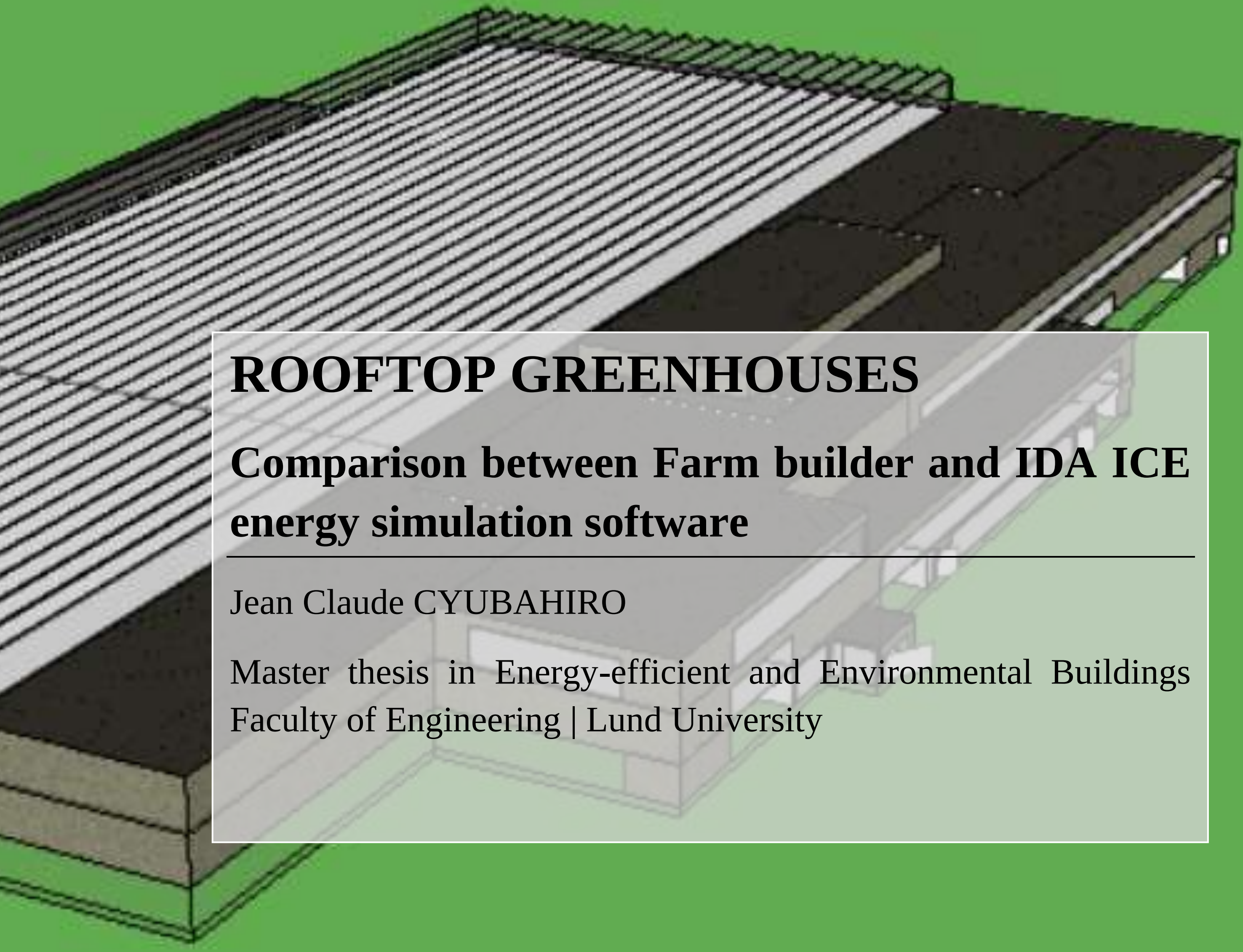

ROOFTOP GREENHOUSES

Comparison between Farm builder and IDA ICE energy simulation software

Jean Claude CYUBAHIRO

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programmes and 2 300 subject courses offered by 63 departments.

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This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Rooftop greenhouses, Farm builder, IDA ICE

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Abstract

Rapid global urbanization is a major concern for the food production system, as it is recognized that relying on conventional methods of distant large-scale farming contributes significantly to greenhouse gas emissions. One of the key strategies to address this challenge is rooftop greenhouses (RTG), which are greenhouses built on unoccupied rooftops. Besides that, this technology goes beyond crop production to offering possible alternatives of reducing the operational energy demand for the host building as well as greenhouse itself. In line with this, a computational based simulation tool (Farm builder) incorporating energy and crop growth models was recently developed for simulation of building integrated agriculture such for RTG and to predict the energy consumption associated with this application. However, as this tool has been able to demonstrate its potentialities in evaluating the implementation of RTG models, it is also needed to reflect on the modelling procedure, inputs, output information and most importantly to investigate these certain aspects in comparison to other simulation tool.

Thus, this thesis aims to present a comparison study between Farm builder and IDA ICE energy simulation software, as one of the simulation tools which have been also used to perform energy simulation involving RTG application. The analytical comparison was based on two case studies: a single zone model defined in the Building Energy Simulation Test (BESTEST) validation procedure and IKEA warehouse building located in Malmö which was integrated with RTG in a previous study. A number of test cases were performed and inputs parameters that are applicable to both tools were assessed including HVAC system operations. The results from this study show that, there exists an acceptable level of agreement between Farm builder and IDA ICE in terms of evaluating the host building model, as the validated EUI results against energy measurement were relatively close to each other. However, the largest discrepancies between both simulation tools were observed for the outcomes of integrated RTG. Overall, the findings of this study suggest that Farm builder provides reasonably promising results, and the analysis of the observed trends in discrepancies also give possible insight on the effect of some limitations, contrasting capabilities and inputs data needs between both tools to perform energy simulations.

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This thesis study concludes my final year courses, and it was the greatest work for my entire studies which, I believe that has extensively helped me in my knowledge acquisition throughout the process. Therefore, it is for this purpose that I would like to express my deepest gratitude to everyone who supported me along the way.

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Abbreviation

AHU	Air Handling Unit
BIA	Building Integrated Agriculture
BPS	Building Performance Simulation
CAV	Constant air volume
CEA	Controlled environment agriculture
COP	Coefficient of performance
DLI	Daily light integral
EDP	Early design phase
ET	Evapotranspiration
EPW	EnergyPlus Weather
EUI	Energy use intensity
IEA	International Energy Agency
GHG	Greenhouse gas
HVAC	Heating Ventilation and Air Conditioning
IDA ICE	IDA Indoor Climate and Energy
LED	Light Emitting Diode
LE	Light Efficacy
LPD	Light power density
NFRC	National Fenestration Rating Council
PPE	Photosynthetic photon efficacy
RF	Rooftop farming
RTG	Rooftop greenhouses
TDLI	Target daily light integral
UBEM	Urban Building Energy Modelling
UA	Urban Agriculture
UF	Urban farming
URF	Urban rooftop farming
UMI	Urban Modelling Interface
UPAF	Urban and Peri-urban Agriculture and Forestry
VAV	Variable air volume
VF	Vertical farming

1 Introduction

1.1 General problem

Urban sites around the world are becoming increasingly crowded. Cities are predicted to host 68% of the global population by 2050, a number increasing from 54% registered in 2016 (Ritchie & Roser, 2018). This rapid escalation is a significant concern, as it will have a huge influence on global resource consumption associated with urban settlements. The food production system, which primarily relies on distant agricultural areas, is one of the imperative sectors that are experiencing the adverse effects caused by global urbanization (Pons et al., 2015). Globally, the agriculture industries are responsible for 26% of greenhouse gas (GHG) emissions, with food supply chain and land-use accounting for around 42% of these emissions (Ritchie & Roser, 2020) followed by an estimation of 14% food losses occurring from harvest to retail (FAO, 2021). There is thus clearly a need to rethink the food production system, especially in relation to the rapid urbanization.

1.2 Breakthrough solutions

1.2.1 Urban and peri-urban agriculture and forestry (UA, UPAF)

The increase pace of global urbanization is inevitable as global population is growing. Numerous solutions have been proposed in recent years to address this issue and keep food production within environmental limits. Amongst the proposed solutions, Urban Agriculture (UA) and Peri-Urban Agriculture and forestry (UPAF) are the most promising frameworks across the planet for establishing sustainable food systems and ensuring food security for future generations (Goldstein, et al., 2016; Benis & Ferrão, 2016). UA allows urban dwellers to cultivate crops in small areas within cities such as vacant lots, gardens, balconies, and containers, including the raising of small livestock for self-consumption or market sale, while UPAF is undertaken around cities for that same purpose (FAO, 2001). Typical horticultural crops (vegetables, fruits, flowers, ornamentals, and lawn grasses) are the most popular crops for these practices since they produce high yields in small areas. Cultivating these crops in the city allows preserving arable land outside the city for cultivation of grains or preserving natural ecosystems.

1.2.2 Building integrated agriculture (BIA)

To maximize the potential of UA for crop production, a variety of strategies and technologies have been explored. Caplow & Nelkin (2007) invented the Building Integrated Agriculture (BIA) concept, which comprises controlled-environment agriculture (CEA) and horticulture under a high-performance greenhouse on top of or within buildings. BIA offers a robust solution for reducing GHG emissions by eliminating food miles and enhancing crop productivity while utilizing locally available resources in a sustainable way (Gould & Caplow, 2014). Currently, Vertical Farming (VF) and Rooftop Greenhouses (RTG) are among the most common forms of BIA technology that have been implemented in the urban context.

1.2.2.1 Vertical farming (VF) vs rooftop greenhouses (RTG)

Vertical farming (VF) is a common form of BIA in which crops are grown indoors in multi-story buildings, new constructions, or abandoned buildings in an urban area (Despommier, 2010). VF does not normally involve daylighting; illumination is provided by light emitting diodes (LEDs) or other types of lamps. However, it is still arguable if VF can replace existing conventional production systems as it was reported that conventional greenhouses are more energy-efficient than VF due to the high purchased energy for lighting and high resource consumption resulting from construction materials (Graamans et al., 2017). In comparison to RTG, it was also demonstrated that, VF of the same size needed 285 kWh of lighting energy use to achieve equivalent crop yields, which was three times higher than RTG extra lighting energy consumption (Zhang, 2021).

Therefore, putting a greenhouse on an unoccupied rooftop area (RTG) has shown a larger potential to minimize lighting energy demand, since a large part of its illumination comes from natural light, while mitigating CO_2 emissions resulting from food miles (Pineda et al., 2020). Moreover, RTG can generate high crop yields with soilless cultivation under different climatic conditions, alleviating the issue of land scarcity, while also improving social-economic factors (creating jobs) in the urban context (Montserrat, 2019).

1.3 Context of the study

Over the last years, related studies on Building Integrated Agriculture (BIA) involving the application of RTG and VF have been performed, using building performance simulation tools (BPS) such as DesignBuilder, TRNSYS, and IDA ICE, with the purpose of investigating the impacts of this technology on energy use of the host building and the greenhouse itself (Pineda et al., 2020; Zhang, 2021). Unfortunately, BPS tools are limited in their ability to analyse RTG parameters (lighting, climate control, moisture, etc.) and provide crop yields in a holistic way (Benis, et al., 2017). However, early studies with BPS tools allowed producing some basic results, which were followed by the implementation of this technology in different urban contexts.

1.4 Objectives

More recently, the fully integrated simulation workflow (Farm builder) was developed by Benis et al (2017). This program integrates all necessary control variables including CO2, humidity, light, nutrients, pests, temperature, ventilation, and water to evaluate BIA models. It is designated to support BIA in the urban context by assisting decision-makers (architects, urban planners, researchers, etc) in determining the feasibility of RTG at the early design phase (EDP).

Therefore, the objective of this thesis is to evaluate the performance of Farm builder simulation tool in comparison to IDA ICE, as one of the simulation tools used in previous studies to compute energy use for models involving application of RTG. The study will focus on identifying relationships and differences between the simulation results of both tools and highlights possible reasonings attributed to divergences.

1.5 Research questions

The following questions guided the development of this study:

- What level of agreement between Farm builder and IDA ICE in performing energy calculations of the host building model and RTG itself.
- How the parameters and calculation methods associated with both tools affect the simulation results.

2 Background

2.1 RTG approach to energy reduction

Rooftop greenhouses (RTG) have shown their capacity to provide a growing environment for crops, while also reducing the energy use of the host building and greenhouse (Zhang, 2021).

Firstly, RTG employs the concept of conventional greenhouses for solar harvesting to maintain optimum crop growth temperatures (13-20°C at night and 20-28°C during daytime, depending on crop types) (Munoz-Liesa et al, 2020). RTG also provides natural light that meets the needs of crops. In doing so, plant leaves will be available to block high solar radiation from reaching the rooftop during the hottest part of the year, substantially reducing overheating on the roof membrane, and thereby cooling the greenhouse and the host building through the evapotranspiration effect of plants (Munoz-Liesa et al, 2020). Thus, RTG saves energy spent on cooling the host building. This is a passive strategy that could potentially mitigate the urban heat island effect. However, this strategy should be supplemented with a natural ventilation system to continuously reduce excess heat and remove high humidity in the air from plants (Gould & Caplow, 2014; Pons et al., 2015), since a closed greenhouse would create a greenhouse effect and potentially increase (instead of reducing) the cooling demand of the host building.

Secondly, RTG benefits from the host building by leveraging synergies through energy flow exchange (low-grade waste heat, water use, and CO_2), which has a significant impact on RTG's heating demand under extreme winter conditions (Montero et al., 2017). According to this synergy, the exhaust air from the host buildings is used for heating rather than being released outside because it has the ideal temperatures for crop growth (Nadal et al., 2017). The heating demand of the RTG is also reduced by taking advantage of heat losses through the roof of the host building. In addition, the artificial lighting system used in RTG for heating can be reduced since it harvests natural light. Also, higher concentrations of CO_2 and humidity from the exhaust air of the host building (if the system is set-up in this way) act as natural fertilizers to increase crop yields (Munoz-Liesa et al, 2020).

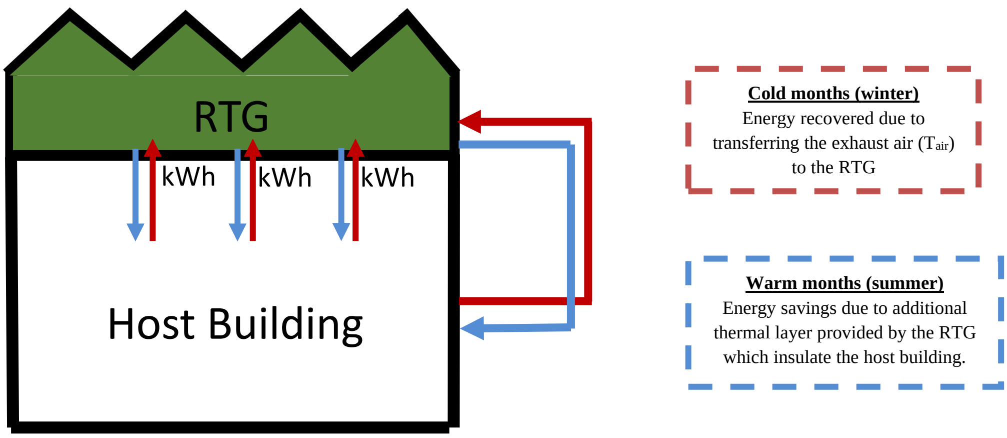


Figure 1: Energy recovered by the RTG in cold months due to transferring the exhaust air from the host building to the greenhouse through AHU and the host building energy savings in warm months due to the insulation effect of the greenhouse.

2.2 Urban cities with RTG

RTG is gaining popularity in many cities around the world as a result of its adaption to the built environment. The Lufa Farms in Montreal has four urban rooftop farms where the smallest covers 2 880 m^2 (Lufa, 2020). The Vinegar Factory in Manhattan, New York City, has a RTG of 830 m^2 (Specht et al., 2015). Gotham Greens operates 15 000 m^2 of RTG while Sky Vegetables holds 130 m^2 of RTG (Sanyé-Mengual et al., 2015). The Mediterranean basin is one of the current locations for RTG technology in Europe. One operation is based in the Barcelona Campus (ICT-ICP building), where it produces 989 kg of tomatoes, with 85 % of them fulfilling commercial product specifications (Nadal et al., 2017). As can be seen, RTG is an emerging technology, which could make a significant contribution to the urban food production system.

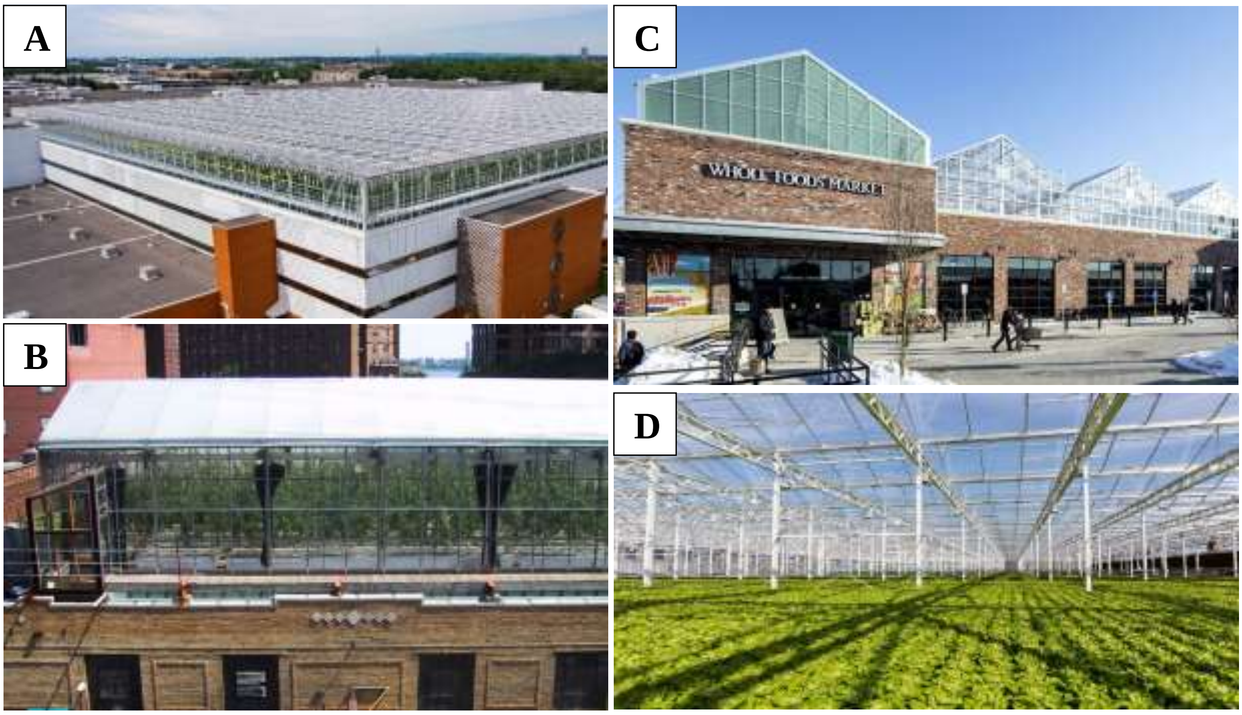


*Figure 2: Examples of rooftop greenhouses existing in different urban world cities. **A**. Lufa farm in montreal, **B**. the vinegar factory in Manhattan. (New York City), **C**. Gotham greens in New York City, **D.** Inside greenhouse of Anjou RTG which produce lettuce crops.*

3 Methodology

The methodology approach which was followed to compare two energy simulation tools (IDA ICE & Farm builder) consisted of three phases. In the first phase, all the information data that was required for the selected case studies were collected. In the second phase, the comparison test of these tools was carried out by using ANSI-ASHRAE'S BESTEST Case 600 model as the test study, to better understand how these tools function on a small scale and identify the differences that could possibly be between these tools before extending to a complex model. The initial assessment focused on steady states calculations and further the test analysis at dynamic calculations was carried out as well. The analysis was also conducted on a multizone building model integrated with rooftop greenhouses (RTG), as the main case study. In doing so, the host building stand-alone model was simulated and compared separately in both tools and then followed with applying the RTG model. Finally, the third phase included evaluation of parameters and comparison analysis of the simulation results obtained from both tools.

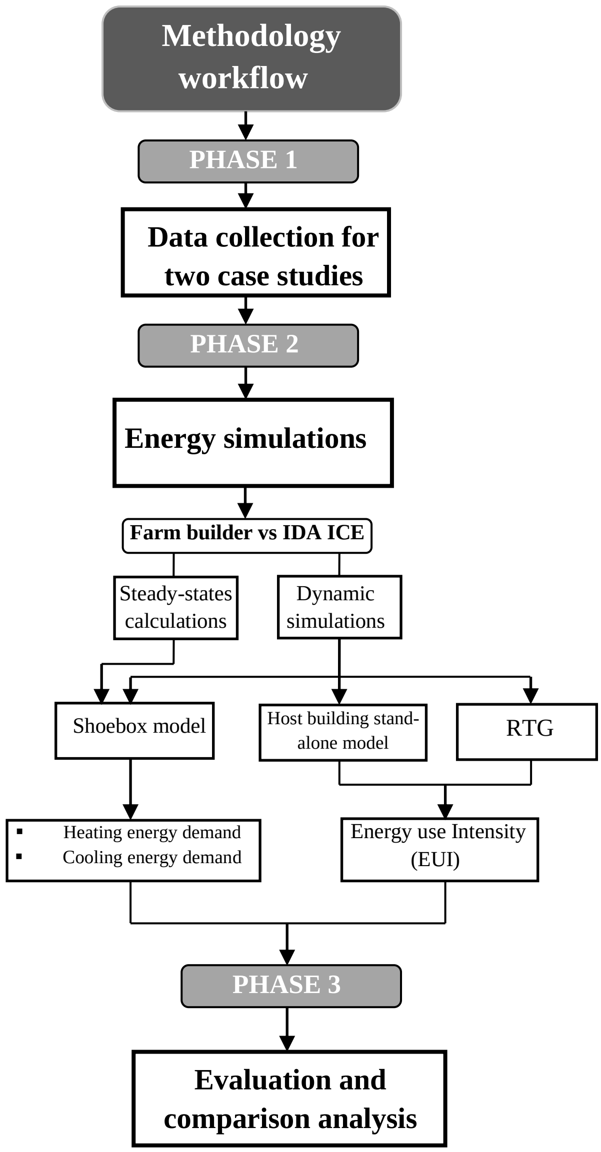


Figure 3: Schematic methodology workflow of the study

3.1 Description of the studied case studies

Two case studies were selected to conduct a comparative study between Farm builder and IDA ICE. The first case study is the shoebox model, which is described as base case test (600) (Low mass building) in ANSI/ASHRAE standard 140-2001 ‘’Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs’’ (ASHRAE, 2004) and is among the qualification cases of the BESTEST ‘’Building Energy simulation Test and Diagnosis method’’ standard cases, used to validate different software program (Judkoff & Neymark, 1995). The building specification data of the base case 600 was also taken from ANSI/ASHRAE standard 140-2001.

