



# NTNU

Kunnskap for en bedre verden

## A Comparative Study between Building Performance Simulation Tools

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# Abstract

As countries are trying to work for more energy efficient designs, the construction industry, being the top end-use sector for energy use for many nations worldwide, is an important target. It has been increasingly important to work for energy efficiency in buildings. These measures can be done with the modern and highly functional building performance simulation tools. Yet, as there are many different tools on the market with varying capabilities. It is important for these tools to give precise results for the future of efficient design.

This paper aims to investigate and compare the thermal and daylighting outputs of different building performance simulation tools, by implementing modern shading and daylighting strategies on a base case. Three of the widely used and accepted building performance simulations, EnergyPlus, IES-VE and IDA-ICE were used for the modelling of the cases. Graphs and tables were used to find correlations and differences between the different simulated model results.

# Sammendrag

Ettersom land prøver å arbeide for mer energieffektive design, er byggebransjen, som er den øverste sluttbrukssektoren for energibruk for mange nasjoner over hele verden, et viktig mål. Det har blitt stadig viktigere å jobbe for energieffektivitet i bygninger. Disse tiltakene kan gjøres med de moderne og svært funksjonelle simuleringsverktøyene for bygningsytelse. Likevel, siden det er mange forskjellige verktøy på markedet med varierende evner. Det er viktig for disse verktøyene å gi presise resultater for fremtiden for effektiv design.

Denne artikkelen tar sikte på å undersøke og sammenligne de termiske og dagslysutgangene til forskjellige simuleringsverktøy for bygningsytelse, ved å implementere moderne skyggelegging og dagslysstrategier på en basissak. Tre av de mye brukte og aksepterte simuleringer av bygningsytelse, EnergyPlus, IES-VE og IDA-ICE ble brukt til modellering av sakene. Grafer og tabeller ble brukt for å finne korrelasjoner og forskjeller mellom de forskjellige simulerte modellresultatene.

# Preface

I would like to thank my family, friends and my supervisors for their constant support.



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# List of Abbreviations (or Symbols)

BPS	Building Performance Simulation
EP	EnergyPlus
IES	Integrated Environmental Solutions
IDA-ICE	IDA Indoor Climate and Energy



# 1 Introduction

## 1.1 Issues and Relevance

A study conducted in the EU indicates that buildings are the biggest end-use sector, which take up to around 40% of the total final energy utilization and about 55% of the electricity consumption [1]. This information alone makes the building sector a target to minimize the energy consumption, not only in the EU, but for all countries and unions which target energy efficiency. Jensen et. al. states that rather than tackling the problems of energy inefficiency during its use phase, it is far more efficient to predict the future behavior, analyze and act accordingly [2]. That is why predictive solutions, which come with the integration of computational building performance simulation tools, have been present since the 1960s. These tools have been increasingly becoming more powerful and widely used, with the detailed implementation of physical and mathematical models, along with the facilitation of graphical user interfaces [3]. Yet, with the integration of such powerful disciplines also comes a price of increased complexity, which might cause theoretical and practical challenges [2]. According to Parker et. al, in standard buildings, differences between the simulation predicted results and the real energy consumption may reach up to 30% [4]. But these studies do not change the fact that the tools are becoming increasingly popular and a wide variety of building performance simulation tools with many different aspects are on the market [5], trying to optimize their solutions towards accuracy. With the increase of the variety of such tools comes many different approaches in solving the same problem of predicting thermal and daylighting performances. Some recent studies have reported that the discrepancies between the results of various building performance simulation tools can go up to 67%, even when the parameters were carefully input within the software [6]. If energy efficient measures are to be taken based on these tools, further investigations must be performed based on these studies.

The reduction in demands for heating and cooling energy, correct ventilation and daylighting strategies, better domestic hot water applications and reduction in the consumption of equipment are the measures that are taken for the increase in energy efficiency in buildings [7]. Studies have shown that the glazed parts of the buildings are the cause of 39% of the heating and 28% of the cooling energy demand in the US [8]. With correct shading on the glazed parts of the structures, energy consumption can be drastically reduced, by preventing solar gains in hot seasons while letting in the sun during cold seasons [9]. Some studies have shown that a decrement of 25% in Milan, 28% in Tallinn and 45% in Cairo in the energy use have been obtained with the correct design and implementation of fixed shading systems [10]. Shading system optimization can also indirectly influence the energy cost of a building by the increase of daylighting performance, which with correct design can reach up to a 30% decrease [11].

This paper aims to investigate and compare the thermal and daylighting outputs of different building performance simulation tools, by implementing modern shading and daylighting strategies on a base case.



## 2 Methodology

### 2.1 Overview

To be able to quantitatively compare the BPS tools, EP, IES and IDA, models on these tools were constructed. Due to studies stating that the increase in the complexity of models would most likely result in discrepancies [6], ANSI-ASHRAE's Bestest Case 600 model has been picked as a base case to reduce possible error margins. The specifications of this model will be later explained in this chapter.

For the comparison regarding the shading implementations, a conventional, an unconventional and a modern shading system have been implemented on the "no shade", Bestest Case 600 base model.

The first shading system has been picked as a regular external louvres system. The shading has blades with equal spacing and equal tilt angles. This shading was picked as the conventional shading mechanism, to check whether the different BPS tools could offer simple design methodologies for a widely used shading system and whether they gave out reasonable results compared to one another. The second shading system, which is the unconventional one, is a parametrically optimized fixed external louvres shading system taken out from a previously conducted study. The study uses multi-objective optimization to determine the number of louvres blades, their tilt angles, and their position along the vertical to increase the energy and daylighting performance of the model [12]. This rather harder-to-model shading configuration, which will later be explained in detail, was implemented in the Bestest Case 600 under the name of "irregular" shaded model.

The third implemented system is a light shelf. Although considered as a shading system in this study, one of its main functions is the ability to reflect part of the sunlight towards the ceiling to improve the daylight performance of a room and has become increasingly popular due to this aspect [13].

The 4 designs, "no shade", "regular", "irregular" and "light shelf" were modelled in the three BPS tools. The same weather file, which was chosen as Amsterdam-Schiphol, was implemented on all modelling approaches.

### 2.2 Description of the BPS tools

#### 2.2.1 EnergyPlus 9.2.0

EnergyPlus is a free, open-source building energy simulation program which takes its roots from the two software programs BLAST and DOE-2, which date back to the late 1970s. According to the "Getting Started" documentation of EP, the aim of the software

is to perform an energy analysis of a whole building and its mechanical equipment as close to the actual building would perform. This analysis is based on the user's input of the building's geometry, materials ("physical make-up"), included mechanical equipment and its characteristics, the thermal comfort set-points, and other various related properties. [14] As the documentation "Tips and Tricks Using EnergyPlus" indicates, the software was not intended to be a user interface, as it was aimed to work with third-party interfaces and software tools.

EnergyPlus works with text files which are called "input data files" or IDF. Because EP does not have a user interface, it is not possible to visualize and create a building geometry without any other third-party tools. Google SketchUp, a 3D design software tool, has a free plugin for it called OpenStudio, which helps import and export IDF files to and from the Sketchup interface. EP-Launch is a component, which kind of works as a very simple user interface, makes it easier to select the created input files, run simulations and check the outputs [15]. In this component, it is also possible to select the desired weather file, which is a text-based data file called epw (EnergyPlus Weather). The desired climate data can be found on the EnergyPlus website.

### 2.2.2 IES-VE 2019.2.0.0

IES-VE, Integrated Environmental Solutions – Virtual Environment, is a set of applications gathered within a common user interface (CUI). In contrast to EP, it is a paid software. To understand how the software works it is important to define the integrated tools and their functionalities.

ModelIT is the tool to create the geometry of the building, the shading components, and its surroundings. It allows the user to create 3D models, by also enabling the model to be seen in the virtual environment through its component Model Viewer.

The Building Template Manager is the tool to define the characteristics of the building and the zones within the building. The Constructions section is used to define materials and material properties and then assign them to the building surfaces. The Thermal tab is used to define the mechanical equipment, the conditioning of the zones, the internal gains, air exchanges and their corresponding schedules.

ApLocate is the tool to pick the location and weather data file, from a wide variety of options within the database.

The SunCast tool is a tool that runs its own simulations related to the solar path of the location, enabling users to visualize shading and solar insolation studies as well as creating files to be used in the whole building simulation.

The RadianceIES section of the software, as can be interpreted from the name, runs with Radiance, an internationally recognized lighting simulation tool. In this paper, for the daylighting analysis, the placement of the sensors was defined, as well as the reflectance values of the inner surfaces of the zones. Simulations were ran in this tool, later to be used in the whole building simulation.

ApacheSim combines all the input data from ModelIT, Building Template Manager, ApLocate, SunCast, RadianceIES, with the desired simulation settings and runs the simulations based on its integrated heat transfer mechanisms combined with the real weather data.

VistaPro is the tool in which results taken from ApacheSim can be taken out, graphically visualized and compared within the software. [16]

### 2.2.3 IDA-ICE 4.8

IDA ICE (Indoor Climate and Energy), developed by EQUA Simulation AB, is an energy simulation software which studies the indoor climatic conditions of a building's zones to predict the energy consumption of the whole building. The software is a paid simulation software. It has a relatively easy-to-use software with a user-friendly interface which can do complex calculations. [17]

The General tab is where most of the input data such as the location, climate, default constructions, site shadings, infiltration values and many other parameters are managed. The "details" tab below enables the user to navigate through the existing zones, surfaces, constructions, windows, and other groups of data. By double-clicking on a previously created zone, one can manipulate all the data contained within the zone, which would not affect any of the properties of the other thermal zones.

The geometry can be created from the built-in 3D geometry creator, which can be accessible from the Floor Plan tab. Within this tab, the user must define the geometrical dimensions of the zone and the building body surrounding the zone. A simple coordinate system with small figures help the user to define the geometry easily.

The built geometry can be visualized from the 3D tab. The user can double click on any of the constructions on this platform to manually define any desired property of the chosen construction. The construction can also be defined from the General tab for the whole constructions. Some geometries can also be imported into this section of the software, such as site shadings or specific shading surfaces.

The simulation tab is used to run the desired simulations, such for heating load, cooling load, energy, overheating or for any other custom simulation settings.

After the simulation is run, the results can be accessed from the Details tab. This tab enables the user to take out results as well as visualize and compare it with any chosen output data.

## 2.3 Description of BESTEST 600 Case (ASHRAE)

The Bestest Case 600 is a rectangular box model defined by ANSI-ASHRAE Standard 140-2001. It is an 8 m wide, 6 m long and 2.7 m high rectangular zone. The zone has no internal partitions and has 2 windows situated 0.2 m above the floor and facing south with each window having a width of 3 m and a height of 2 m [18].

The following image defining the material properties and constructions is taken from ANSI-ASHRAE Standard 140-2001.

enproet.xls, May 10, 2004

EXTERIOR WALL (inside to outside)				
ELEMENT	k (W/(m*K))	Thickness (m)	U (W/(m <sup>2</sup> *K))	R (m <sup>2</sup> *K/W)
Int Surf Coef			8.290	0.121
Insulation (Note 1)	0.010	1.000	0.010	100.000
Ext Surf Coef			29.300	0.034
Total air - air			0.010	100.155
Total surf - surf			0.010	100.000
FLOOR (inside to outside)				
ELEMENT	k (W/(m*K))	Thickness (m)	U (W/(m <sup>2</sup> *K))	R (m <sup>2</sup> *K/W)
Int Surf Coef (Note 2)			8.290	0.121
Insulation (Note 1)	0.010	1.000	0.010	100.000
Ext Surf Coef			29.300	0.034
Total air - air			0.010	100.155
Total surf - surf			0.010	100.000
ROOF (inside to outside)				
ELEMENT	k (W/(m*K))	Thickness (m)	U (W/(m <sup>2</sup> *K))	R (m <sup>2</sup> *K/W)
Int Surf Coef (Note 2)			8.290	0.121
Insulation (Note 1)	0.010	1.000	0.010	100.000
Ext Surf Coef			29.300	0.034
Total air - air			0.010	100.155
Total surf - surf			0.010	100.000
SUMMARY				
COMPONENT	AREA (m <sup>2</sup> )	UA (W/K)		
Wall	75.600	0.755		
Floor	48.000	0.479		
Roof	48.000	0.479		
Infiltration (Note 3)		0.000		
Total UA		1.713		
	ACH	VOLUME (m <sup>3</sup> )	ALTITUDE (m)	
	0.00	129.6	2.0	
Note 1: This level of insulation defines a near-adiabatic condition such that conduction gains are < 1% of the total cooling load. If your software does not allow this much insulation, then reduce the floor, roof and wall areas to achieve the listed UA values. Note 2: The interior film coefficient for floors and ceilings is a compromise between upward and downward heat flow for summer and winter. Note 3: Infiltration derived from: ACH*Volume*(specific heat of air)*(density of air at specified altitude)				

**Figure 1: Bestest Properties**

The windows, being identical double-pane windows with air gaps, were constructed as stated in the standards. The resulting U-value for the glazing is 3 W/m<sup>2</sup>K (with no frame), a g-value of 0.789 and a visible transmittance value of 0.742. (Refer to "ANSI/ASHRAE 140-2001" for more detailed information)

As opposed to no air changes which is stated in image xx, a value of 0.5 air changes per hour has been set to be compliant with some prior research.

The internal load has been set to 200 W, which is continuously on, 100% sensible gain and 60% radiative to 40% convective.

Simulations were run with free-floating (not conditioned zone) and with ideal heating / cooling systems depending on the desired outputs. In the case of using mechanical equipment, the system is set to be 100 % convective air system with no losses and 100 % efficiency. The set-points for the mechanical systems were set to 20°C and 27°C.

The soil temperature is set to a constant temperature of 10°C for the whole year.

The ground reflectance values were set to a value of 0.2. [18]

Due to the inner surface reflectance values not being specified in the standards and the property being a crucial point in the daylighting part of the analysis, a value of 0.4 was implemented in all the inner surfaces of the models.

Additionally, no ventilation settings were implemented as it would impact the results in a great way and the focus is to investigate the impact of the shadings on simple modelling settings.

