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Comparative Studies of Building Performance Simulation Tools (EnergyPlus, IES-VE, IDA-ICE)

Supervisors: Prof. Giuliana IANNACCONE

Prof. Francesco GOIA

Co-Supervisors: Assoc. Prof. Gabriele LOBACCARO

Ellika Taveres-CACHAT

Erolcan ERDOGAN

10677053

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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 thesis investigates and compares 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 simulation tools, EnergyPlus, IES-VE and IDA-ICE were used for the modelling of the cases. The comparative studies include the comparison of the thermal and daylighting results among the building performance simulation tools (EnergyPlus vs IES-VE vs IDA-ICE), and within the tools (user-built vs in-built shading implementations). Graphs and tables were used to find correlations and differences between the different simulated model results. A user-based commentary on the use of the tools has also been implemented within the study.

Keywords: Building performance simulation, Building energy modelling, EnergyPlus, IES-VE, IDA-ICE, Shading, Thermal analysis, Daylighting

Sommario

Poiché i paesi stanno cercando di lavorare per progetti più efficienti dal punto di vista energetico, l'industria delle costruzioni, essendo il settore di utilizzo finale più elevato per l'uso di energia per molte nazioni in tutto il mondo, è un obiettivo importante. È stato sempre più importante lavorare per l'efficienza energetica negli edifici. Queste misure possono essere eseguite con strumenti di simulazione delle prestazioni degli edifici moderni e altamente funzionali. Tuttavia, poiché sul mercato sono disponibili molti strumenti diversi con capacità diverse, è importante che questi strumenti diano risultati precisi per il futuro di una progettazione efficiente.

Questo documento indaga e confronta i risultati termici e di illuminazione diurna di diversi strumenti di simulazione delle prestazioni degli edifici, implementando moderne strategie di ombreggiatura e illuminazione diurna su un case base. Per la modellazione dei casi sono stati utilizzati tre degli strumenti di simulazione delle prestazioni degli edifici ampiamente utilizzati e accettati, EnergyPlus, IES-VE e IDA-ICE. Gli studi comparativi includono il confronto dei risultati termici e di illuminazione diurna tra gli strumenti di simulazione delle prestazioni degli edifici (EnergyPlus vs IES <VE> vs IDA-ICE) e all'interno degli strumenti (implementazioni di ombreggiatura incorporate rispetto agli utenti). Grafici e tabelle sono stati utilizzati per trovare correlazioni e differenze tra i diversi risultati del modello simulato. All'interno dello studio è stato anche implementato un commento basato sugli utenti sull'uso degli strumenti.

Parole chiave: simulazione delle prestazioni degli edifici, modellazione energetica degli edifici, EnergyPlus, IES <VE>, IDA-ICE, ombreggiamento, analisi termica, illuminazione diurna

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
nZEB	Nearly Zero Energy Building
EU	European Union
EN	European Norms (Standards)

1 Introduction

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 thesis investigates and compares 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 simulation tools, EnergyPlus, IES-VE and IDA-ICE were used for the modelling of the cases. The comparative studies include the comparison of the thermal and daylighting results among the building performance simulation tools (EnergyPlus vs IES-VE vs IDA-ICE), and

within the tools (user-built vs in-built shading implementations). Graphs and tables were used to find correlations and differences between the different simulated model results. A user-based commentary on the use of the tools has also been implemented within the study.

1.1 Issues and Relevance

To prevent the possible negative consequences of the current course of the traditional building industry, measures have started to be taken to shift the direction into a more climate friendly, economic, and sustainable future scenario. The Paris Agreement, being the most inclusive climate-change act, has set ambitious targets for the future built environment. The agreement sets aims for 2030 to reduce carbon emissions by 40%, mainly with enhancements in energy efficiency, of at least 32%, and renewables, of at least 32.5%. These mutually dependent targets put a high pressure on the building industry, the largest energy consuming sector [1, 12]. These measures have brought about an important definition for the future of the industry, nearly-zero energy buildings (nZEB). The term refers to a building with very high efficiency. A building which demands very low energy aimed to be covered by renewables, which in turn reduces the carbon footprint drastically [13]. Even though the US, a country of almost 18% of the globe's greenhouse gas emissions [14], has withdrawn from the Paris act [15], its state of California has set targets to achieve zero energy buildings for its new residential and commercial buildings by 2020 and 2030, respectively [16]. Strategies towards shaping the new building industry have been defined and initiated. The global shift towards an energy efficient and sustainable future is inevitable. Yet, the European standard, EN-15251, states that declarations on energy efficient measures are senseless without defining the criteria of the internal environments of buildings [17].

A building's primary aim is to provide humans with internal comfort zones by filtering the outdoor environment and its phenomena with its enveloping components. These comfort zones must maintain a degree of thermal, visual, and ventilative characteristics determined by national standards which are administered within most countries. The boundaries of these characteristics which define the human comfort are of utmost importance in preserving the health, productivity and comfort of the people occupying these spaces. The standard EN-15251 states that the social and economic cost of maintaining a comfortable indoor environment is much less than that of a poorly monitored internal zone [17], which emphasizes the importance of these measures. This thesis focuses on the two aspects of the internal comfort parameters: the thermal and the visual comfort. Thermal comfort, as defined by Senin et al., is a psychological state of mind of being cold, cool, slightly cooler, neutral, slightly warmer, warm, and hot, depending on the bodily perceptions of the occupant. It somewhat determines how successful a building is, not only for its satisfied people but for its close correlation with the sustainability and efficiency aspects of the structure [18]. Visual comfort, defined by EN-12464, is the feeling of well-being of the occupants for being able to be productive and produce high-quality work in a sufficient and appropriate lighting setting. Adequate visibility is necessary for the safety of the occupants, and for them to be able to perform the necessary tasks efficiently and accurately [19]. Both comfort indices, the thermal and visual, play an imperative role in the functioning of the building's interior environment. Not only do they provide the necessary work and living conditions, they define the necessary

boundaries to be met. These criteria are therefore closely linked to the energy performance of the building and the future global targets of the building industry. The building components which have a significant impact on these aspects, as the EU Directive states, should be defined, and optimized for energy efficient and cost-optimal measures [13]. This thesis therefore focuses on one of the most important components of a building's envelope, the shading.

Shading devices prevent the incoming solar irradiation from reaching the building's envelope, thus reducing the heat gains, and controlling the daylighting. Shading systems are then effective means of managing the interior environment. Yet, they must be carefully designed as they affect a variety of linked causes such as heating, cooling, building's energy for lighting, as well as the thermal and visual comfort of the occupants. Therefore, the compromise between these aspects must be attentively evaluated [20]. The design process must be done carefully, not just because of the various causes it affects, but also because of the significant impact on these causes. Numerous studies have validated the influence of shading implementation on the building's performances. According to 2030 Architecture, an external shading system can reduce the solar heat gains transmitted through the glazing to up to 80% [21], a very large sum. A study conducted in the Malaga Business Park located in Malaga used external louvres systems and have acquired a 60% reduction in cooling demands, while also improving the visual performance of the interior by reducing the excessive illuminance values by around 12% [22]. Another study on light shelves resulted on a 23% in energy savings, in addition to the enhancements in the daylighting performance of the whole room [23]. These are just some of the findings throughout the many, which prove the importance of shading elements. Thus, it is of utmost importance to prevent any small discrepancies and errors which might be caused during the design process. These seemingly small yet impactful inaccuracies might result in imprecise performance estimations and wrong choices in design considerations, ultimately impairing the global shift towards an energy efficient and climate friendly future. That is why, this thesis focuses on the implementation of shading and daylighting strategies, and the possible discrepancies which might be caused by the different choices of design, mainly within the chosen building performance simulation tools.

2 Literature Review

The increment in the use of building performance simulation tools has undoubtedly encouraged the academic field to conduct various research studies about these software kits. Studies have approached the analysis of the BPS tools with different methodologies, varying in several different aspects. After an initial overview of related work, specific studies on, comparative testing of simulation tools, surveys conducted on the use of the tools, and implementations of shading elements were examined.

2.1 Comparative Studies

Some comparative studies have explored the differences of simulation tools, with the number of compared BPS tools varying from 2 to up to 20. These comparative studies also differ in compared aspects, whether it be simulation results, capabilities of the tools or user usability [24-27]. All in all, there exists an extensive literature on the topic of interest, with varying approaches.

The simulation models built within the tools for the comparative studies have mostly been simple models with a gradual increase in complexity, such as the addition of thermal mass, infiltration, internal loads, HVAC systems and so on [24,25]. Some studies have even modelled and analyzed real buildings such as residential buildings [27] and university campuses [26], with all their complexity. Although prior comparative testing on simple and complex models have proven useful, as far as the extensive literature review conducted, studies are lacking in the added complexity and comparison of one particular element. This thesis aimed to increase the complexity of shading and daylighting elements, maintaining all other parameters at a constant value, and compare the results of the conducted simulations within the BPS tools.

2.2 Survey Studies

Another type of research, mentioned above, is the study of surveys conducted on several users about the topic of interest. The surveys were conducted on a multitude of people ranging from 11 to 249 eligible respondents with various backgrounds. Some questions of the surveys, related to the current research, aimed to explore the usability, information management and the types of the software used in the respondents' analyses. [28-31]

The information gathered from the surveys have managed to pinpoint issues, distinguish the capabilities, and give information of the use of BPS tools with "yes" or "no" answers. Although the studies have achieved to answer questions in wide and narrow perspectives, they lack in giving specific details to the reasonings of these choices, as it is hard to include commentary from numerous respondents. One of the main objectives of this work is to derive

specific user-based commentaries on the use and findings of the analyses in the light of prior surveys.

A review of the literature in the survey-based studies and of other prior research have shown that a multitude of BPS tool applications have been conducted with the use of EnergyPlus, IES<VE> and IDA-ICE. The decision of investigating these three tools have been made due to the pre-dominance of their use within the community.

2.3 Shading Implementation Studies

Considering the research done by implementing and analyzing shading devices with the help of simulation tools, a vast number of studies have been conducted. A study analyzing 109 papers on the use of shading devices within BPS tools also exists, which helps to clarify and give insight on the general scope of the research community. Authors have indicated that a vast majority of studies have included external fixed louvres and light shelves, which highlights the importance of the applications [32].

With the increased use of parametric design, the external fixed louvres system of a research conducted with multi-objective optimization has also been implemented into this study [33]. This implementation is aimed to add complexity in the design and analyses carried out, which will further question the capabilities of the BPS tools in this aspect. As a result, three shading and daylighting applications have been considered in this research: a regular fixed external louvres shading, a parametrically optimized external louvres system and a light shelf.

3 Methodology

3.1 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 [33]. 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 [34].

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.

3.2 Description of the BPS tools

3.2.1 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. [35] 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 [36]. 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.

3.2.2 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.

ModellT 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 thesis, 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 ModellT, 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 [37].

3.2.3 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 [38].

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.

3.3 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 [25].

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

enproj.xls, May 10, 2004

EXTERIOR WALL (inside to outside)				
ELEMENT	k (W/(m*K))	Thickness (m)	U (W/(m ² *K))	R (m ² *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 ² *K))	R (m ² *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 ² *K))	R (m ² *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 ²)	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 ³)	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 [25]

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/m²K (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. [25]

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.

3.4 Description of the Shading Systems

3.4.1 “Regular” External Louvres System

This conventional external louvres shading has 10 blades with a slat angle of 15° . 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.