The second case study is the IKEA warehouse building located in Malmö, Sweden (latitude 55.6°N, longitude 13.0°E) with a total built area of 44 000 m^2 elongated along the East-West orientation.

Figure 4: IKEA warehouse building

This IKEA building is comprised of multiple zones distributed over three floors with a total height of 15.4 meters (two levels above the ground and one below), the ground-level is used for car parking and other rooms are mostly for storage while the two levels above the ground are equipped with marketplace, offices, hall, showrooms, and restaurants, see Figure 5 for the building layout. The construction of facades is of lightweight concrete; the insulation is unknown and, for this study, it has been inherited by a previous study on the same building.

The ground floor, intermediate floors and roof are of concrete constructions. The roof and ground floor both have similar type of insulation. The HVAC system type used in this building is a variable air volume (VAV) system operating in a standard AHU placed on the rooftop.

Figure 5: Floor plans layout of the IKEA building

In a previous research study carried out by Zhang (2021), this building was integrated with a rooftop greenhouse (RTG) for crop production and to reduce energy consumption of the host building (warehouse) and greenhouse. The RTG reported in the previous study is of a Venlo-type (typical greenhouse of steel structure renowned for its sturdy construction) as shown in Figure 6 covering 15 898 m^2 of rooftop area and it was oriented in East-West direction to maximize daily light transmission especially in winter when there is limited sunlight. It has 4.2 m post height with two-span gable roof (3.2 m width × 1m gable) and roof slope of 45^o. The floor structure type of the greenhouse is of lightweight concrete slab. The side walls as well as roof covering materials are double pane tempered glass to comply with the characteristic nature of the greenhouse of allowing high solar transmittance. The RTG applies natural ventilation to reduce overheating during summer months and it is achieved by opening 40% of roof glazing. It is also reported that it was supplemented with an independent mechanical ventilation system (VAV) to satisfy the optimum growth conditions of the selected crops (lettuce).
All other inputs information that were required to perform the energy simulations are described later in the section 3.4.3 and 3.5.3 and they were also inherited from the previous study.

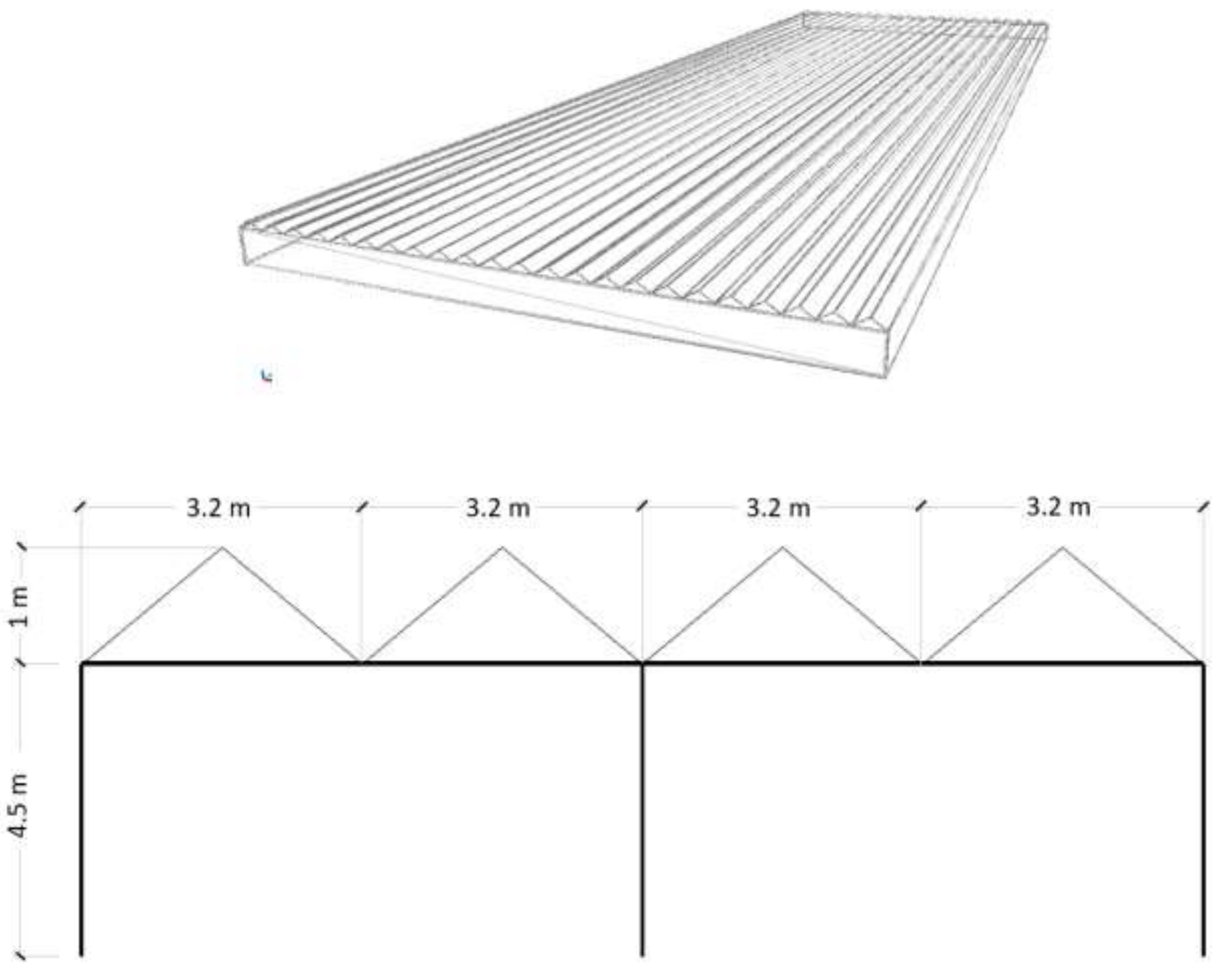


Figure 6: Perspective view of the integrated Venlo-type greenhouse (above) and Typical structure of Venlo-type greenhouse (below)

3.2 Description of energy simulation tools

3.2.1 IDA ICE simulation tool (version 5.0)

IDA ICE (Indoor Climate and Energy) is a dynamic multi-zone simulation software tool developed by EQUA Simulation AB which is mainly used for accurate study of indoor climate of individual zones and energy consumption of the whole building. IDA ICE is based on IDA, a general-purpose simulation environment and it consists of mathematical models that have been developed by KTH Royal Institute of Technology and Helsinki University of Technology (EQUA, 2022).

Its user interface is divided into three different levels: The wizard for simplest level where the user has no control of the physical model or mathematical model of the simulated system. The standard level where the user has the full control of the physical model and uses existing models taken from the library but has no direct control over the mathematical model. And the advanced level where the mathematical models can be changed, and own models can be written by the user using an equation-based modelling language. These three levels are all designed with different scope to make it easier for the beginners and experts for being able to model a building of single zone or multiple zones and carry-out simulation (EQUA, 2009).

In this study, the generally used standard level as shown in Figure 7 below, was utilized for constructing and simulating the building models of all the studied cases.

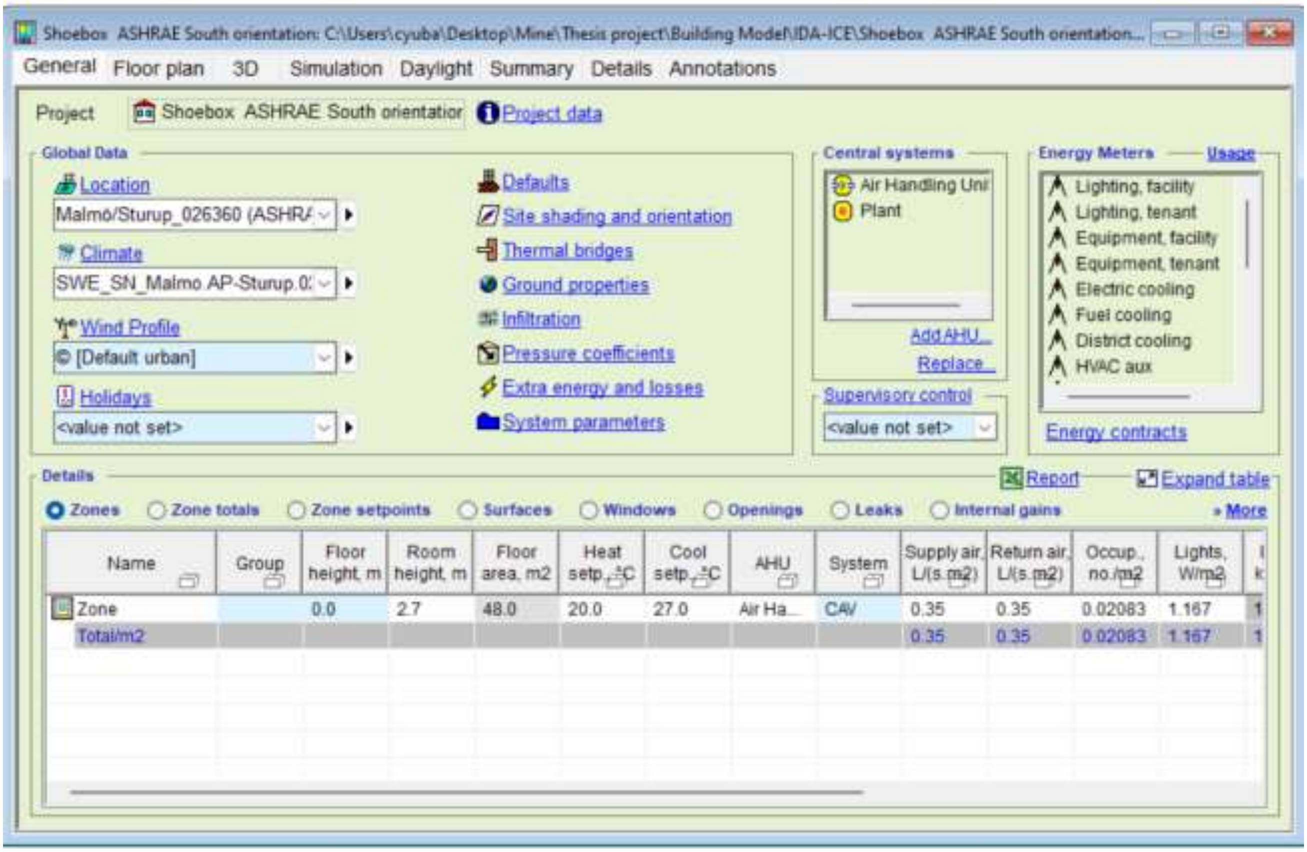


Figure 7: Standard level user interface for IDA ICE

The standard level contains various main user tabs where each tab has specific application that allows the user to define information required for designing a building model.

In the General tab, the location and climate for each studied case are defined and the default construction settings can be edited such as (U-values, g-values, solar and visible transmittance) as well as access to the structure and parameters of air handling units (AHU).

In the Floor plan tab, the building body and zones can be inserted and edited. Also from this tab, the zone information such as (room units, HVAC inputs, operating schedules, loads) can be defined. In the 3D tab, the model can be visualized. In the simulation tab, different options of simulation runs are given such for heating load, cooling load, annual energy use, overheating or for custom simulations. In the Details tab, detailed simulation results are shown.

3.2.2 Farm builder simulation tool

Farm builder is a plugin for the UMI program (Urban Modelling Interface). It estimates food yields and their associated energy use, water use and carbon emissions in different types of urban farms including rooftop greenhouses (RTG) and indoor vertical farms (VF) (Reinhart & Benis, 2017). It is also supported by Rhinoceros 3D modelling software as a design environment to build farm or building geometry models from scratch.

Farm builder uses two harvest energy simulators (greenhouse and closed farm), which are based on the EnergyPlus engine to generate and simulate the energy model of the selected farm type. In addition, it uses the algorithmic model called UMI shoeboxer to perform energy simulation for host building model. All three different energy models are shown in Figure 8 below.

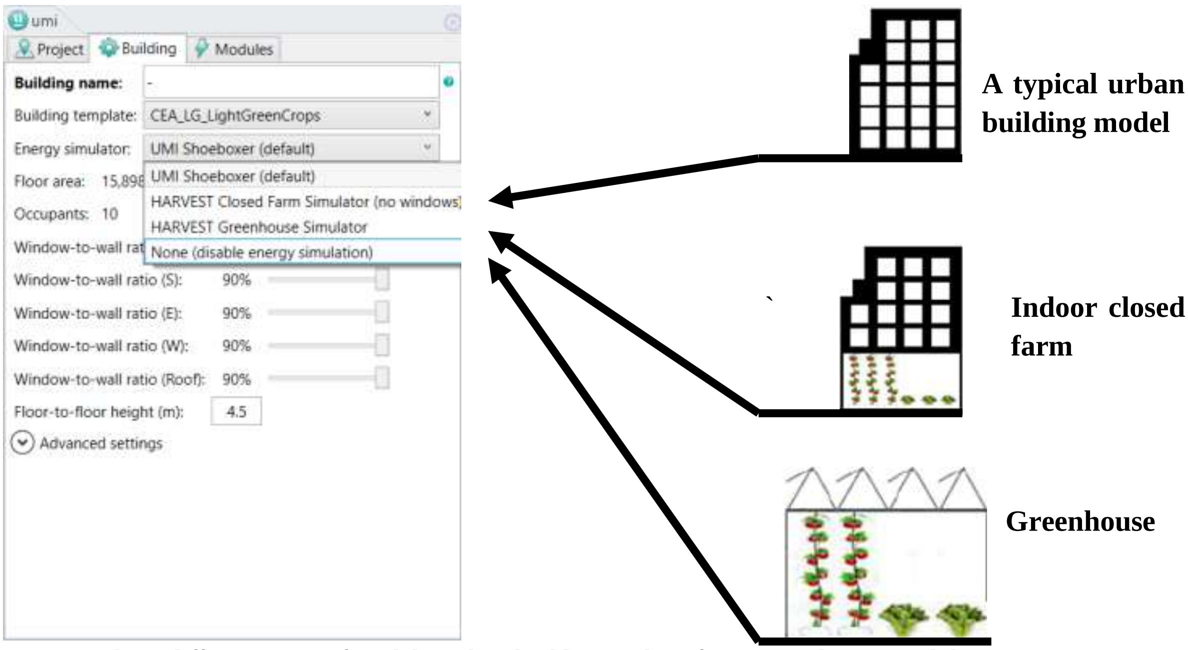


Figure 8: Three different types of models (urban building, indoor farm, greenhouse) and their respective energy simulators.

- **UMI shoeboxer:** is an algorithmic model with calculation methods based on EnergyPlus simulation engine and it was developed to evaluate and perform operational energy calculations of urban building energy models (UBEM) (Dogan & Reinhart, 2017). Farm builder also employs this model for such calculations to the host building model.

- **HARVEST Greenhouse and Closed farm:** These modules are designed to operate specifically when a box geometry modelled at chosen location for the urban farm (rooftop or at any chosen building floor) is selected either as greenhouse or indoor closed farm. By that, it runs the simulations using EnergyPlus engine, and simulated energy use intensity of the farm is displayed. In addition, window-to-wall ratios (WWR) are automatically set to 0% when the selected harvest farm type is a closed farm while for a greenhouse the user can set to 90%. (Benis & Ferrao, 2017)

These modules also integrate mathematical equation for plant process into the simulations. The evapotranspiration (ET) calculation model of greenhouse crops proposed by Stanghellini (1987) is built in the simulation workflow and it has been proven that is reliable for predicting ET in controlled agriculture environment (Guerrero, et al., 2012).
ET mathematical model is described by equation below:

$$E\lambda = \frac{\delta \cdot R_n((2 \cdot LAI \cdot \rho_a \cdot C_p)/r_e)(VPD)}{\gamma \cdot (1+(\delta/\gamma)+(r_i/r_e))} \quad (1)$$

Where $E\lambda$ is the evapotranspiration flux (W m^{-2}), R_n is the net radiation above the canopy, *LAI* is the leaf area index, *VPD* is the vapor pressure deficit of the air (Pa), γ is the psychrometric constant (Pa $^0C^{-1}$), δ is the slope of the vapor pressure-temperature curve (Pa $^0C^{-1}$), ρ_a is the density of air (kg m^{-3}), C_p is the specific heat capacity of air at constant pressure (J kg^{-1}°C^{-1}), r_i is the internal crop resistance to vapor transfer (s m^{-1}), r_e is the external crop resistance to sensible heat transfer (s m^{-1}).

Farm builder user interface comprises of three main tabs namely: Project, Building and Modules as shown in Figure 8. The Project tab consist of a location and template library panel. The location panel is where Meteorological Year (TMY) or EnergyPlus weather files (EPW) can be manually imported while a template library panel is designated to import the template library file which contains model thermal inputs for simulation. This file type stores and exchanges information data about farm or building characteristics such as material properties and construction, thermal loads, and air conditioning systems.
The building tab is for assigning the building template to specific zone within the building and to select the energy simulator for performing simulation. It also provides a feature which allows the user to specify the window to wall ratio (WWR) values per each façade orientation, since it cannot be possible to manually size the glazing window. The Module tab is for displaying annual energy use results, crops yield, and the estimation of their associated water use as well as the carbon emissions.

According to the scope of this study, it was planned to perform the energy simulation by focusing exclusively on heating and cooling demands. In doing so, this tool was further explored on the concern of understanding all steps required to generate results of space heating and cooling demand for the case studies. Other parameters such as crop yields, water use, and carbon emissions calculations were overlooked.

3.3 Case study 1- Shoebox model test (Case 600)

To choose the case 600 as a starting point in this study was because it has the simplest geometry with least input data, which would help to easily indicate variables influencing most the output results in both tools. In order to achieve this, the comparison test procedure was performed in two parts.

- **Part1: Steady states calculations**

The first part focused on testing of these two simulation tools by comparing the energy use obtained at steady state conditions and validate with the results of Excel EnergyCalc.

According to (Gentile, et al., 2020), Excel EnergyCalc is an excel spreadsheet for calculating the annual heating energy demand and the energy peak load of a simple shoebox at steady states condition, which is based on Swedish Building Code BBR (Boverket, 2018). The Excel EnergyCalc includes calculations of transmissions losses for the building envelope, ventilation losses, and infiltration losses.

In this part, the approach was to evaluate how the building envelope u-values mainly without considering windows are interpreted in these two simulations tools which could be the initial basis of information to proceed further with other comparison tests. Therefore, different insulation thicknesses of the walls, roof and the ground were tested at time with all input parameters (infiltration rate, internal heat gains and mechanical ventilation) being excluded in both simulation tools as well as in Excel EnergyCalc.

To perform this test, these two energy simulation tools were forced to carry simulation at static condition by using a weather file that had constant ambient temperature of 0˚ and no solar radiation. In this case the available weather file'CPH_amb0_rad_0' of Copenhagen was imported. The heating set point for both simulation tools and Excel EnergyCalc was set at 20°C, and the cooling set point was turned off in both tools.

- **Part2: Dynamic simulation**

The second part was to perform the comparison test of these two simulation tools with dynamic simulations. This was done in sequence by assessing how each input parameter affects the output results of these two simulation tools. It started with narrowing influencing factors as much as possible for the first simulation case and followed with testing one parameter at time. In doing so, the annual energy results could be compared, and the analysis could also be performed for the variables that might have significant impacts on the results such as, infiltration rate, window to wall ratios (WWR) and internal heat gains. All different test cases performed in this part are explained and presented in Figure 9. The weather file of Malmö location (SWE_SN_Malmo.AP-Sturup.026360) was used for all studied test cases, and it was imported from TMYx file weather data formats of 2007-2021 (Climate.OneBuilding, 2022).

The first case was similar to the case tested at static condition which also excluded windows with no other input parameters considered. The heating set point was at 20^0C in both tools and the cooling setpoint was turned off. For the second case, the settings defined in the first case remained the same and different infiltration rate values from lowest to highest were assessed in both simulation tools to test how these tools evaluate the airtightness.

For further analysis, infiltration value of 0.5ach was selected. In the third case, two windows were introduced into the model to evaluate the solar heat gains in both simulation tools and the cooling setpoint was turned on and set to 27^0C. Then, the analysis could be performed by varying different WWR. In the fourth case, the occupancy level was enabled, and the schedule was set to All-on with considering 1.2 Met (metabolic rate) in both simulation tools. Then, the simulation test was done for 1 to 5 people to evaluate how internal heat gains from occupants are calculated. For further case analysis, one person was considered as the occupancy level. In the five case, mechanical ventilation was activated with minimum fresh air per area set to 0.35 L/s.m^2 and the cooling setpoint was turned on and set to 27^0C in both simulation tools.

For the case six, the equipment load was also activated, and the schedule was set to All-on in both tools, and the simulation test was carried out on values from 1W/m^2 to 5W/m^2. In the case seven, the equipment was turned off and lighting load was activated and set to All-on in both tools and the approach for testing was similar to case six where values from 1W/m^2 to 5W/m^2 were also evaluated.