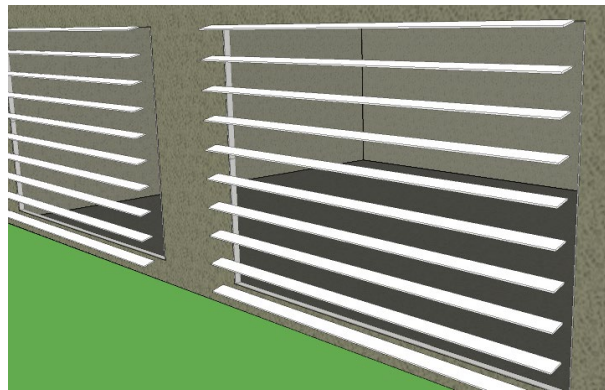
## 2.4 Description of the Shading Systems

### 2.4.1 "Regular" External Louvres System

This conventional external louvre shading has 10 blades with a slat angle of  $15^\circ$ . The blades have an equal spacing of 0.22 m and the center-point distance of the blades from the glazing surface is 0.16 m.

The length of each blade is equal to the width of the window, which is 3 m. The width of each blade is 0.105 m, having a thickness of 0.01 m.

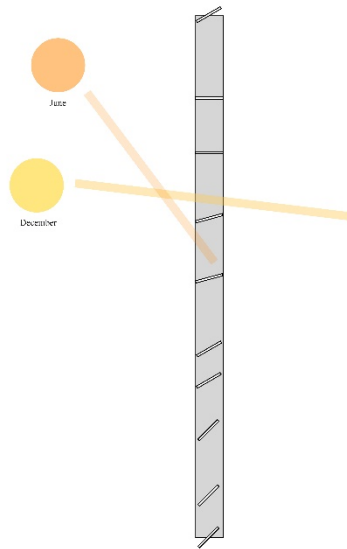
The material of the surface is an opaque surface (transmittance is 0), with a reflectance value of 0.65.



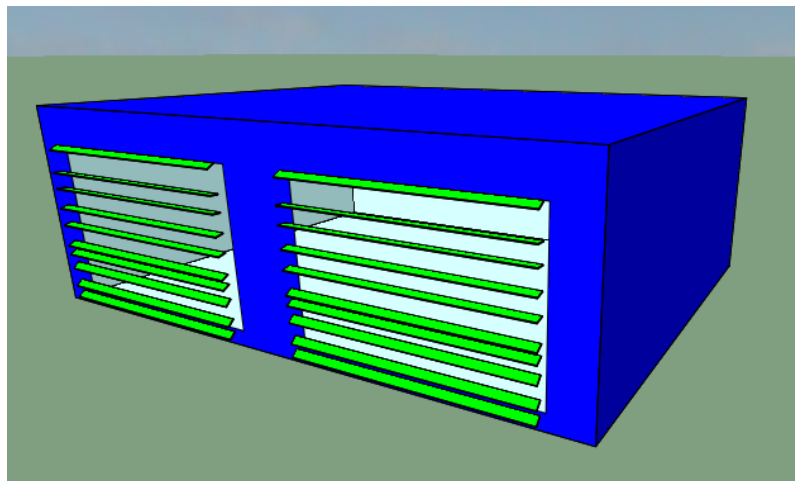
**Figure 2: Regular Louvres**

### 2.4.2 "Irregular" External Louvres System

For the optimized "irregular" external louvres system, the previously mentioned blade properties for the "regular" configuration were used, except for the spacing and tilt angles. The parametric study aimed to increase the daylight performance and PV production by minimizing the net energy use of the zone, by changing the spacing and tilt angles of the fixed system [c1]. Image xx illustrates the resulting optimized configuration of the shading system.



**Figure 3: Configuration**

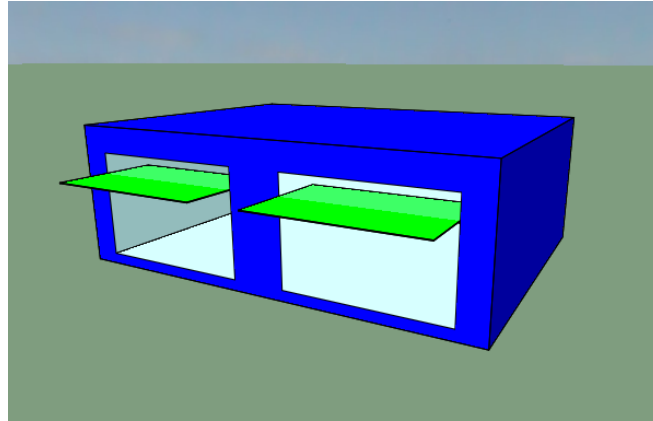


**Figure 4: Irregular Configuration**

### 2.4.3 "Light Shelf" System

The light shelf system is put 1.8 m above the floor level, at a 1.6 m height from the bottom of the window construction. There are two parts to the shelf, the inner and the outer parts. Each part of the shelf is 3 m wide (same as the window width), and they extend 1 m inwards and outwards from the window. To be clearer, the whole shelf system is 3 m by 2 m of which the middle of the shelf is situated on the window. The reflectivity has been selected to be 0.7 m, to be highly reflective.





**Figure 5: Light Shade**

## 2.5 Constructing the Models and Running Simulations

The models were built, and yearly simulations were run using 3 BPS tools, which are EnergyPlus, IES-VE and IDA-ICE.

### 2.5.1 EnergyPlus

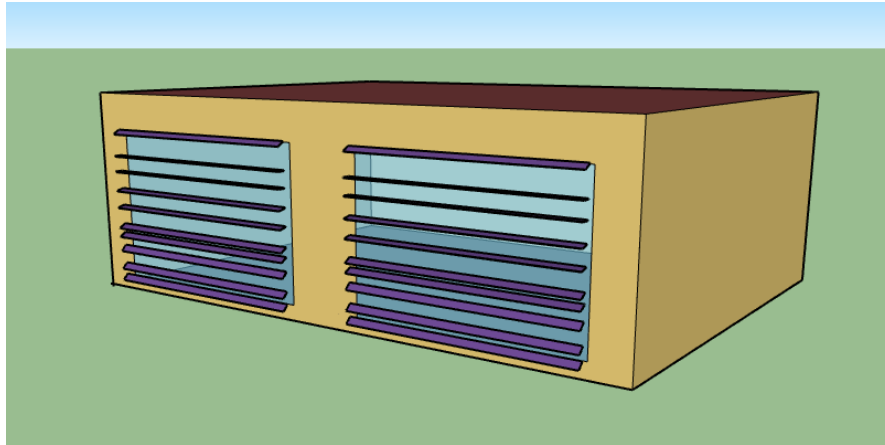
For building the geometry of the Bestest Case 600 in EnergyPlus, the 3D modelling software SketchUp 2019 was used. The geometry of the model being rather simple, constructing it would not be a troublesome task even for a beginner user of the software. Yet, SketchUp 2019 is a paid software kit, which makes it harder for the accessibility of any user. There are other ways to import a geometry into EP but because of the availability of the plugin OpenStudio, which is another building energy software tool, SketchUp was chosen to easily import and export data to and from EP.

Because the geometry being rather simple, it is possible to construct the model by using EP's IDF-Editor. Which would require defining the coordinates for the edges of the walls, floor, roof, and window constructions. Yet, more complex geometries such as external louvres systems would be challenging and time consuming to model with just coordinate inputs.

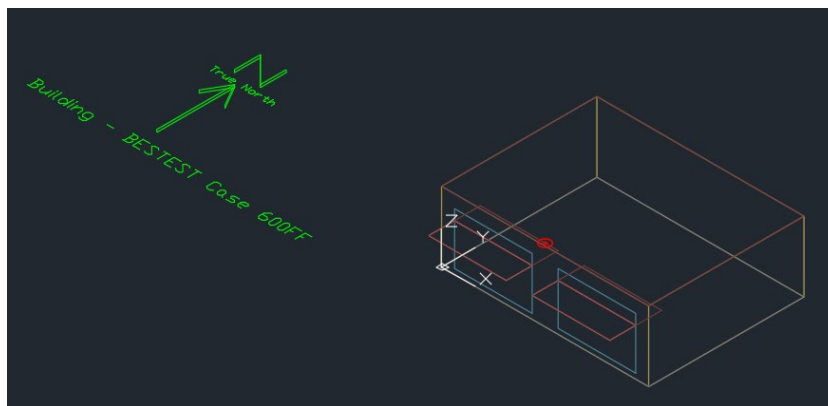
After the geometry was built in SketchUp, the OpenStudio plugin was used to create an IDF (input data file), which is the file which contains all the necessary data to define the building's properties and its systems for simulation [GettingStarted].

To define the external louvres shadings, SketchUp was used along with OpenStudio, as the shading surfaces could be defined as a shading group with the plugin, which would be later used within the IDF. For the shelf shading, EP offers an input called "Daylighting:Device:Shelf" where the user can define its characteristics. The outer surface of the shelf is defined as an external shading element defined in "Shading:Zone:Detailed" and the inside surface is defined as a part of the building's surface, defined in "BuildingSurface:Detailed".

Once the IDF file is ready for use, EP-Launch, which is a component of EnergyPlus which makes it easier for users to select input files, run simulations and check results, [gettingstarted] is launched. The created IDF file was edited according to the ANSI-ASHRAE requirements for the Bestest Case 600 and for the desired conditions, such as for free floating or with conditioned zones. When the file was ready the EP-Launch was used to select the IDF and the weather file, and simulations were conducted. If errors existed, a pop-up appears stating that errors caused the simulation to terminate. Debugging processes take place until the software runs smoothly and gives results which are reasonable.



**Figure 6: EP Irregular Shade on SketchUp**



**Figure 7: EP dxf output – Light Shelf**

## 2.5.2 IES-VE

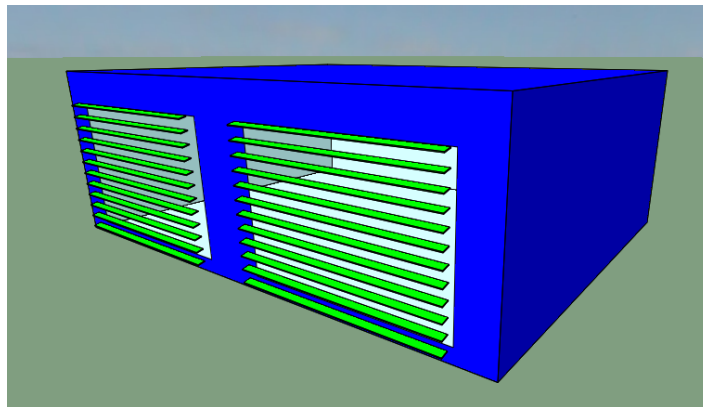
For building the geometry in IES, the ModelIT part of the software is used. The tool offers a variety of options to construct the model in a flexible way. Once the model is built, the software assigns the default constructions, materials, and material properties to the created surfaces. To input the characteristics of the Bestest Case 600, the Building Template Manager tool is used. The constructions section of this tool was used to define the materials, their properties and assign them on the desired surfaces. The created base model was then copied and pasted further apart, for them not to shade or effect each other, to prepare the base for the shaded configurations and the light shelf. The external

louvres shadings and the light shelf were easily constructed within the ModelIT geometry creator. The formed constructions were then assigned thermal constructions for them to have the desired properties, which were also defined in the Constructions section.

The weather file and location were assigned from ApLocate.

Once the models were built, SunCast must be run first to create the files to be used in ApacheSim. Then, in the RadianceIES tool, sensors were defined in each zone, as well as the surface reflectance values. Another simulation was run in that part of the software to create the files to be linked with ApacheSim.

ApacheSim was run with the selected desired simulation configuration and the results were obtained from VistaPro.



**Figure 8: Regular Shades - IES**

### 2.5.3 IDA-ICE

The geometry of the building was constructed on the Floor Plan tab of the simulation program. When the Bestest Case 600 was defined, it was possible to copy the zone and building body and paste them further apart in the model. This way, all the analyses could be carried out with only one file.

The weather file, location, default constructions and their material properties, infiltration and ground properties were all defined in the General tab.

The external louvres shadings were imported from SketchUp (saved as 2013 version) and implemented in front of the windows within the 3D tab of the software. The surface properties were easily managed from the tab opened by double clicking on the shading devices.

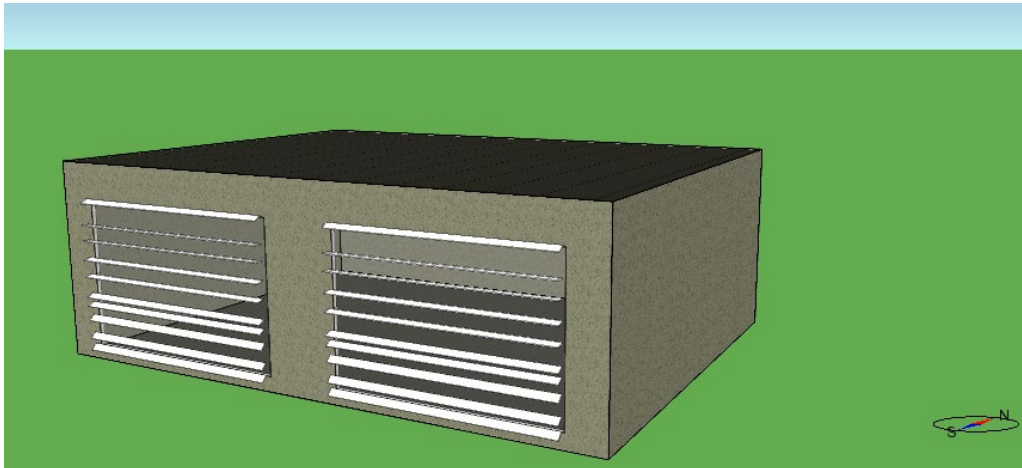
The light shelf was defined in the 3D tab of the tool. On the left-hand side of the tab, there is a section called Palette, in which the user can "drag and drop" any desired in-built feature, shading or construction onto the visual model. The horizontal shade option, which could also be implemented through the window construction, was taken from this set of shadings, and simply put in the desired location of the zone. The surface properties were managed by double-clicking on the construction.

