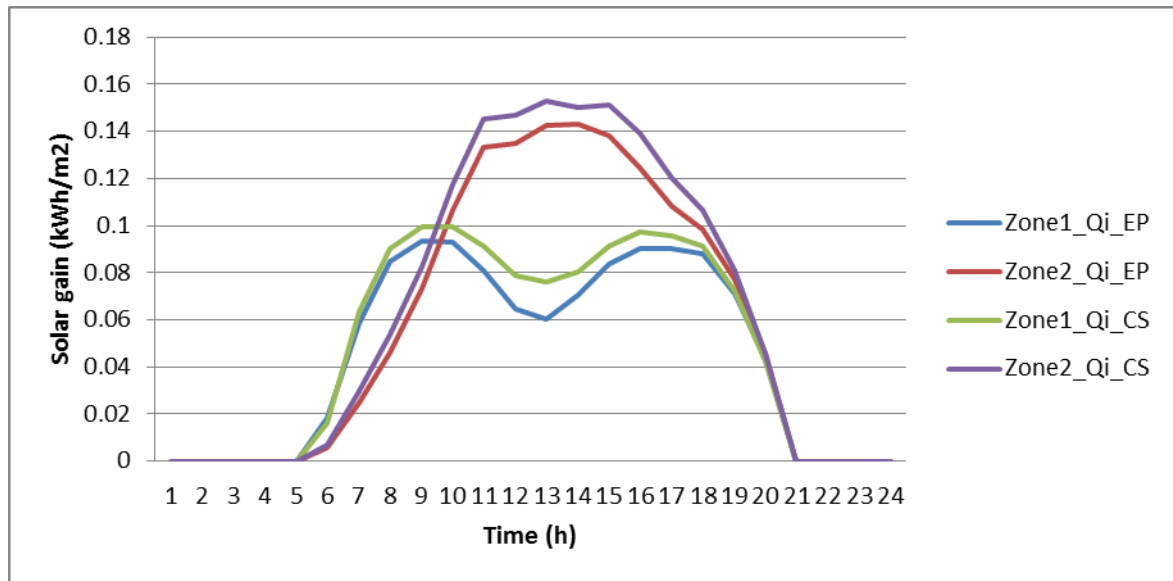
Figure <u>21</u>: Solar gain in July

Figure 21 shows the solar gain in July for zones in both software. The major difference between the two zones in both software is due to the shadow casted by the roof, the solar gain of zone 1 decreases at noon and two peaks are formed in the morning and late afternoon. It is worth noticing that the curve of EnergyPlus drops more sharply comparing with CitySim, which might indicate that there is more shadowing generated in EnergyPlus based on the same geometry. This could also be due to the different SHGC calculated in these two models. For zone 2, since there is no shadow casted on it by the roof, the solar gain reaches the peak at noon and the CitySim also gets higher solar gain in this zone. As shown in the curves, the solar gain is higher in CitySim for both zones and differences is the largest at noon.

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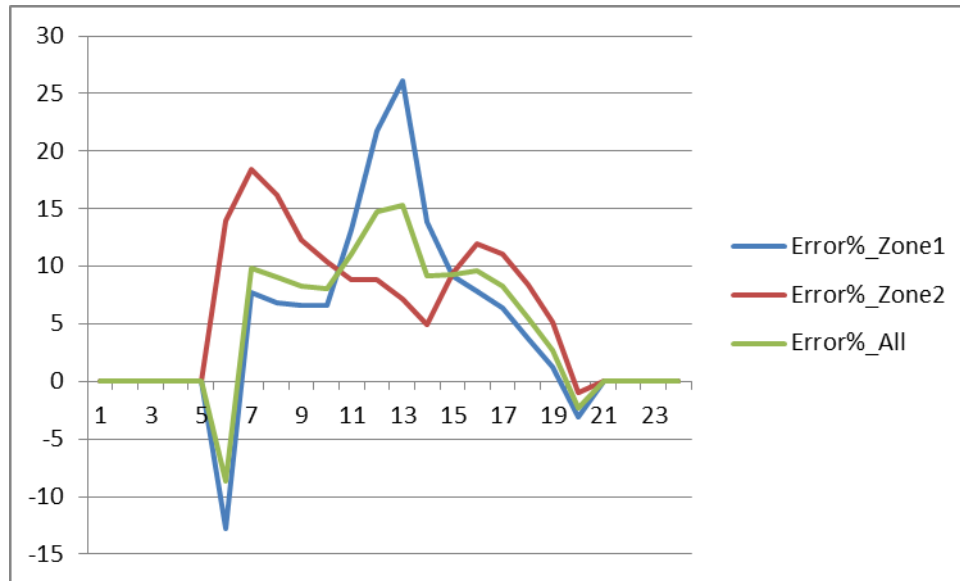
Figure 22: Solar gain differences in July (EnergyPlus as reference)