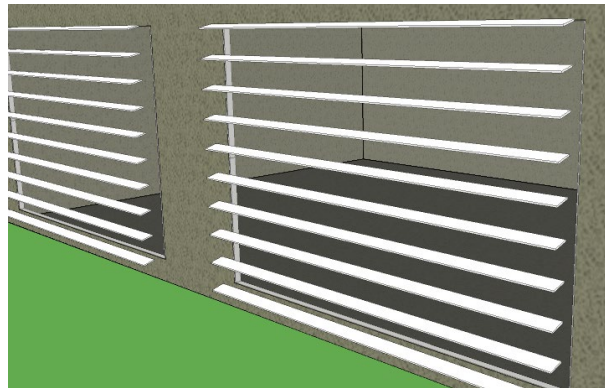


Figure 2: Regular Louvres



Figure 3: Exemplary image for Regular External Louvres, Thurston Elementary School, Malum Architects Inc., Oregon US [21]

3.4.2 “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 [33]. Figures 4 and 5 illustrate the resulting optimized configuration of the shading system.

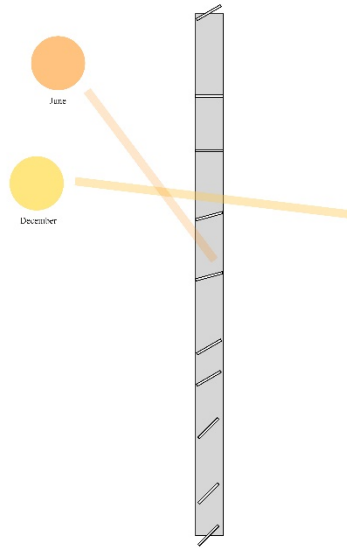


Figure 4: Optimized Configuration [21]

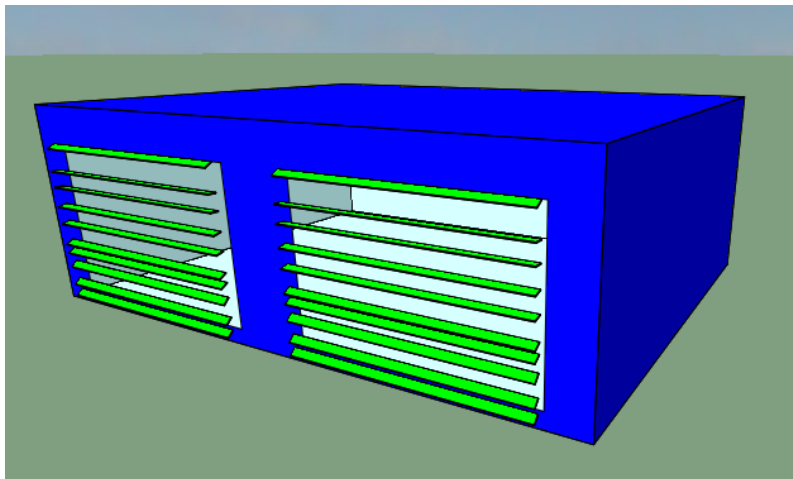


Figure 5: Irregular Configuration



Figure 6: Exemplary Image for Irregular External Shading, The Joel and Dena Gambord Business and Information Technology Building, HMC Architects, California State University US [21]

3.4.3 “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.

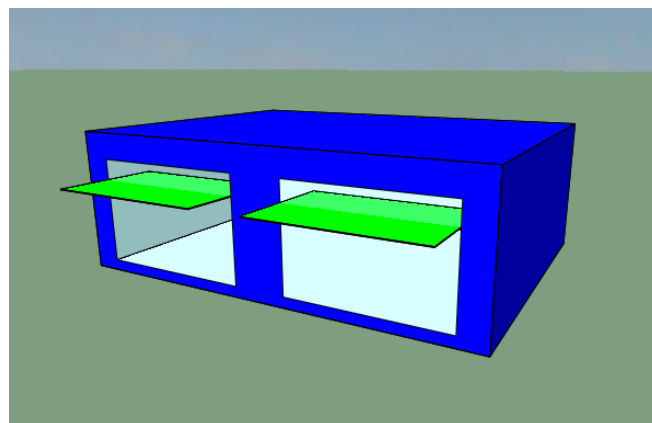


Figure 7: Light Shelf



Figure 8: Exemplary Image for Light Shelf, Thurston Elementary School, Mahlum Architects Inc., Springfield, Oregon US [21]

3.5 Constructing the Models and Running Simulations

3.5.1 Defining Geometry, Materials and Implementing All Shadings

The construction of the geometry, assignment of the material properties and the implementation of all 3 shading and daylighting systems are defined for EnergyPlus, IES and IDA in the following chapter. Yearly simulations were run within the 3 considered BPS tools.

3.5.1.1 *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 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 [35].

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 light shelf, 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, [35] 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.

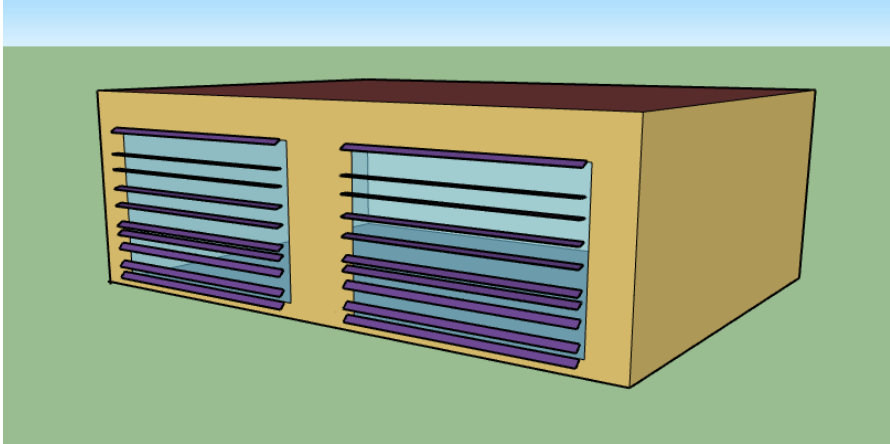


Figure 9: EP Irregular Shade on SketchUp

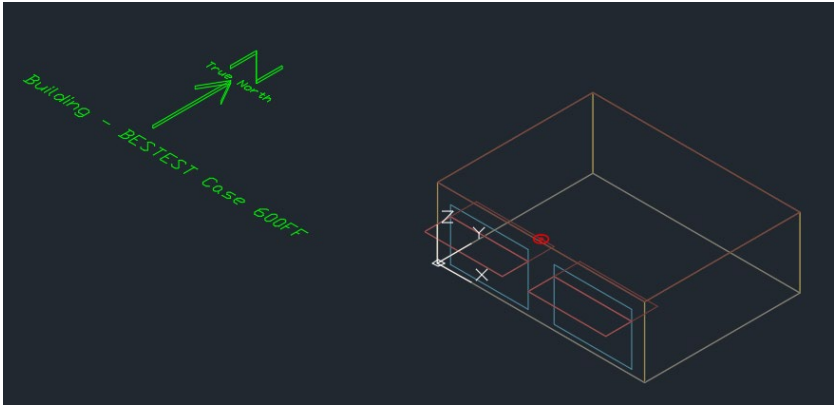


Figure 10: EP dxf output – Light Shelf

3.5.1.2 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.

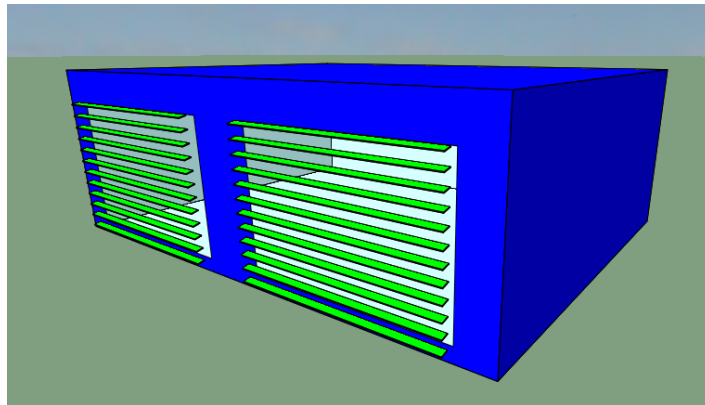


Figure 11: Regular Shades - IES

3.5.1.3 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.

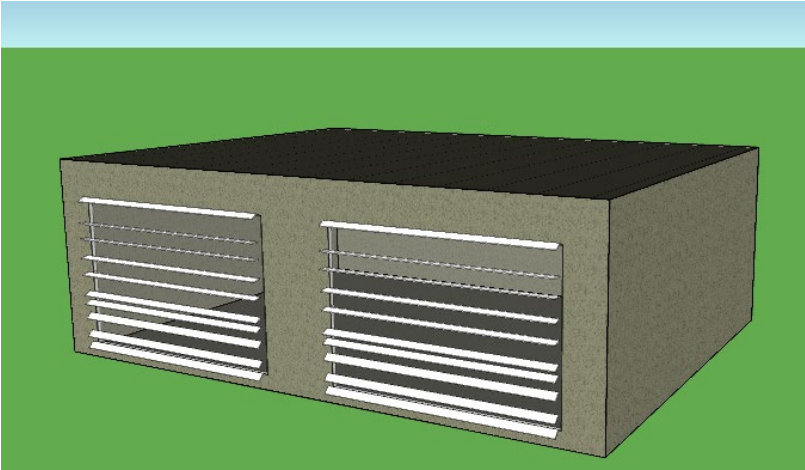


Figure 12: Irregular Shades - IDA

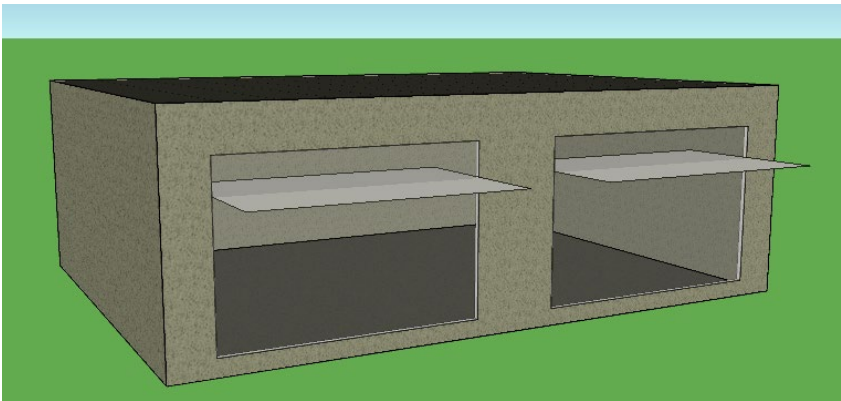


Figure 13: Light Shelf - IDA

3.5.2 Defining and Implementing User-built and In-built External Louvres

The aim of building energy modelling is to create designs for a building and work towards energy efficiency, by trying to optimize the implemented design strategies. To carry out the design process in an efficient way, it is important for the BPS tool to be able to offer fast and coherent means of modelling and simulation, by also being able to give out results in which the user can rely on. The application of various shading strategies, being an important design consideration, is implemented in BPS tools as an effort to reduce the time and effort the user must put into the design process. It is important to check the availability and usability of these “quick” design options and check their reliability by comparing their results to the results of their correspondent, user-built models. The following chapter investigates the availability and ease of designing an in-built external louvres shading system for the regular (equal spacing and tilt angle), conventional configuration by defining how they were modelled in each BPS tool.

3.5.2.1 Implementation of User-Built External Louvres

Constructing the shading system with a CAD software or a similar feature gives the user more control over the design. The user can construct the shading surfaces with the exact geometrical aspects, and then assign the desired properties on the surfaces within the tools' capabilities. This method also provides a visualization of the constructed shading, enabling the user to have an oversight of the application and limit any possible error.

3.5.2.1.1 EnergyPlus

EP, aimed to work with several third-party software tools, offers a variety of options to build and import geometries [35]. As also described in chapter 2.5.1, the software used for modelling the user-built shading system was SketchUp's OpenStudio plugin. The geometry was built using the capabilities of the SketchUp modelling tool, yet the geometry definition (“Shading group”) and import as an idf was done by the OpenStudio plugin.