The ideal heating and cooling systems could be implemented by selecting a zone from the General tab, and again dragging and dropping "Ideal heater" and "Ideal cooler" units

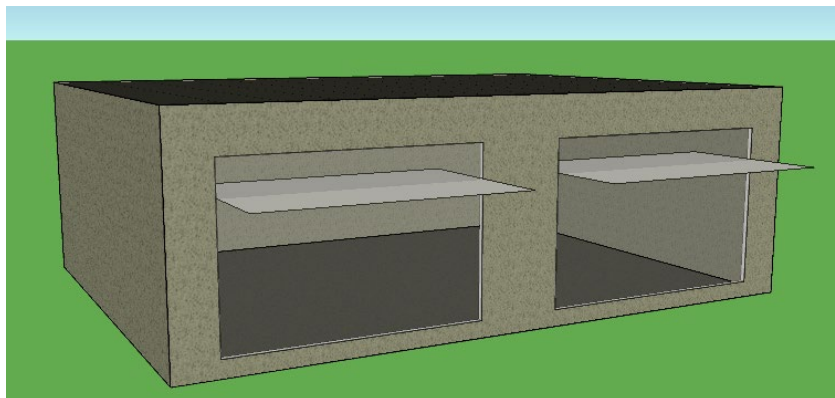
within the Room units. The efficiency and power of these units were managed for the desired settings, so for infinite power, 100 % efficiency and 100% convective air system.

The daylighting analysis was carried out by the daylighting function within the software (not the Daylight tab, as this version does not give annual, hourly results for illuminance). An occupant was placed on the desired location of the sensor, with no energy emission, and the sensor location was set as the occupant location, from the System Parameters.

Simulations were run in the Simulation tab for Energy results, and results were taken out from the Details tab.



**Figure 9: Irregular Shades - IDA**



**Figure 10: Light Shelf - IDA**

## 2.6 Setup for Simulation

The building geometry and material properties were implemented in the models according to the previously mentioned ANSI ASHRAE 140-2001 Bestest Case 600.

The weather file was chosen as "Amsterdam Schiphol". The same weather file was used for all the simulation tools, which is an epw (EnergyPlus weather) file, taken from the EnergyPlus website [ep web].

The sensors for the daylighting analysis were placed 2 m inward from the center of the left window (when facing the South exposed wall where the windows are located), and at a 0.8 m height from the floor. The sensors are facing upwards.

4 different geometrical models were constructed within each BPS tool. These models were all built upon the Bestest Case 600 and were (1) without shading, with (2) regular external louvres, (3) irregular (optimized for Oslo) external louvres and (4) light shelf. The models were simulated in free-floating condition i.e. without any mechanical conditioning system and with ideal heating and cooling systems. The ideal heater and coolers are air systems which have unlimited power, are 100% efficient with no duct losses. So, in other words, we can say that each BPS tool had 4 models with 2 different scenarios, which made in total 8 simulations per simulation tool. There were 3 different simulation tools in the research conducted, which sums up to 24 different models with different results which were analyzed.

## 2.7 Comparison Method

The comparative studies have mostly been conducted between either all the three BPS tools, or by two-by-two comparative studies. The comparisons were done in terms of thermal and daylighting analyses. Interpretations from these results were made and commentary, with the help of prior studies on the topic, have been performed.

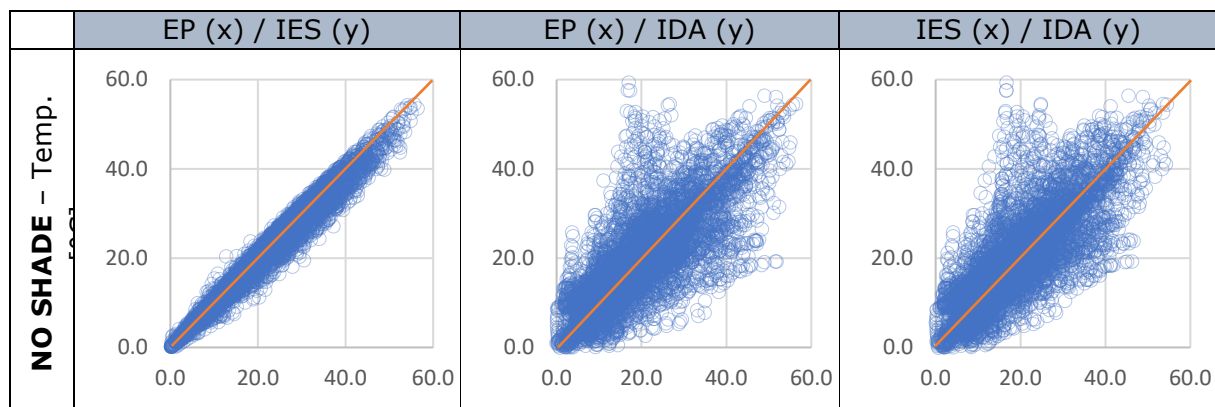
# 3 Results

## 3.1 Thermal Analysis

### 3.1.1 Free Floating

#### 3.1.1.1 Indoor Mean Air Temperature

The following tables, Tables x,y,z,q, are composed of a series of comparative scatter graphs between the results for the indoor mean air temperatures of two BPS tools. The row on the top of the table gives which BPS tools are plotted against each other, also indicating the axes in which they belong to in parentheses. The left-hand side of the tables indicate which models are analyzed, including the analyzed parameters (axis titles).

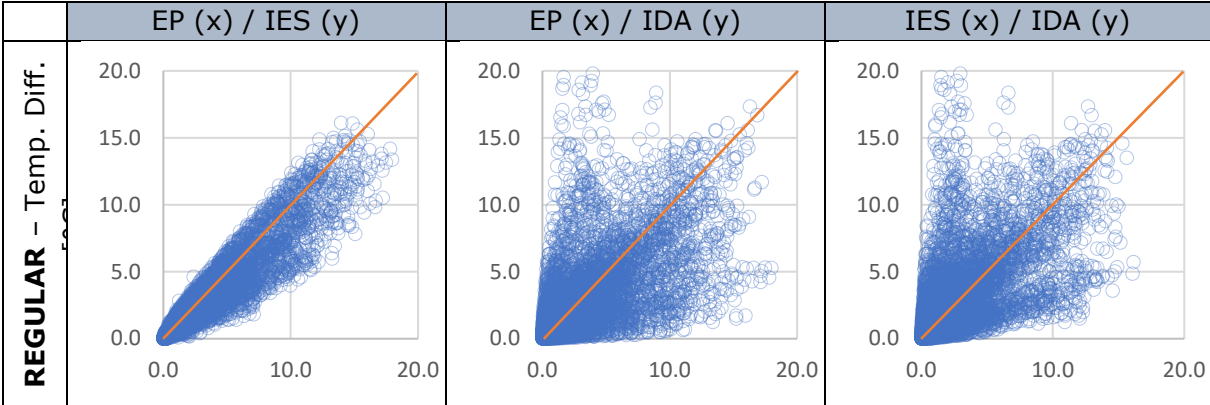


**Table 1: No shade**

Table 1 gives a comparison of the “no shade” base case. A strong correlation can be seen between EP and IES, as the values are tightly gathered along the bisector (orange line) of the graph. A more scattered distribution can be seen in the case of IDA’s comparative scatter distributions. Some extreme hourly temperature differences can be observed.

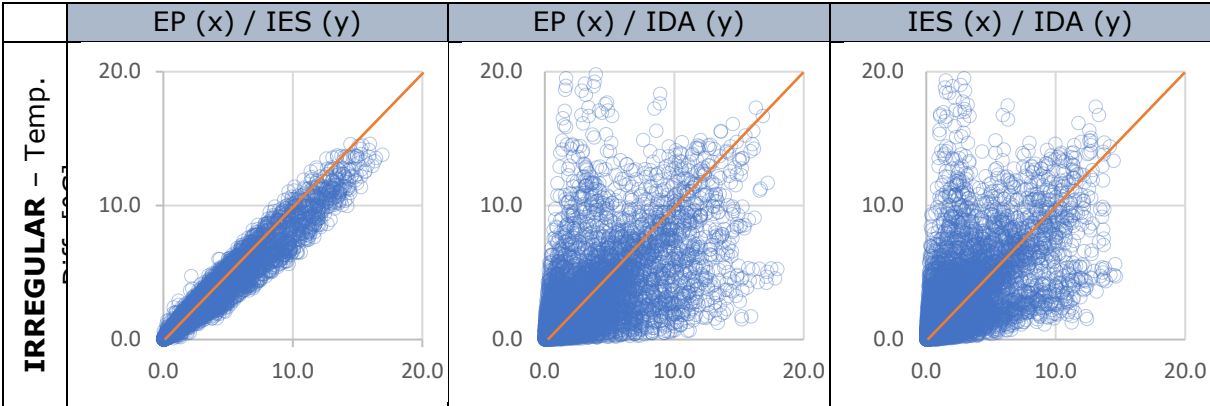
Tables 2, 3 and 4 are plotted for the models with regular, irregular, and light shelf shadings, respectively, yet normalized temperature values were used for the plotting. The normalization of values was achieved by subtracting the temperature values of the 3 cases (regular, irregular and shelf) from their corresponding “no shade” case. So, for example, the shelf shaded IES model’s values to be plotted would be achieved by subtracting the “light shelf” temperature values from the “no shade” temperature values

of the corresponding timestep. Due to implementing a shading system resulting in a decrement of temperature values, it is possible to obtain the impact of each shading system within every BPS tool and compare these changes between the tools with the scatter graphs.



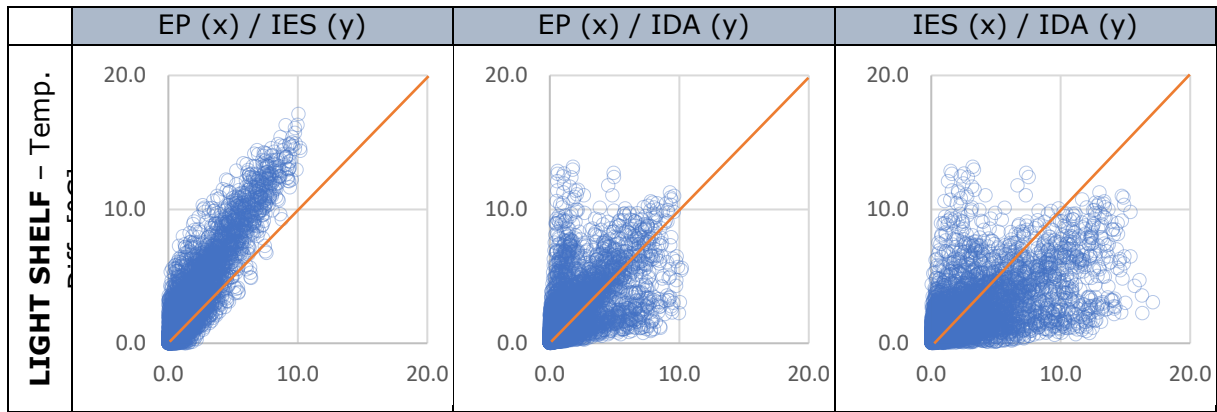
**Table 2: Regular Shade**

From table 2 we can see that the correlation between EP and IES has slightly decreased compared to the “no shade” case. For the comparison of Ida to the other tools, the scattering has slightly moved towards the axes, especially towards the y-axis, where IDA values are plotted. This means that IDA, compared to the other BPS tools, underestimates the effects of the shading.



**Table 3: Irregular Shade**

The correlation between EP and IES for the “irregular” shading case is slightly higher compared to the “regular” shading case, which is an interesting finding. This means that the increment in complexity does not affect the thermal calculations in a negative way, improvements in correlation may even be observed. A similar correlation exists between IDA and the other tools compared to the “regular” shading case.



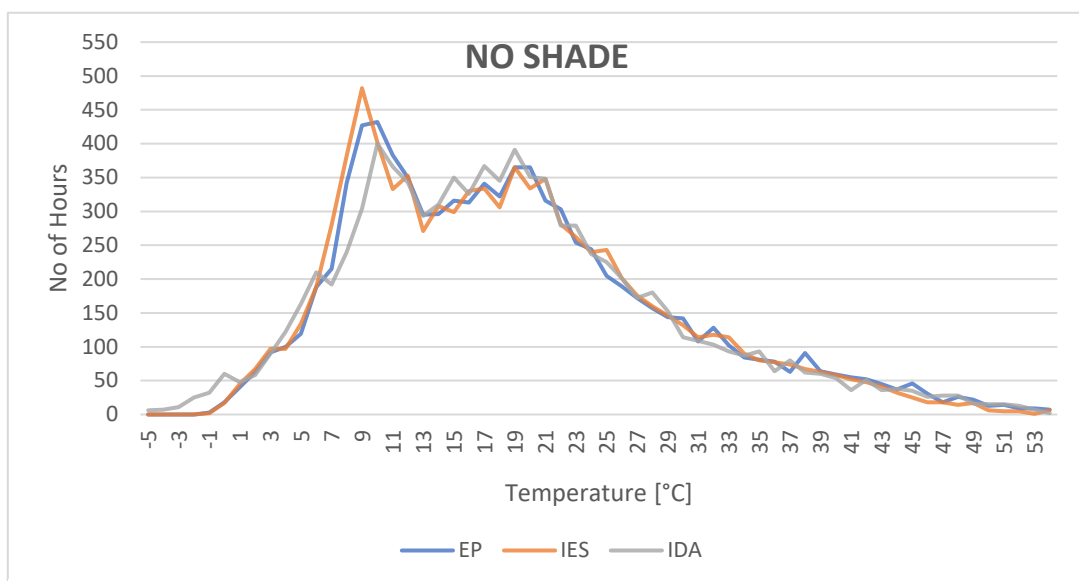
**Table 4: Light Shelf**

The first graph in table 4 shows a clear shift of the values which were densely situated around the bisector of the table towards the y-axis. This tells that EP seems to overestimate (or IES seems to underestimate) the contribution of the light shelf.

At first glance, the correlation between EP and IES is noticeable as the values are more concentrated, especially around the bisector. The first three cases, tables x, y and z, show strong correlation between the two tools, except for the shift occurring in the light shelf case.

In all of the cases, even though the dispersion seems quite symmetric around the bisector, a tendency of IDA to underestimate the effect of shading can be seen from the values being scattered towards the y-axis, where the other two tools are plotted against. This scattering analysis also portrays the extreme hourly temperature differences that IDA may have compared to EP and IES.