Figure 22 shows the errors of solar gain for both zones and whole building in two software. As can be read from the figure, the error for the whole building is within 15% for all the time. CitySim gets more solar gain in both zones for most of the time and for zone 1, the error reaches its peak at noon with a value about 25%. For zone 2, the error reaches its peak at morning with a value less than 20%.
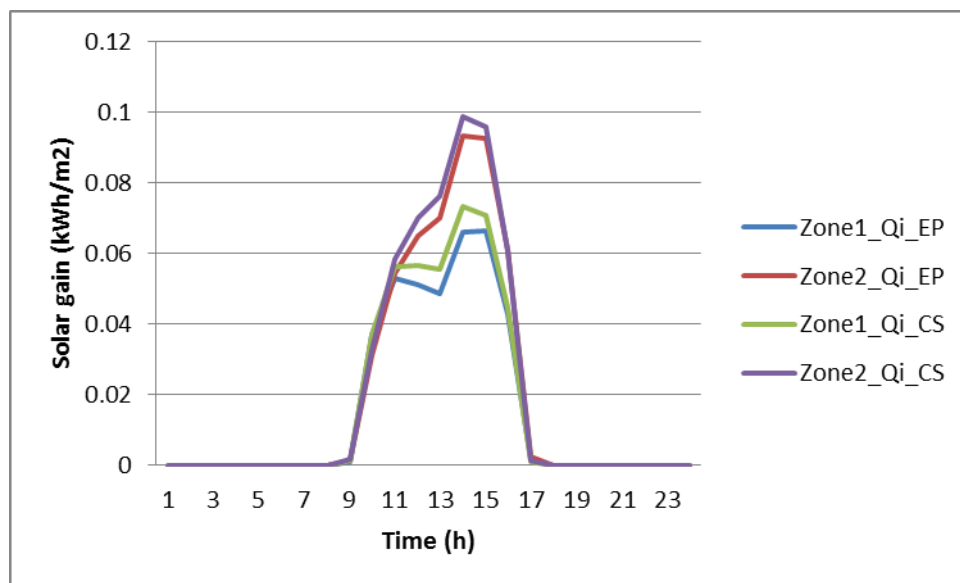
Figure 23: Solar gain in December