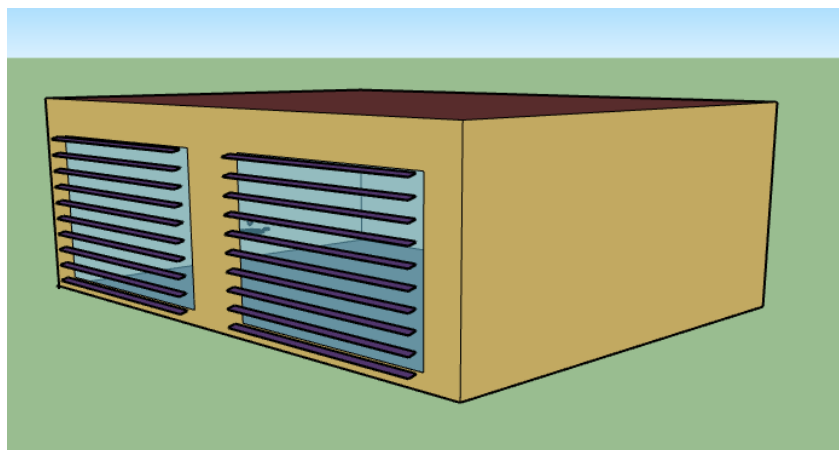


Figure 14: User-built Shading, EP-SketchUp

3.5.2.1.2 IES-VE

The user-built geometry for the shading was done within IES's geometry building platform, ModellT. Even though IES also offers compatibility features with several third-party CAD tools, the modelling within the tool offers quick and easy design, without having to import from another software.

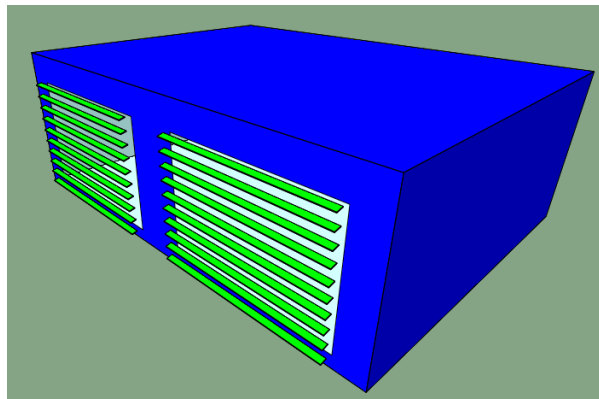


Figure 15: User-built Shading, IES

3.5.2.1.3 IDA-ICE

IDA, having a wide variety of “drag and drop” features for implementing components, also offers a variety of shading objects, which expedites most design processes. Although the “fixed shade” component located under the “shading objects” category proves useful for creating non-regular or regular shaped planar shades, it is not convenient for modelling the desired external louvres shading, as it takes time and a thickness cannot be defined for the blades. So, importing the geometry from SketchUp, also offered by IDA, was chosen as the way for designing the shading system.

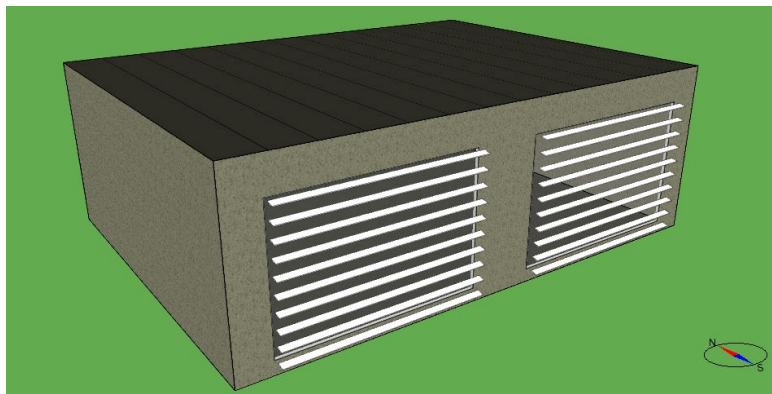


Figure 16: User-built Shading, IDA

3.5.2.2 Implementation of In-Built External Louvres

The in-built modelling method depends on what the tool offers for designing the specific shading. The two advantages of using the in-built method are that the user can apply the shading to the desired glazing constructions with just one setting, and that a control mechanism can be implemented to manage the operating degree and conditions of the shading. This research does not focus on the control mechanism of the in-built shading implementation but questions the availability and functioning of the in-built modelling aspect of the BPS tools.

3.5.2.2.1 EnergyPlus

Considering the external fixed horizontal louvres, EnergyPlus offers an in-depth modelling approach for the shading, referred to as “blinds” within the tool. The software offers a wide variety of input parameters to model the system, by also providing a visual guide in its manuals, as illustrated below.

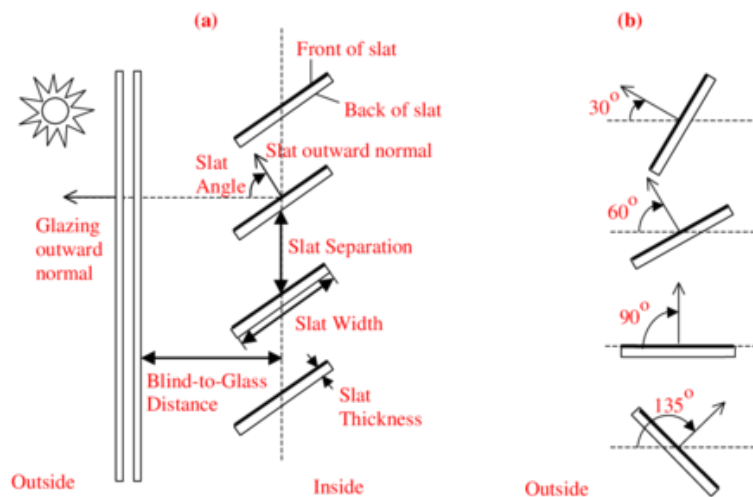


Figure 17: EP Blind Illustration [39]

The desired “blind” is defined in “WindowMaterial:Blind” and is then referred to in the object “WindowProperty:ShadingControl” in which the user can also further expand the definition and implement control strategies by choosing pre-defined schedules. The figures 18 and 19 below show parts of the afore-mentioned objects within EnergyPlus which include the input parameters.

[0001] WindowMaterial:Blind		
Field	Units	Obj1
Name		10 Louvres 15deg F
Slat Orientation		Horizontal
Slat Width	m	0.105
Slat Separation	m	0.22
Slat Thickness	m	0.01
Slat Angle	deg	15
Slat Conductivity	W/m-K	221
Slat Beam Solar Transmittance		
Front Side Slat Beam Solar Reflectance		0.65
Back Side Slat Beam Solar Reflectance		0.65
Slat Diffuse Solar Transmittance		
Front Side Slat Diffuse Solar Reflectance		0.65
Back Side Slat Diffuse Solar Reflectance		0.65
Slat Beam Visible Transmittance		0

Figure 18: EP Object, WindowMaterial:Blind

[0002] WindowShadingControl			
		Enter a alphanumeric value	
Field	Units	Obj1	Obj2
Name		ShadeControl1	ShadeControl2
Zone Name		ZONE ONE	ZONE ONE
Shading Control Sequence Number		1	1
Shading Type		ExteriorBlind	ExteriorBlind
Construction with Shading Name		Double Pane Windc	Double Pane Windc
Shading Control Type		AlwaysOn	AlwaysOn
Schedule Name			
Setpoint	W/m2, W or deg		
Shading Control Is Scheduled		No	No
Glare Control Is Active		No	No
Shading Device Material Name			
Type of Slat Angle Control for Blinds		FixedSlatAngle	FixedSlatAngle
Slat Angle Schedule Name			
Setpoint 2	W/m2 or deg C		
Daylighting Control Object Name			
Multiple Surface Control Type		Sequential	Sequential
Fenestration Surface 1 Name		ZONE SUBSURFA	ZONE SUBSURFA

Figure 19: EP Object, FenestrationSurface:Detailed

3.5.2.2.2 IES-VE

IES has an option to implement external shading devices to a glazing construction through “Building Template Manager > Constructions”. There are two types of in-built external shading devices; the shutter and the louvres, yet, according to the user guide, they do not have any differences in performance [37].

External Shading Device ×

Type of external shading device: None Shutter Louvre

Control

Operation profile:

Continuously variable

Condition to lower device: ✓ Metric

Condition to raise device: ✓ IP

Nighttime resistance: m²K/W Typically between 0.00 and 2.50

Daytime resistance: m²K/W Typically between 0.00 and 2.50

Ground diffuse transmission factor: Calculate Typically between 0 and 1

Sky diffuse transmission factor: Calculate Typically between 0 and 1

Transmission Factors at 15 degree increments (values in range 0.00 - 1.00)

0°	15°	30°	45°	60°	75°	90°
0.87	0.75	0.60	0.40	0.07	0.00	0.00

Figure 20: In-built Shading Implementation IES

As seen from Figure 20, the used inputs for setting the external shading device have been highlighted in red. The shading type has been set to “louvre”, the operation profile has been set to “on continuously”, as the louvres system is fixed and is present the whole time.

The transmission factor, as defined in the user guide, is the amount of direct solar radiation transmitted through the shading device. The values to be inputted in the software require the calculation of the transmission factor values of the shading device for the sun’s angle with the plane perpendicular to the glazing, with 15° angular increments [37].

Figure 21 illustrates the calculation of the transmission factor values for the external horizontal louvres shading in question, as also been implemented in the software. The angles of 75° and 90° are not represented in the figure as the shading system blocks all the incident radiation at those solar altitude angles.

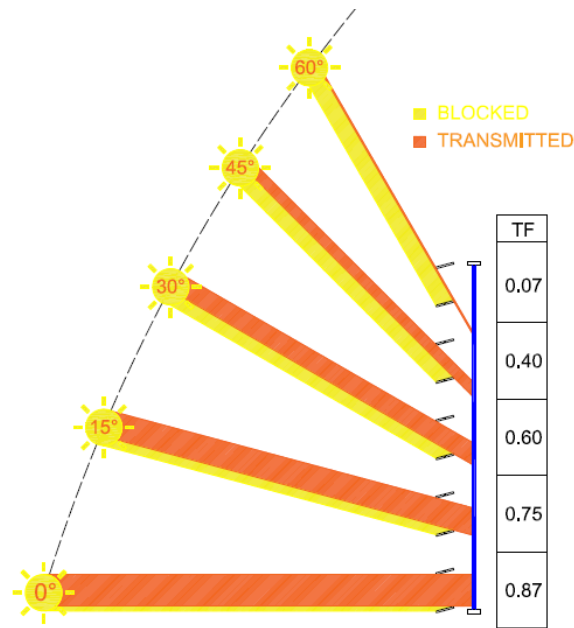


Figure 21: Transmission Factor Calculation

The calculation of the transmission factors is another step that the designer must consider with IES's in-built shading implementation. The explanations presented in the user manual does not guide the user through the process of the calculation and does not present any illustrations, only providing some data of a commercial shading system. This important parameter is left unclear, leaving the users on their own initiatives. This, simple-to-calculate-parameter might prolong the design process and increases the risk of user error.

3.5.2.2.3 IDA-ICE

IDA offers a wide variety of shading systems which can be referenced to a glazing construction. The user can see a simplified image of the systems, making it a very simple and effective design process. Although the options do not have an option for the design of an external fixed louvres system, it offers an option for designing "external venetian blinds", which can be modified in the desired way.