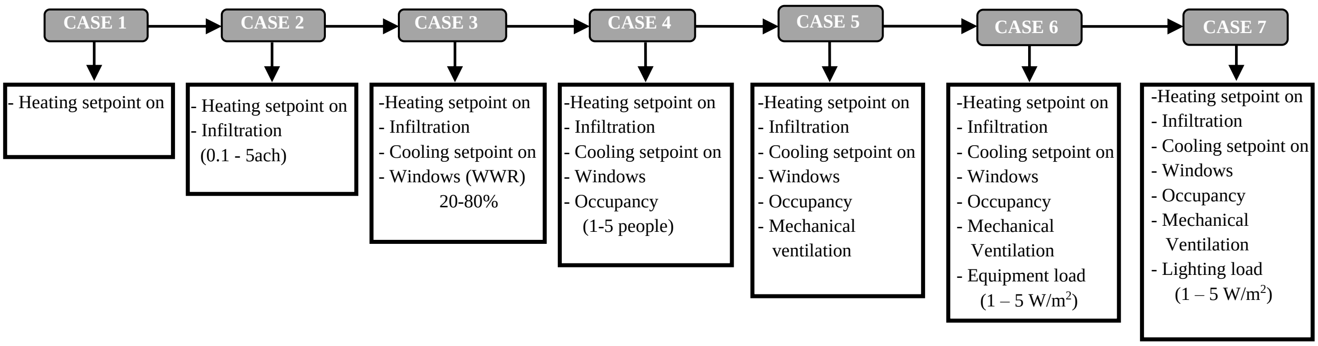


Figure 9: Shoebox case study analysis workflow

In addition, to ascertain that IDA ICE and Farm builder give reasonable values, both tools were compared with a set of reference programs that represent the IEA BESTEST suite. Therefore, for this comparison, the input data were defined as described in BESTEST for case 600 model (Judkoff & Neymark, 1995). The setpoints and infiltration rate remained the same as previously described. While the considered internal gains were 200 W (60% radiation, 40% convection) and the system was ideal air heating and cooling. The weather data that have been used for BESTEST case 600 (ASHRAE, 2004) is for Denver location and for this study, it was extracted from Climate.OneBuilding weather data files (Climate.OneBuilding, 2022).

3.3.1 Shoebox model geometry

The test building (shoebox model) is a rectangular single zone as shown in Figure 10 with dimensions of (8m wide × 6m long × 2.7m high) and two windows of 12m^2 on the south orientation and with no interior partitions.

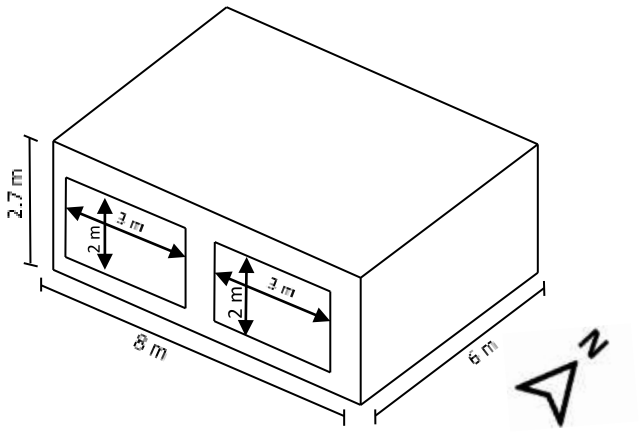


Figure 10:Isometric view of the shoebox case study

3.3.2 Shoebox envelope details

The building is of lightweight construction with envelope characteristics as described below.

Table 1: Construction properties of the shoebox wall layers

Wall layers	Thermal conductivity (W/m.K)	Thickness (m)	U (W/m².K)	R (m²K/W)	Density (kg/m³)	Cp (J/kg.K)
Plasterboard	0.160	0.012	13.330	0.075	950	840
Fiberglass Quilt	0.040	0.066	0.606	1.650	12	840
Wood siding	0.140	0.009	15.560	0.064	530	900

Table 2: Construction properties of the shoebox roof layers

Roof layers	Thermal conductivity (W/m.K)	Thickness (m)	U (W/m².K)	R (m²K/W)	Density (kg/m³)	Cp (J/kg.K)
Plasterboard	0.160	0.010	16.000	0.063	950	840
Fiberglass Quilt	0.040	0.1118	0.358	2.794	12	840
Roof Deck	0.140	0.019	7.368	0.136	530	900

Table 3: Construction properties of the shoebox floor layers

Floor layers	Thermal conductivity (W/m.K)	Thickness (m)	U (W/m².K)	R (m²K/W)	Density (kg/m³)	Cp (J/kg.K)
Timber Flooring	0.140	0.025	5.600	0.179	650	1200
Insulation	0.040	1.003	0.040	25.075	-	-

Table 4: Window glazing thermal properties of the shoebox building

Window type	U-value (W/m²K)	Solar heat gain coefficient (SHGC)	Solar transmittance (τ_{sol})	Visible transmittance (τ_{sol})	Emissivity (ε)
Double pane glazing (4 -12 - 4)	2.90	0.79	0.76	0.82	0.83

3.4 Case study 2- Host building stand-alone model

The simulation of the host building model was also performed and the predictions of these two simulation tools were compared to each other. Therefore, this section discusses the construction of the host building model as well as the thermal inputs parameters used for simulations.

3.4.1 Model geometry

Based on the detailed architectural drawings of the IKEA warehouse building, the modelling of the host building geometry was carried in IDA ICE and then followed with applying the same geometry model in Farm builder as shown in Figure 11.

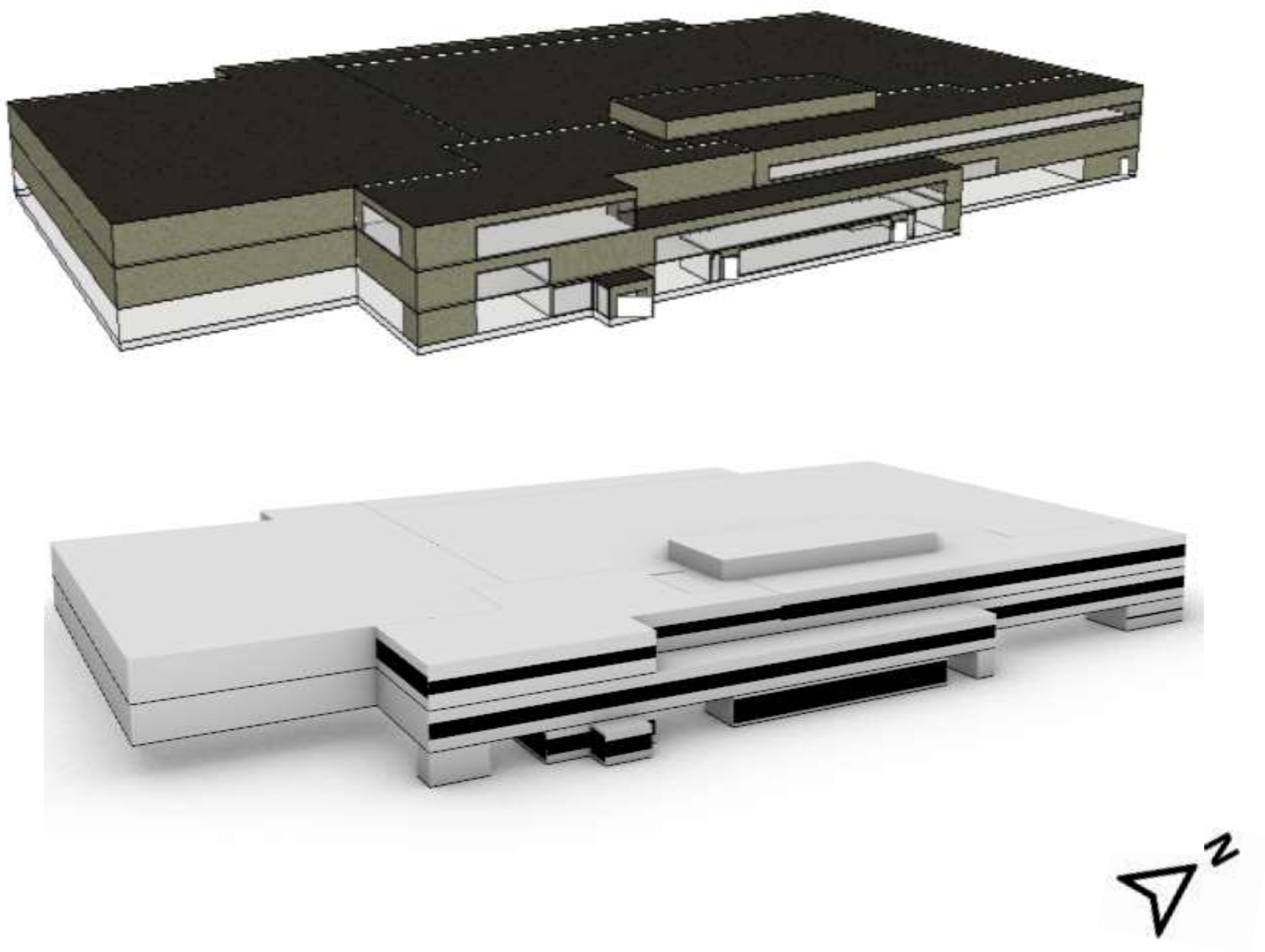


Figure 11: Warehouse (host building) energy simulation model as modelled in IDA ICE (above) and Farm builder (below)

3.4.2 Envelope details

The material construction and properties of the walls, roof, intermediate floors, and ground as well as window thermal properties for the host building model are described in Table 5, Table 6

Table 5: Construction material properties of the building envelope. (Zhang, 2021)

Building envelope	U-value (W/m^2K)	Total thickness (m)	Material layers	Layer thickness (m)
External walls	0.31	0.51	Render	0.03
			L/W Concrete	0.45
			Render	0.03
Internal walls	0.62	0.15	Gypsum	0.03
			Air in 30mm vert. air gap	0.03
			Light insulation	0.03
			Air in 30mm vert. air gap	0.03
			Gypsum	0.03
Intermediate floors	0.45	0.32	Render	0.04
			Wood	0.28
Roof	0.2	0.32	Concrete	0.15
			Light insulation	0.17
Slab towards ground	0.45	0.35	Wood	0.04
			Light insulation	0.06
			Concrete	0.25

Table 6: Window glazing thermal properties of the host building (Zhang, 2021)

Window type	U-value (W/m^2K)	Solar heat gain coefficient (SHGC)	Solar transmittance (τ_{sol})	Visible transmittance (τ_{sol})	Emissivity (ε)
Triple pane glazing (4-12-4-12-4)	1.30	0.49	0.27	0.27	0.84

3.4.3 Input data for simulation

- **Weather data**

The annual climate file is obtained from the TMYx. file weather data formats of 2007-2021 (Climate.OneBuilding, 2022) for Malmö-sturup in which the building is located.

- **Infiltration**

The infiltration rate was 0.5 air changes per hour (ACH) at a pressure coefficient of 50 Pa.

- **Internal loads**

Building internal loads (equipment, and lighting) were defined as shown in Table 7, by associating each zone with its respective thermal loads. The occupancy schedule is the same for all building zones, and it was set from 10h to 20h during weekdays (Monday-Friday) and 10h to 19h during weekends (Saturday-Sunday).

Table 7: Input data for the equipment load, lighting power density (LPD) and their operating schedules. (Zhang, 2021)

Building zones	Equipment load (W/m^2)	Lighting power density (W/m^2)	Equipment schedule	Lighting schedule
Checkout/Exit	5.0	9.4	Monday-Friday: (10-20)h	Monday-Friday: (09-21)h
			Saturday-Sunday: (10-19)h	Saturday-Sunday: (09-20)h
Entrance	27.5	4.6	Monday-Friday: (10-20)h	Monday-Friday: (09-21)h
			Saturday-Sunday: (10-19)h	Saturday-Sunday: (09-20)h
Equipment room	5.0	2.0	Always on	Monday-Friday: (09-21)h
				Saturday-Sunday: (09-20)h
Refrigerant room	250.0	2.0	Always on	Monday-Friday: (10-20)h
				Saturday-Sunday: (10-19)h
Hall	5.0	9.9	Monday-Friday: (10-20)h	Monday-Friday: (09-21)h
			Saturday-Sunday: (10-19)h	Saturday-Sunday: (09-20)h
Kitchen	400.0	12.0	Monday-Friday: (10-20)h	Monday-Friday: (10-20)h
			Saturday-Sunday: (10-19)h	Saturday-Sunday: (10-19)h
Office	3.0	3.5	Monday-Friday: (10-20)h	Monday-Friday: (10-20)h
			Saturday-Sunday: (10-19)h	Saturday-Sunday: (10-19)h
Restaurant	-	4.2	-	Monday-Friday: (09-21)h
				Saturday-Sunday: (09-20)h
Self serve	-	4.1	-	Monday-Friday: (09-21)h
				Saturday-Sunday: (09-20)h
Stair	-	2.0	-	Monday-Friday: (09-21)h
				Saturday-Sunday: (09-20)h
Showroom	5.0	9.5	Monday-Friday: (10-20)h	Monday-Friday: (09-21)h
			Saturday-Sunday: (10-19)h	Saturday-Sunday: (09-20)h
Technical space	-	3.0	-	Monday-Friday: (09-21)h
				Saturday-Sunday: (09-20)h

- **HVAC system**

As mentioned earlier, the system type used for heating and cooling as well as ventilation purposes was a variable air volume (VAV) system operating in a standard air handing unit (AHU). The controller setpoint inputs were 18ºC and 25ºC for heating and cooling respectively and the system's primary energy demand was delivered by electricity using COP of 1. Other inputs related to HVAC operating schedules and supplied air flow are described in Table 8.

Table 8: HVAC operating schedule of the host building (Zhang, 2021)

Building zones	Minimum air supply/return (L/s.m²)	Maximum air supply/return (L/s.m²)	HVAC schedule
Checkout/Exit	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Entrance	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Equipment room	0.35	0.35	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Refrigerant room	0.35	1.00	Always on
Hall	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Kitchen	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Office	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Restaurant	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Marketplace	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Stair	0.35	0.35	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Showroom	0.35	1.00	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h
Technical space	0.35	0.35	Monday-Friday: (09-21)h Saturday-Sunday: (09-20)h

3.5 Case study 2- Rooftop greenhouses (RTG)

The RTG model was applied in both simulation tools and the comparison was done on the associated annual energy use of the RTG model to evaluate how these tools interpret this type of model. Therefore, this section discusses the envelope details of the RTG model and the respective thermal input data that were used for simulation.

3.5.1 Model geometry

The RTG model with geometry details as mentioned in the description of the second case study was added to in both simulation tools as shown in Figure 12. However, the geometry shape was modelled in form of a rectangular box in both tools instead of Venlo-type since Farm builder, can only model and simulate farm models of this type.

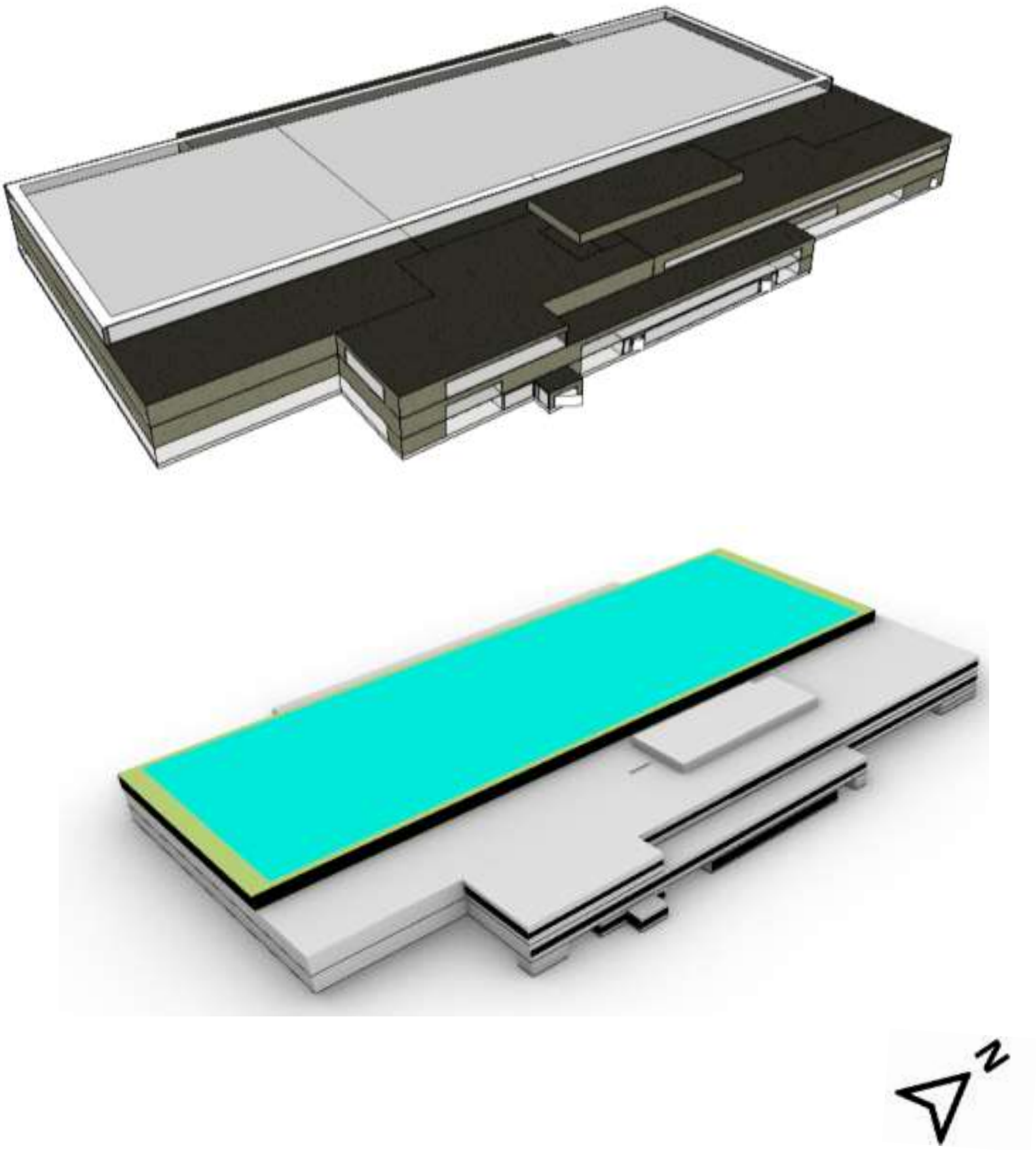


Figure 12: host building energy model integrated with RTG as modeled in IDA ICE (above) *and Farm builder (*below*)*

3.5.2 Envelope details

Table 9 shows properties of the glazing type used for the RTG model.

Table 9: Window glazing thermal properties of the greenhouse

Window type	U-value (W/m^{2}K)	Solar heat gain coefficient (SHGC)	Solar transmittance (τ_{sol})	Visible transmittance (τ_{sol})	Emissivity (ε)
Double pane glazing (4-12-4)	2.90	0.76	0.70	0.81	0.84

3.5.3 Input data for simulation

- **Crop type**

The selected crop type, which was considered in this study, was Leafy greens such as Lettuce. This type of crop is classified by Welbaum (2015) as cool season vegetables that can be grown under temperature ranging between 15ºC and 18ºC and it requires photoperiod of at least 16 hours (umidocs, 2019).

- **Infiltration**

The infiltration rate was the same as for host building with 0.5 ach at a pressure coefficient of 50 Pa.

- **HVAC system**

The HVAC system were operating based on optimum growth conditions of the selected crop (Lettuce) with heating and cooling control setpoints of 15ºC for winter and 18ºC for summer respectively. The active heating and cooling of the greenhouse was covered by electricity operating at a coefficient of performance (COP) of 1.

- **Internal loads**

The internal loads considered for the RTG were occupancy estimated to ten farmers operating from 10h to 20h during weekdays (Monday-Friday) and 10h to 19h during weekends (Saturday-Sunday). The lighting power density (LPD) calculations are discussed in the next section. And no equipment load was considered as described in the previous study (Zhang, 2021).

- **Electric lighting**

In principle, crops growth requires specific quantity of the Daily light integral (DLI_{crops}) for triggering photosynthesis process (Dorais, 2003). DLI_{crops} is expressed in (mol/m^2, day) which represents the total number of photons that reach a plant whether by daylight or artificial light during the daily photoperiod. DLI from daylight is usually supplemented with DLI from artificial light mainly in winter period when days are shorter to achieve the target DLI of the crops.

According to Morgan (2016), the type of crop (Lettuce) considered in this study require DLI of 12-14 $mol/m^{-2}/day$ for maximum growth rates and the most common LED chips used in horticulture applications was also considered in this study with a photosynthetic photon efficacy (PPE) of 3 $\mu mol \cdot J^{-1}$. (Kusuma, et al., 2022).

The term PPE refers to a measure of light's efficiency to convert photons into useful chemical energy or growth (Ashdown, 2020).

Therefore, the lighting power density (LPD) was calculated by using the following equation.

$$LPD = TDLI / PPE \quad (2)$$

$$LPD = 14 \text{ mol } m^{-2} d^{-1} / (3.0 \cdot 10^{-6} \text{ mol } J^{-1} \cdot 3600 \text{ s} \cdot d^{-1} \cdot \text{photoperiod in h}) = 81 \text{ W/m}^2 \quad (3)$$

Where LPD is the lighting power density
TDLI is the target daily light integral
PPE is the Photosynthetic photon efficacy

Based on the average daily light integral obtained inside the greenhouse at plant canopy level on a cloudy day for Malmö location (Agronomist, 2020) as shown in Appendix E, and the sunrise and sunset of winter period, the electric lighting schedules were also set from 5h30-8h and 17h-20h30 in Farm builder and IDA ICE respectively.

Table 10: Summary of the simulation inputs for RTG model

GEOMETRY	
Orientation	E-W
Footprint (m^2)	15 898
Height (m)	4.5
WWR (%) (all sides)	90
MATERIALS	
Structure	Steel
Slab	Lightweight concrete
SUPPLEMENTAL LIGHTING	
Lighting system	LED
CLIMATE CONTROL	
Tmin (°C)	15
Tmax (°C)	18
Relative humidity (%)	60-90
Heating COP	1
Cooling COP	1
CROP (Lettuce)	
Photoperiod (h)	16
DLI ($mol/m^{-2}/day$)	14

4 Results and analysis

In this report, the demonstration of results follows the same sequential order as the methodology of the study. First, the comparison of energy use results of the two simulation tools were performed on the shoebox model test cases, and then followed with the host building as well as the RTG model.

4.1 Shoebox model test

4.1.1 Part1: Steady states calculation

This part contains the simulation results obtained at steady states conditions when assessing how insulation thicknesses (wall, roof, ground) affect energy demand in both simulation tools and compared to Excel EnergyCalc. The energy use results only consist of heating energy demand since simulations were run with cooling turned off.