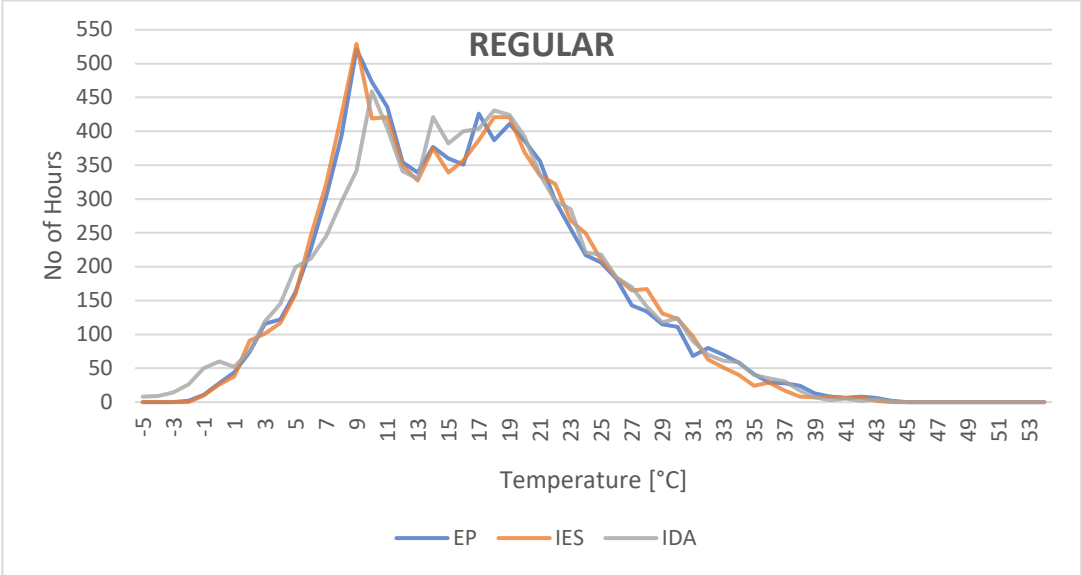
The following graphs represent a frequency graph plotted from the annual mean indoor air temperature values of the three BPS tools for the four different modelling approaches. The temperature interval was set to 1°C and the number of hours which fall within these intervals are obtained for the plotting of the graphs.



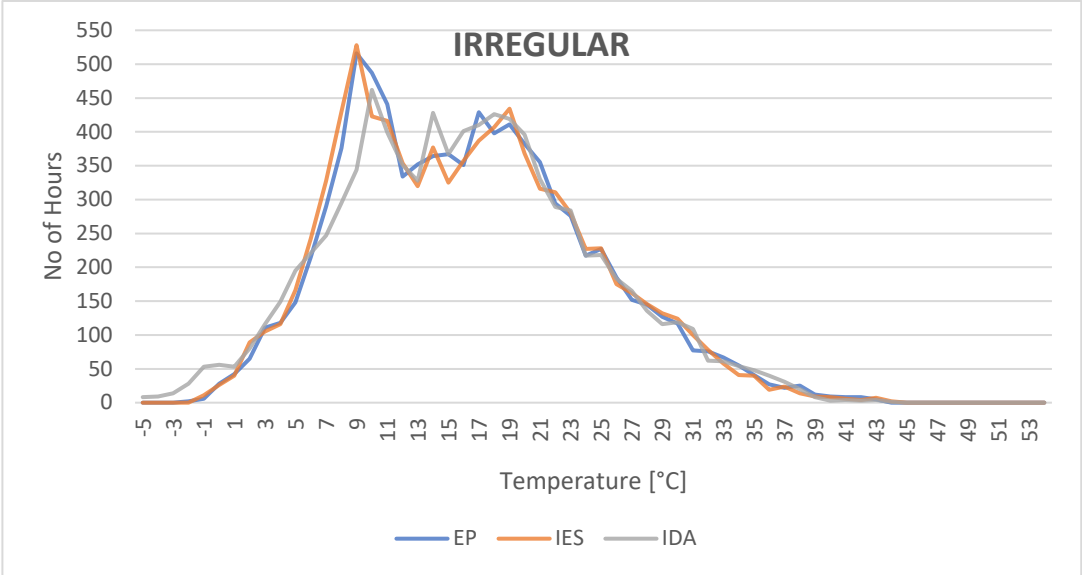
**Table 5: No Shade**



Table 5 displays the frequency distribution for the "no shade" model. The results from the IDA model show a slightly different trend compared to the other 2 BPS tools. The results from IDA show more values on the lower temperature side of the graph when the other tools hardly have any hours which fall below -1°C. The temperature frequency lines after 21°C give almost the same trend with slight deviations.



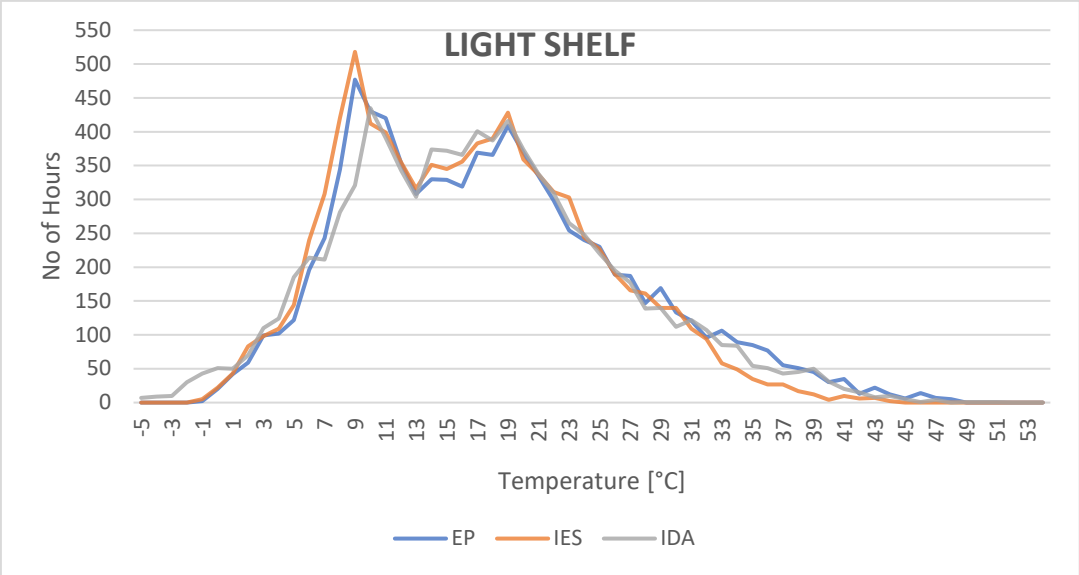
**Table 6: Regular**



**Table 7: Irregular**

The two tables, 6 and 7, above give almost the same trend as they are both modelled in a similar fashion, yet there is a slight difference in the correlation of EP and IES. In the

“regular” external louvres configuration the trends are almost identical, yet some small deviations occur in the case of “irregular” shades. We can say that the two considered BPS tools might be taking the changes in orientation in a rather different way.



**Table 8: Light Shelf**

Table 8 gives the results for the “light shelf” model. The only considerable difference would be the trend of IES in the higher temperatures. We can see a considerable drop after 30°C for the frequency distribution of the model.

All the graphs and the results from the 3 BPS tools give very close trends, especially on the higher temperature zones, except for the slight deviation of IES for the light shelf model. This can be interpreted as the models having more correlation in considering the shading and solar heat gain mechanisms. The results of EP and IES, in general, give a slightly similar trend compared to the ones from IDA. This was also seen from the scatter tables before. The IDA results give more values on the lower extreme side of the graphs and more values between 14 and 16°C. EP and IES results make considerably higher peaks between 8 and 9°, whereas IDA’s peak is on the 1°C higher interval. These differences might be a cause of the simulation tools’ different heat exchange mechanisms, or, even though all models are lightweight constructions, the thermal mass considerations might be taken into consideration differently.

### 3.1.2 Conditioned (Ideal Heating / Cooling)

When comparing BPS tools, it is also important to compare the climatized (mechanically controlled) conditions as it is more realistic since analyzed zones will most likely be occupied, and yet controlled.

The following tables display the same scattering concept as described earlier for the free-floating condition. This time the analysis is made between the set-point temperatures which are 20 and 27°C. The set-point temperatures are also included in the scatter graphs as it is important to see if there are differences in heating and cooling functions taking place during the same hourly timesteps.

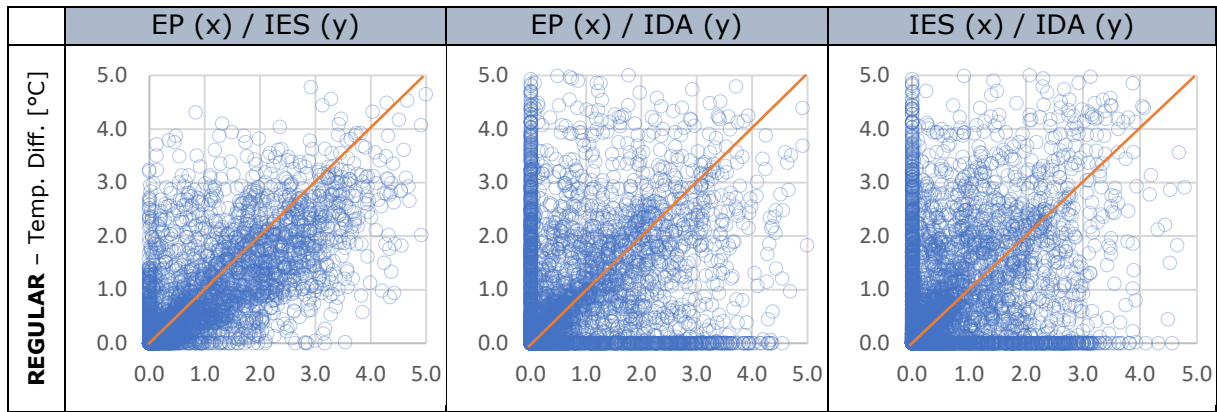
	EP (x) / IES (y)	EP (x) / IDA (y)	IES (x) / IDA (y)
<b>NO SHADE</b> – Temp. [°C]			

**Table 9: No Shade**

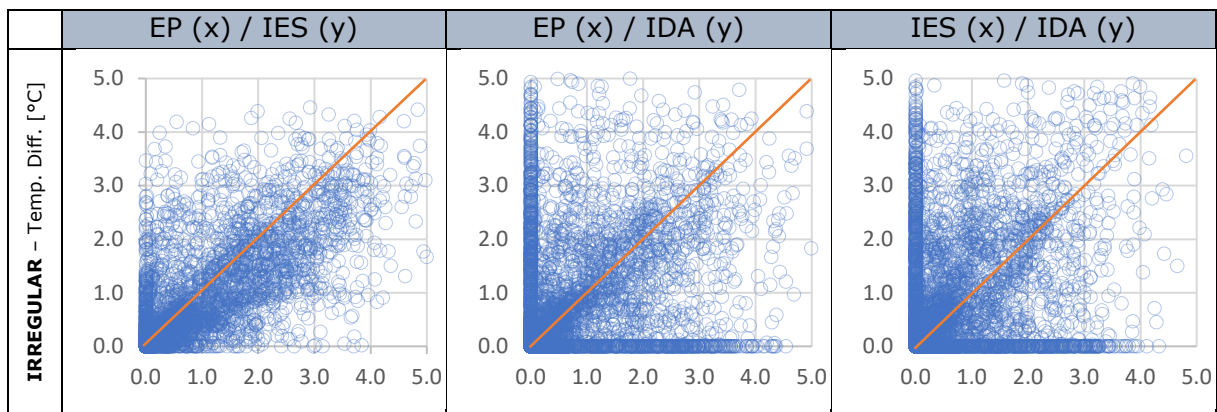
In this scenario, it is important to see where the results are being densely present. The tendency of the scattering being denser are the 2 endpoints of the bisector, points (20, 20) and (27, 27). This means that both compared simulation tools heat and cool at the same instant, where the temperature of the outdoor is low, or overheating of the zone is taking place.

The graphs in table 9 illustrate a great amount of population on the two ends of the bisector as previously expected. Yet, an interesting finding is that IDA, in quite a considerable number of hours, show distribution on the edges of the tables. This means that when the other two BPS tools, EP and IES, are in heating mode, IDA might be in free-floating or even in cooling mode and vice versa. This case confirms the large temperature differences between IDA and the other tools, and as a result differences in zone conditioning.

The following graphs in tables 10, 11 and 12, as in the previous study with the free-floating case, compare the results of the temperature differences of the “no shade” case of each BPS tool with their corresponding shaded case results. An important point to mention is that the temperature difference between these two cases would be in a range of 0 and 5 (both included), because of the set-point temperatures of which the ideal heaters and coolers function with.



**Table 10: Regular**

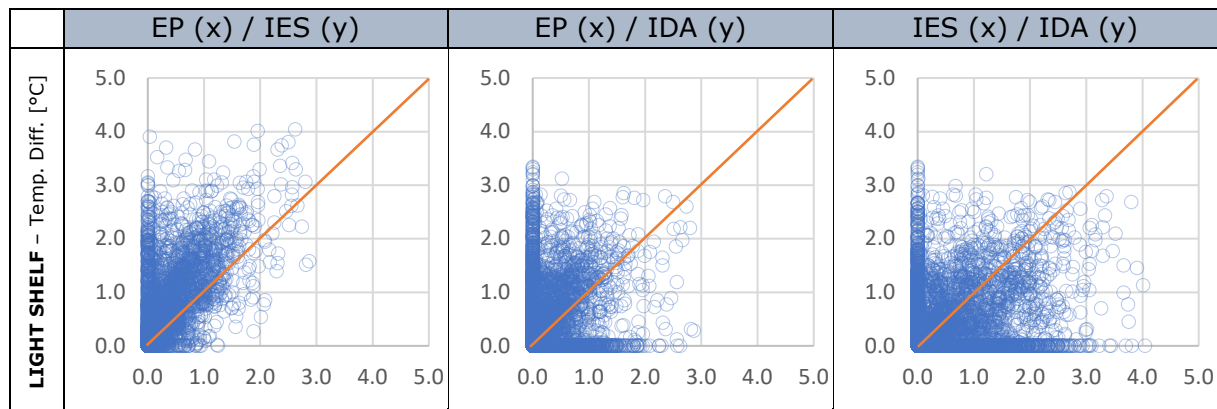


**Table 11: Irregular**

Tables 10 and 11 display mostly the same scattering, as they are very similar in design. It is best to explain some situations to make the analyses clearer and understandable. The temperature difference values vary between 0 and 5 as mentioned previously. When the resulting temperature difference value (between the "no shade" and a shaded configuration) gets a value of 5, this means that the "no shade" model temperature will be 27°C (cooling mode) and the shaded model temperature will be 22°C (heating mode), as the "no shade" configuration will always result in higher (or equal) temperatures. So, this means that the shading is preventing the solar gains to heat up the room, much that it may go down to the heating set-point temperature, which is unlikely yet may occur depending on the shading configuration. We can interpret that, in this extreme scenario, the shaded configurations would be under heating conditions whereas the unshaded zone would be under cooling. The value 0, would mean that both the shaded and unshaded cases are under the same conditioning mode. The values in between these values might mean that, both shaded and unshaded might be under free-floating but at different points, or the shaded zone is being heated while the unshaded would be under free-floating, or vice versa.