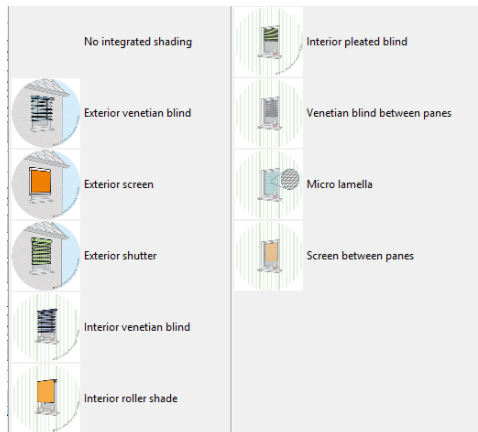


Figure 22: In-built Shading Illustrations, IDA

Figure 22 shows the interface of IDA for defining the external blinds, which includes specific parameters for the modelling of the geometry. As seen from the figure, the clear and simplistic approach makes it a very user-friendly shading implementation. The user is also able to set the material properties and assign them to the slats.

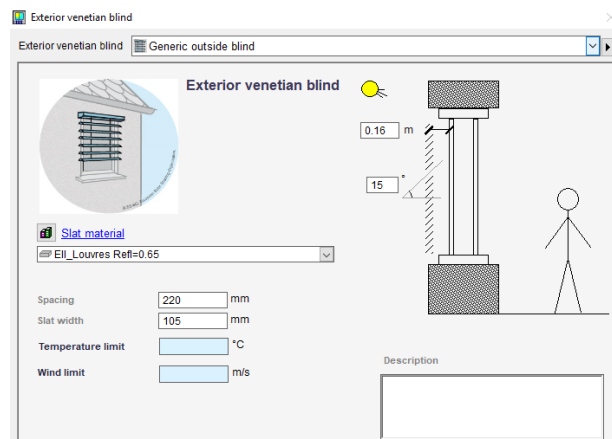


Figure 23: In-built Exterior Blinds Implementation, IDA

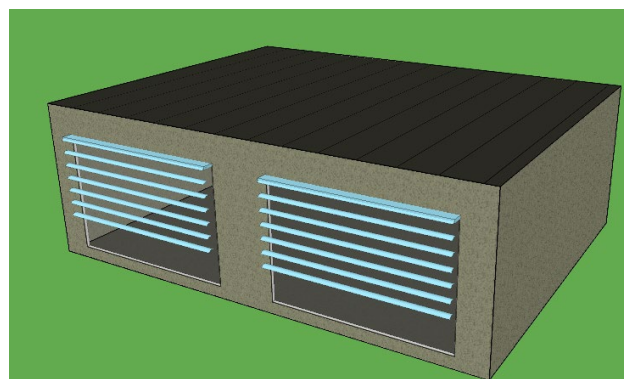


Figure 24: Exterior Blinds Visualization, IDA

As shown in Figure 24, after the implementation of design, a visualization on the model is automatically constructed.

3.6 Setup for Simulation

3.6.1 Overall Setup

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 [40].

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, from outside), and at a 0.8 m height from the floor. The sensors are facing upwards.

3.6.2 Setup for the Comparison among the Tools (EP v IES v IDA)

4 different geometrical models were constructed within each BPS tool. These models were all built upon the Bestest Case 600 and are (1) without shading, with (2) regular external louvres, (3) irregular external louvres and with a (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.

3.6.3 Setup for the Comparison within the Tools (User-built vs In-built)

The regular external louvres system, with 10 blades of 15° tilt angles (more information on section 3.4.1), has been implemented in the three BPS tools with two methods: by manually building the specific geometry (within the tool or imported from a CAD software), and, if exists, within the tools' quick design capabilities. The shading geometry built by the user will be shortly referred to as user-built, and the shading device implemented through the options of the BPS tools will be referred to as in-built shading system.

3.7 Comparative Studies

3.7.1 Comparison among the BPS Tools (EP v IES v IDA)

The results derived from the 4 models, (1) without shading, with (2) regular external louvres, (3) irregular external louvres and with a (4) light shelf were used. 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, where indoor air temperature, heating and cooling demands and illuminance values were obtained. Interpretations from these results were made and commentary, with the help of prior studies on the topic, have been performed.

Graphs and tables derived from hourly, total, peak, or cumulative values have been derived to identify the differences visually and numerically. The aim of this comparative testing approach is to determine the differences among the BPS tools, with a base case (no shade) model and models with implemented shading and daylighting strategies.

3.7.2 Comparison within the BPS Tools (User-built vs In-built Shading)

The comparison between the 2 shading implementation methods, the user-built and the in-built, intended to represent the exact same shading model have been executed. The study has been carried out by comparing the results from thermal and daylighting analyses, as with the comparative study among the BPS tools. Yet, some comparative metrics have been differently implemented. The root-mean-square-error (RMSE), a mathematical measure indicating how spread out the residuals are, is used for the hourly temperature and illuminance values for yearly, monthly, and daily results.

The RMSE between the user-built and in-built external louvres temperature and illuminance results have been determined according to the following formula.

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(\hat{y}_i - y_i)^2}{n}}$$

The difference between the results of the heating and cooling analyses have been presented in percentage values.

3.7.3 User Assessment

The user assessment part of the report is done towards the construction and importing of the geometries and shading devices. Bullet points on the specifics of the results from the comparative studies have also been included in the analyses. The information has been gathered throughout the making of the research, by experience of the user, a master's student in engineering and architecture.

4 Results

4.1 Comparative Study among the BPS Tools (EP v IES v IDA)

4.1.1 Thermal Analysis

4.1.1.1 Free Floating (Indoor Mean Air Temperature)

The following tables, Tables 1,2,3,4, 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).

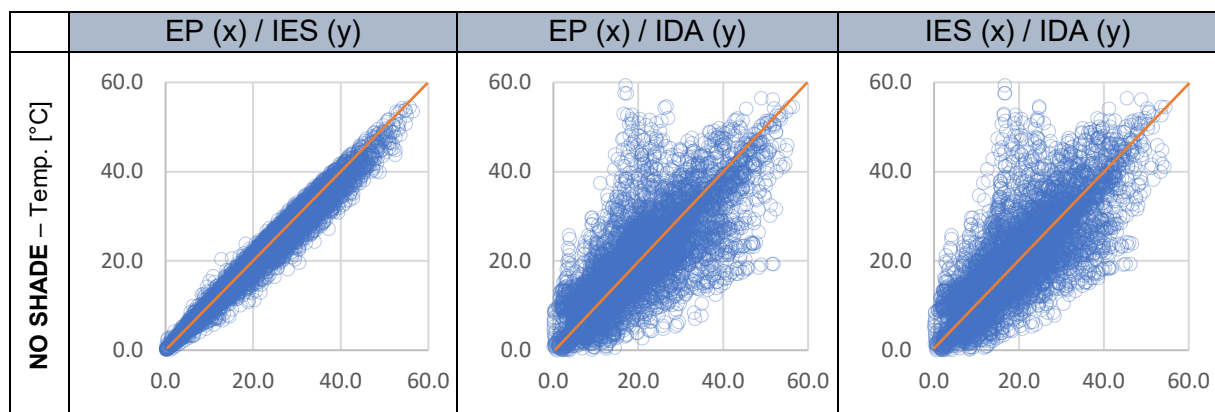


Table 1: No shade

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.

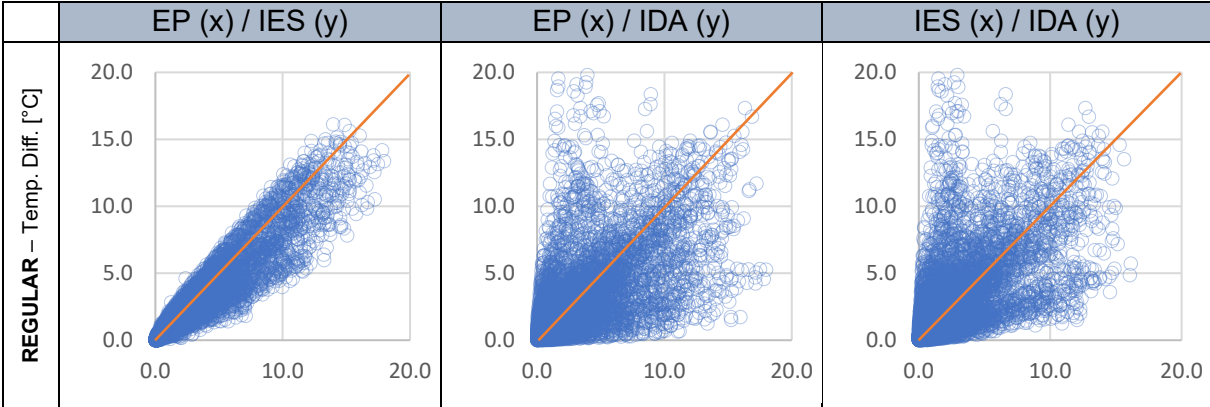


Table 2: Regular Shade

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.

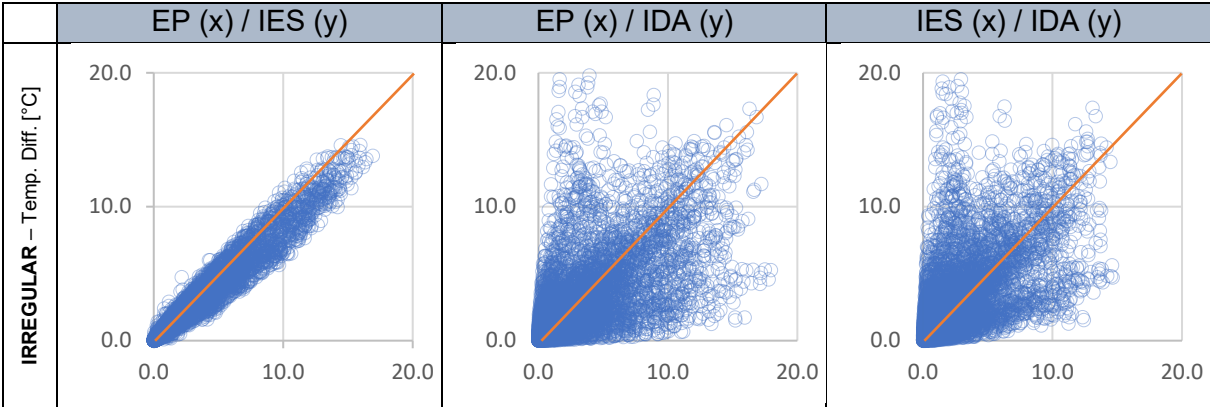


Table 3: Irregular Shade

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.

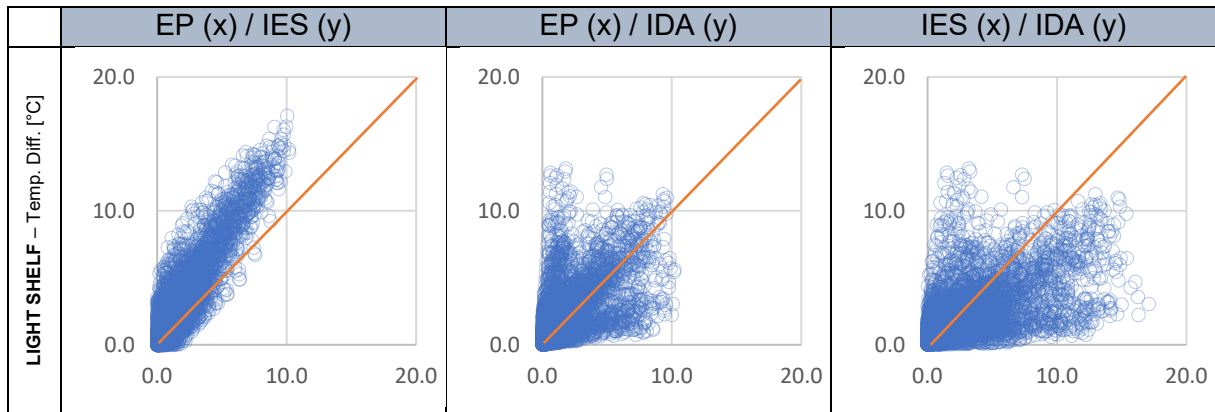


Table 4: Light Shelf

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 1, 2 and 3, 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.