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Figure 23 shows the solar gain in December. Since in winter the position of sun is relatively low, the effect of shadowing for zone 1 is less and curves for both zones reach the peak at around 14 pm. The solar gain in CitySim is still higher and the difference is the highest at the peak.
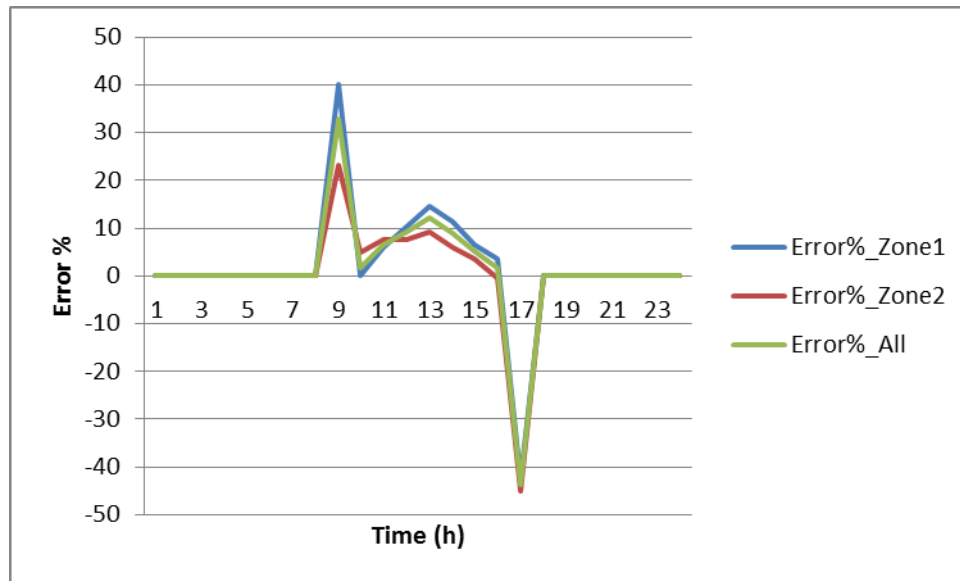
Figure <u>24</u>: Solar gain differences in December (EnergyPlus as reference)

Figure 24 shows the errors of the solar gain in December. The overall error is within 10% during most of the daytime except morning and late afternoon where the error can reach 40%.

Solar gain calculation is quite important for this project considering the very large glazing ratio of the surfaces. From the comparisons one can see that there are some differences between the two models which definitely influence the accuracy of the simulation. More detailed investigation into the solar gain calculation models is required in order to improve our understanding of these discrepancies.

4.2.3.3 Thermal loss comparison

We selected the data from 1 to 6 am in December to check the thermal loss differences in two models. As seen from Figure 23, the indoor average temperature is

constant at 20 °C and since there is no solar gain, the thermal loss should equal to the heating need.
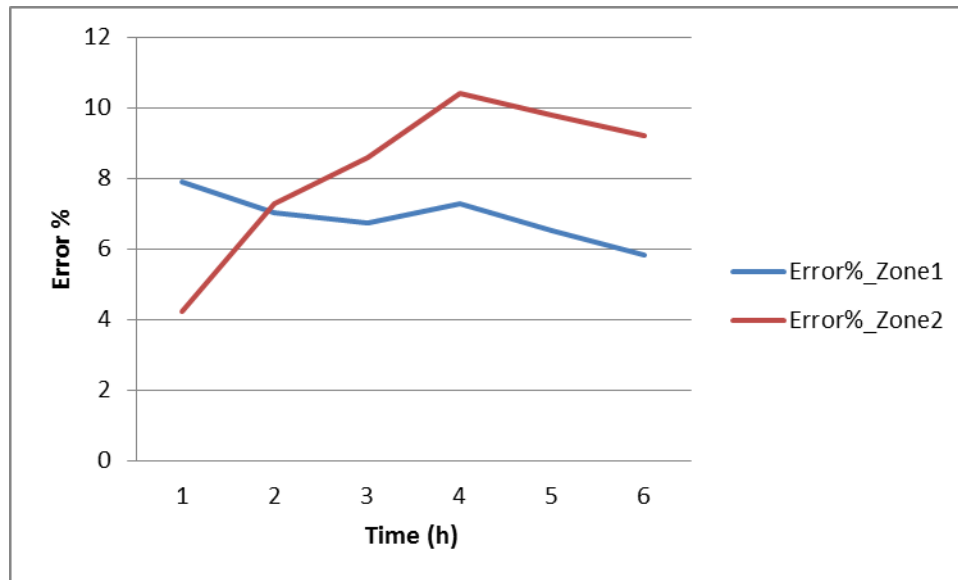
Figure 25: Thermal loss comparison in winter night

From Figure 25, when compared with EnergyPlus, there is more thermal loss in CitySim but the difference is within 10% for most of the time.