When the values are populated on the axes of the graphs, i.e. the cases with the IDA comparisons, this means that there are numbers of hours of which the conditioning of the zones of IDA and the other two tools differ from each other at certain timesteps. This is

an important indicator as it could cause differences in design. The farther the points go along the axes, the more differences exist between the tools.

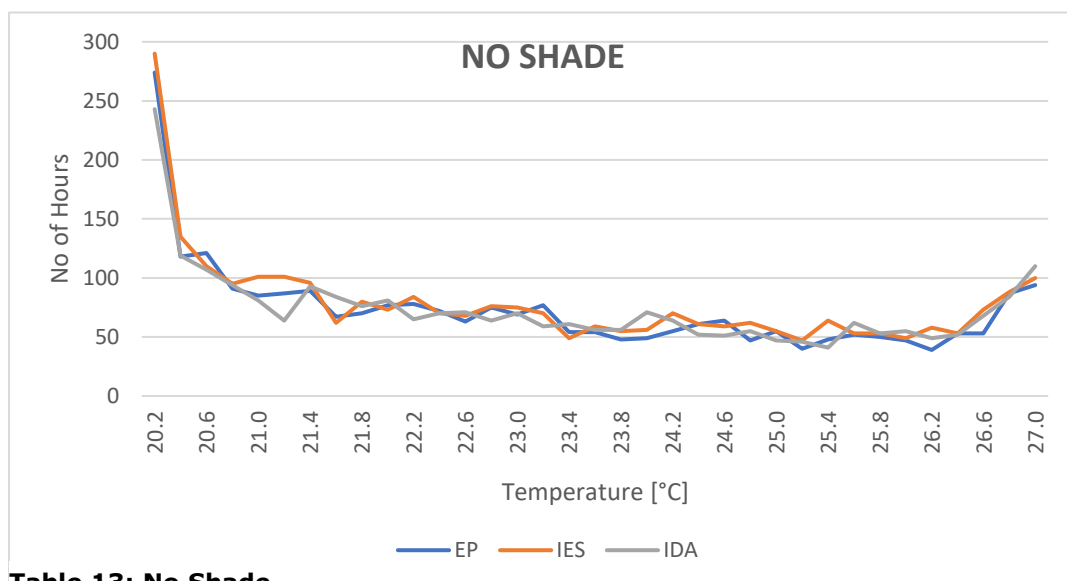


**Table 12: Light Shelf**

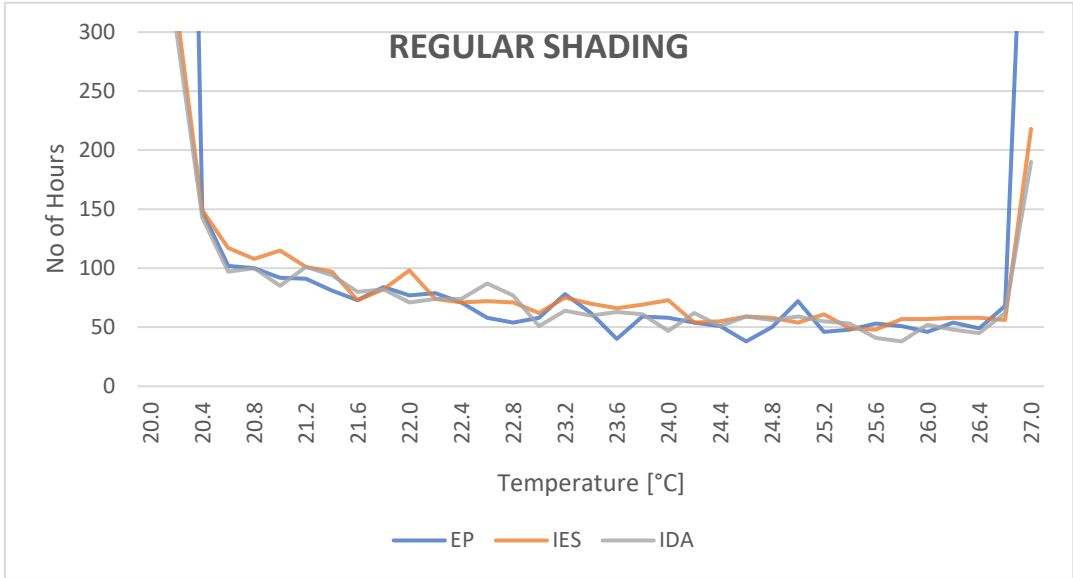
The light shelf gives more values towards the (0, 0) point of the graphs compared to the external shading configurations, which means that the tools are in more correlation in terms of cooling and heating modes. Yet, there are also a decent amount of values situated on the axes, meaning that while one BPS tool has the same conditioning between the shaded and unshaded mode, the other tools' shaded, and unshaded configurations differ in conditioning.

This analysis gives more complex interpretations and is hard to interpret at first glance, as it displays information for a lot of probabilities. Yet, it is important to think about it and interpret as much as possible.

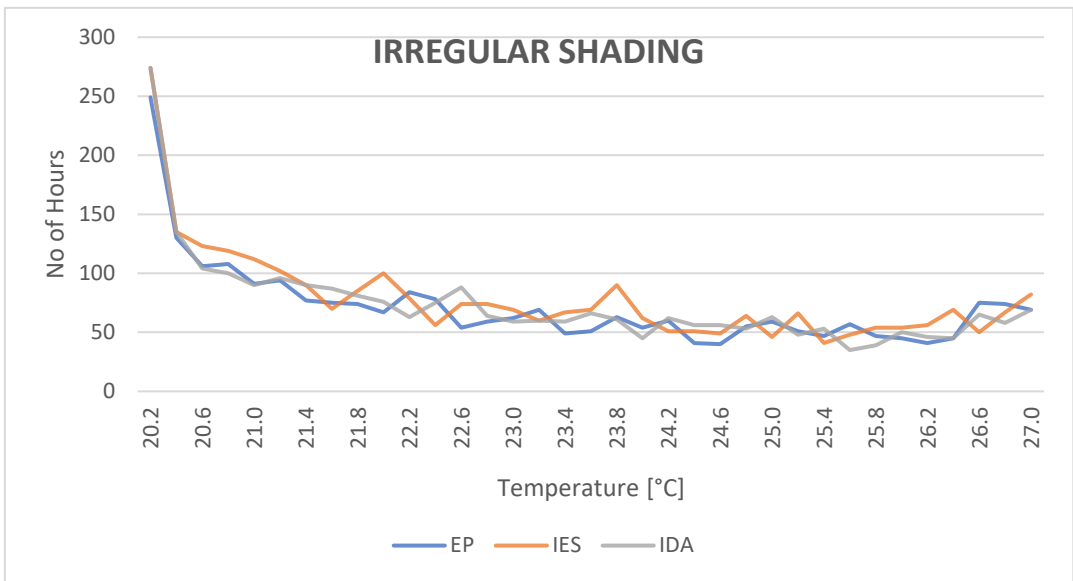
The following graphs display the frequency distribution of the air temperatures between the set-point temperatures 20 and 27°C, as the climatized cases are analyzed. The graphs' temperature intervals are set to 0.2 °C as it is a smaller gap and the set-point temperatures are not included in the frequency distribution to have a more detailed look at the line behavior because of scaling.



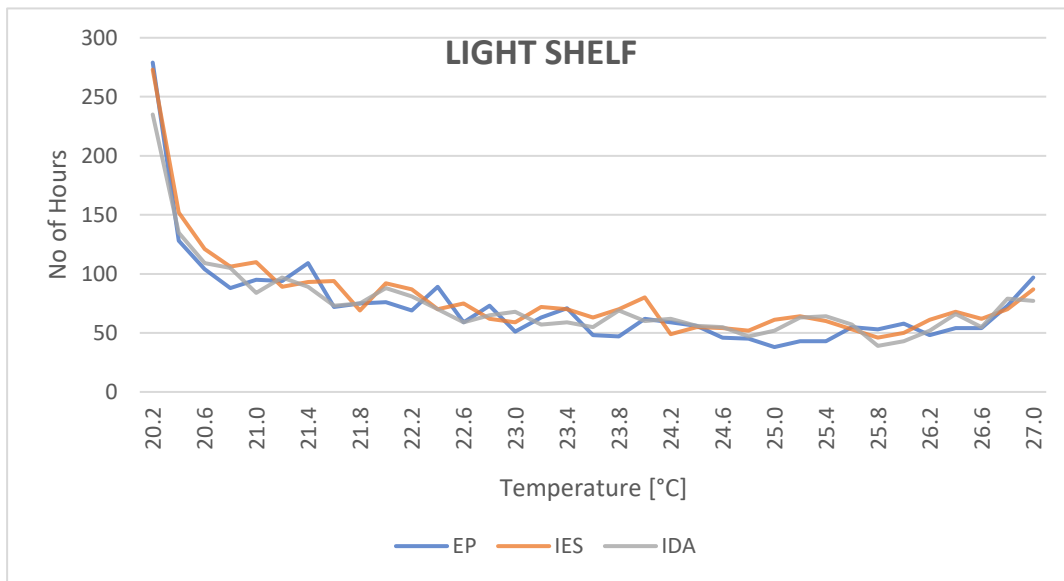
**Table 13: No Shade**



**Table 14: Regular**



**Table 15: Irregular**



**Table 16: Light Shelf**

All the graphs above show very similar trends. An accumulation of values in the lower front of the interval, between 20 and 20.6 °C, and a gradual decrease from there until 27 °C, with a slight peak towards the end.

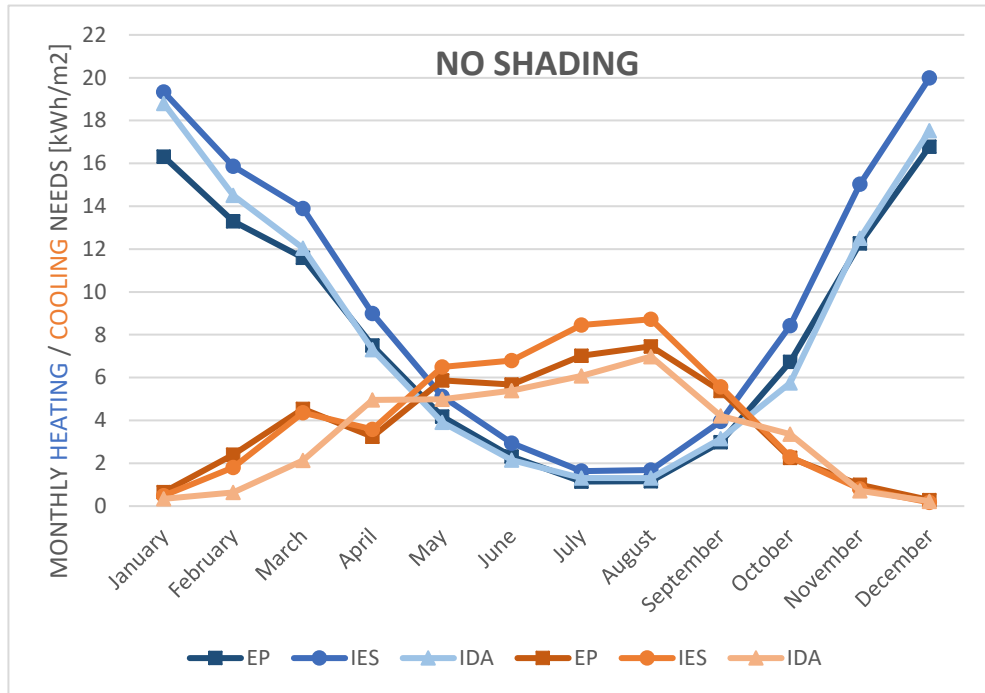
As Amsterdam being a cold climate and as can be interpreted from the previous free-floating graphs for frequency distribution, most of the hours, in free-floating condition, are distributed below 20°C, compared to higher values. This results in the ideal heaters to keep the indoor air temperature just at 20°C and when the heat balance favors the heat gain, the temperature immediately falls within the interval 20 and 20.2°C and the ideal heater is turned off. That is why there is an accumulation of hours in the lower end of the interval.

Almost all the cases on all the BPS tools show the same trend. Yet, this does not confirm that they have correlation within each other as the temperature values might not be coinciding, or better put, not at the exact timesteps.

### 3.1.2.1 Heating / Cooling Demand

#### 3.1.2.1.1 Monthly Heating and Cooling Needs [kWh/m2]

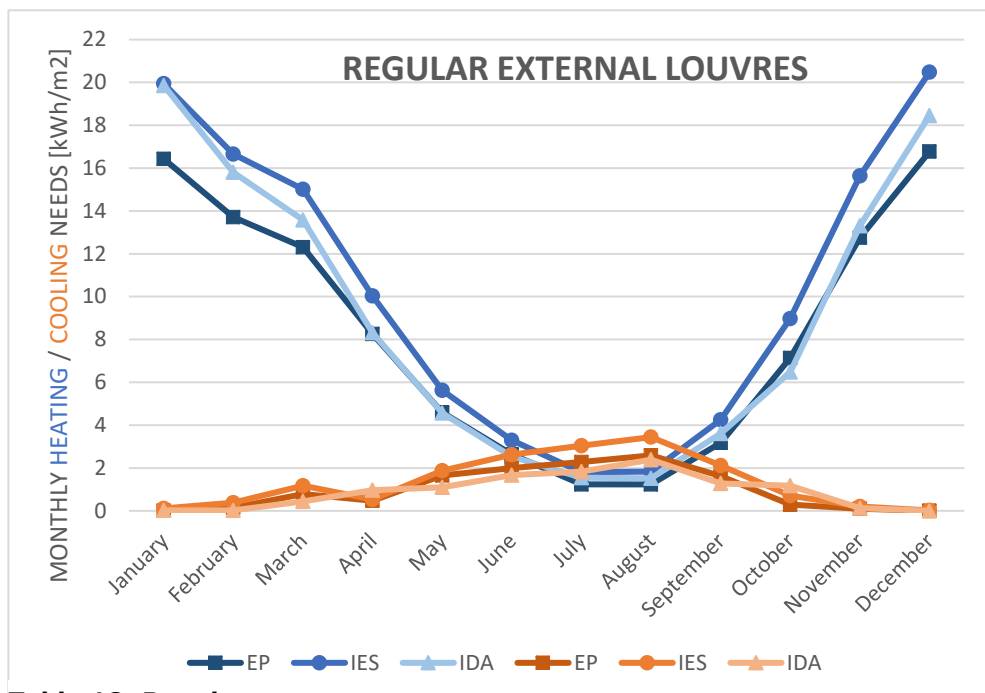
The following graphs give the heating and cooling needs per square meter for each of the cases on a monthly basis. The lines with the tones of blue are the heating needs and the orange toned lines represent the cooling needs of the cases.