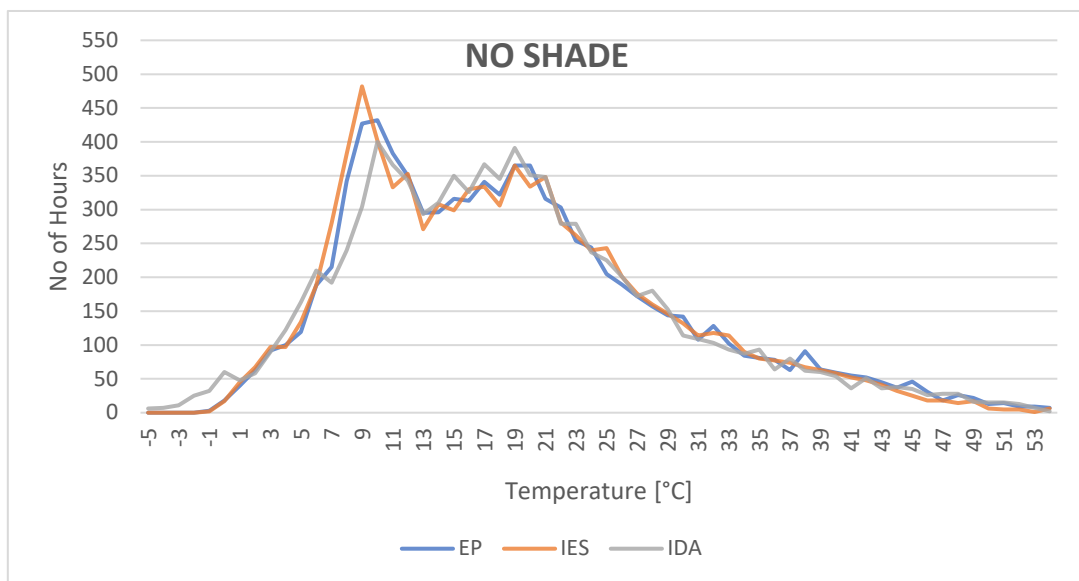


Table 5: No Shade

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.

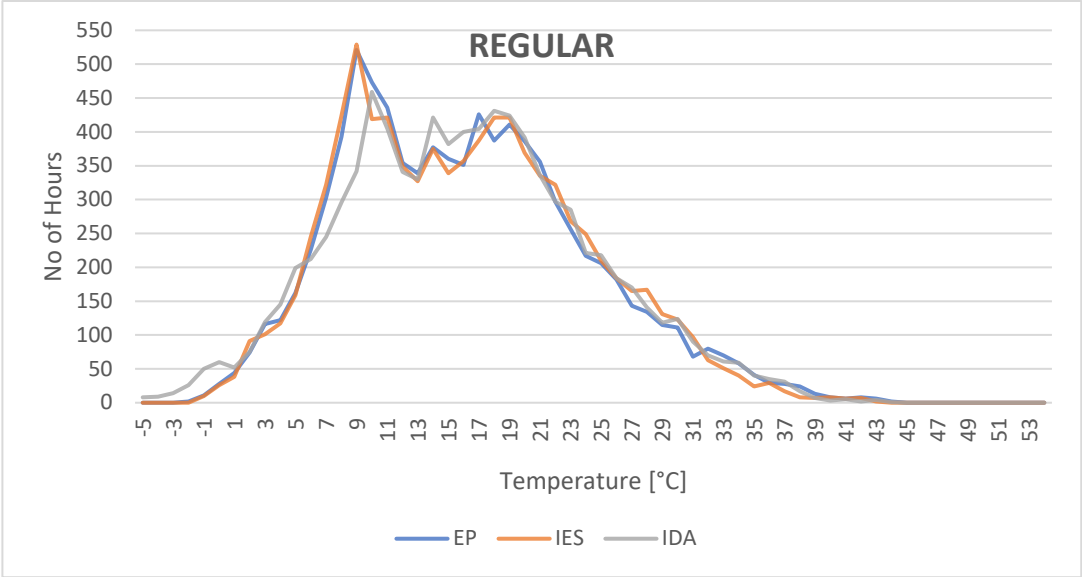


Table 6: Regular

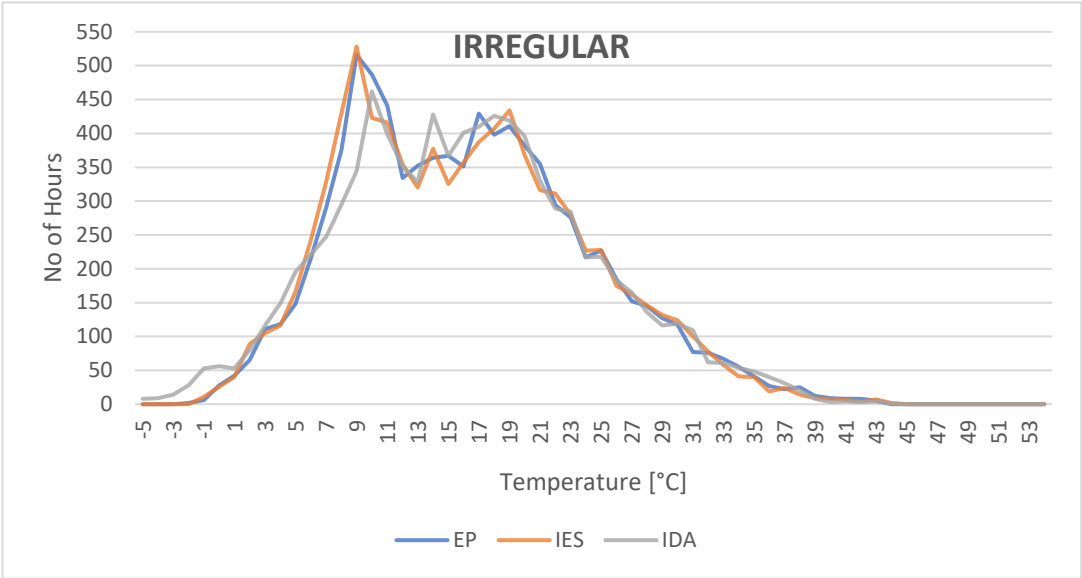


Table 7: Irregular

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.

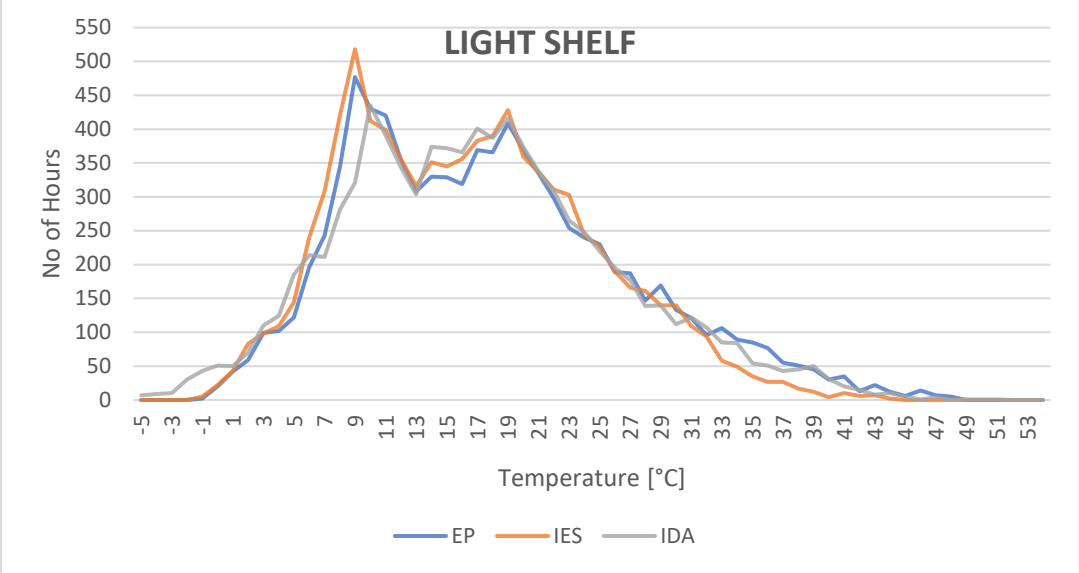


Table 8: Light Shelf

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.

4.1.1.2 Conditioned (Ideal Heating / Cooling)

4.1.1.2.1 Indoor Mean Air Temperature (between set-points)

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.

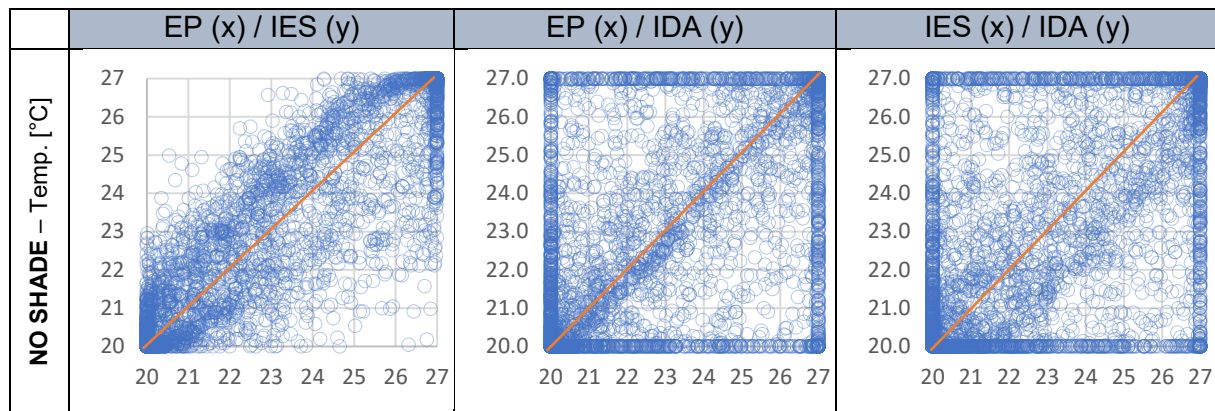


Table 9: No Shade

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 indoor would become low, or overheating of the zone would be 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.