As presented in Figure 13, IDA ICE and Excel EnergyCalc are always very close to each other, and the difference is small which can be negligible, while a slight deviation can be noticed for Farm builder. The highest difference is found for smaller thickness (0.05m) which had a deviation of 7%. Also, the graph shows that for thicker insulation (from 0.2 to 0.5m) Farm builder results are slightly higher than IDA ICE and Excel EnergyCalc.

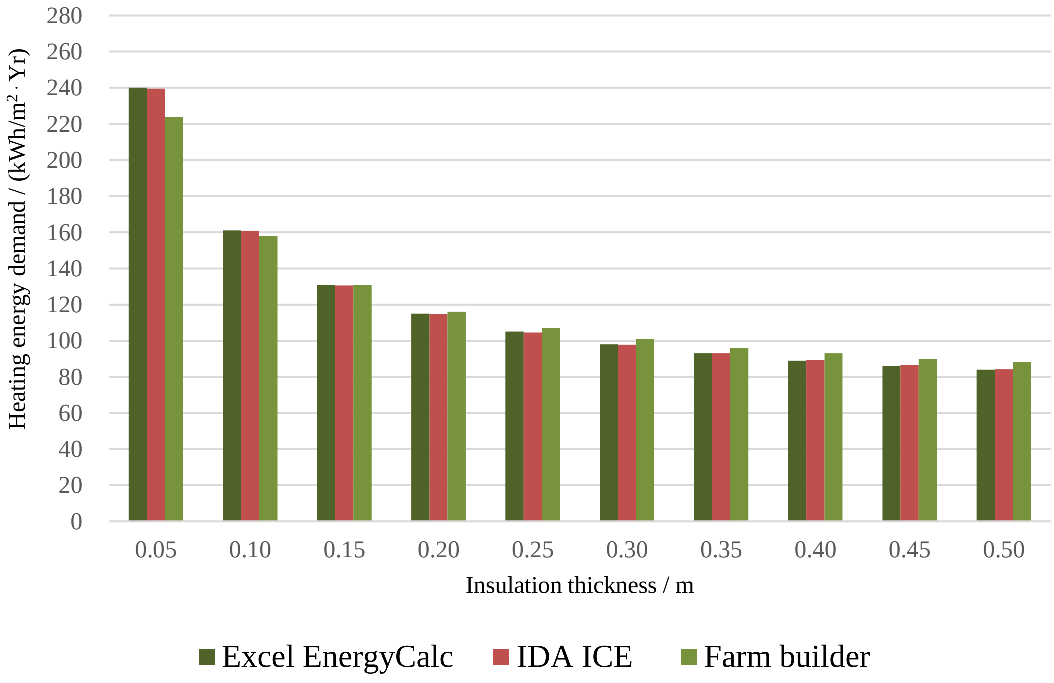


Figure 13: Annual heating energy demand for different wall insulation thicknesses

As presented in Figure 14, the similar trend was observed on annual heating demand results for roof insulation thicknesses. IDA ICE had equivalent results to Excel EnergyCalc while Farm builder results were slightly different to Excel EnergyCalc. The highest difference was found on thicker insulation thicknesses 0.45 and 0.5m which both had a deviation of 8%.

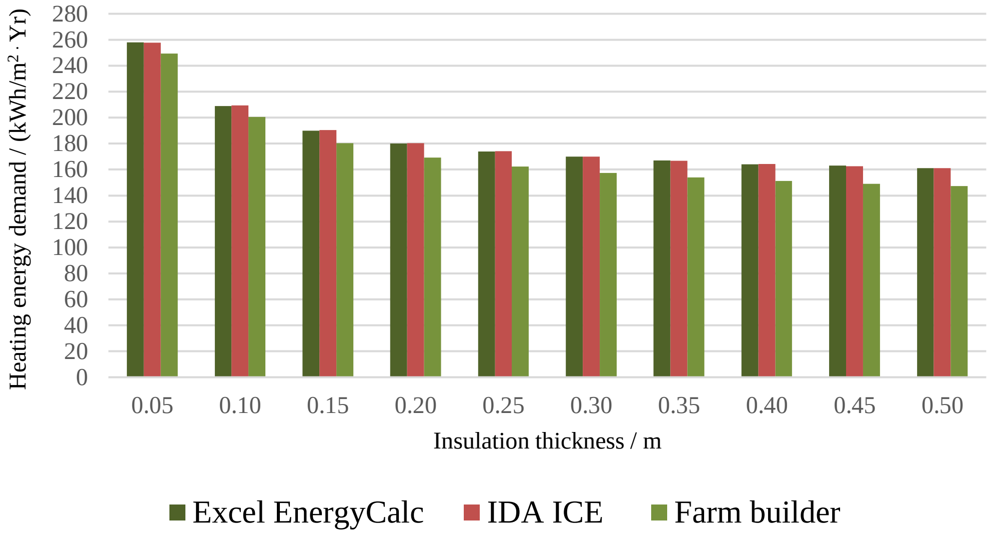


Figure 14: Annual heating energy demand for different roof insulation thicknesses

Figure 15, depicts that, results of the annual heating energy demand for ground thicknesses assessed in Farm builder had significant difference compared to Excel EnergyClalc and IDA ICE. It can be noticed that the differences were much higher for smaller insulation which then reduced by getting closer to thicker insulation. In fact, IDA ICE and Excel EnergyCalc had very close results and they were decreasing gradually along the insulation increments while Farm builder results as it can be seen were rather not changing and seemed to be more or less the same. The highest difference was about 27% which was found on smaller thickness of 0.05m. The calculation method used in both tools could be the reason of these difference since IDA ICE and Excel EnergyCalc both use the same calculation method which is based on ISO-13370 standard while in Farm builder, the Kiva Foundation approach is used within the simulation engine to perform ground heat transfer calculations.

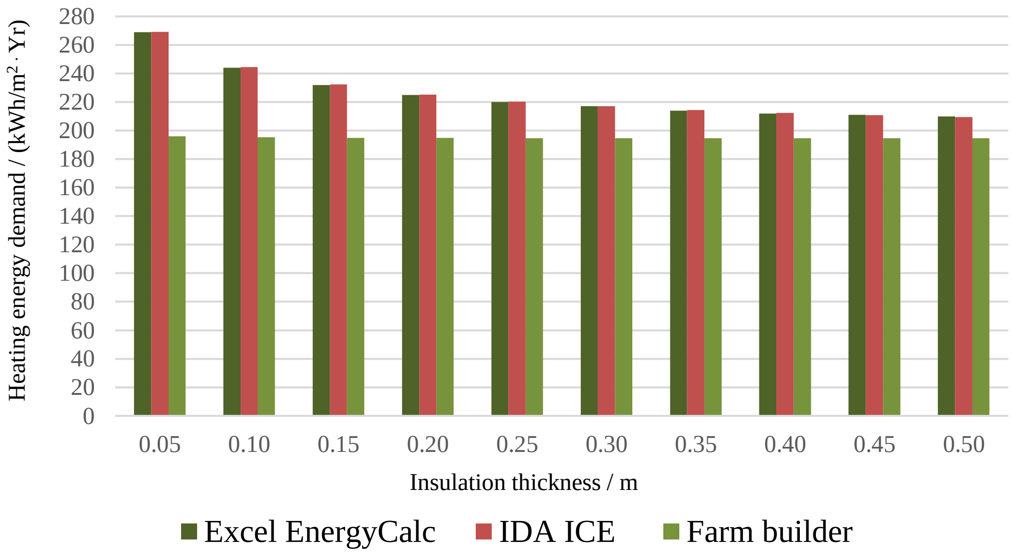


Figure 15: Annual heating energy demand for different floor insulation thicknesses.

4.1.2 Part 2: Dynamic simulations

This part contains number of energy simulation results generated from IDA ICE and Farm builder for all the test cases described in Figure 9.

- **CASE 1: Windowless**

Figure 16 presents the results of annual heating energy demand for these two simulation tools with only considering the building opaque surfaces and no other input parameters. Farm builder tool had slightly lower heating energy demand compared to IDA ICE with a difference of 3.6%. This margin is small, but it can be due to the differences of applied methods for these simulation tools in modeling the heat transfer phenomena and computing the surface heat fluxes of opaque walls. IDA ICE uses RC-wall model for modelling the thermal behavior of a wall. While for Farm builder, the simulation engine uses state space method in their conduction transfer functions calculations. Additionally, different calculation method used in both tools for ground heat transfer as mentioned earlier on steady states analysis, also can contribute to these differences.

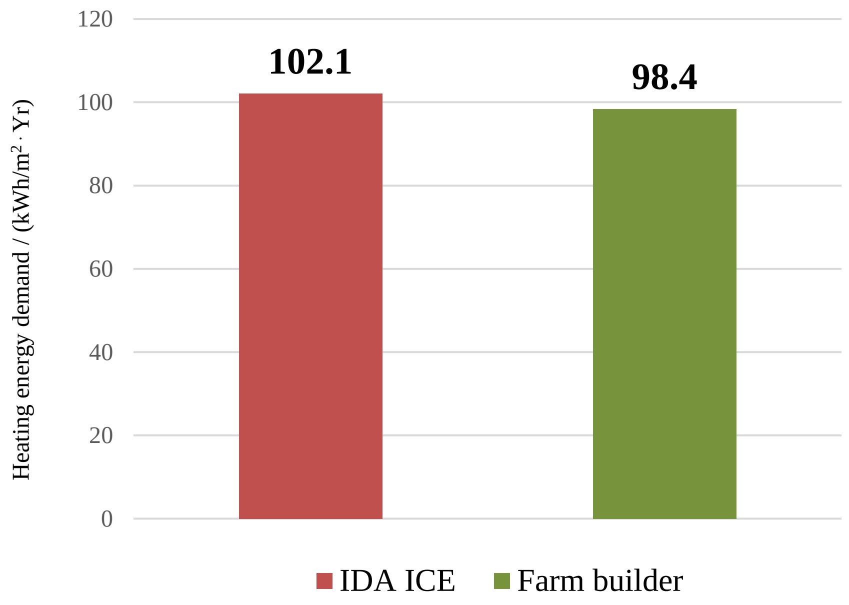


Figure 16: Annual heating energy demand when no loads, infiltration, and HVAC are assigned.

- **CASE 2: Infiltration**

Figure 17 presents the annual heating energy demand for different infiltration rates analyzed to test how these simulation tools evaluate airtightness. The comparison analysis shows that both simulation tools had similar trend from lower to increased infiltration values. IDA ICE results were slightly higher than Farm builder and the differences between both tools were so minimal. The highest margin between these simulation tools was 3% which was found on lowest infiltration values of 0.1 and 0.2 ACH.

These differences can be due interpretation of air leakage rates in both tools and their calculation methods. IDA ICE uses CELEAK model for leaks calculation between zones or between zone and environment while in Farm builder, the simulation engine uses ‘’ZoneInfiltration:EffectiveLeakegeArea model for infiltration air calculations derived from the ASHRAE Handbook of Fundamentals.

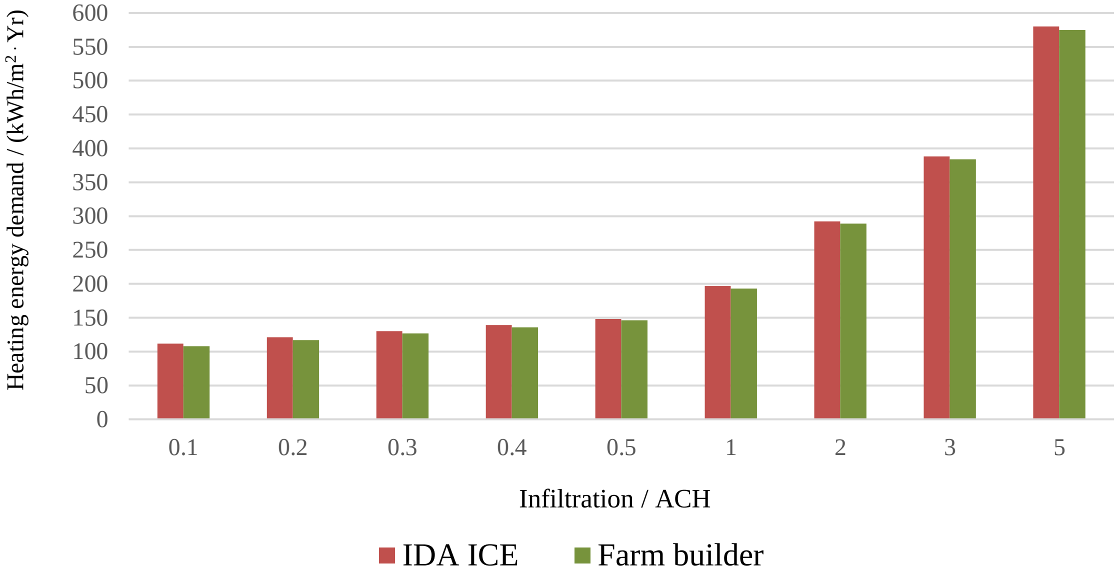


Figure 17: Annual heating energy demand based on different infiltration rates.

- **Case 3: Windows**

Figure 18 presents the annual heating energy demand for different window to wall ratio (WWR) that were assessed in both simulation tools. The results show that annual heating energy demand was increasing gradually with increased WWR in both tools. This is because transmission losses are much higher than radiation gains which can be understandable given the condition of heating dominated climates. However, IDA ICE had slightly higher heating energy demand compared to Farm builder for all the tested scenarios. The difference between IDA ICE and Farm builder was found to be slightly higher particularly at 60% and 80% WWR, which varied to 2% and 3% respectively compared to 1% which was the same for all other scenarios.

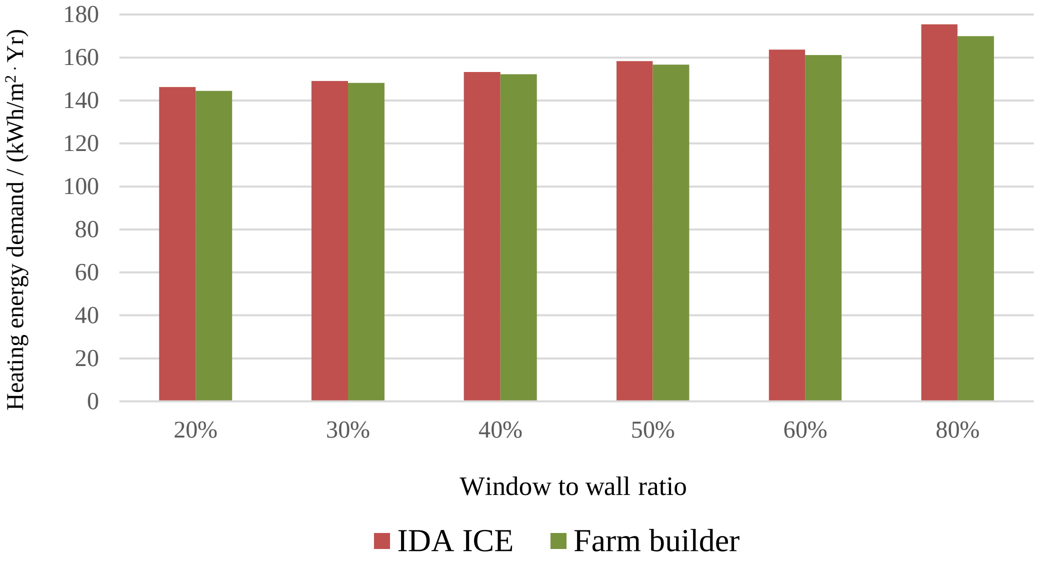


Figure 18: Annual heating energy demand based on different WWR.

As described in the methodology section, the cooling system was activated starting from this case onwards. Figure 19 presents the annual cooling energy demand of both tools for different window to wall ratio (WWR) studied. The results show that the cooling energy demand of both tools increased significantly with bigger window area. However, Farm builder had highest cooling energy demand compared to IDA ICE for all the tested scenarios. The highest demand was reported on 80% WWR where the difference was 26 kWh/m^2 which represent a margin of 25%. This can be due to higher solar heat gains calculated by the simulation engine in Farm builder.

Solar heat gains of a zone can be obtained by directly transmitted radiation through a window and absorbed solar radiation in window glazing layers. In IDA ICE, the window model computes these two types of radiation by calculating first the direct shortwave radiation through window, and later calculates the indirectly via absorption based on shading coefficient factors of the window. While for Farm builder, the simulation engine uses algorithm model from ISO 15099:2003 standard. To evaluate the amount of solar heat gains calculated for both tools, the solar radiation received through windows (WWR of 50% was considered in both tools) for each month was compared. Figure 20 shows that, the solar radiation was higher for Farm builder compared with IDA ICE for all months.

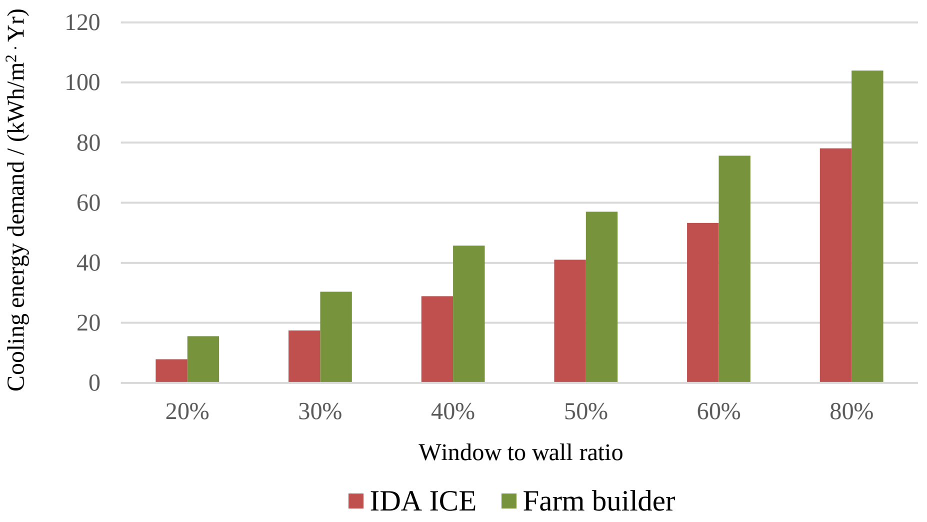


Figure 19: Annual Cooling energy demand based on different WWR.

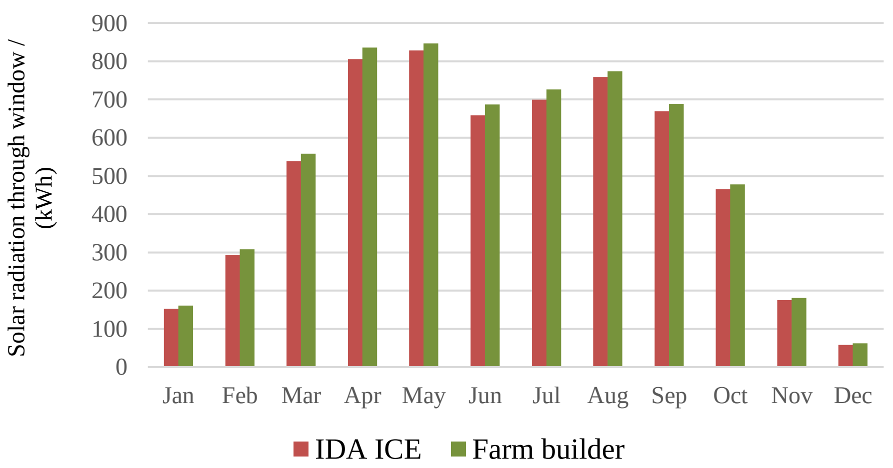


Figure 20: Solar radiation received through windows for IDA ICE and Farm builder.

➢ Case 4: Internal heat gains – Occupancy

Figure 21 presents the annual heating energy demand for different scenarios of occupancy level that were evaluated in both simulation tools. A similar trend was observed for both simulation tools, however IDA ICE had slightly higher heating energy demand compared to Farm builder. The difference increases significantly with higher level of occupancy, where for one person and two people, the difference between these tools was 3 kWh/m^2 and 5 kWh/m^2 with a margin of 2% and 4%. While, for four and five people, the difference between IDA ICE and Farm builder was 8 kWh/m^2 and 9 kWh/m^2 with a margin of 7% and 8% respectively.

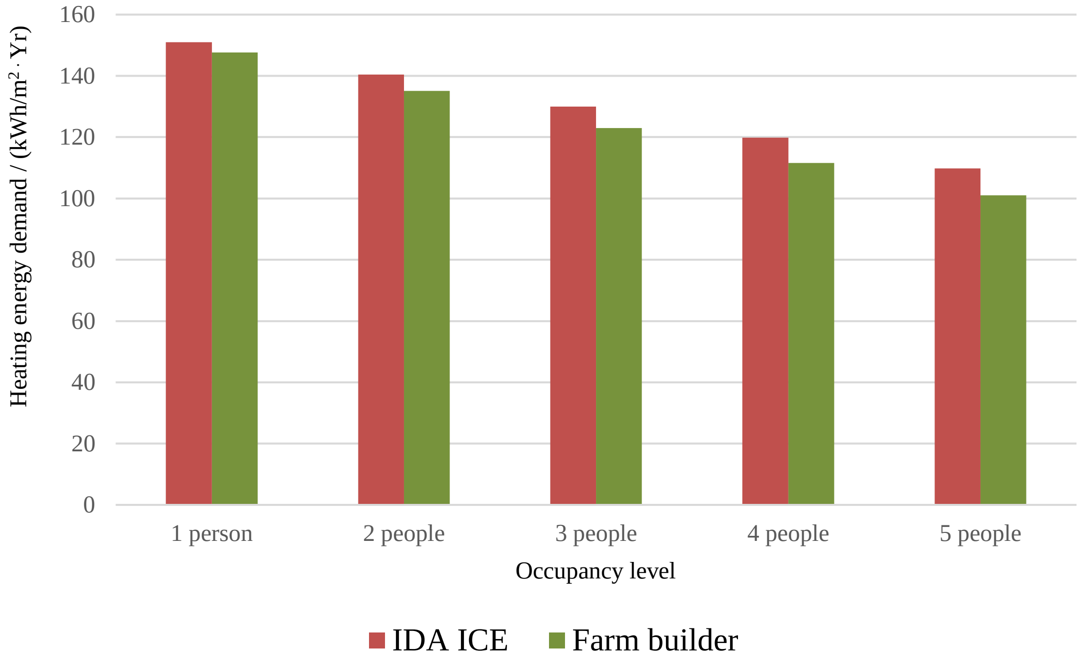


Figure 21: Annual heating energy demand based on different occupancy levels

Figure 22 presents the annual cooling energy demand of both simulation tools with different occupancy level studied. The results show that the cooling energy demand of both tools increases with increased occupancy level, however, Farm builder tool had higher cooling energy demand compared to IDA ICE for all the scenarios. The highest difference was 28 kWh/m^2 with a margin of 36% which was found for one person while for five people the difference was 17 kWh/m^2 with a margin of 21%. It can be also seen that, cooling energy demand for Farm builder was not increasing at the same extent as IDA ICE. This difference is a result of previous simulation, how both tools interpret internal heat gains for occupants and different calculation method. IDA ICE uses a calculation model which is based on ISO 7730 1984 standard to perform the internal heat load calculation from occupants. While for Farm builder, an internal algorithm is used by the simulation engine to divide the total metabolic heat gain into sensible and latent portions.