4.3 Neighbourhood level simulation

Based on the satisfying result from the compatibility check, neighbourhood level simulation is done in both models. The geometry model of CL building added as shown in Figure 26.
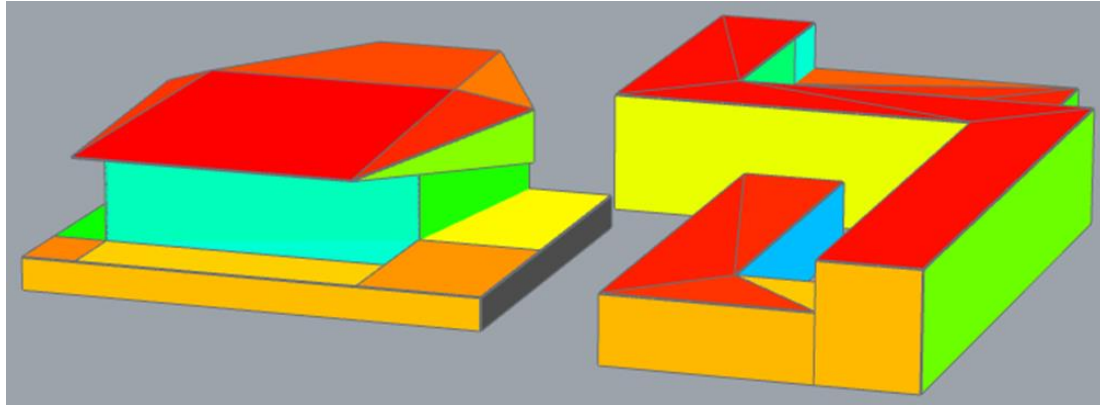
Figure 26: Quartier Nord model

	EnergyPlus	CitySim	Error%
Heating (GJ) B	1087.43	1003.53	-7.72
Heating (GJ) N	1102.95	1020.92	-7.44
Change %	1.43	1.73	
Cooling (GJ) B	1160.26	1484.72	27.96
Cooling (GJ) N	1090.45	1397.66	28.17
Change %	-6.02	-5.86	

Table 10: Benchmark of simulation on different scales

(B represents building level and N is for neighbourhood level)

Table 10 shows the simulation results on different scales in two models. On neighbourhood level, the cooling demand decreased by about 6% in both models as the CL building works as shading and decreases the solar gain. The heating demand increases by about 1.5% in both models since the change of solar gain in winter is less significant.

Worth noticing, the CL building is defined as shading surfaces as otherwise, it will not cast shadow on the STCC. It also tells us in this case the longwave emission and reflection is not playing a big role since the changes in two models are quite close.

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4.5 Conclusions

The ideal load of STCC is simulated in both CitySim and EnergyPlus to compare their differences. As compared to EnergyPlus, CitySim does not need such an enhanced level of detail information about the structure of the building (for ex. the windows). Necessary changes are hence made in EnergyPlus model to make the simulation condition as close as possible to CitySim.

The energy consumption error between the two models is about 14% but the error for cooling is larger than heating. In order to figure out the sources of the differences, a quantitative analysis of the average air temperature, the solar gain and the thermal loss through the surfaces was made.

For the average air temperature, it is relatively constant and there are no obvious differences between the two models. For the solar gain, there are some observable differences, especially in the summer time, when the error can reach 25% at noon. The errors of the solar gain can be caused by several models implemented such as the model for calculating the angular performance of the windows, the shadowing effect, etc. More detailed investigation need to be done in the future to better understand these differences as other studies (Thomas et al. 2014) have shown better agreement but with buildings with lower glazed surfaces.

Furthermore, by selecting the data of winter nights, one is able to check the thermal losses in the models. From the results we learned that the difference between the models is within 10% for most of the time. Since the construction of the surfaces as well as the temperature differences of indoor and outdoor environment are very close in two models, it is important to check the surface area which might be different due to the method of defining surfaces in the software.

5. Net-zero Energy Building

In this section, the potential of STCC being a net-zero energy building is studied in CitySim. First of all, an HVAC system mainly featured with a heat pump is integrated into the model, then solar panel is added in the model to supply electricity and finally batteries are considered for storage.