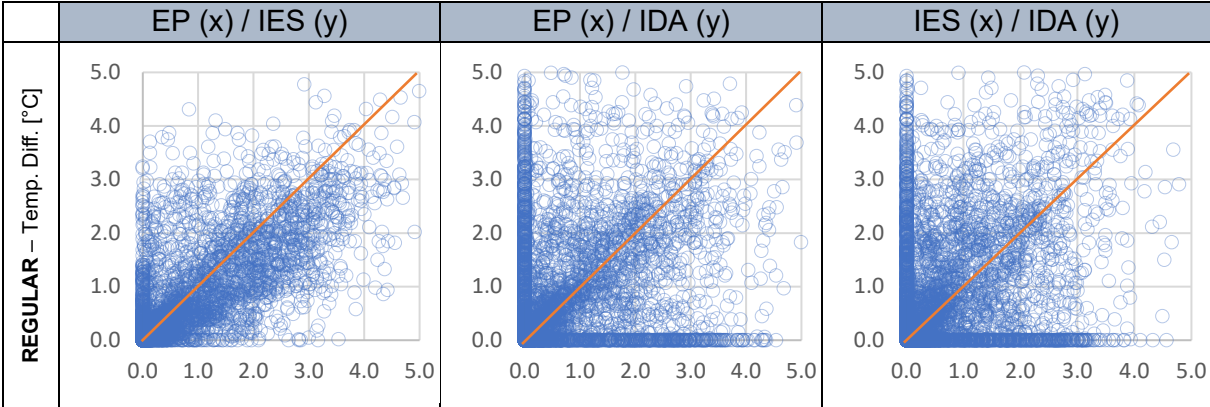


Table 10: Regular

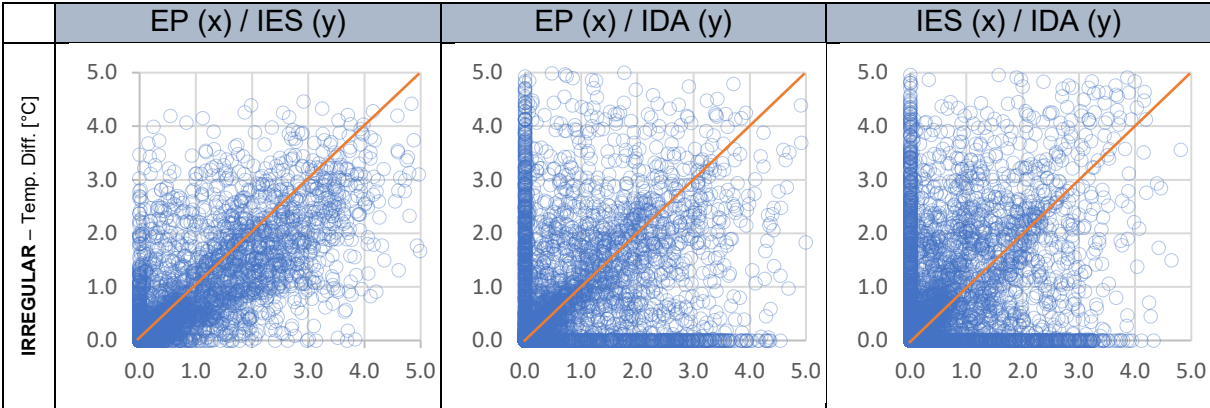


Table 11: Irregular

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.

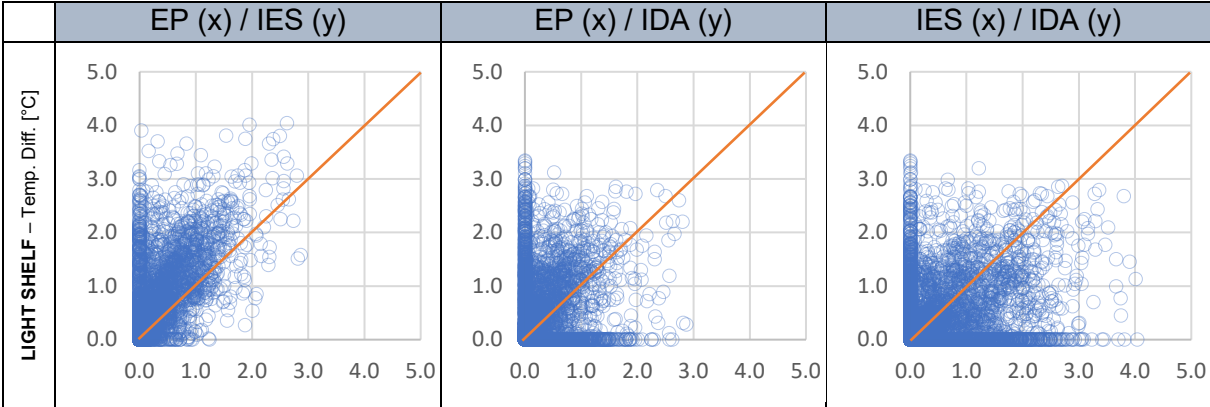


Table 12: Light Shelf

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 first intervals from the set-point temperatures were not included in the plot of the graphs to have a more detailed look at the line behavior because of the scaling of the values.

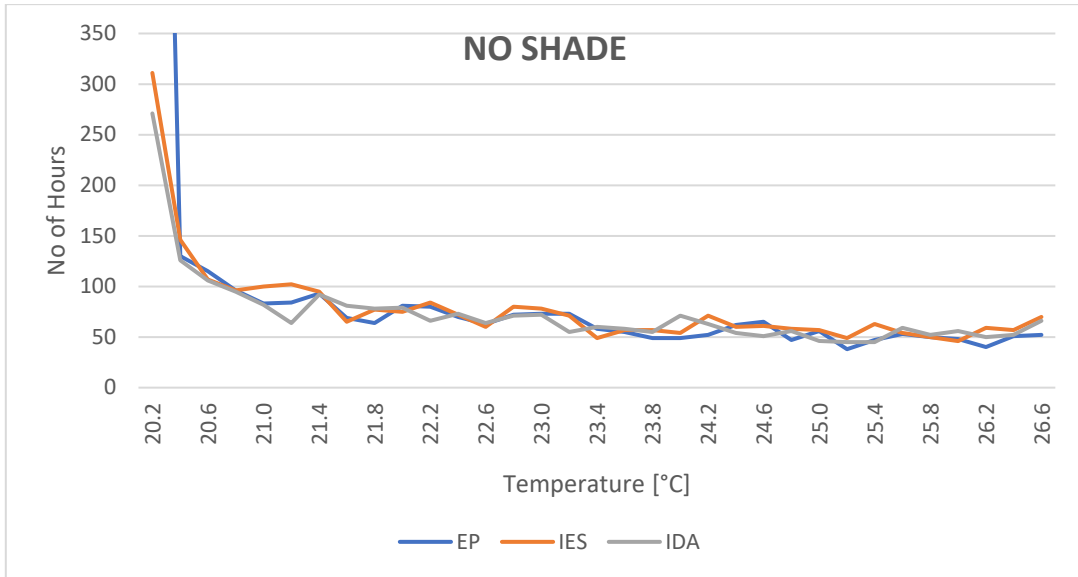


Table 13: No Shade

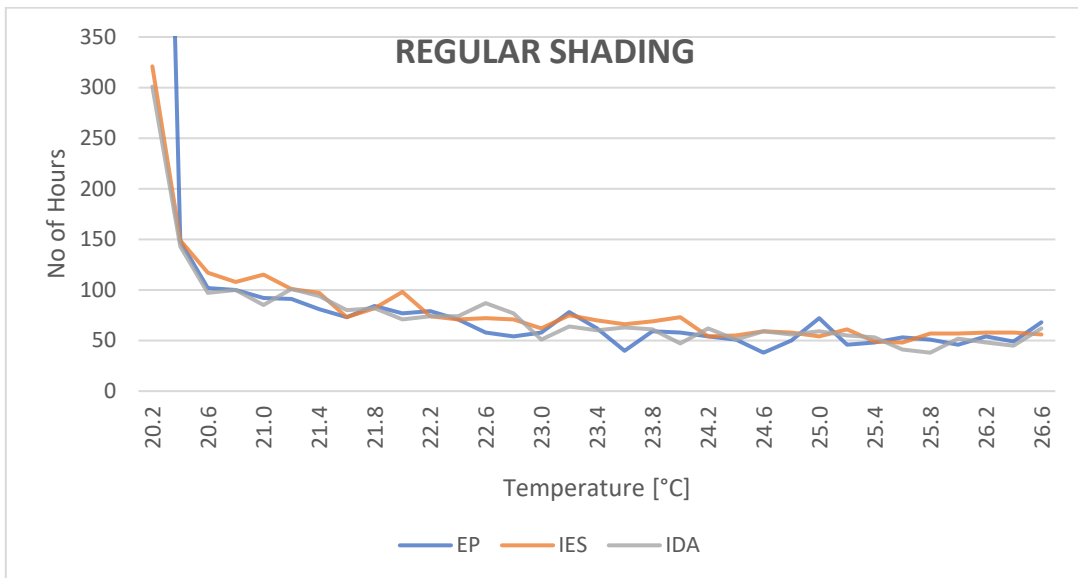


Table 14: Regular

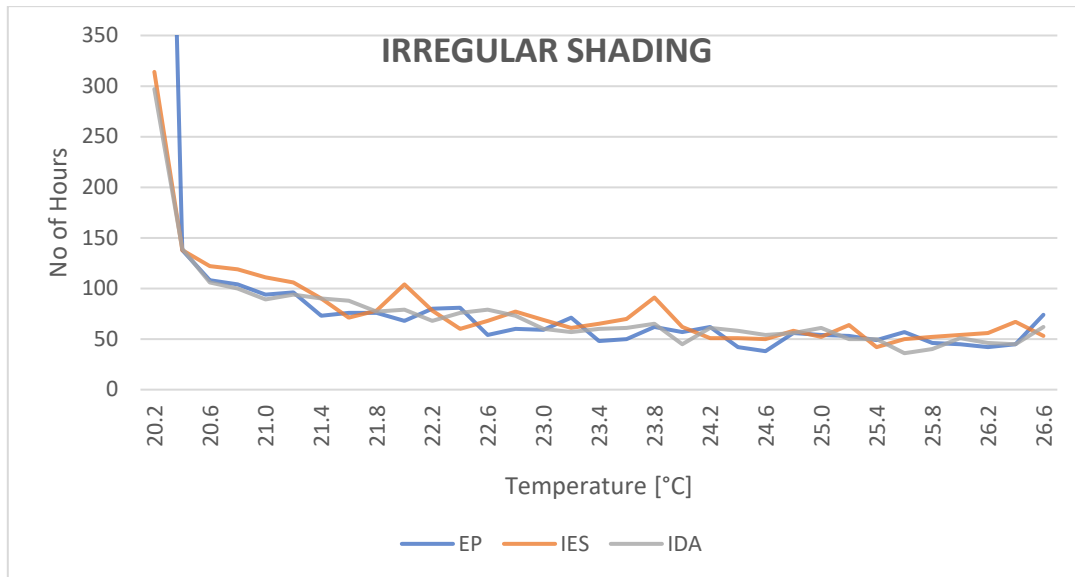


Table 15: Irregular

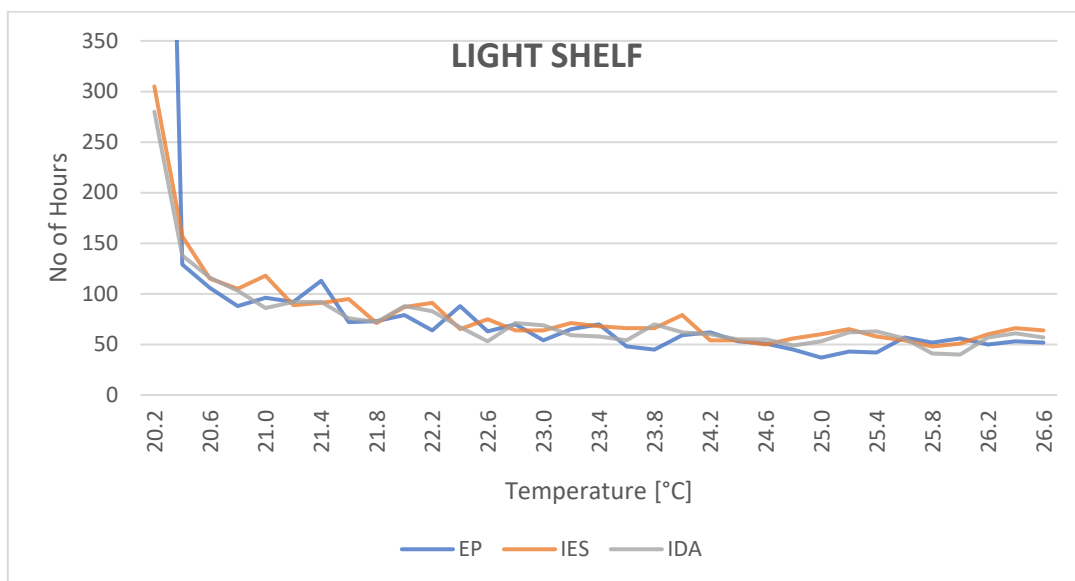


Table 16: Light Shelf

All the graphs above show very similar trends. An accumulation of values in the lower front of the interval, between 20.2 and 20.6 °C, and a gradual decrease from there until 27 °C.