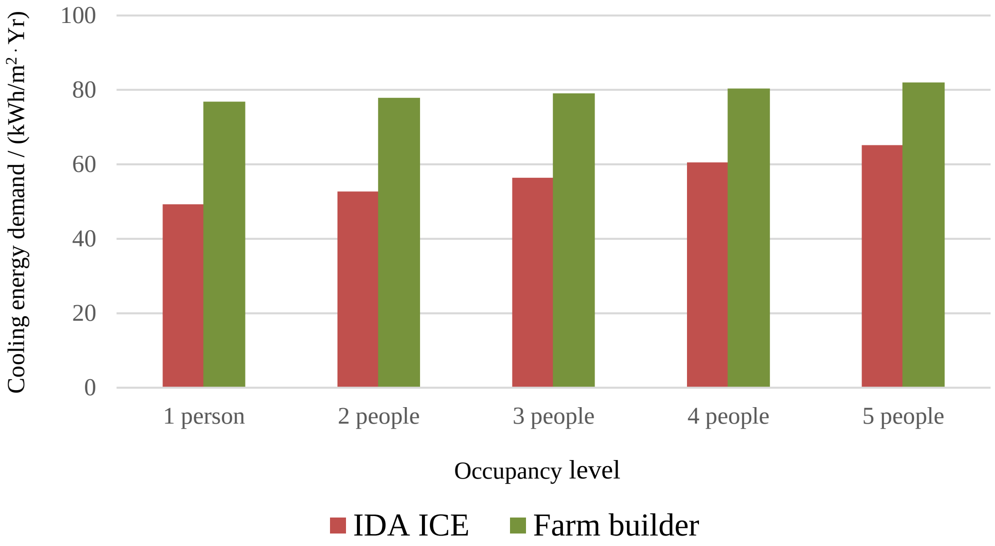


Figure 22: Annual cooling energy demand based on different occupancy levels

➢ Case 5: Mechanical ventilation

Figure 23 presents the annual heating and cooling energy demand of both simulation tools with activation of HVAC system. The results show that IDA ICE had slightly higher heating energy demand compared to Farm builder. The difference was 5kWh/m^2 with a margin of 2.8% between both tools. While for cooling energy demand, IDA ICE was significantly lower than Farm builder with a difference of 17 kWh/m^2 which represent a margin of 24.3%. This can be because in IDA ICE, the VAV system uses a control signal CentralMode which controls the air flow based on the outdoor temperature conditions while the air system used by the simulation engine in Farm builder is only controlled by schedule and zone temperature.

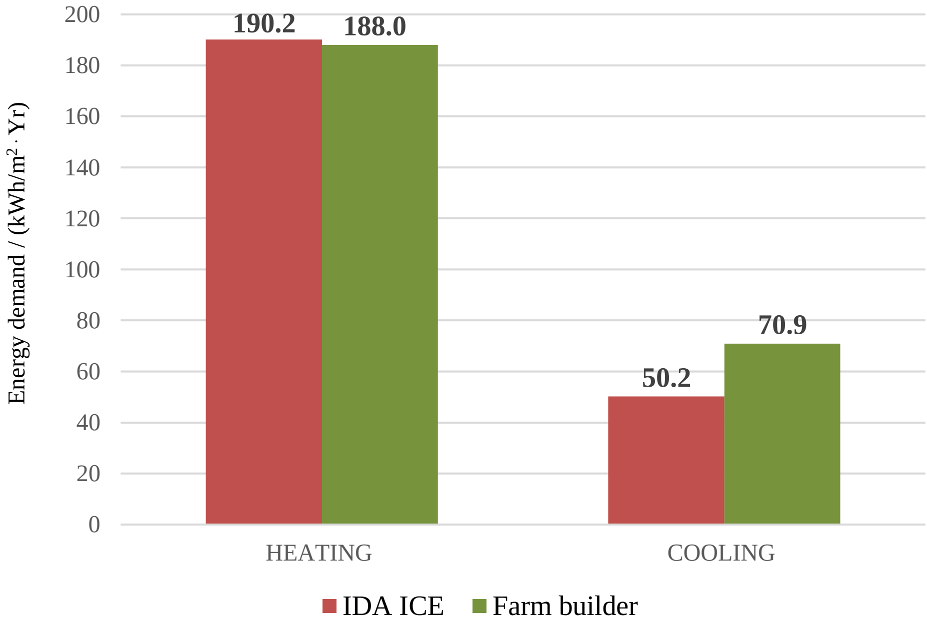


Figure 23: Annual energy demand when HVAC system was activated.

➢ Case 6: Equipment load

Figure 24 presents the annual heating energy demand obtained in both tools from lower to increased equipment loads. The results show that IDA ICE was slightly higher than Farm builder, with minimal differences across all scenarios. However, the trend indicates that; as the load increases, so does the difference in results. For 1 W/m², the difference was 1.7 kWh/m² with a margin of 1%, while for 5 W/m², the difference was 6.5 kWh/m² with a margin of 4.1%. This could be because of how equipment heat load input are defined and interpreted by both programs.

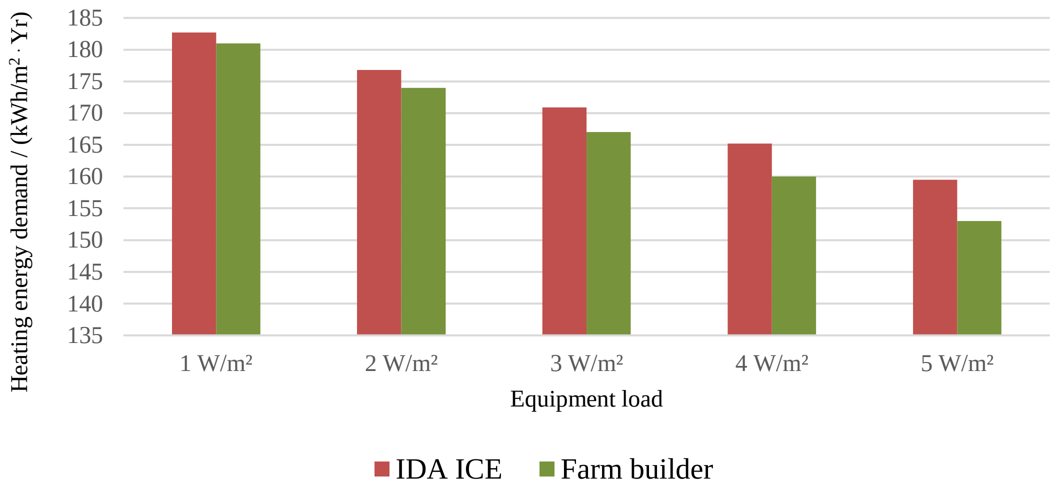


Figure 24: Annual heating energy demand based on different equipment loads.

Figure 25 presents the annual cooling energy demand obtained in both tools from lower to increased equipment loads. For all scenarios, the results show that Farm builder had higher cooling demand than IDA ICE, which is due to results of the previous simulation. Also, the trend shows that the difference in results decreases with increasing load, where a difference of 22.3 kWh/m² with a margin of 30% was found for 1 W/m², and a difference of 25 kWh/m² with a margin of 19% found for 5 W/m².

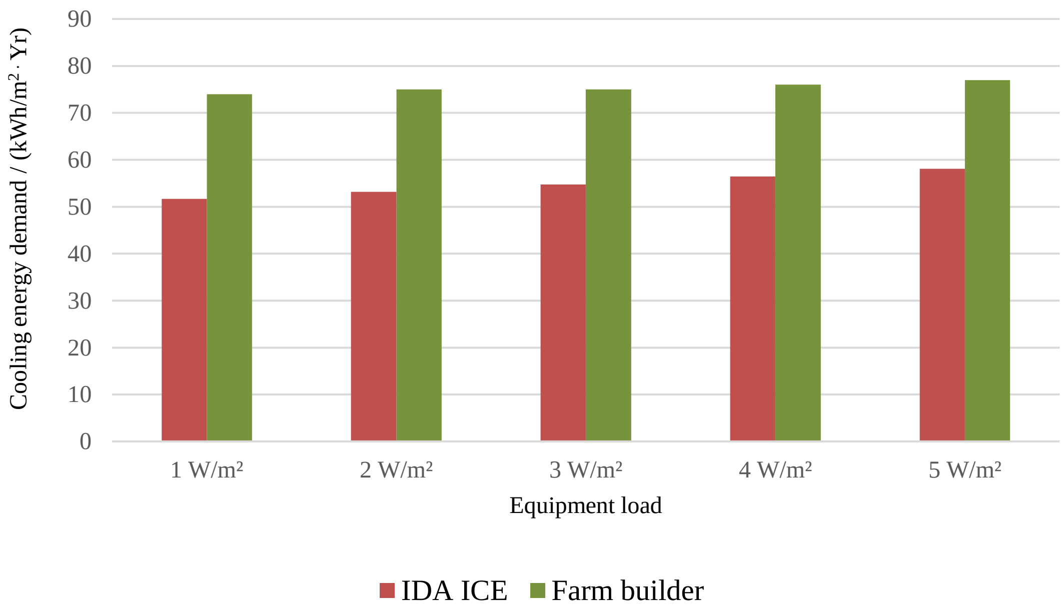


Figure 25: Annual cooling energy demand based on different equipment loads.

➢ Case 7: Lighting load

Figure 26 presents the annual heating energy demand obtained in both tools from lower to increased lighting loads. IDA ICE was slightly higher that Farm builder, with minimal distinctions for all scenarios. Similar to the previous case, the tendency of inclination indicates that; differences in results increase with load increases. For 1W/m², the difference was 1.9 kWh/m² with a margin of 1%, while for 5W/m², the difference was 5.5 kWh/m² with a margin of 3.4 %

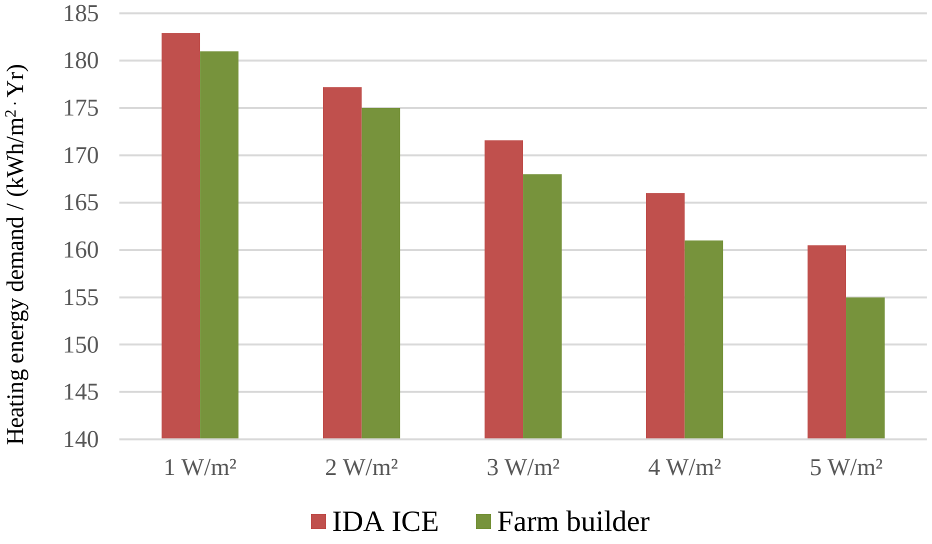


Figure 26: Annual heating energy demand based on different lighting loads.

Figure 27 presents the annual cooling energy demand from lower to higher equipment loads for both tools. Similar to the previous case, the results show that Farm builder had higher cooling demand compared to IDA ICE for all the scenarios. The trend indicates that; the difference in results decreases with increasing load. The difference found for 1W/m² was 22.4 kWh/m² with a margin of 30 % while for 5W/m², it was 19.2 kWh/m² with a margin of 25%.

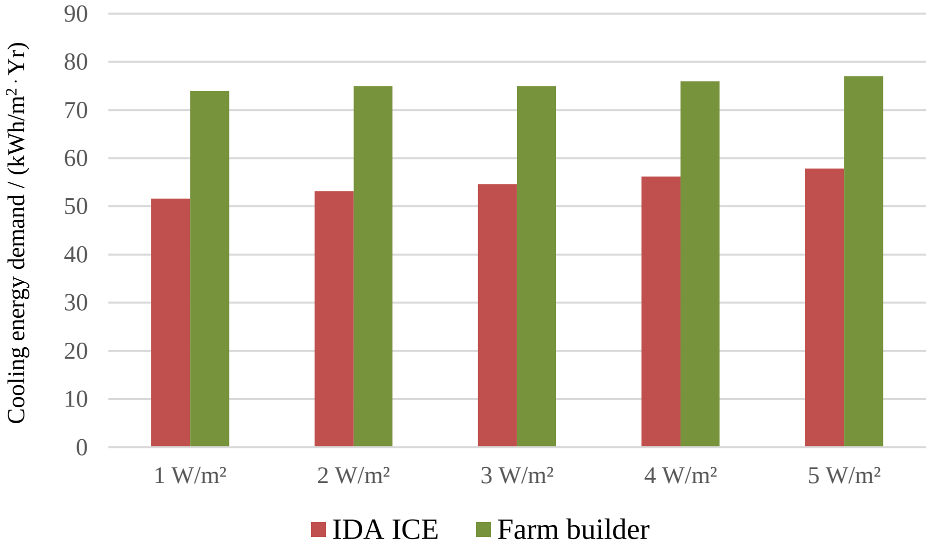
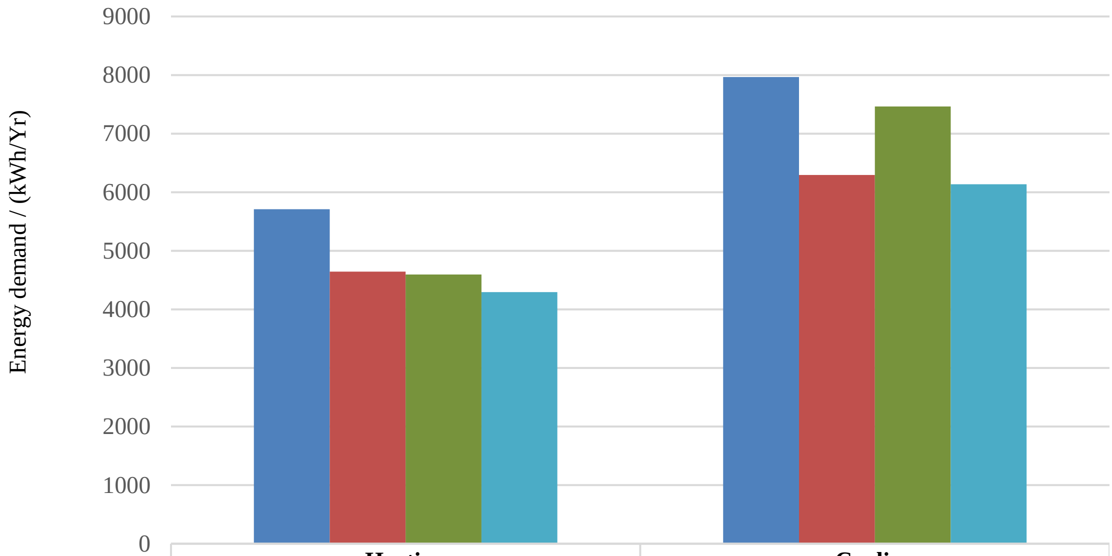


Figure 27: Annual cooling energy demand based on different lighting loads.

➢ BESTEST comparative test

Figure 28 compares the energy results of IDA ICE and Farm builder to the BESTEST results for the considered case. Since the BESTEST consist of results for various programs, the comparative approach was based on BESTEST max and BESTEST min of the reference programs (Judkoff & Neymark, 1995). As it can be seen, both tools are within range of limit, where the results of annual heating loads for both tools are close to the lower limit of BESTEST. And, for annual cooling loads, Farm builder is concentrated to the upper limit, while IDA ICE is close to the lower limit of validity range.



	Heating	Cooling
BESTEST Max	5709.0	7964.0
IDA ICE	4645.4	6296.1
Farm builder	4593.0	7462.0
BESTEST Min	4296.0	6137.0

Figure 28: Annual heating and cooling demand for IDA ICE and Farm builder compared with BESTEST results.

4.2 Host building stand-alone model

Figure 29 presents the energy use intensity (EUI) obtained from IDA ICE and Farm builder simulation tool for the host building model. According to the results, EUI of both tools are quite similar to each other. However, a notable difference was found in results of heating energy demand. This can be because of how infiltration rate input values are defined in both tools, where in IDA ICE was inserted as wind driven flow at 50Pa while in Farm builder, the simulation engine accepts infiltration rates at normal pressure conditions.

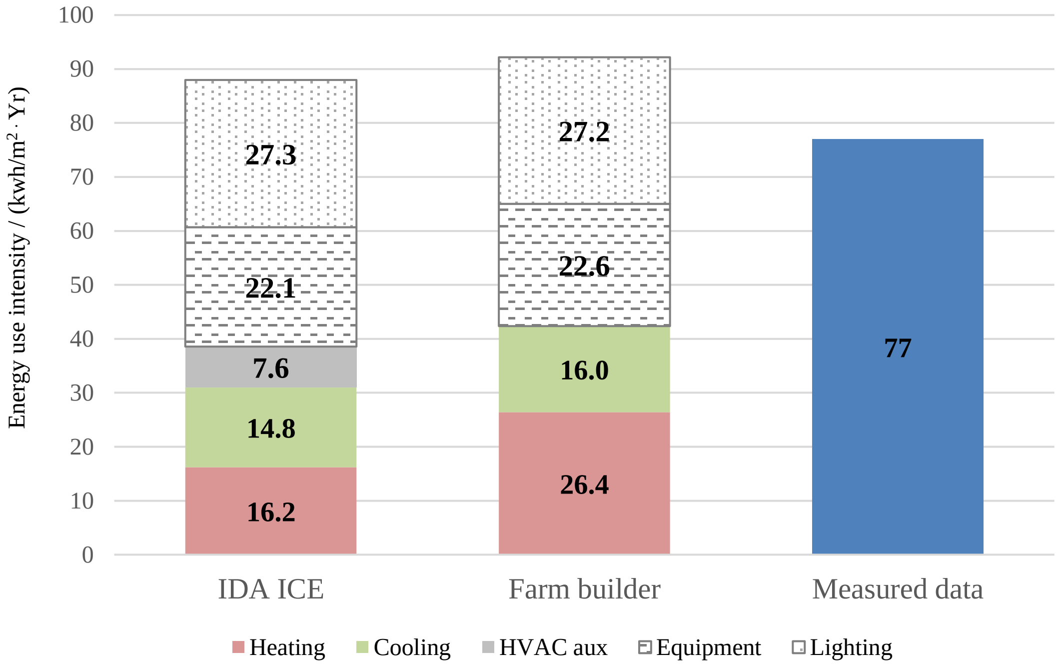


Figure 29: Energy use intensity of the host-building stand-alone model from both tools compared to measured data.

In order to validate the simulation results of the host building model, the EUI results obtained from both tools as illustrated above was compared to the data from the energy declaration of 2012 reported in a previous study for the same building (Zhang, 2021). As shown in Figure 29, IDA ICE presents a difference of 12.5% to the measured data while Farm builder reaches 16.5%. This can be judged fairly reasonable since both tools does not exceed 20% which is a minimum acceptable level of discrepancies according to ASHRAE Guideline 14 (ASHRAE, 2014) .

4.3 Rooftop greenhouses (RTG)

For this test analysis, the internal gains, infiltration rate and mechanical ventilation were all initially excluded. However, the lighting load was taken into consideration since Farm builder could not run simulation with this parameter turned off. Simply, because the farm templates used by harvest greenhouse model in the simulation workflow defines this parameter as the input data of artificial lighting when there is deficit of DLI_{crops} required for the selected crop. Therefore, the simulation results obtained under this analysis are displayed in Figure 30 below, and it can be observed that Farm builder yields the highest results of EUI compared with IDA ICE mainly due to the substantial cooling demand. This can be because of the evapotranspiration model integrated within Farm builder while being a limitation for IDA ICE tool, as it does not incorporate such model.

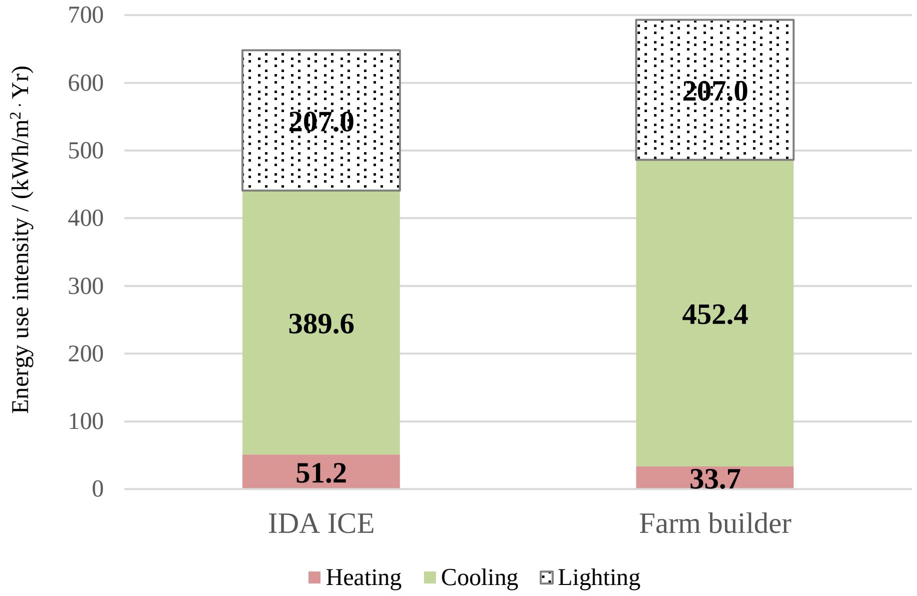


Figure 30: Energy use intensity of the RTG model when inputs for (loads, infiltration and HVAC system) were excluded.