5.1 Heat pump integration

As described above, the building mainly uses heat pumps to recover heat from waste water to meet the heating and cooling demand. In CitySim, a ground sourced heat pump model is already integrated and in order to mimic the original system, one needs to calculate the depth of the ground where the underground water is at the same temperature with the waste water.

Another important parameter required is the technical efficiency (η_{tech}), which is defined by the reference operating temperatures and the given COP:

$$\eta_{tech} = COP * \frac{|\text{Ttarget} - \text{Tsource}|}{\text{Ttarget}}$$

where T_{target} (K) is the ideally aimed temperature for cooling and heating and T_{source} (K) is the temperature of the source medium.

The parameters (power and COP) given by DII are shown in Table 11.

	Heating	Cooling
Power (KW)	750.00	1000.00
COP	4.20	3.50
Ttarget (K)	323.15	279.15
Tsource (K)	286.15	286.15
Technical efficiency	0.48	0.09

Table 11: Parameters of heat pump

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5.2 Photovoltaics integration

At the designing phase, a large area of the roof was planned to install solar panels in the future and in our calculation, 2/3 of the roof surface is used. Other parameters required, as shown in Table 12, are the maximum power (Pmp), area of collectors (Ac), reference temperature for nominal efficiency (Tref), collector temperature under nominal working condition (Tcnoct), temperature coefficient of the open circuit voltage (muVoc) and voltage under maximum power (Vmp).

Area (m^2)	Pmp (W)	Ac (m^2)	Tref (°C)	Tcnoct (°C)	muVoc	Vmp (V)
3124.73	250.00	1.07	25.00	45.70	-0.08	31.00

Table 12: PV parameters of <u>Mitsubishi Electric MLU series</u>

5.3 Battery integration

Figure 27 shows the monthly electricity consumption of the heat pumps and the electricity generation of the solar panels. It is clear that the total amount of generated electricity is more than enough to cover the need of the building annually. However in winter time like December and January, although the demand for electricity is less than in summer due to the higher COP, the solar gain is much less and not all the needs can be supplied by PV. In summer from June to August, since the COP for cooling is lower than heating, the demand for electricity is the highest. Due to the stronger solar incidence in this season, all of the demand can be met by PV.
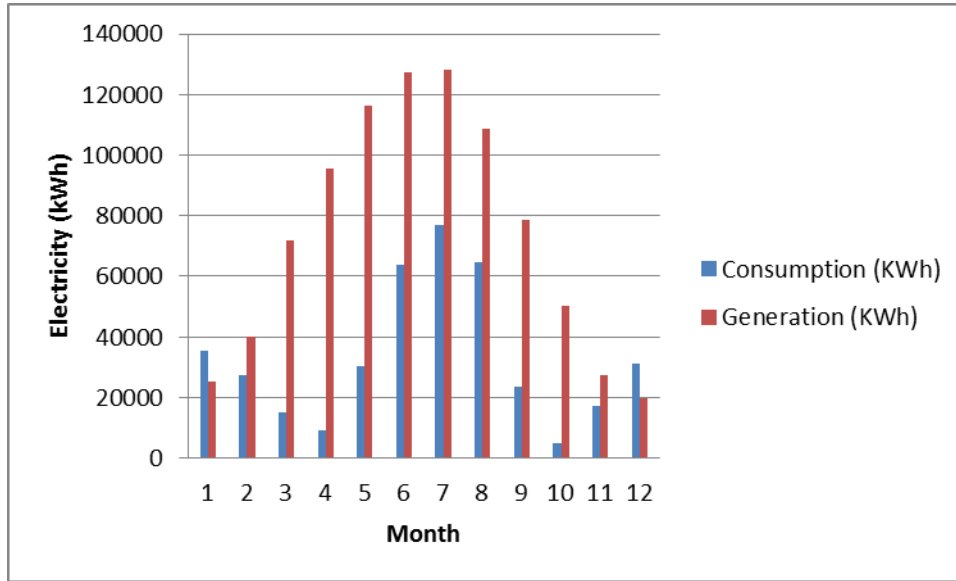
Figure 27: Monthly electricity consumption and generation

In order to utilize the surplus electricity generated from the PV, a battery is integrated in the model. We used a simple methodology to analyse the electricity consumption and generation data from CitySim to include in the storage.