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.

4.1.1.2.2 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.

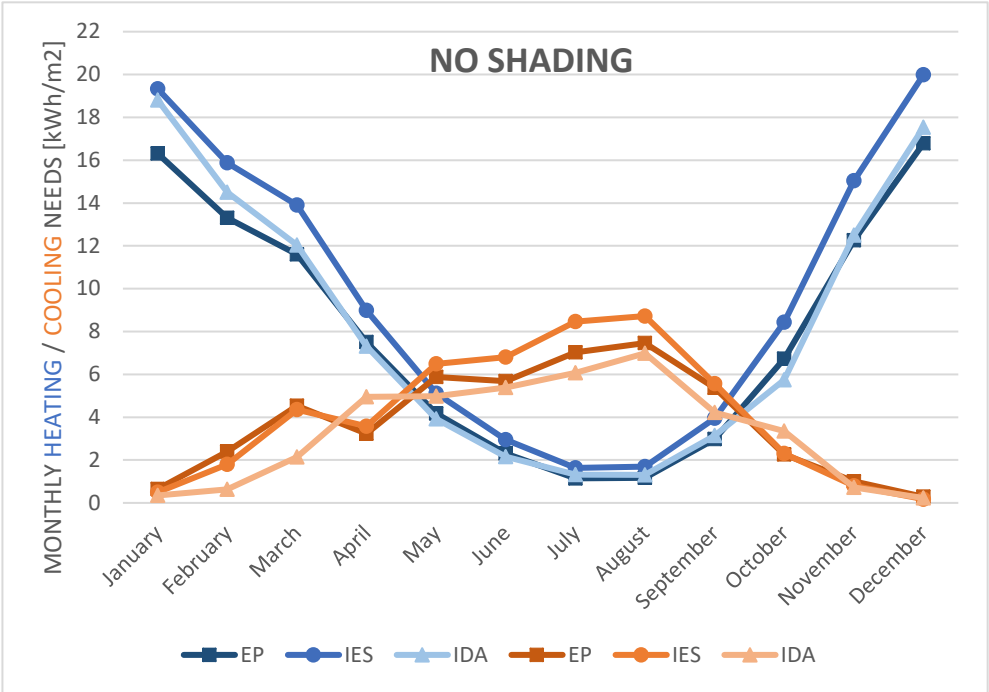


Table 17: No shading

Even though the graphs show very similar trends, in some months, as in January, the difference can reach up to around 4 kWh/m², 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, in table 17, 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.

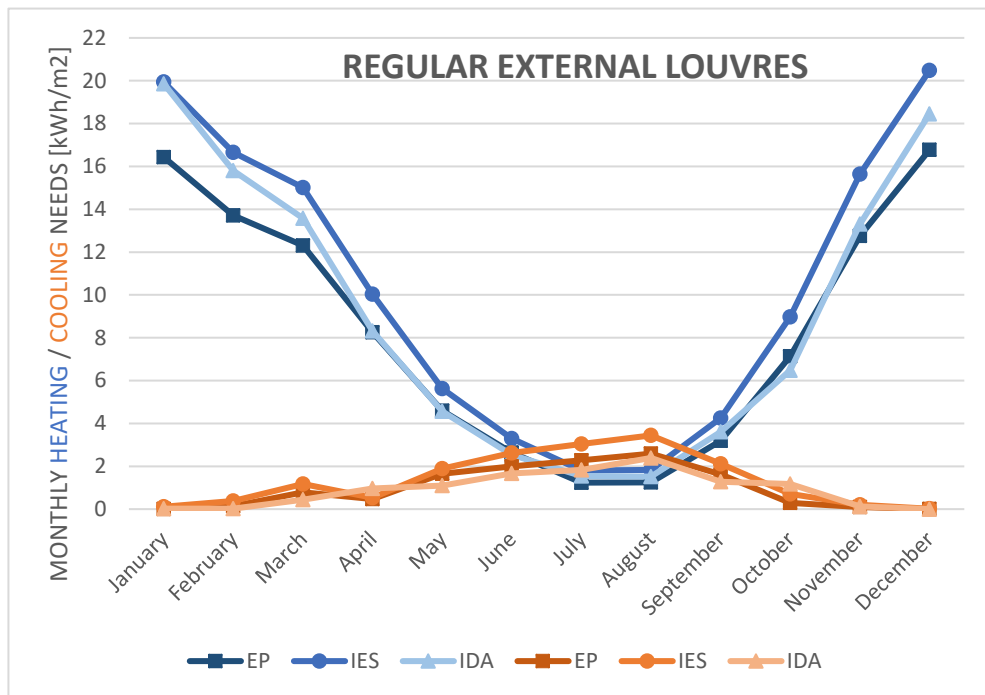


Table 18: Regular

The scaling of the graphs has been kept the same, so the decrement of cooling can be seen more clearly. The implementation of shading has caused the cooling needs during the summer period to decrease from around 7 kWh/m² to around 2 kWh/m².

As seen from the difference between tables 17 and 18, some significant increments in the heating loads for the IDA model during March and December is noticeable, as opposed to the small changes in the EP and IES values. There is evident correlation between the results of IDA and EP in table 18, as in the “no shade” configuration.

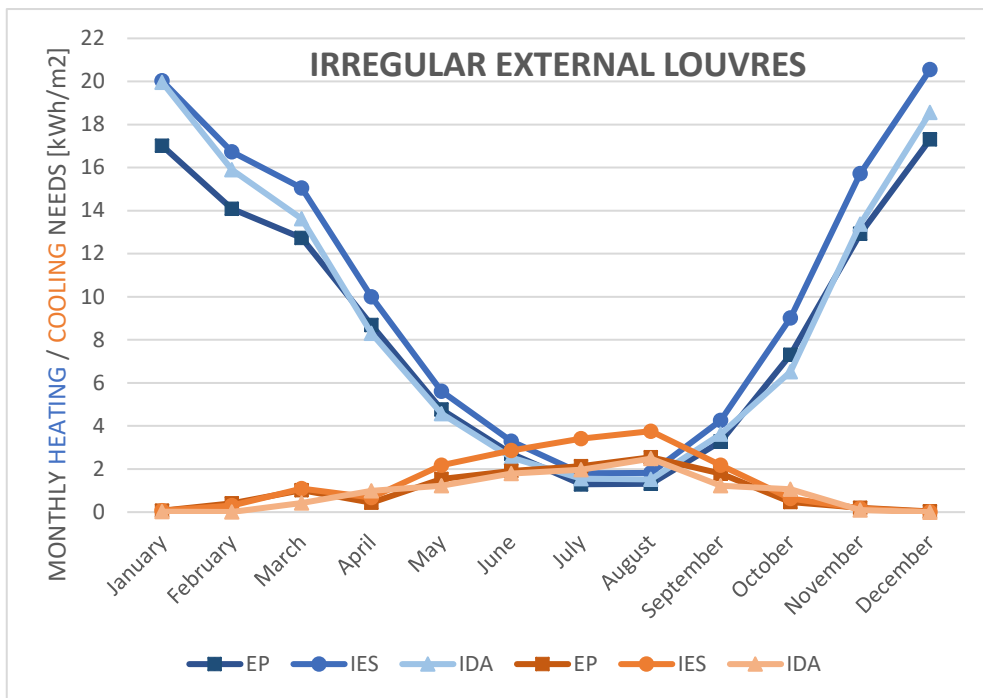


Table 19: Irregular

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

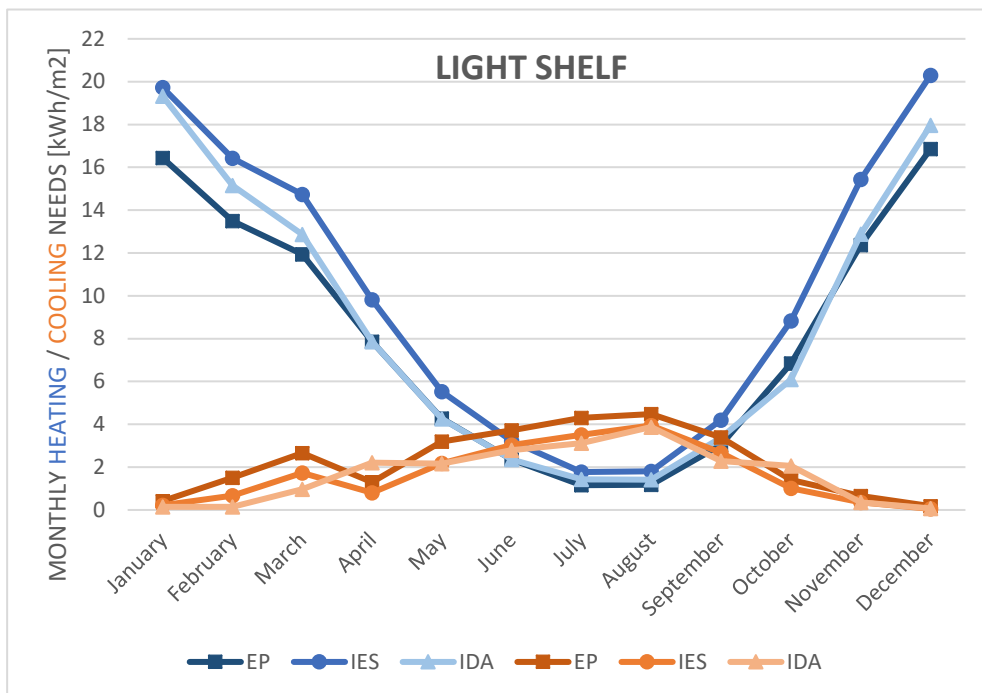


Table 20: Light Shelf

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.

4.1.1.2.3 Annual Heating / Cooling Needs [MWh]

Tables 21 and 22 show the total amount of heat, in MWh, needed to be delivered to/extracted 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.