Figure 31 presents EUI results after all internal loads, schedules, infiltration and HVAC system was applied in both tools. According to the displayed results, EUI value stays almost on the same level with a trivial change, however, there are still differences as Farm builder had higher cooling energy demand compared to IDA ICE while energy demand for heating returned to be lower.

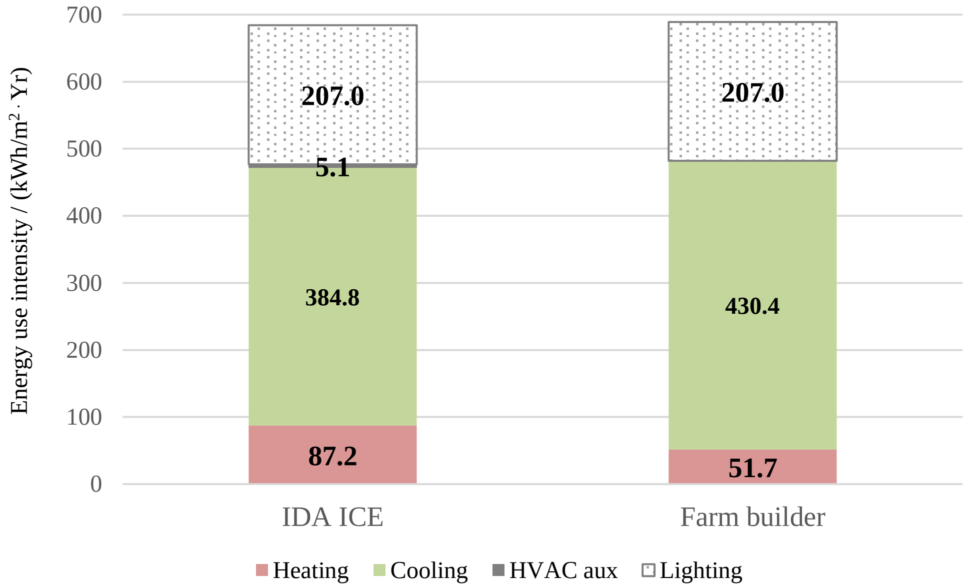


Figure 31: Energy use intensity of the RTG model when all inputs were assigned.

5 Discussion

This section discusses the interpretation, analysis and differences of simulation results found between IDA ICE and Farm builder tools by focusing on their calculation method and other aspects used to perform the simulation of energy demand for heating and cooling.

5.1 Building energy model comparison

In terms of static calculations, the analysis conducted on opaque surfaces (wall, roof and ground) of the shoebox model to evaluate the impact of insulation thicknesses on heat transmittance showed no major differences between simulation results of both tools unless for ground thickness variations. By validating both tools in comparison to Excel EnergyCalc, produced results for IDA ICE presented no differences while Farm builder still shown divergences on ground variations. And it was revealed that the differences are significant, particularly on smaller insulation thicknesses. Besides, from the different calculation method applied by both tools as mentioned earlier in result section. Another key factor to explain this difference could be values of the thermal resistance (Rsi, Rse) and their calculation algorithm used within both tools.
A study that compared both simulation tools in terms of dynamic simulations also pointed out differences between results for both case studies evaluated. From the results taken out from the analysis conducted on the shoebox model, IDA ICE indicated highest heating demand for all the cases evaluated in this study whereas Farm builder had lowest heating demand. On the other hand, Farm builder reported the highest values for cooling demand for all the cases while IDA ICE had the lowest values. This can be explained by the fact that IDA ICE uses algorithmic model which accounts for more losses due to infiltration and radiation in the energy balance calculation compared to Farm builder.

In addition, a slight difference that was noticed between the thermal values calculated from both simulation tools as shown in Appendix C can contribute to the differences of simulation results obtained. This is especially evident for case 1, when no other influencing factors are introduced, a different way of U-value calculation for opaque surfaces in both tools could be substantial on differences between losses due to transmission. In terms of windows analysis, a notable difference between IDA ICE and Farm builder was found on cooling energy demand. This is due to the solar transmission through windows, which were relatively higher for Farm builder compared with IDA ICE as shown in Figure 20. It was also indicated that, given the same thermal properties of glazing unit, both tools provide divergences among calculation of windows U-value and SHGC as shown in Appendix C. This can be due to different boundary conditions used for window U-values calculations in both tools. IDA ICE uses boundary conditions set according to EN 673:2011 while in Farm builder, the EnergyPlus engine calculates window thermal properties with boundary conditions set according to NFRC 500 documentation (Bülow-Hübe, 2001).

There were also significant differences for occupancy variations, with Farm builder resulting in higher cooling energy demand overall. As mentioned earlier, both tools interpret occupancy levels differently and their calculation methods apply different way of determining sensible and latent heat gains.

For mechanical ventilation, the differences can be attributed to the air system control as both tools uses different approaches to predict the air system responses and adding to the fact that the calculation equation applied in order to determine the air system output are different. Another prominent reason could be the coil air supply temperature used by both tools. In Farm builder the supply air temperature is set by default to 16˚C and was constant for heating and cooling. On the other hand, Farm builder tool does not offer the option for this input parameter which instead is controlled within the program.

In second case study for the host building stand-alone model, the EUI results obtained for both tools indicated differences majorly in energy demand for heating. As mentioned in result section, this difference can be influenced by interpretation of infiltration rates values. In IDA ICE, the wind driven infiltration flow of 0.5 ach at 50Pa was used and in Farm builder, it was converted to infiltration value of 0.1ach with the help of infiltration converter Excel file as shown in Appendix A, because this tool requires infiltration rate at 4Pa.

With validation of host building simulation results to measured data, both tools showed deviations. This could be explained with the fact that some of the inputs used in simulation does not exactly reflect the actual performance of the building. For instance, the setpoints may not be constant throughout the whole year as occupants have individual choices of temperature set-points in different zones. Also, the uncertainties in the occupancy behavior such as from their presence or windows opening affect equivalent heat gains and may play a big role in the difference between simulated results and measured data. Another reason which can be considered is the weather file, since the simulation results were obtained under a weather file of 2021 and there is no guarantee that these climatic data correspond to actual climate of 2012.

5.2 Rooftop greenhouse model comparison

The energy use requirement of the RTG for Lettuce crop production was simulated and compared between both tools. During evaluation of simulation results, both tools reported significant difference in the energy demand for heating and cooling. The differences of this results, however, could depend on the fact that the calculations in Farm builder include the influence of crops transpiration which is a key factor in energy demand of RTG. On the other hand, this is a limitation for IDA ICE in simulating greenhouse models since it does not employ calculation models to process this phenomenon.

The crop transpiration has an impact on sensible and latent heat exchange within the RTG environment, leading to large amount of energy demand required mainly for cooling purpose. In Farm builder, the evapotranspiration model is integrated in harvest greenhouse model for calculations related to the energetic behaviour of such crop processes, for how it transpires and exchange heat between leaf canopy and the surrounding air. To achieve this, the mathematical equation as shown in section 3.2.2, includes calculations of the heat flux derived from the absorption of solar radiation (shortwave and longwave) in a multilayer canopy and account for energy exchange from multiple layers of greenhouse plants. (Pamungkas & Hatou, 2014)

In spite of that, these differences are also associated to the number of factors elaborated earlier on building model comparison.

6 Conclusion

Rooftop greenhouses (RTG) is an emerging technology for growing crops in urban areas and has recently resulted in the development of Farm builder simulation tool for predicting energy use of such application. This study aimed to comprehend the certain aspects of the functioning for this tool and the way it performs energy calculations in comparison to IDA ICE.

The use of Farm builder and IDA ICE was initially evaluated on the building-scale. Based on steady states calculations, the findings can confirm that, different method applied by both tools to calculate the heat resistance for ground surfaces, impact at a large extent the differences obtained in energy demand results. However, such information can be insufficient for assessing performance for these tools given the fact that, all parameters were excluded on this case analysis.

Considering dynamic calculations, the study revealed challenges which could be regarded as the impacts of the differences in energy use results of the evaluated case studies. The impacts of different calculation methods, the way both tools calculate thermal values of the building envelope and interpretation of input parameters, were discussed in this study.

For parametric analysis, the reported results for energy demand were different for each tool, however they followed similar trend. All differences are mainly due to different calculation methods. Normally, because the simulation engine that works behind in Farm builder is based on different calculation methods compared to mathematical algorithmic models of IDA ICE. Additionally, the differences highlighted for each tool in defining input specification such as infiltration rate, occupancy, operating schedules and limitation regarding output information especially for HVAC system can be considered to cause the differences in the energy results obtained.

A comparative study on these tools to evaluate their performance with addition of RTG was also achieved. The outcome that, Farm builder calculate higher energy demand compared to IDA ICE due to the evapotranspiration model built in the program might be the possible reasoning for the differences found between the results of both tools. This model accounts for the energetic fluxes of sensible and latent heat and the corresponding vapor production associated with the production of crops in RTG.

In conclusion, the comparison test suggests that IDA ICE reasonably outperforms Farm builder for assessing building models as it shows smaller deviations from the measured data of the host building. Nevertheless, its capability to allow more user control, such as detailed customization options for some important parameters makes it more favorable. Although, it is important to note that Farm builder also yields comparable results with IDA ICE, as in most cases, it has been shown that it provides low level of disparity. In terms of RTG model performance, Farm builder is distinguished as the best option, as its simulation workflow offers sub models that calculate and control variables affecting the energy use intensity of the agriculture environment, while IDA ICE tool would require further development to integrate mathematical equation that can calculate energetic requirement of such model as well as creating new features to help defining related inputs specifications.

Additionally, Fam builder was identified as the most appropriate in terms of simulation time and its simplicity makes it perceived as user-friendly simulation tool. However, its limitation can also be seen in both simulation input and output information.

Lastly, as this study overlooked some of other areas such as thermal comfort and climate analysis, it is of great importance for future studies to take into consideration such analysis. Also, further investigation is needed on Farm builder regarding the performance of other types of BIA.

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Appendix A

INFILTRATION RATE CALCULATOR		
EXAMPLE ONLY, please fill in your own data (C5, C7, C10, C17)		
Infiltration rate @50Pa acc. to case studies from literature (e.g. the above source)	1.2187	$l/s/m^2$
	0.0012187	$m3/s/m^2$
External envelope area (excluding ground: no air leakage, excluding internal walls)	36024.7	m^2
Volume of air leakage per hour	158051.887	m^3/h
Volume of the building	290568.6	m^3
INFILTRATION RATE @ 50Pa	0.54	ACH
INFILTRATION RATE @ 4Pa	**0.1108**	ACH
INFILTRATION COEFFICIENTS:		
A. Constant Term Coefficient	0.606	
B. Temperature Term Coefficient	0.03636	
C. Velocity Term Coefficient	0.1177	
D. Velocity Squared Term Coefficient	0	

Figure 32: Infiltration rate calculator excel sheet

Appendix B

Transmision

U-values for doors and windows are given by the supplier

	U (W/m^2,K)	A (m^2)	UA (W/K)	UA (W/K) effective
Windows	0.00	0.00	0.00	
Doors	0.00	0.00	0.00	
Wall	0.31	170.15	52.44	
Roof	0.20	102.00	20.48	
Ground	0.45	102.00	45.90	
Total			118.82	118.8

1

Write a multiplication value to include thermal bridges here.
1.1 for a modern passive house
1.4 for an old house

Swedish green building council use a value of 1.25.
http://www.sgbc.se/dokument-och-manualer

$$Q_{vent} = \rho * c_p * q_{vent} * (1 - \eta) + \rho * c_p * q_{leakage}$$

ρ_{air} densiy for air typical value for room temperature is 1,2 kg/m³	1.2	
$c_{p\,air}$ Specific heat capacity for air, typical value 1000 J/(kg·K)	1000	
η (temperature efficiency), typical value for heat exchanger is 75% (0,75	0	
Atemp, totala living area for all floors	102	m^2
Intentional ventilation:		
$q_{vent,need}$ Swedish standard says 0.35 liter/s/m²	0.00	l/s/m^2
q_{vent}	0	m^3/s
Unintentional ventilation:		
q_50 (0.0003 m³/m²/s = 0.3l/m²/s for a passive house)	0	m³/m²/s
k	30	
q_leakage	0	m³/m²/s
A_surrounding (sum of wall, roof, window och door area.)	272.15	m²
$q_{leakage}$	0.0000	m^3/s
$Q_{int\_vent\_with\_heat\,recovery}$	**0.0**	**W/K**
$Q_{leakage}$	**0.0**	**W/K**
$Q_{total\_vent\,and\,infiltration\,with\,heat\,exchanger}$	**0.0**	**W/K**
$Q_{int\_vent\_without\,heat\,exchanger}$	**0.0**	**W/K**
$Q_{leakage}$	**0.0**	**W/K**
$Q_{total\_vent\,and\,infiltration\,without\,heat\,exchanger}$	**0.0**	**W/K**

$q_{vent} = q_{vent,behov}$ * Atemp

q_leakage = q_50 / k
where;
q_50 is the leakage at 50 Pa over pressure (SS-EN 13829)
k is 20 for natural and och balanced ventilation and 30 for evacuation fan driven systems
SS 24300-1, p 13-14

Dimensioning outdoor temperature with heat recovery		°C
Dimensioning outdoor temperature without heat recovery	-7.9	°C
Effictive indoor temperature	20	°C
Annual average outdoor temperature	8.3	°C
Degree hours	102492	Kh
Transmission losses	119	W/K
Ventilation losses without heat recovery	0	W/K
Ventilation losses with heat recovery	0	W/K
Powerneed for heating, without heat recovery on the ventilation	3315	W
Powerneed for heating, without heat recovery on the ventilation	33	W/m^2
Powerneed for heating, with heat recovery on the ventilation	2376	W
Powerneed for heating, with heat recovery on the ventilation	23	W/m
Annual energyneed for heating without utan heat recovery on the ventilaiton	12178	kWh/år
Annual energyneed for heating without utan heat recovery on the ventilaiton	119	kWh/m^2,year
Annual energyneed for heating without utan heat recovery on the ventilaiton	12178	kWh/år
Annual energyneed for heating without utan heat recovery on the ventilaiton	119	kWh/m^2,year

Se sheet DVUT for dimensioning outdoor temperature

Note tha the sun and the internal gains heat the house. This allows us to heat the house only to 17°C instead of to 20°C. This simplification is only true for "normal" houses. Passive houses have different behaviour.

Annual outdoor temperature in Malmö is approximately 8-9°C.

Figure 33: Energy calculation excel sheet representing calculation of transmission losses, Ventilation losses and Heating energy demand results

Appendix C

Table 11 : Estimated heat transfer coefficient values by both tools for opaque surfaces

Opaque surfaces	Farm builder	IDA ICE
Façade (W/m^{2}K)	0.516	0.51
Roof (W/m^{2}K)	0.319	0.316
Floor (W/m^{2}K)	0.039	0.038

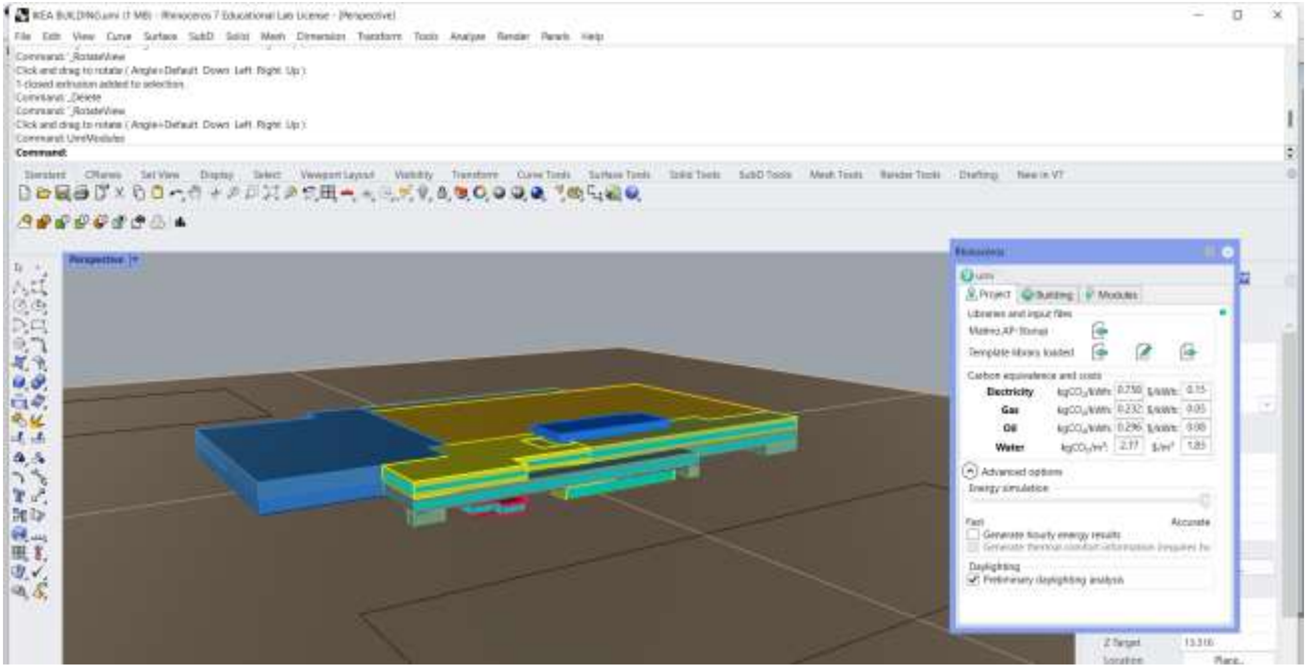
Table 12 : Estimated heat transfer coefficient and SHGC values by both tools for window glazing

Double pane glass window (D4-12)	Farm builder	IDA ICE
U-value (W/m^{2}K)	2.725	2.9
SHGC	0.788	0.79

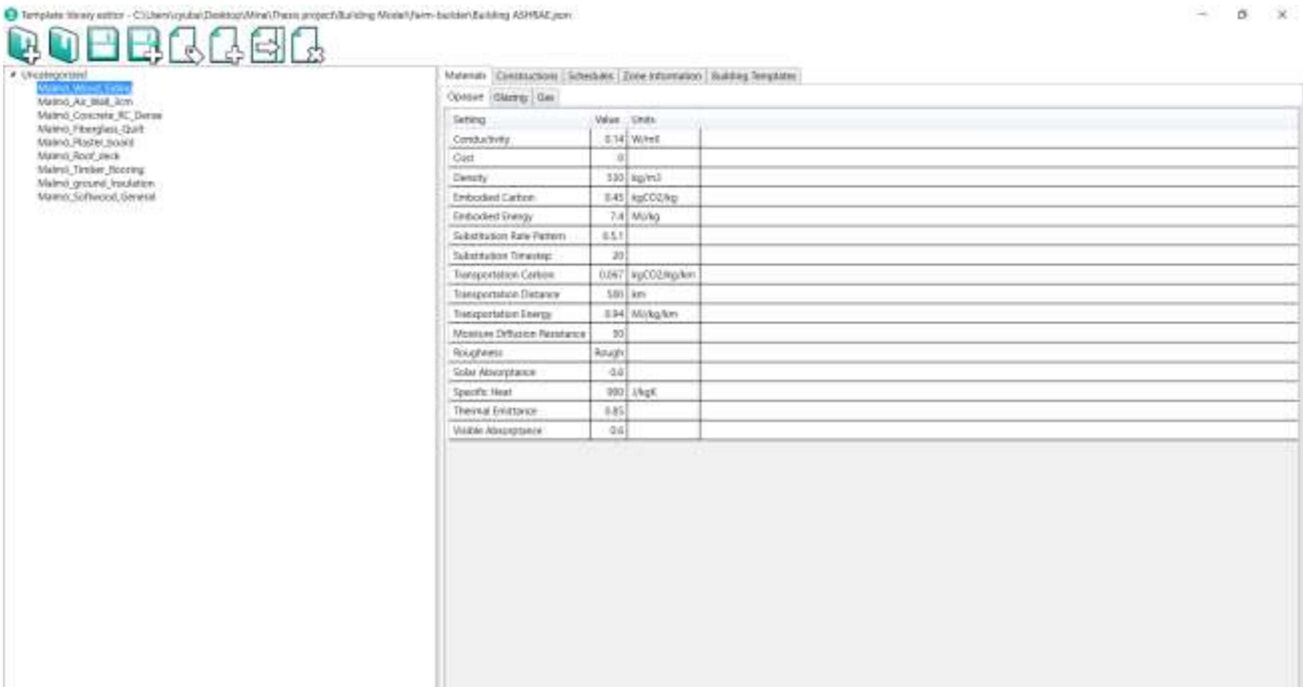
Appendix D

Simulation workflow of Farm builder energy simulation software

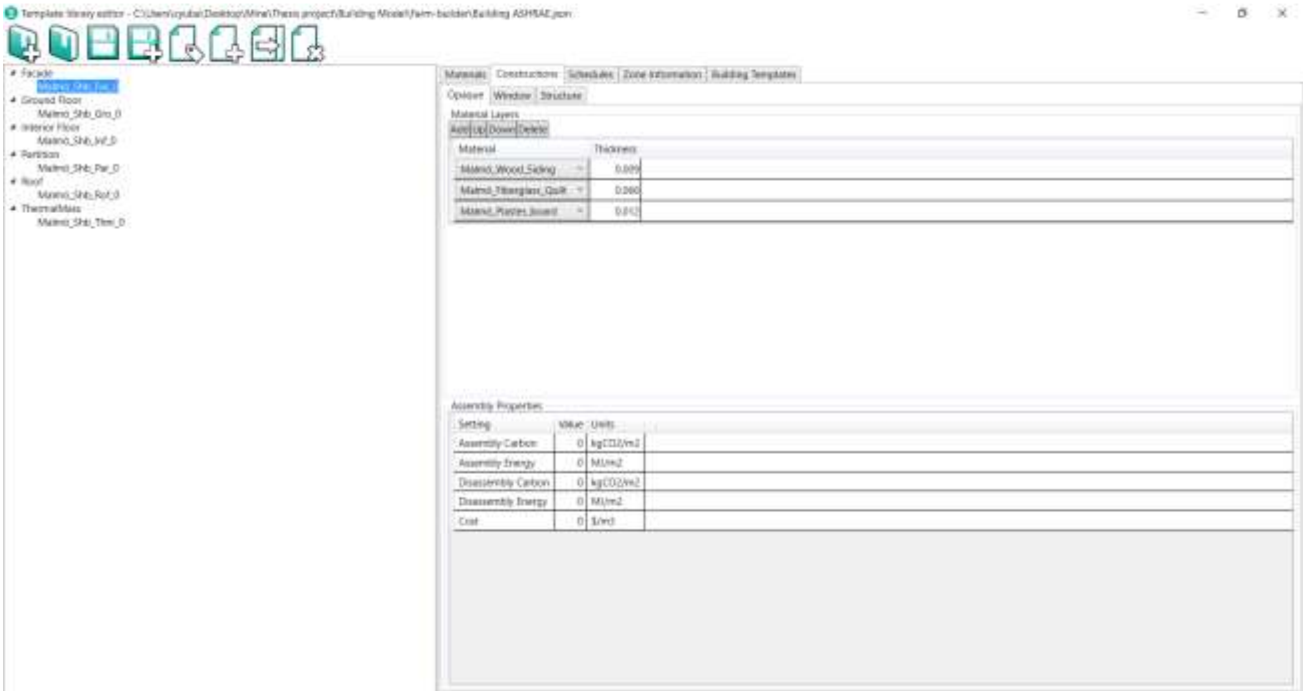
- Open Rhino
- Model the building geometry