The working principle of the battery is quite simple. When there is electricity surplus, the battery will be charged until it reaches its maximum capacity. When there is electricity deficit, the system will start using the storage of the battery before it reaches a minimum number. After that the demand will be supplied by electricity from the grid.

Based on the maximum daily electricity demand in the model, the capacity of the battery system is set at 4900 kWh (one Powerwall battery is around 250 kWh and can be used in a typical household) and the round trip efficiency is considered as 0.92 to take into account the losses in the conversion process and the hourly leakage is considered as 0.01.
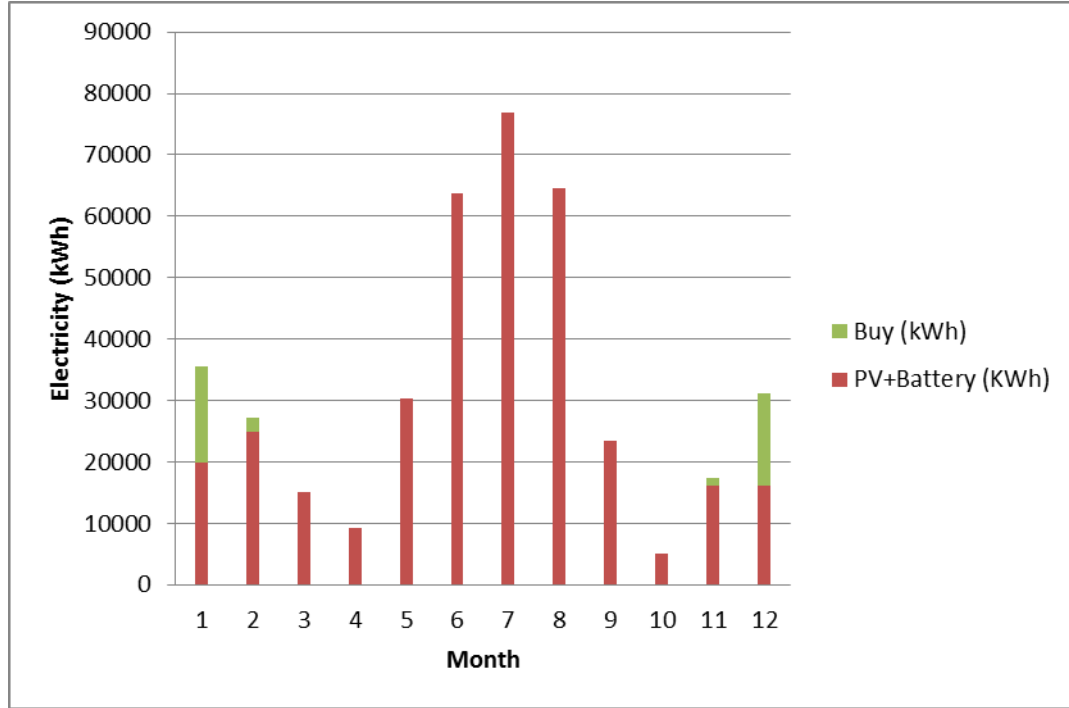
Figure <u>28</u>: Components of electricity consumption

Figure 28 shows the monthly components of electricity consumption. The demand can be completely supplied by the PV and battery system for the whole year except January, February, November and December. In typical winter time like in December and January, about half of the demand can be met.

5.4 Conclusions

In this section, the potential of STCC to work as an autonomous building is investigated in CitySim due to its good compatibility with energy conversion systems.

First of the all, the existing HVAC system using waste water sourced heat pumps were integrated in the model based on the parameters provided by DII. Following that, solar panels are integrated and it was assumed that 2/3 of the roof surfaces is covered by solar panels.