**Table 17: No shading**

Even though the graphs show very similar trends, in some months, as in January, the difference can reach up to around 4 kW/m<sup>2</sup>, which is approximately a 20 to 25% difference (between EP and IES). IES seems to have the higher heating and cooling demand as opposed to the other two BPS tools.

Although EP and IDA follow almost the exact trend within their heating needs results throughout the whole year (except for January and February), they follow slightly different trends in terms of cooling sensible loads.

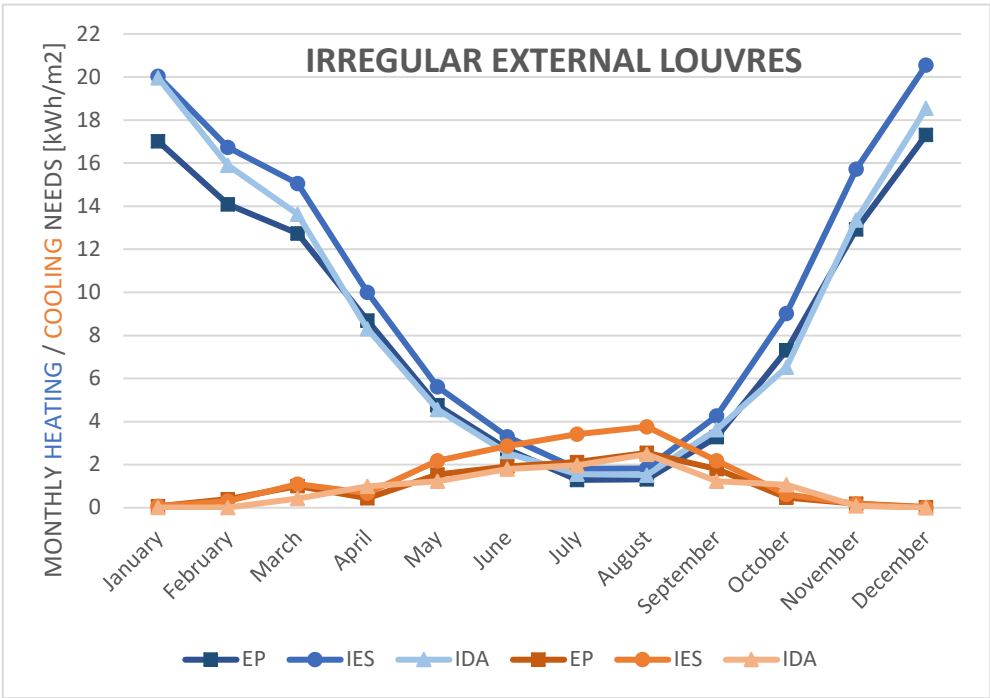


**Table 18: Regular**



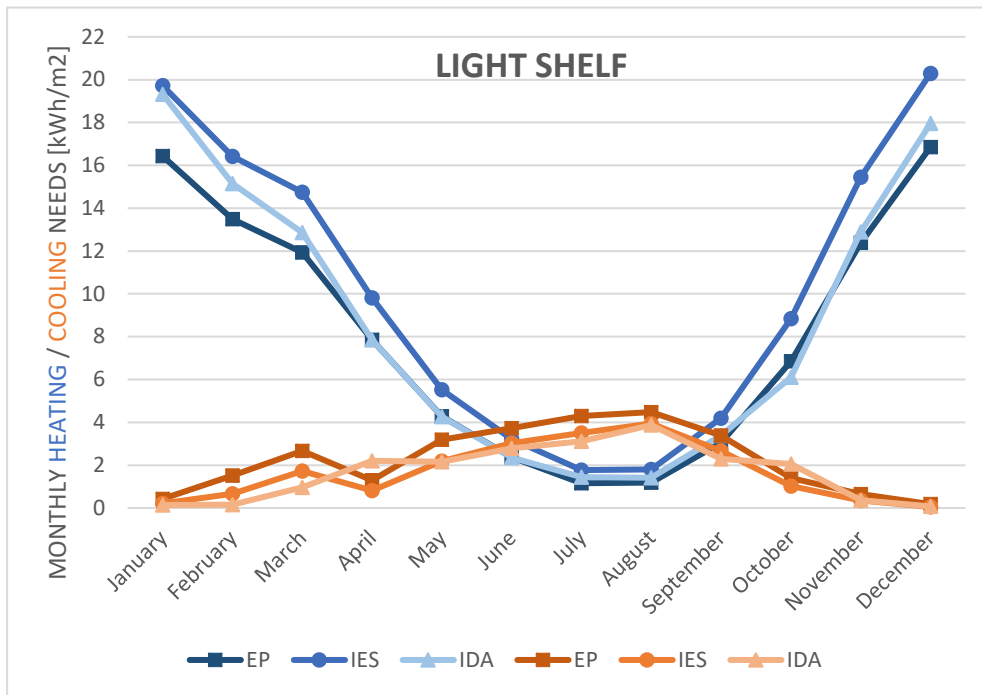
The scaling of the graphs is the same, so the decrement of cooling can be seen clearly. The implementation of shading has caused the cooling needs during the summer period to decrease from around 7 kWh/m<sup>2</sup> to around 2 kWh/m<sup>2</sup>.

Some significant increments in the heating loads for the IDA model during March and December is opposed to the small changes in the EP and IES. There is a noticeable correlation between the results of IDA and EP as in the "no shade" configuration.



**Table 19: Irregular**

The optimized, irregular shading configuration shows very slight differences compared to the regular shading configuration.



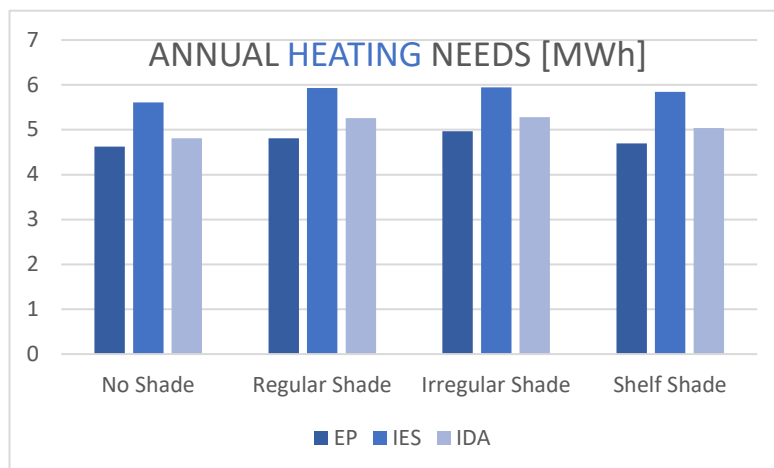
**Table 20: Light Shelf**

The noticeable change of the light shelf model results is that the IES cooling needs have decreased more significantly compared to the other BPS tools, yet this has made all the results more correlated with one another.

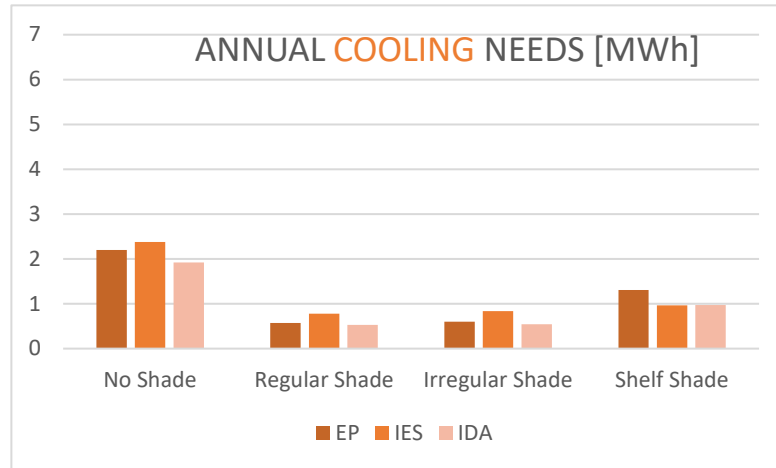
The heating needs in general have not made any noticeable change during the whole analysis.

### 3.1.2.1.2 Annual Heating / Cooling Needs [MWh]

Tables 21 and 22 show the total amount of heat, in MWh, needed to be delivered/extracted to/from the zones to satisfy the set-point temperatures of 20°C and 27°C. As mentioned earlier, ideal heating and cooling systems, with 100% efficiency, were implemented to be able to determine these values.



**Table 21: Annual Heating Needs**



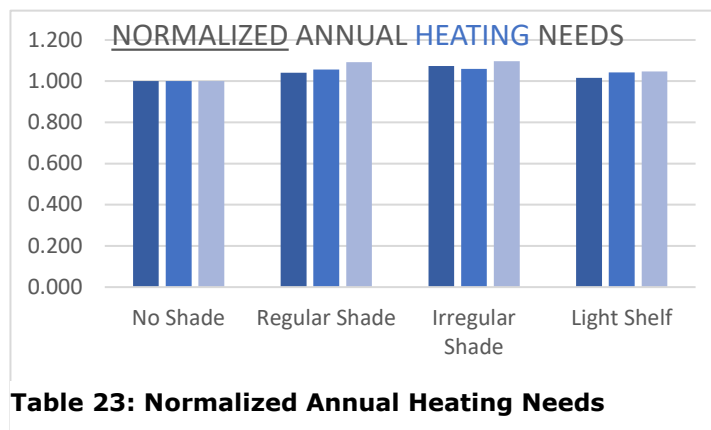
**Table 22: Annual Cooling Needs**

The graph for annual heating needs does not seem to differ too much throughout the different cases as the shading would far more likely to affect the cooling needs due to problems of over-heating. We can see that all cases seem to follow the same trend, with slight increments in the heating loads. We can observe that the increase in heating needs are slightly greater with the external louvres systems (regular and irregular) in comparison to the shelf shading system.

The graph for the annual cooling needs gives us more information regarding the effects of the shadings. The first three cases seem to have very similar trends, meaning that, despite the small base differences from the “no shade” models, the changes caused from the external louvres systems are quite the same in all tools.

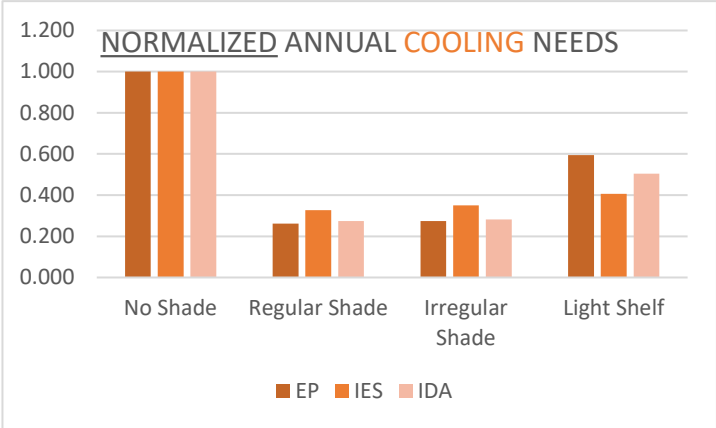
The last scenario, with the light shelf, seems to give rather different results. We can tell that the external louvres systems block more of the incident solar irradiation in comparison to the light shelf, as the aim of the light shelf is to provide more daylight to the room rather than preventing solar gains [21]. We can also tell that the IES light shelf model might be overestimating the effect of the shading, as the decrement is larger compared to the other tools.

The following 2 graphs, table 23 and 24, represent the dimensionless, normalized heating and cooling needs of the cases. All the results were simply divided by their corresponding “no shade” heating/cooling value. This can also be seen by the “no shade” cases in both



**Table 23: Normalized Annual Heating Needs**

graphs having a value of 1. This representation gives a clearer understanding on how much change has occurred with the implementation of the shadings.



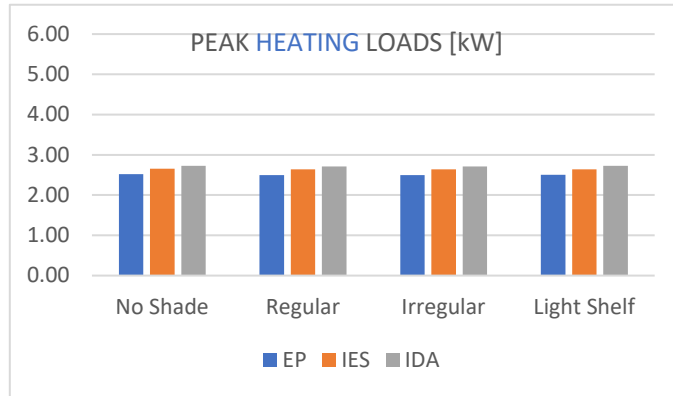
**Table 24**

The change on the annual heating needs, as can be seen from the ratios, are rather small, compared to the “base” heating needs of the cases. The increments are within the range of 5 to 10%. The solar gains which would help to keep the model’s indoor temperature above 20°C are not a considerable contribution as the location is in Amsterdam.

The graph above illustrates the decrease in the cooling needs in a clearer way. The cooling needs have decreased to less than half of the initial values, some going below a quarter. This gives us an understanding of how the shading systems work to prevent overheating within the zone. Although the models in all the software show similar trends, EP and IDA show more similarity, especially including the light shelf model. The difference of IES within the light shelf model shows a significant modeling consideration compared to the other tools.

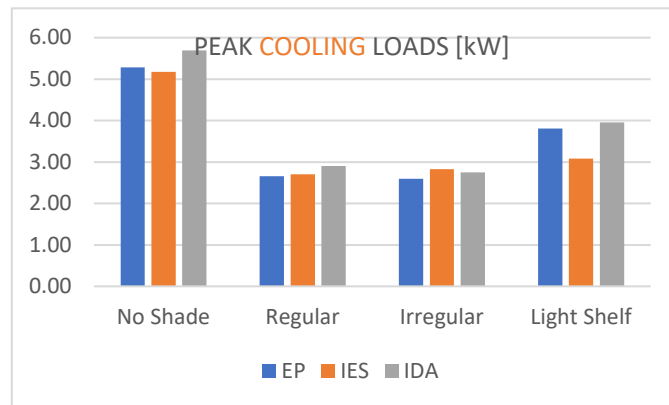
**3.1.2.1.3 Peak Heating / Cooling Loads**

It is important to investigate the peak heating and cooling loads as these values are generally used for the sizing of the plants. So, it is important for the tools to be coherent for the accuracy of design considerations when model predictions are taken into consideration.