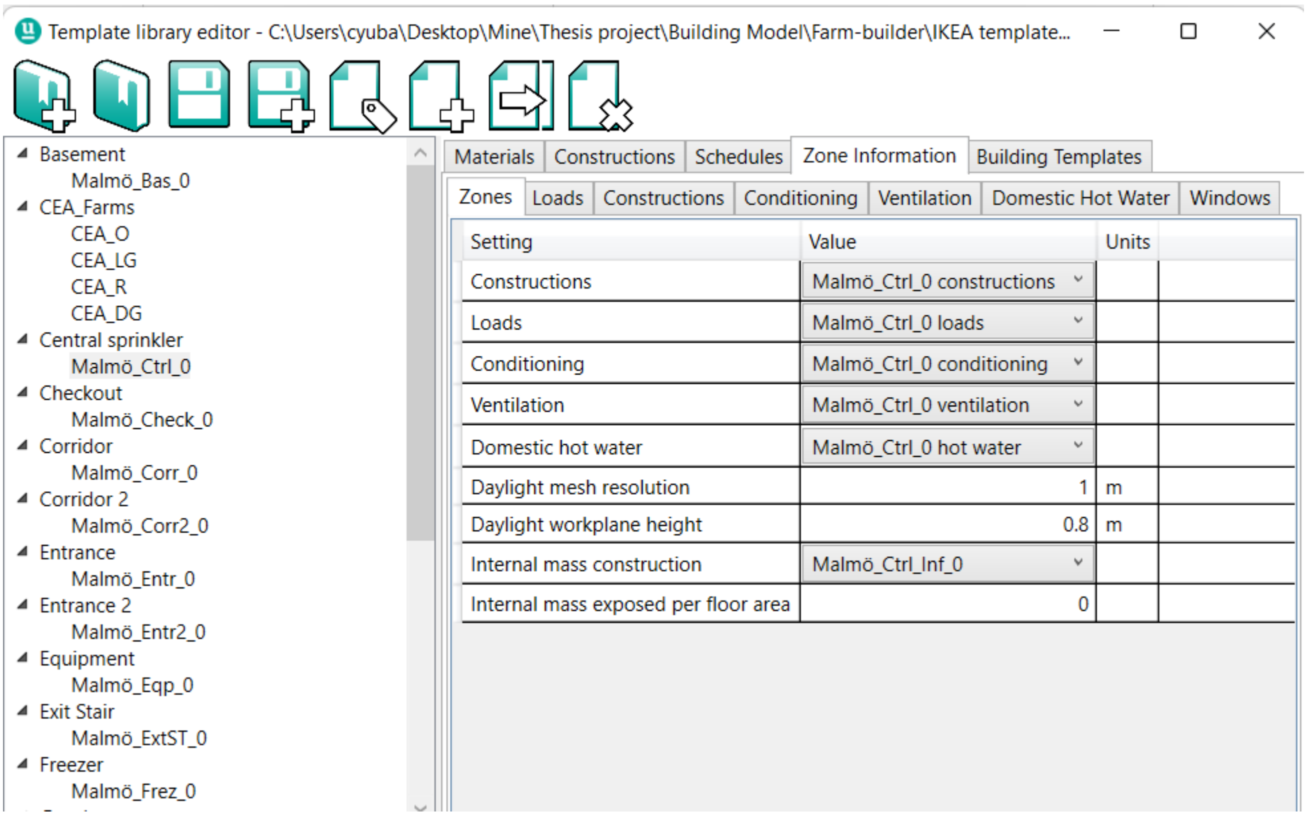
- Open the template editor to define inputs settings
  - Define thermal properties of construction materials



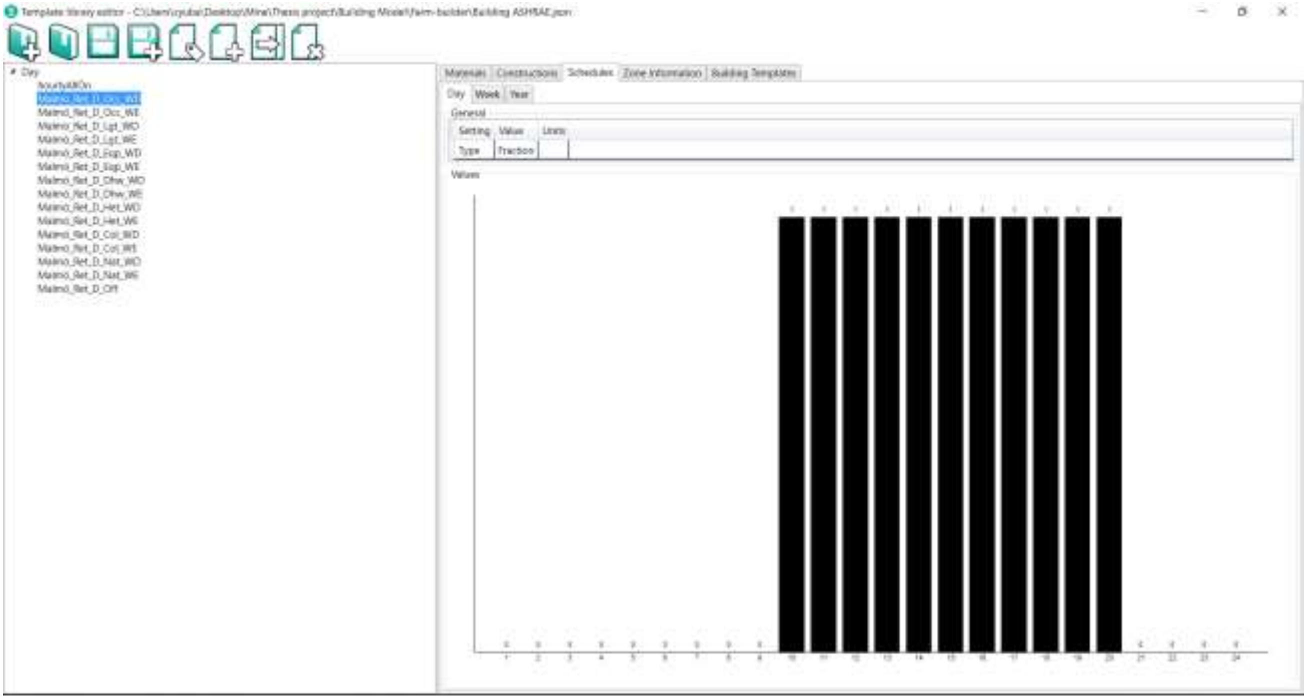
➢ Add thicknesses for opaque surfaces



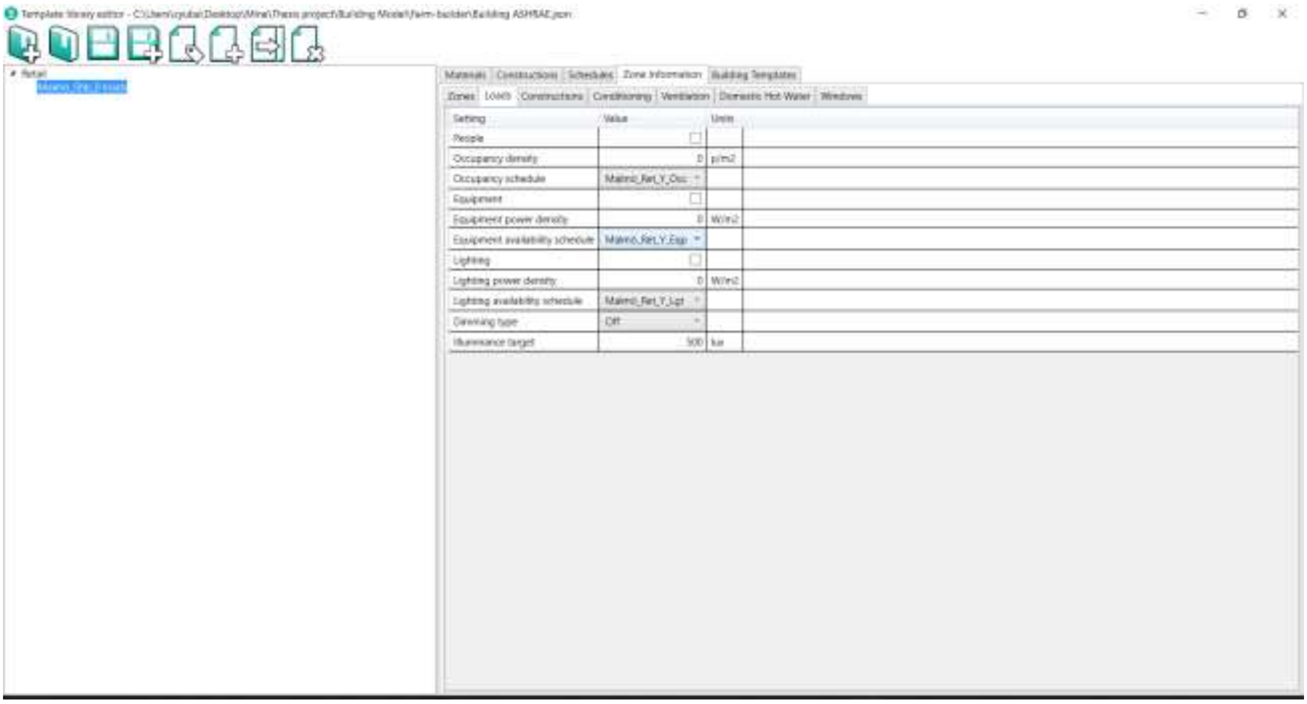
➢ Define building zones



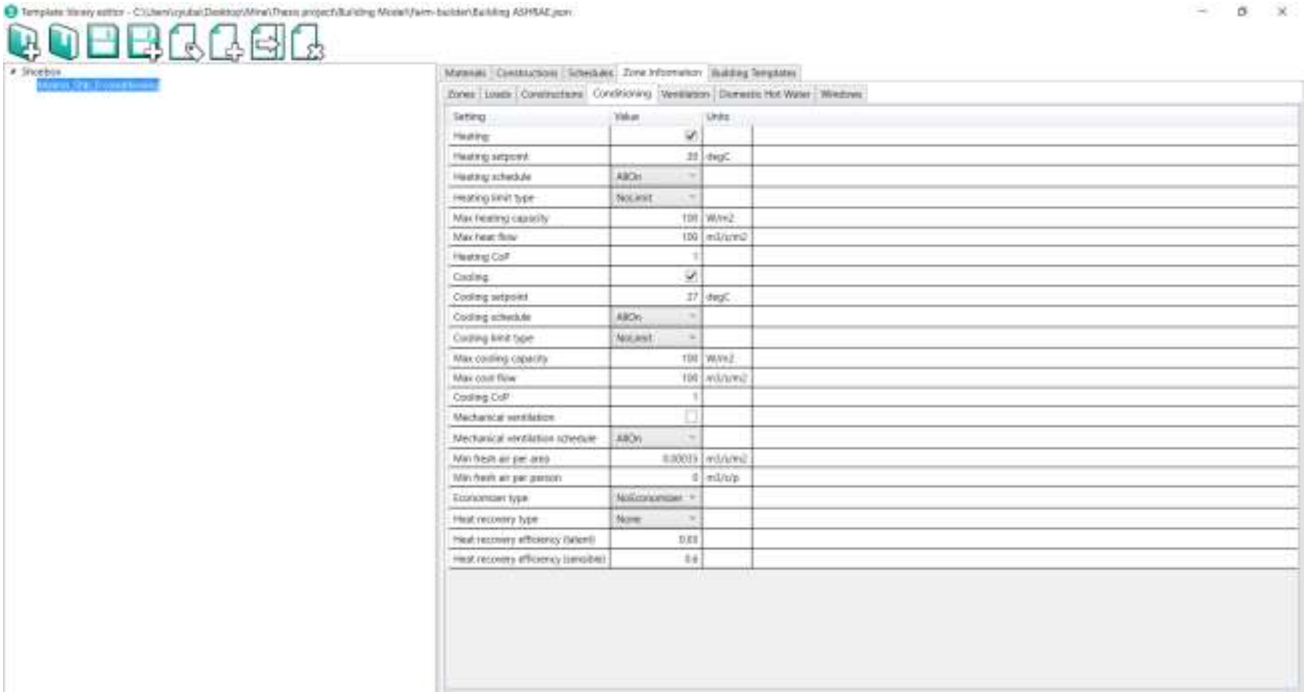
➢ Define schedules



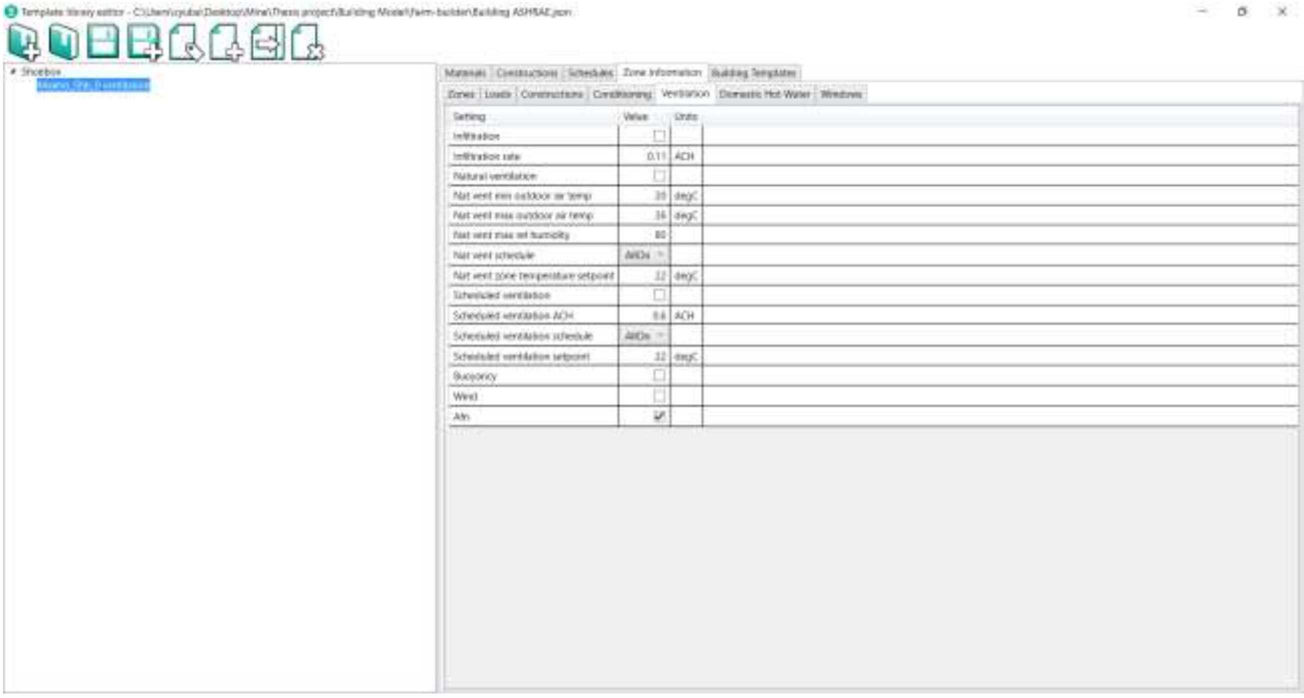
➢ Define internal heat loads



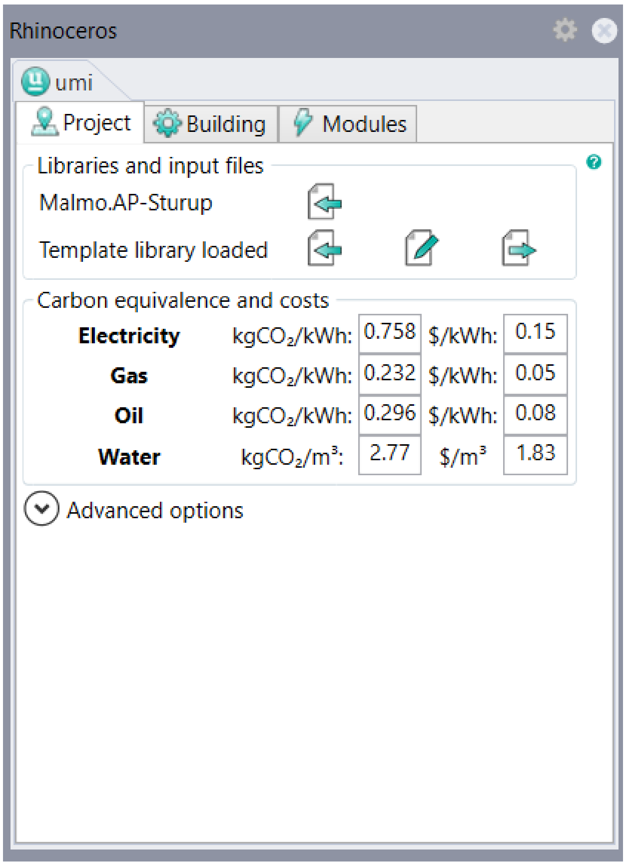
➢ Define the heating and cooling setpoints and mechanical ventilation inputs



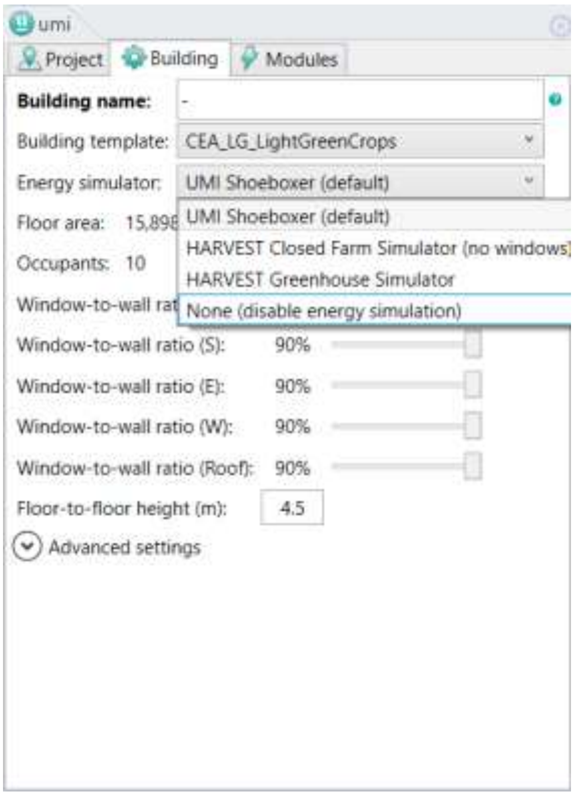
➢ Define the air infiltration and natural ventilation inputs



- Import the weather and the input template files



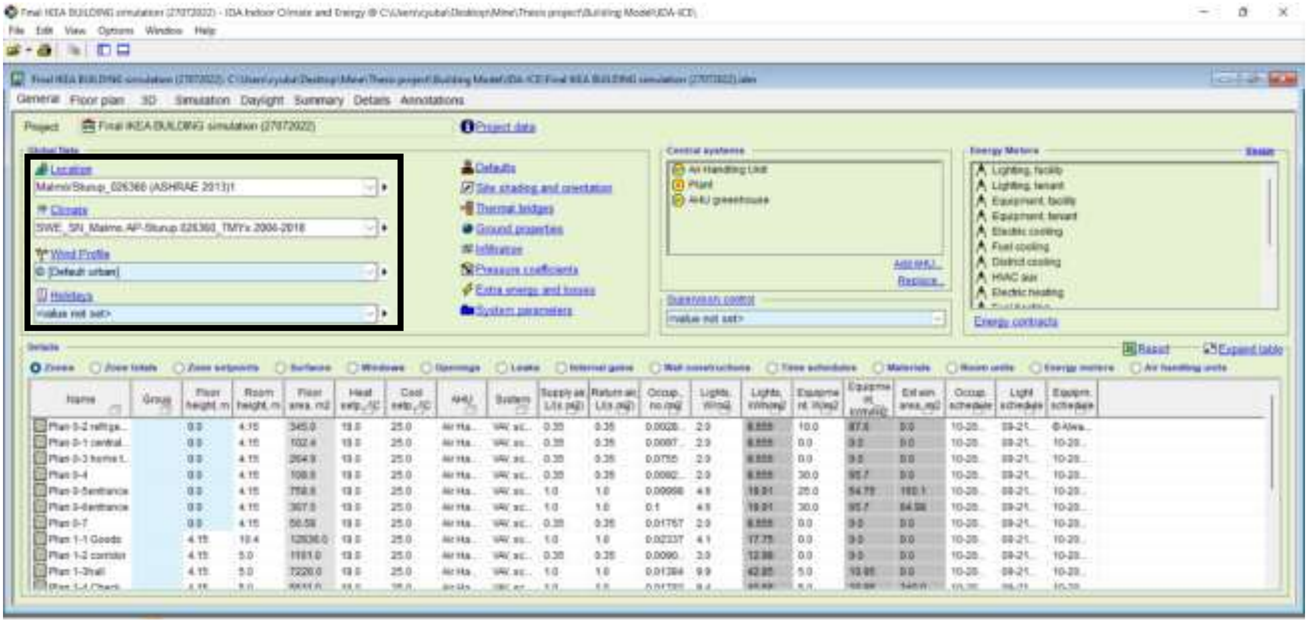
- Select the energy simulator and run simulations