A battery storage system was also used to make full use of the surplus electricity generated by the solar panels when the solar incidence is high. The evaluation of the

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value of using the storage was done using a simple methodology developed during this project.

Thanks to the solar and storage system, the electricity needs can be met for most of the time during the year. However, in order to make the whole neighbourhood autonomous or even more, one needs to increase the solar panel cover ratio or the capacity of the battery, which is already quite large. Other renewable resources should also hence be considered if the aim is to reach 100% autonomy.

The capacity of the battery is determined based on the maximum daily load and due to the extreme weather condition, it is quite large and it does not make sense from the economic point of view. In any case (reality or our simulation), the building is still connected to the grid and the capacity of the battery should be determined by the cost optimization and a trade-off should be made between the initial investment and profits.

6. Discussions and Conclusions

Aimed at reducing the primary energy consumption as well as the corresponding CO2 emission, various standards were created and focused on the designing phase. In order to validate the standard and more importantly, check the energy consumption condition in operation, STCC, a building which plays important role in its neighbourhood, has been selected for studying.

The energy consumption condition of the building was planned to be simulated at two scales, the building level and neighbourhood level respectively. At building level, the simulation was done in EnergyPlus, both for operational and ideal loads. When the operational results were compared to the monitored data, it was found that they were quite different. The errors could come from the missing operational information (for ex. the actual daily occupancy profile) and unregulated operation conditions (ventilation functioning continuously from 7am to 23pm). However, when the result for ideal load was then compared to the Minergie standard they showed very good agreement. This highlighted the need for better understanding of the operational conditions and also to make sure that buildings constructed under such standard should be carefully monitored once under operation.

In the second part of this study, CitySim was selected to run the simulation on a larger scale. Using building energy simulation tools at different scale is essential if we want to capture the various processes influencing the energy consumption. However, for the purpose of this study and in order to compare the differences between the EnergyPlus and CitySim, only one building is modelled in both software. A benchmark was done between them in which the ideal load of the building was simulated. The results were in good agreement with an error not larger than 14%. However, some differences were shown in the models for solar gain. This comparison has been done in studies before, but not with buildings with such a high glazing ratio.

Investigations hence need to be conducted to better understand these differences. Following that, the simulation was conducted on neighbourhood level and in both models, the cooling demand decreased by about 6%.

At last, we evaluate the possibility of working towards a 100% autonomous district. Although we have not yet included other residential and commercial buildings in this neighbourhood, we implement more renewable energy sources on the building in CitySim. We also integrate battery storage so as to fulfil the electricity demand from the heat pumps in time of need. The results show the building's potential of being an autonomous building as most of the energy needs can be met with the systems installed.

7. Future Work

We have shown in this study that there is an important gap between the energy consumption evaluated before construction and under operational conditions. At building level, more case studies (and with data over a longer period of time) are needed to get more reasonable operational input like the occupancy and lights schedule. By far the thermal bridge effect has not been implemented in the model due to the some technical difficulties in EnergyPlus, but this should be possible with the help of other software like DesignBuilder. We are confident that these changes will increase the accuracy of the simulation. Besides, the use of an average dataset for the meteorological boundary conditions might also impede the ability of the software to reproduce the energy use at the building scale. More appropriate yearly data would certainly enhance these calculations.

At neighbourhood level, most of the analyses of the two software have provided satisfactory results, but we still need to check more in details some parameters such as the volume calculation, windows system model, ground model, etc. At a later stage, the whole neighbourhood can be included and hence involved in the model to simulate the energy interactions. As we have shown, in the present study, there are differences between these models as they work best at different scale. A co-simulation between the two software would definitely give more appropriate boundary conditions and hence help to improve the simulation at both the neighbourhood and the building scale.

It is also interesting to us to explore more about the building's potential of being an energy hub which can work as the energy centre of the region. As we have shown further integration of renewable energy is possible and would lead to an increased independence of the district. More investigations are needed, to improve the methodology and optimize the battery use, for instance, optimize the battery capacity

base on the cost analysis. It is expected to continue using CitySim for this part of the work.

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