**Table 24**

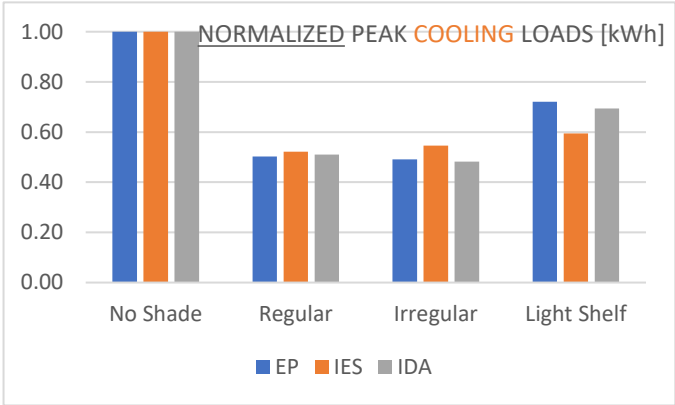
Table 25 shows the peak heating loads, which does not differ throughout the whole design changes. As also previously seen, the shading has little to no effect on the heading needs, and no effect on the peak heating loads.



**Table 25**

Table 26 displays the peak cooling loads of all the models within all the BPS tools. The results show very similar values, except for IDA having slightly higher peak loads. There is a very high correlation of peak loads within both the external louvres configurations of "regular" and "irregular". The only difference which stands out is the

As expected, there are significant differences in the peak cooling loads with the implementation of the shadings.



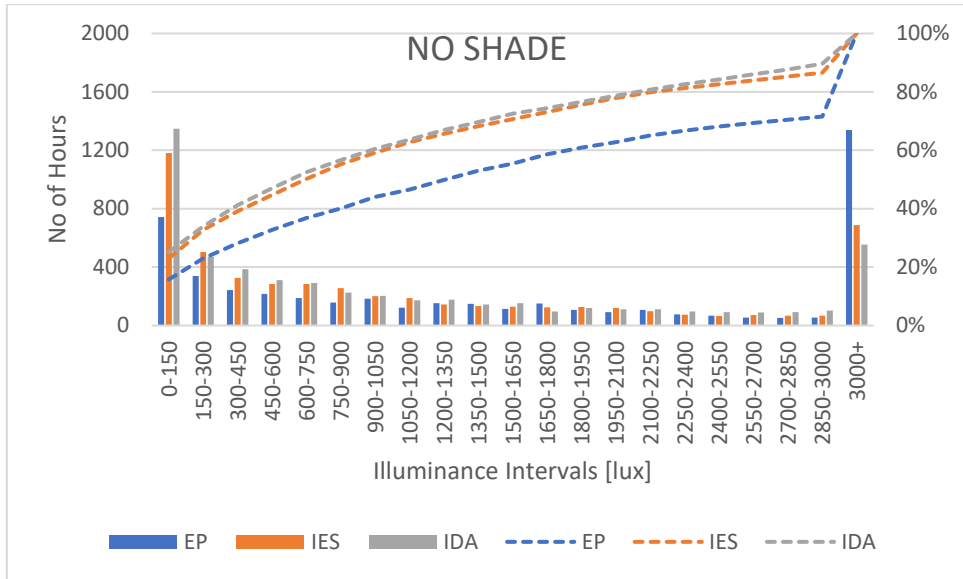
**Table 26**

To put the results on the same relative scale, which is their own “no shade” case, a normalization of the peak loads has been performed. With this graph we can see a clearer picture on how the shadings have affected the cooling loads within each tool and how these differences are within the BPS tools compared to one another. The effect of the “regular” shading configuration shows almost identical decrements in relation to the base configurations. The irregular shading configuration shows a noticeable increment in the peak cooling load, whereas the other BPS show little to no difference. The light shelf, as previously stated too, shows that the IES model overestimates the shading of the implementation compared to the other two tools EP and IDA.

### 3.2 Daylighting Analysis (Illuminance)

#### 3.2.1 Yearly Analysis

The following frequency distribution charts illustrate the annual illuminance values on the previously specified reference point (2 m inward from the center of the left south facing window, at 0.8 m height) within an interval of 150 lux. The bar charts correspond to the primary y-axis (left) and represent the number of hours within a year which fall within the corresponding illuminance interval. The secondary y-axis (right) represents the percentage of the cumulative frequency for the illuminance values, which are plotted with the dashed lines. The 4 charts include the illuminance results of the 4 different cases, modelled in EP, IES and IDA, and have the same axis scales for better comparison.

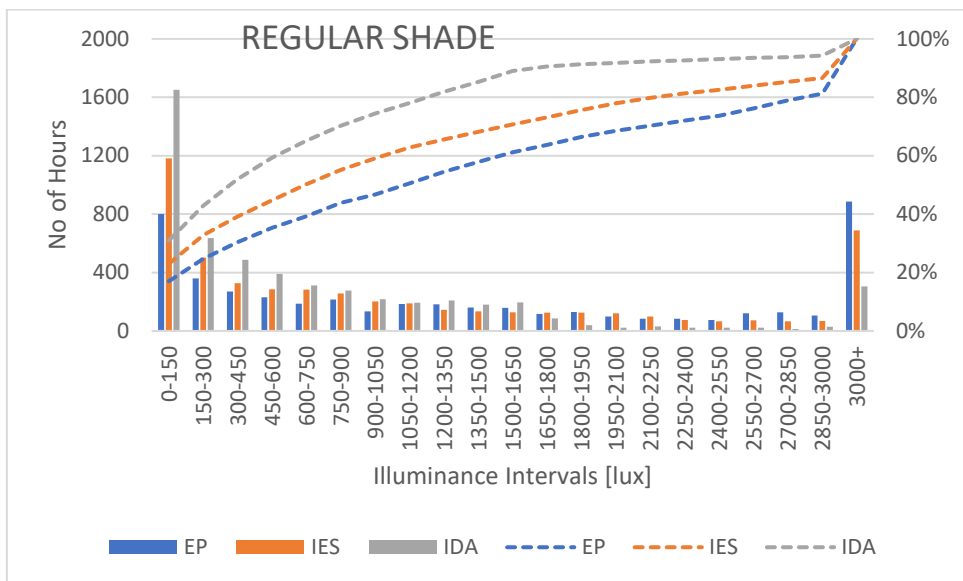


**Table 27**

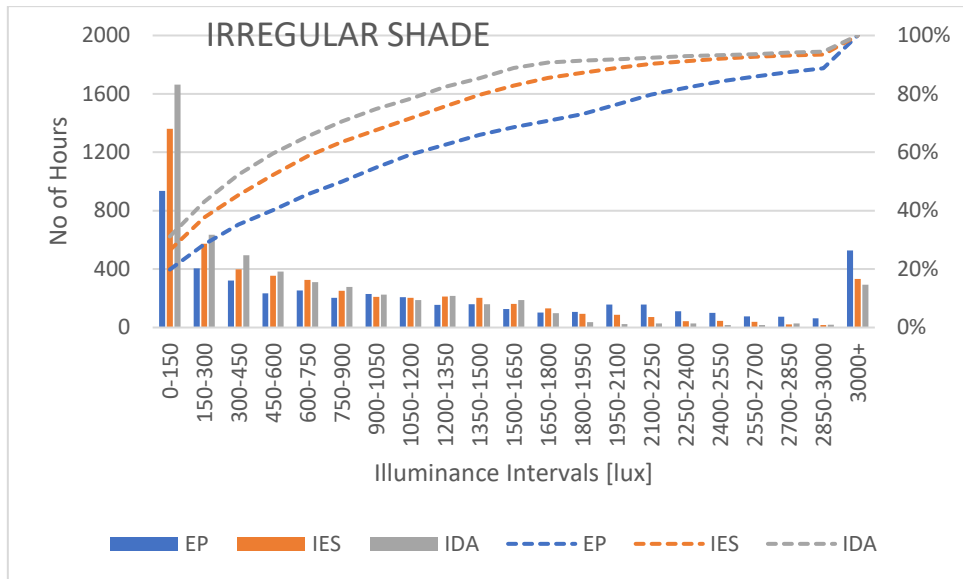
Table 28 illustrates the frequency distribution of the “no shade” case. Compared to the other 3 cases, as expected, the distribution of the illuminance levels is more concentrated on higher values.

In this case, we can see that IES and IDA’s illuminance values are more concentrated in the 0-150 lux interval in contrast to EP’s concentration on values which exceed 3000 lux. The intervals in-between show relatively similar trends, as can also be seen from the slope of the cumulative frequency (dashed) lines.

The results which IES and IDA give are very similar to each other, which can also be interpreted from the cumulative frequency trends, whereas EP values seem to overestimate high illuminance levels.



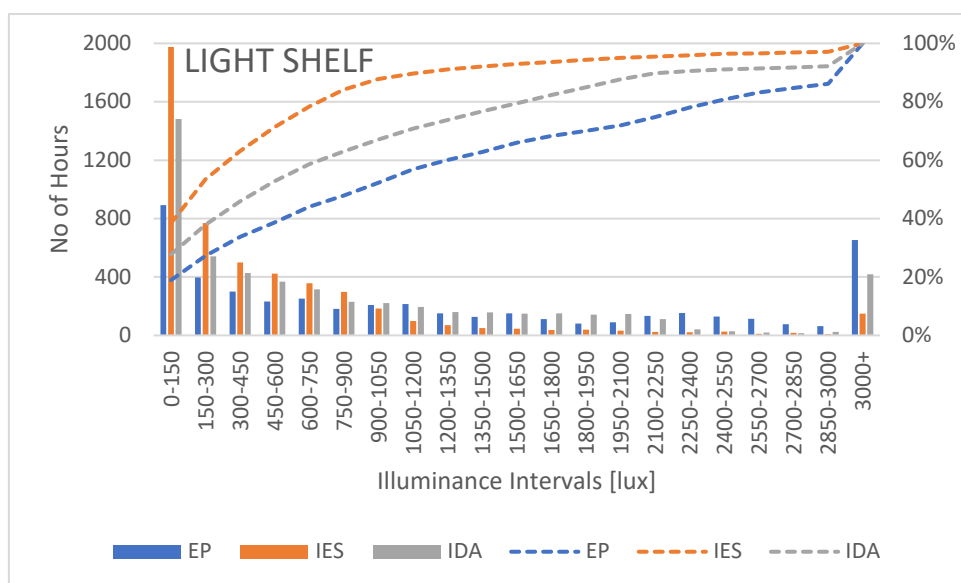
**Table 28**



**Table 29**

The two tables, 29 and 30, are plotted for the external louvres models and are going to be taken into account together as the graphs show fairly similar results. With the case of the external louvres, we can say that IDA’s illuminance values are more concentrated on the lower side of the scale. IES has slightly lower concentrations on the lower values and EP has the lowest.

In comparison to the normal shade graph’s cumulative frequency line, the convergence of the dashed lines towards the 100% value in the graphs for regular and irregular shades show a more sharp trend with a slower rise at the end. The behavior of the line in graph x tells us that there are more values concentrated on the higher illuminance values. This means that the higher values of the “no shade” case have been redistributed towards the lower scales because of the implementation of the shading.



**Table 30**



Table 31, the results from the "light shelf" case, displays a more different finding compared to the previous cases. The difference in results is mainly caused by the findings from the IES model. The light shelf seems to be more of a overhang-like shading system rather than a system which aims to increase the daylighting within the zone.

It is important to highlight that using 1 single reference point to measure the illuminance values does not give an understanding of the whole daylighting performance of a room. Yet, to keep every aspect equal and as simple as possible, the position of the sensor was kept the same throughout the models. As Selkowitz, et al. [21] states, a light shelf's primary aim is to increase the light penetration towards the back of the room by the surface's reflective properties and increase the daylighting performance. Due to this paper being more focused on the design aspects of the shadings and their differences within the BPS tools, the implementations have been kept as simple as possible. Although IES's results being rather off, compared to the other two tools, a conclusion of the tool being inaccurate or more accurate cannot be made sure at this point.

### 3.2.2 Daily Analysis

#### 3.2.2.1 21st of June

The following graphs show the daily illuminance values from the performed analyses, to have a more detailed look into the results taken out from the different BPS tools. The results are shown for the 21st of June on an hourly basis. The scales of the axes have been kept the same to observe the difference from the shadings and light shelf.