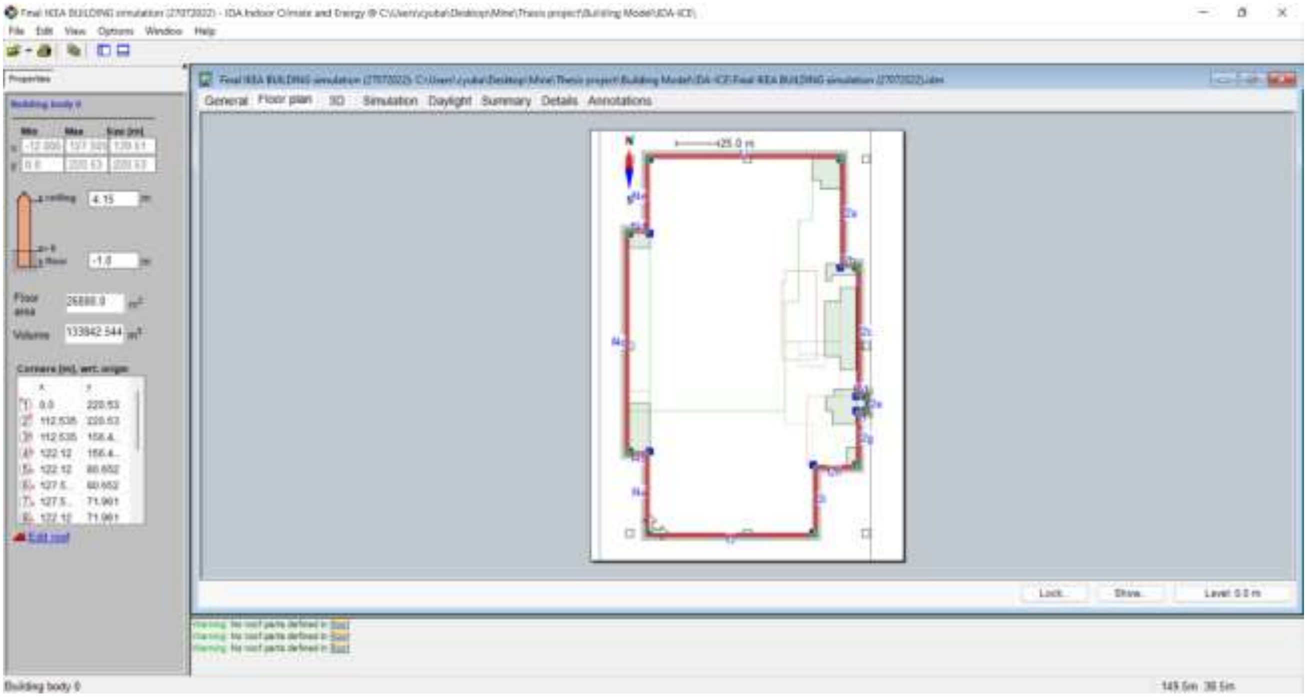
Appendix D

Simulation workflow of IDA ICE energy simulation software

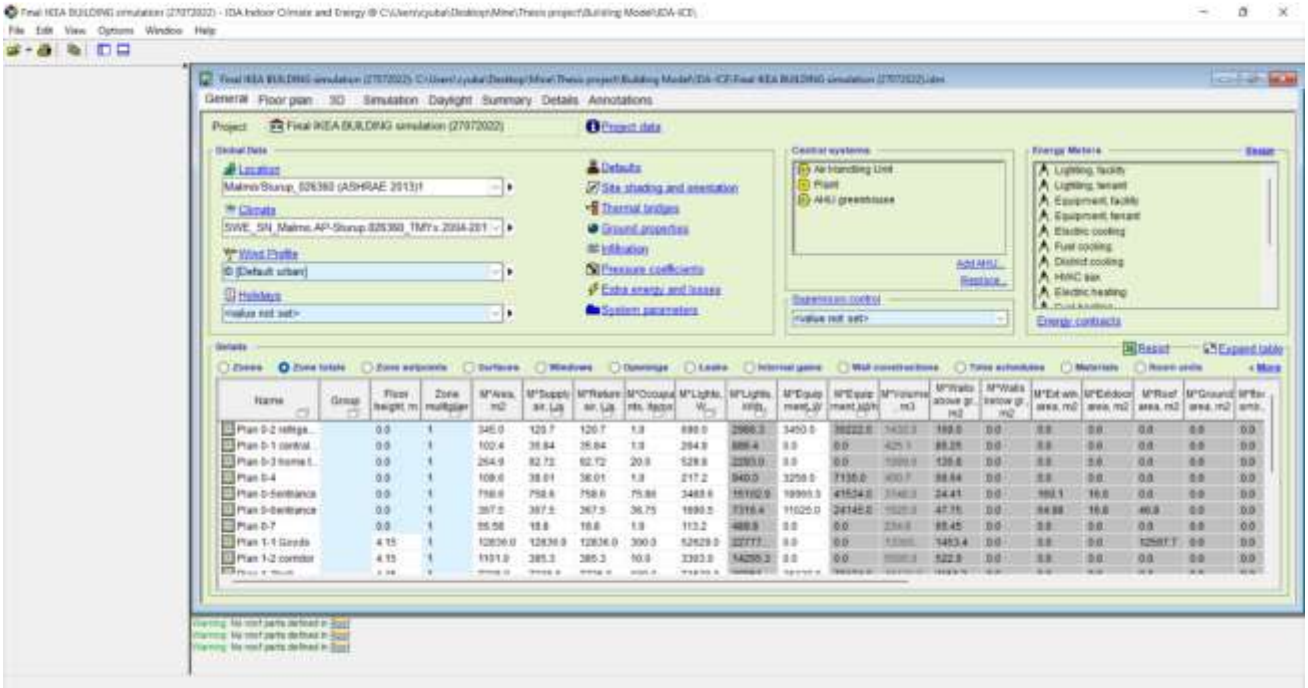
- Open IDA ICE
- Load or import the climate file of the studied case



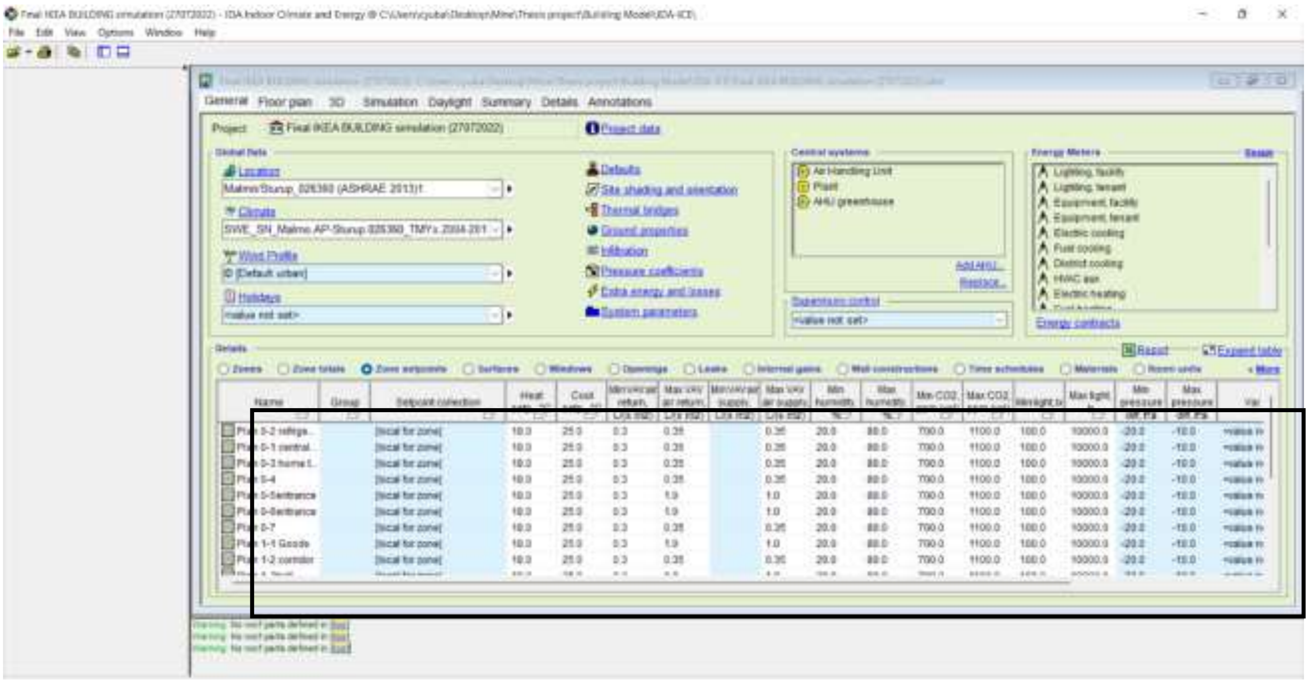
- Modelling the building geometry



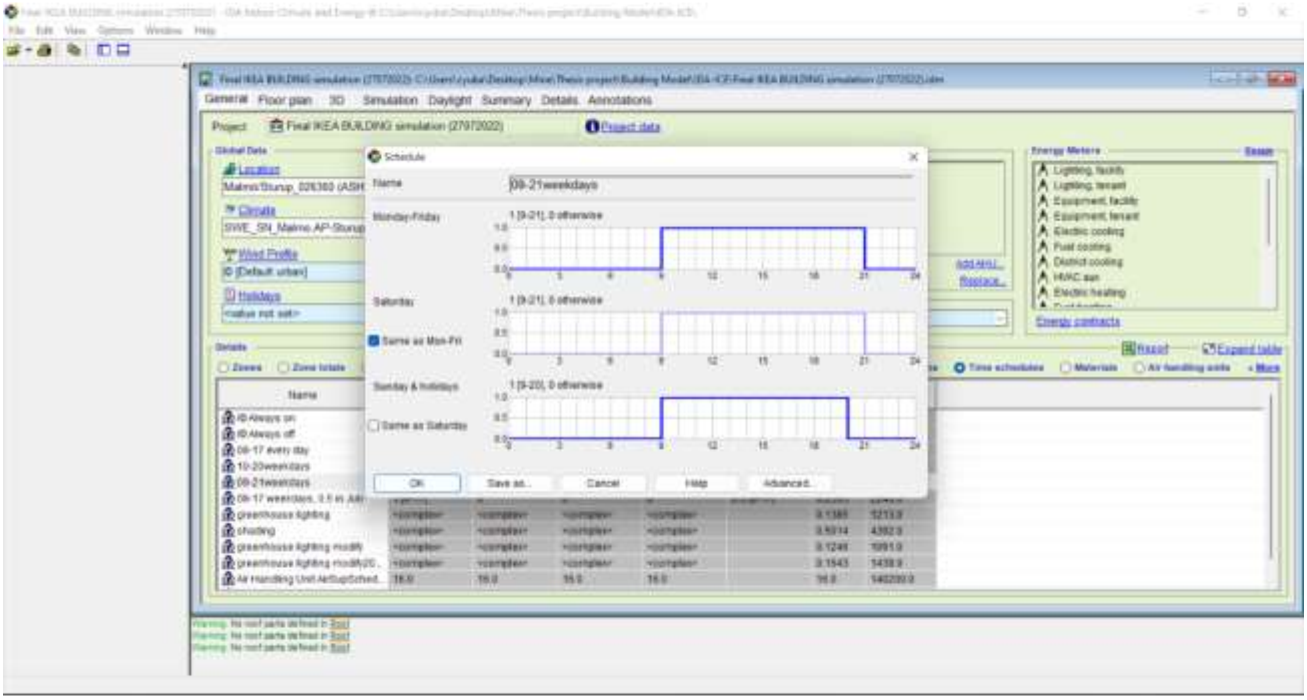
- Define building zones

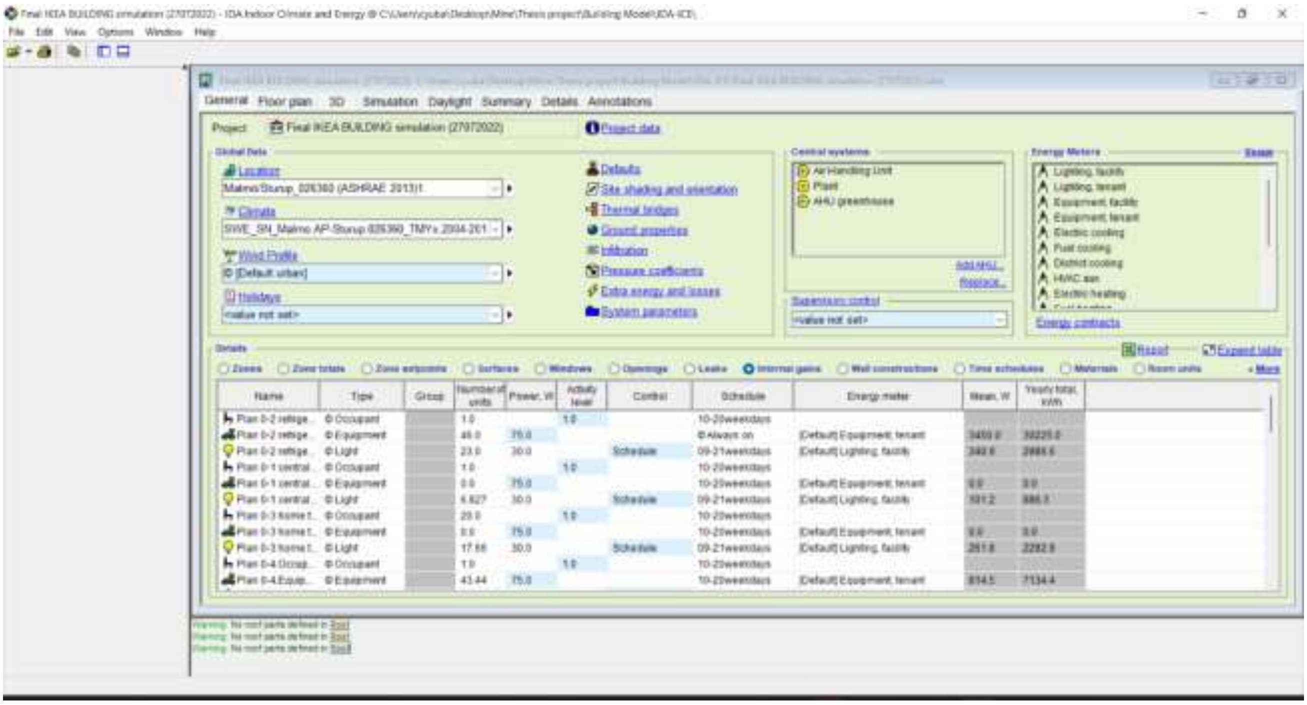


- Define zone setpoints

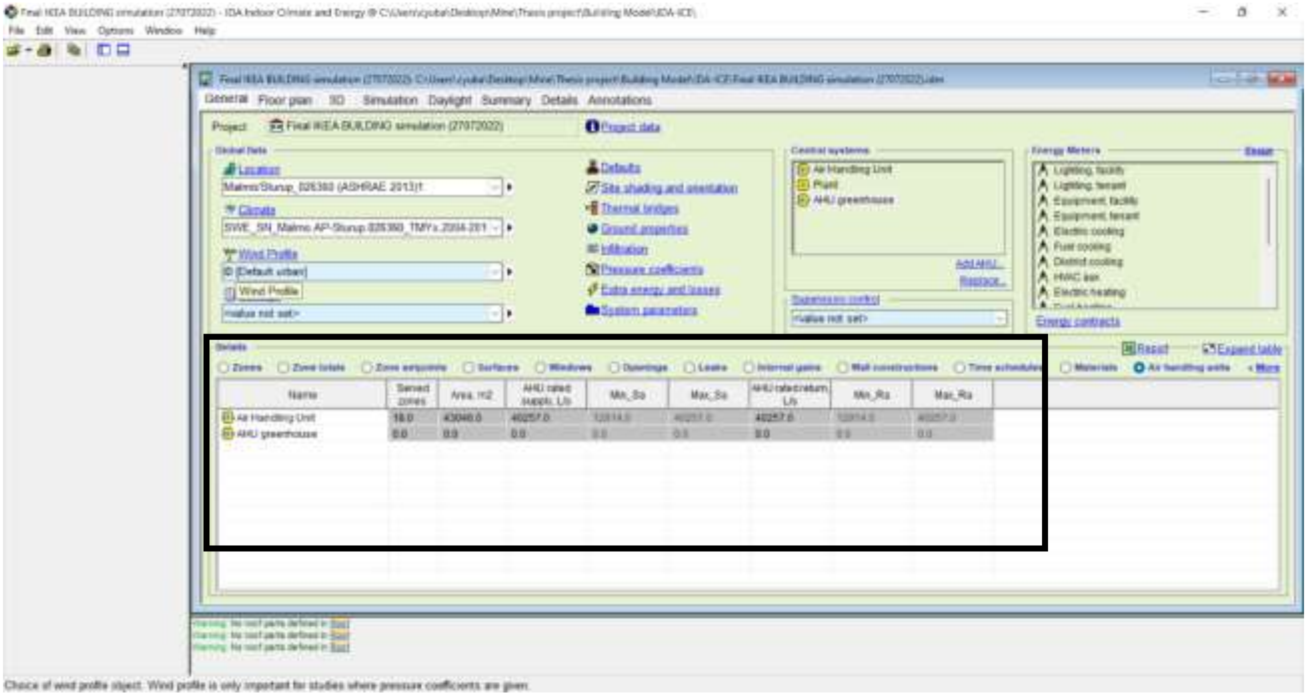


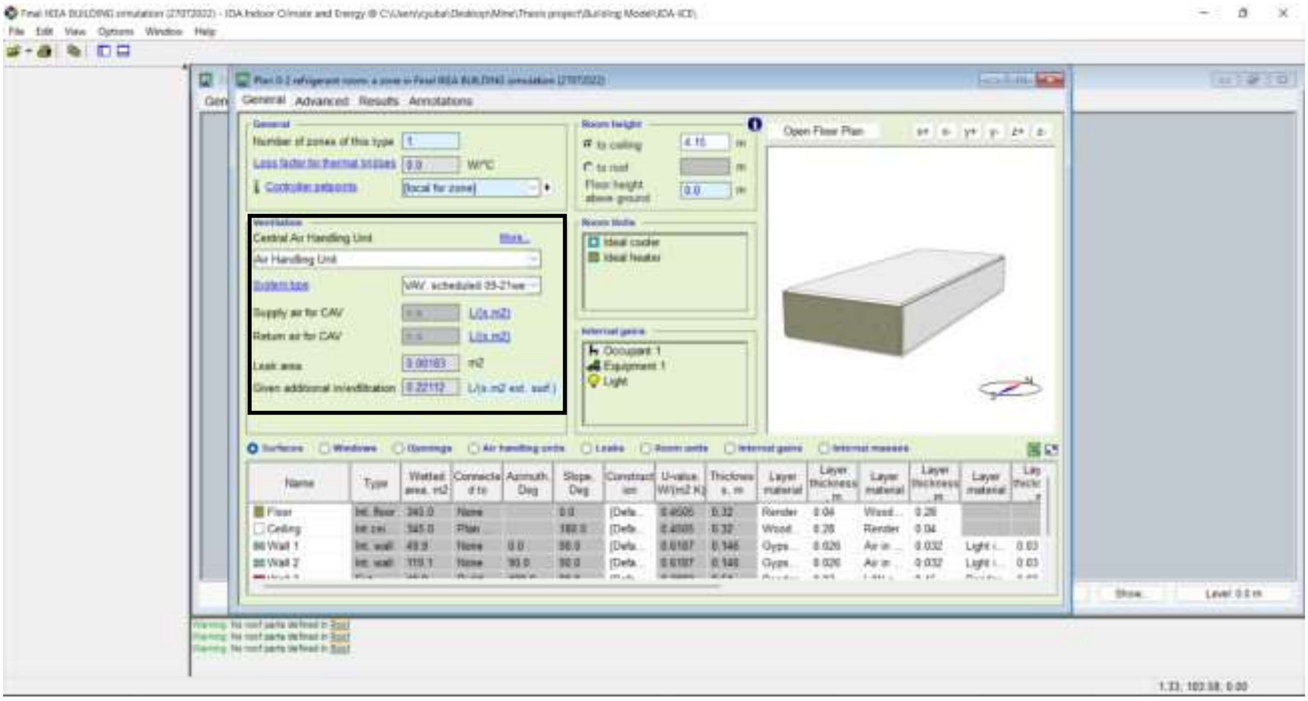
- Define schedules and internal heat loads





- Choose and define the HVAC system type





- Run simulations

Appendix E

Table 13:Average Daily DLI (mol/ m^2) for Malmö location

January	3.0
February	5.7
March	10.3
April	15.6
May	20.0
June	22.0
July	21.0
August	17.3
September	12.1
October	7.1
November	3.6
December	2.3

Table 14:Average sunshine hours for Malmö location

Month	Average	Total
January	1.5	45.0
February	2.0	60.0
March	5.0	150.0
April	7.5	220.0
May	8.5	265.0
June	9.0	270.0
July	8.5	270.0
August	7.5	230.0
September	6.5	190.0
October	4.0	120.0
November	1.5	50.0
December	1.0	30.0
Year	5.2	1895.0

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