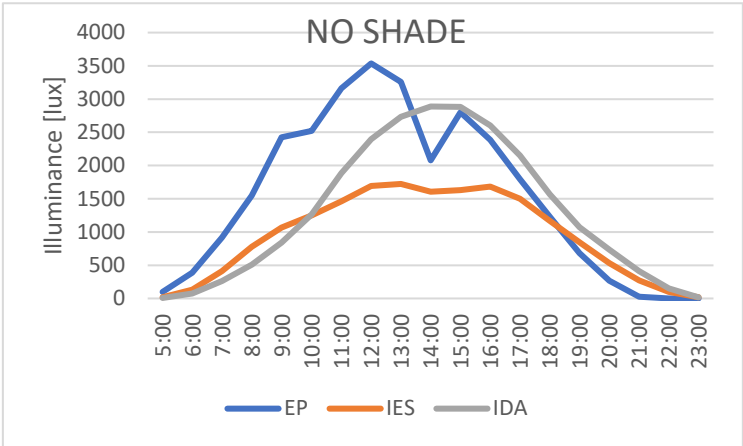
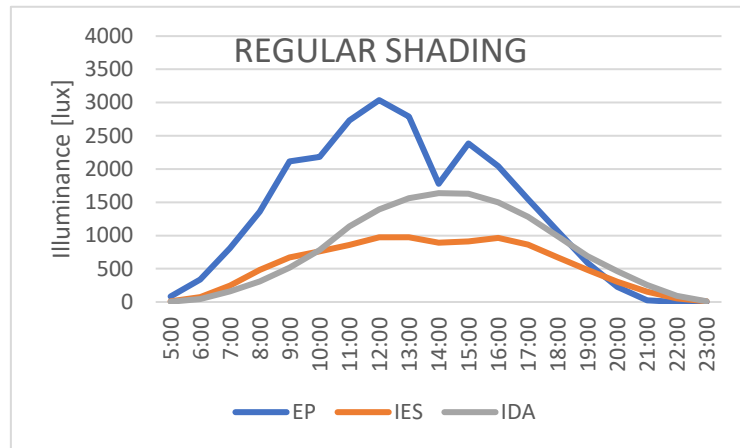


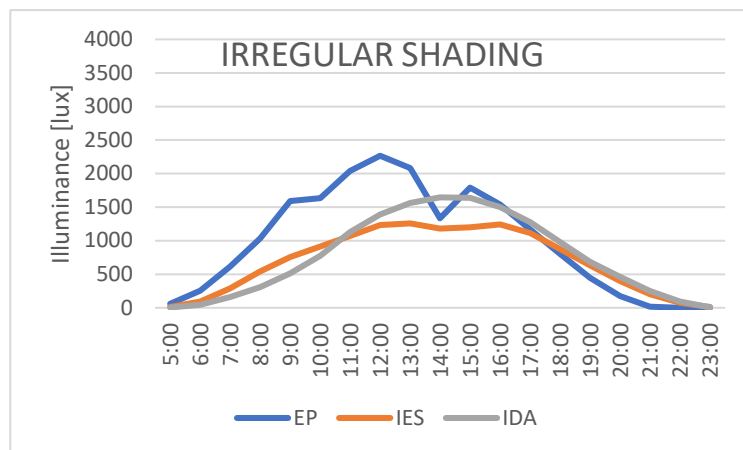
Table 31

Considerable differences can be seen in many aspects. All three of the tools show different shapes, peaks, and peak times. This shows that the daylighting calculation is relatively different on all the tools. While EP and IES results show more sharp changes in the hourly illuminance values, IDA’s resulting line is more curve-like. A slight similarity between IES and EP can be seen as their lines break at similar points with a similar behavior.



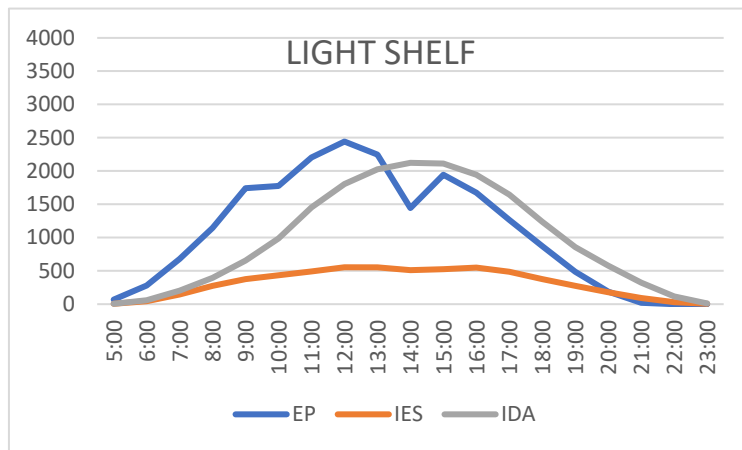
**Table 32**

There are significant decrements in the results of the illuminance levels due to the shading implementation. Yet, still little correlation can be seen.



**Table 33**

The correlation seems to have increased between the three models, especially between IES and IDA. It is an interesting finding as the “regular” shading showed less of a correlation.

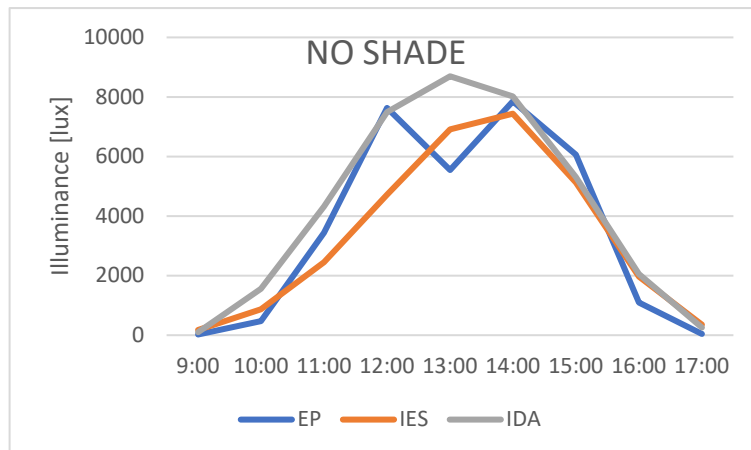


**Table 34**

IES highly overestimates the effect of the shading that the light shelf provides compared to the other two tools, as also previously discussed. IDA and EP show a closer correlation between the tools.

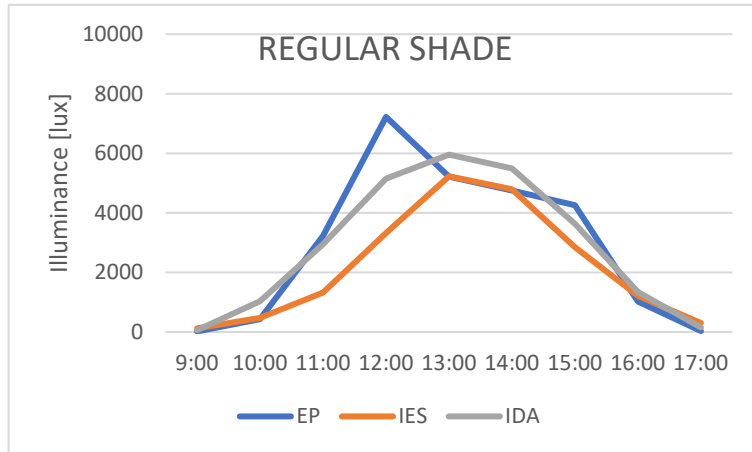
### 3.2.2.2 21st of December

The graphs show the illuminance values from the 21st of December. The illuminance levels are higher, as the sun is lower in December, so the shadings have less of an effect on the incoming light. The y-axis scales are different compared to the previous analyses of 21st of December.



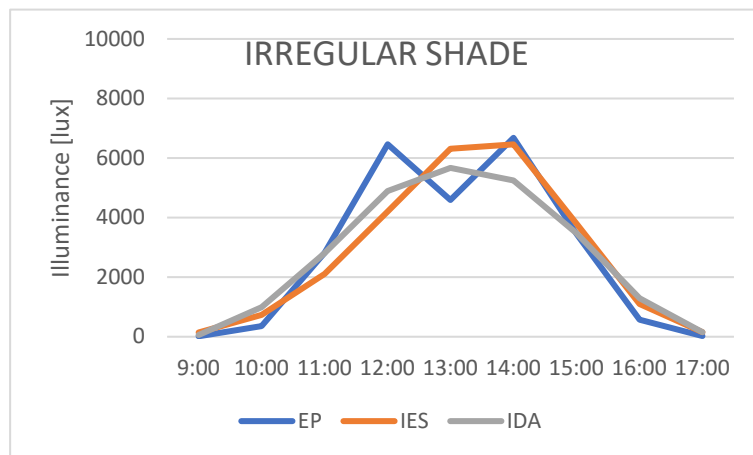
**Table 35**

Compared to 21st of June a much stronger correlation can be seen between the three BPS tools. EP is considering an unknown effect on midday which causes the illuminance to go down and back up again, as both the other tools almost peak around those times of the day. This might be the shadow which is created by the wall between the two windows or it might be because of the weather file data, such as cloud cover at that instance.



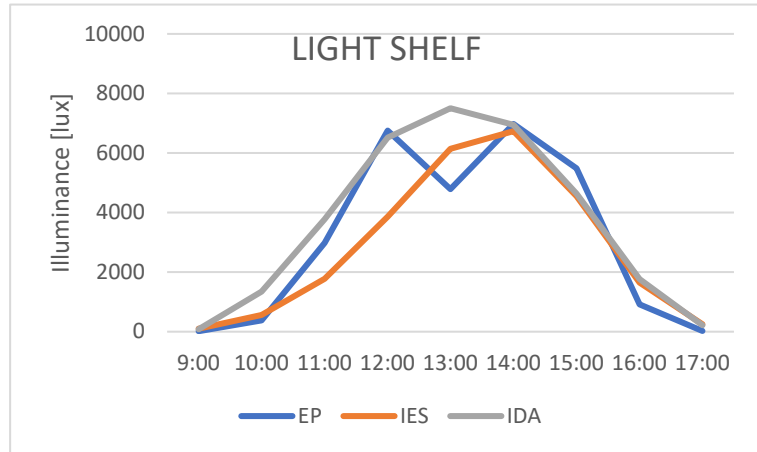
**Table 36**

The correlation steel seems to be similar with the regular shade configuration. Yet, the behavior of the lines is quite different. EP peaks at around 12:00, whereas IES and IDA peak at 13:00.



**Table 37**

The "irregular" shading configuration shows the highest correlation along with the light shelf implementation. Even though the lines behave in a different manner, they give out very similar results.



**Table 38**

Even though the IES overestimation for the effect of shading for the light shelf has been discussed, in this graph we see a strong correlation between the three results. The reasoning might be because the sun was low enough to go below the shelf shading, so the shelf did not cause the blockage of sunlight.

The illuminance values were much higher on the 21st of December as opposed to the 21st of June, due to the sun's position. When the sun was higher on the 21st of June, the shadings were being more present in blocking the sunlight, causing discrepancies between the results. This might be because the tools have different calculation mechanism for the shading effects.

# 4 Discussion

## 4.1 Thermal analysis

### 4.1.1 Indoor Mean Air Temperature

In terms of temperature values for the free-floating models, EP and IES gave more similar trends in almost all the modelling approaches. Even though this does not validate both the tools EP and IES in comparison to IDA, it is still an interpretation from results and must be taken into consideration.

One of the differences which IDA gave from the results was the number of hours which IDA had in the extreme ends of the temperature values. The differences for this case can be due to the differences between the heat transfer mechanisms considered within the tools or maybe the thermal mass considerations, even though the models were lightweight constructions.

A study which compares several models also shows that IDA gives the highest maximum zone temperatures as well as the highest mean annual temperature. The reasoning for this has been explained due to IDA calculating the shading coefficients for the direct radiation only and that the diffuse part is done without correction [19]. The difference can be attributed to the core code of the model, yet more detailed investigations must be done for validation.

Another study, aiming to compare EP and IES in free-floating conditions, concluded that EP over-predicted air temperatures compared to IES due to difference in the calculation of the convective heat transfer coefficients which could not be manipulated by the users [6]. This proves a relatively strong point, which the unchangeable core of the software might not correlate with the real values and because the user can not manipulate the value the software tool can be considered "rigid". This can cause a huge problem in design, thus simulation tools must work for more flexibility in input or source code change.

### 4.1.2 Heating / Cooling

From the results taken out from the conducted analyses, monthly heating and cooling needs showed quite similar results. Yet, some monthly values showed differences up to 25%. When trying to predict energy consumptions of a building these differences might be transferred into larger discrepancies, as this difference is just between building performance simulation tools. It is hard to say whether these differences would cause troubles in the design of the building considering some desired targets, yet it can surely be said that it gives some unreliability towards these tools.

Some studies in these fields manage to validate some BPS tools by comparing them with one another. The study conducted between EP and IES shows that there is a high consistency between the total energy consumptions and that the results are encouraging for the LEED certification. Such studies aim to correlate and compare tools, yet it is still not completely validated until they are validated with realistic data, as was also mentioned in the "limitations" part of the paper [6].

Another important finding is the difference in the heating and cooling mode differences within some timesteps of the predicted results. In some extreme cases, the temperature differences were such that it resulted in different conditioning strategies. Even though this aspect might be balanced when the heating and cooling needs are investigated on a monthly or annual level, it is interesting to comment on.

The peak heating and cooling loads are also an important factor to consider as they will be taken into consideration while sizing the mechanical equipment. The results of all three BPS tools, from the conducted analyses, showed very similar results. The only big difference was caused by IES's light shelf model, which is an interesting finding and one to investigate in further works. This might also be caused by the user error, which is also an error margin to consider as people construct and run these models.

## 4.2 Daylighting Analysis

When considering the daylighting analysis conducted in this paper, it is important to be critical against the methodology of the research. The illuminance value of 1 point of a 48 m<sup>2</sup> room does not represent the condition of the whole room, nor does it give an understanding of a possible energy saving strategy for the lighting. Yet, if the average daylight factor of the room were to be checked, it would have given very rough results. It is important to highlight that the research conducted was to compare the BPS tools in some respects to investigate and give possible reasoning for the differences. It might not always be easy to determine what parameters to compare the BPS tools, which are also important in the design phase of the building.

In the yearly frequency and cumulative frequency analyses of the models, it was evident that EP overestimated the higher illuminance values compared to the other two BPS tools. IES and IDA values were more concentrated in the lower side of the illuminance interval.

An interesting finding from the daily illuminance value comparisons was that the increase in the shading contribution drastically decreased the correlation between the results. Studies also show that as the complexity of a model increases, the discrepancy is highly likely to increase [6].





## 5 Conclusion

The paper aimed to investigate certain aspects of the functioning of BPS tools by looking at the outputs taken out from the simulations. The main comparative aspects were the thermal and daylighting results, from an hourly, monthly, and yearly basis. These aspects were compared by the addition of complexity with shading implementations and the daylight improvement strategy, the light shelf. Some interesting points have been obtained from the findings.

The thermal analyses were close to each other, yet it is hard to determine relativity within the tools as there is no way to determine the more "correct" result. Yet, these kinds of comparative studies are important for input debugging and in improving engineering judgment, yet it still does not change the fact that the complexity in the studies are high [18].

Even though the models were kept as simple as possible some increments in the complexity of shadings resulted in discrepancies, especially in the daylighting analysis, as the tools consider the shading calculations in different ways. So, it is important to be simple in modelling, yet precise enough to cover the important aspects.

A study gives possible reasonings for the differences within these analyses. The research states that the three reasons between the discrepancies between the different simulation tools are due to: the unchangeable core of the software, the graphical user interface of the program and the user's imprecise modelling [12]. That is why Crawley et, al. suggests users to endorse in using several BPS tools when doing analyses, as the range of possible results would be achieved instead of 1 single reference point [20].

There are works constantly being put forward on the topic of the accuracy of BPS tools, each targeting different aspects of the capabilities and incompetence of them. It is crucial for the academic field to make constructive criticism towards the topic as these tools are the backbone of the future's efficient and sustainable designs.

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