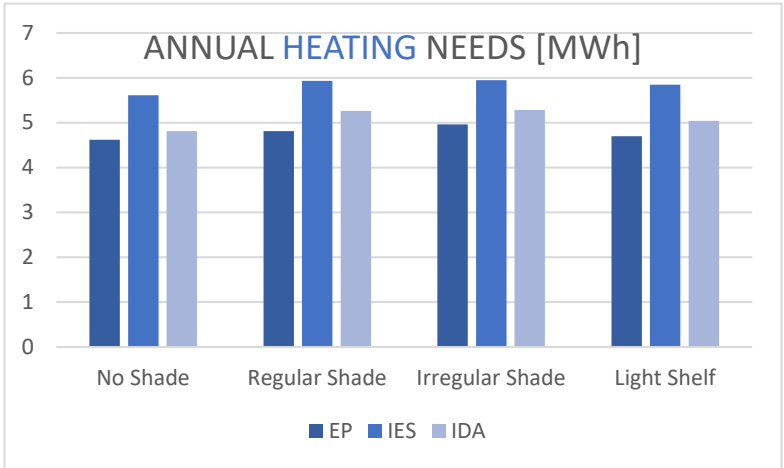


Table 22: Annual Heating Needs

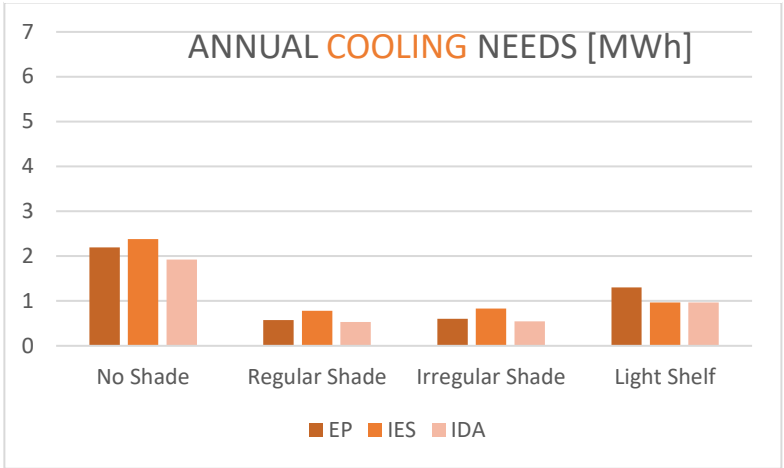


Table 21: Annual Cooling Needs

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

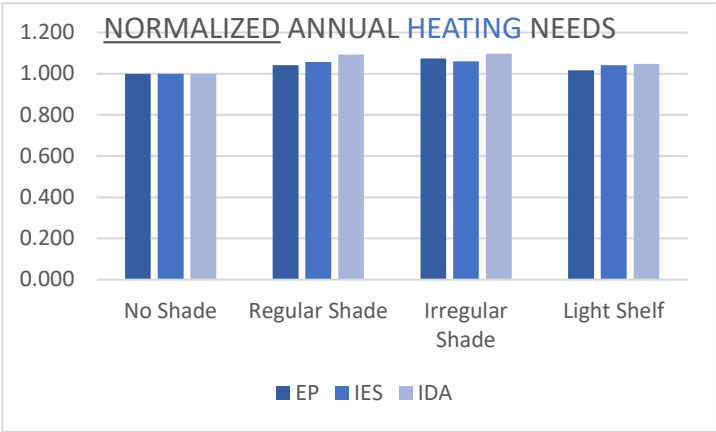


Table 23: Normalized Annual Heating Needs

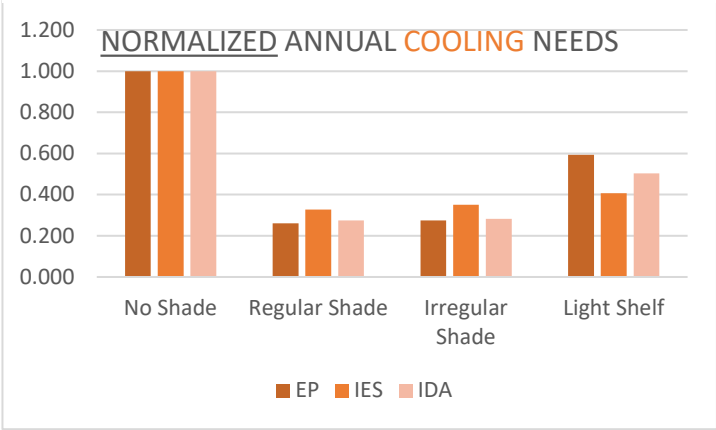


Table 24: Normalized Annual Cooling Needs

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.

4.1.1.2.4 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.

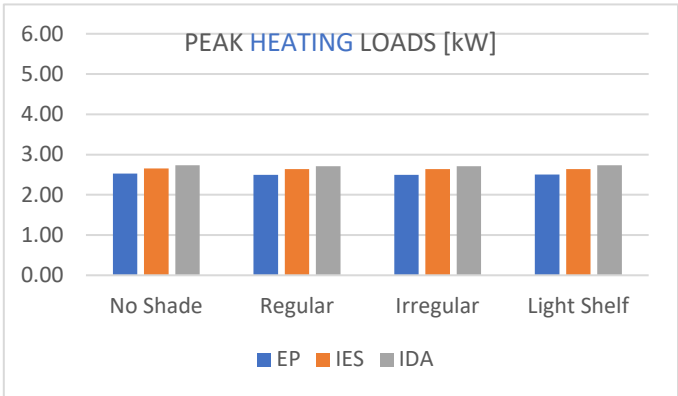


Table 25: Peak Heating Loads

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.

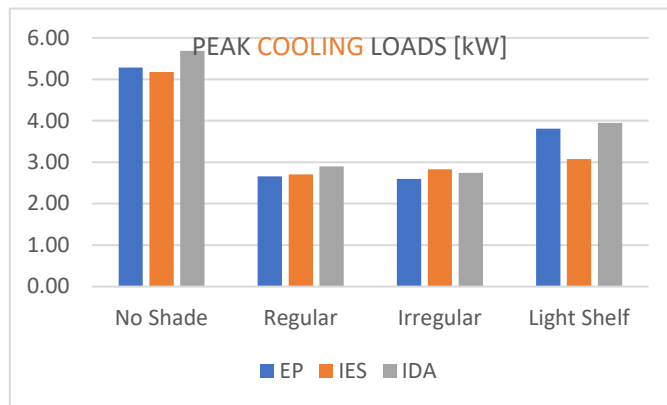


Table 26: Peak Cooling Loads

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.

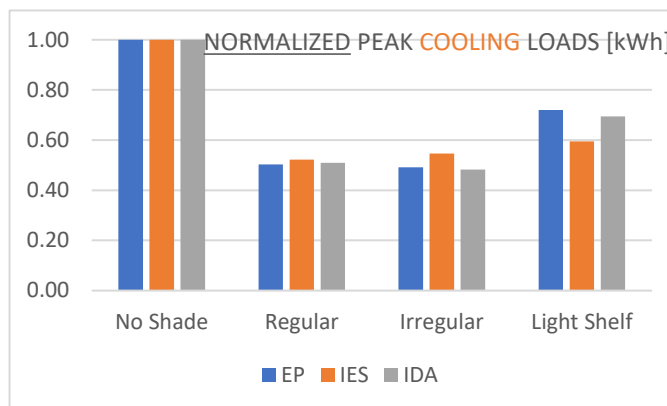


Table 27: Normalized Peak Cooling Loads

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.

4.1.2 Daylighting Analysis (Illuminance)

4.1.2.1 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.

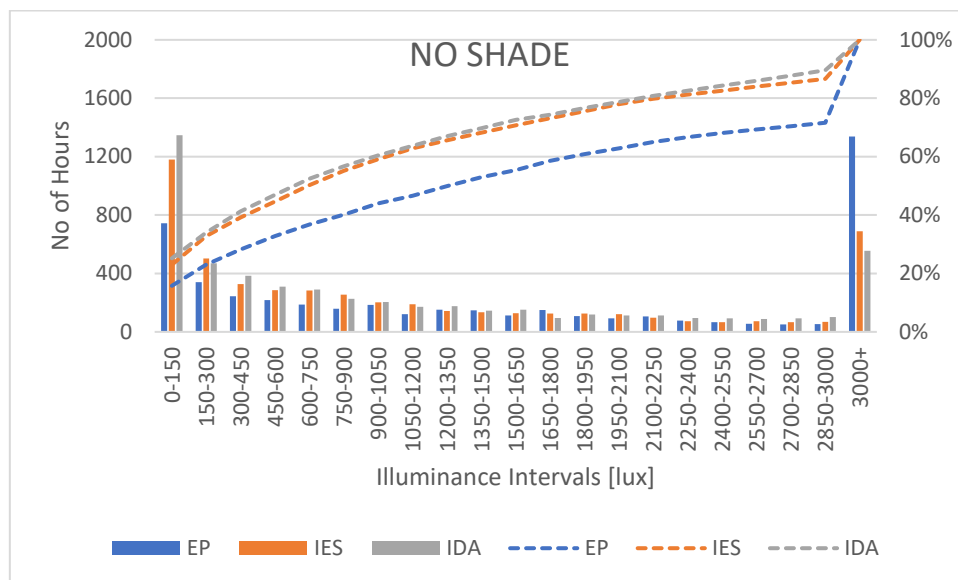


Table 28: No Shade

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.

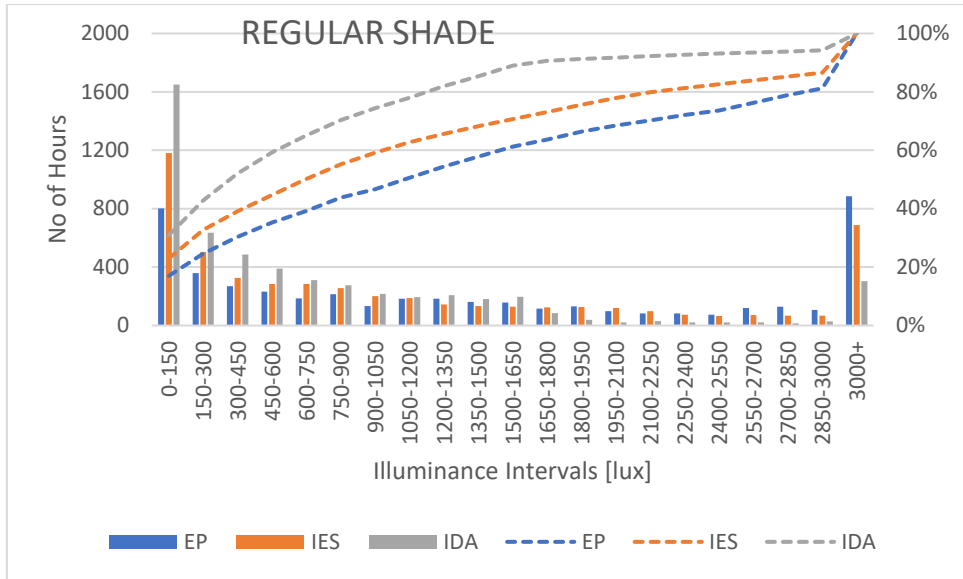


Table 29: Regular Shade

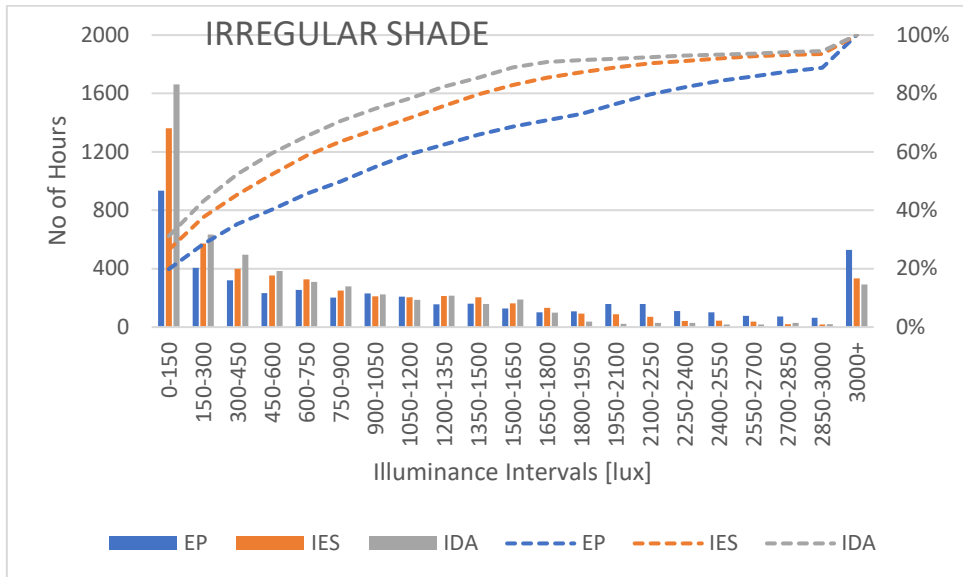


Table 30: Irregular Shade

The two tables, 29 and 30, are plotted for the external louvres models and are going to be considered 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 sharper 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.

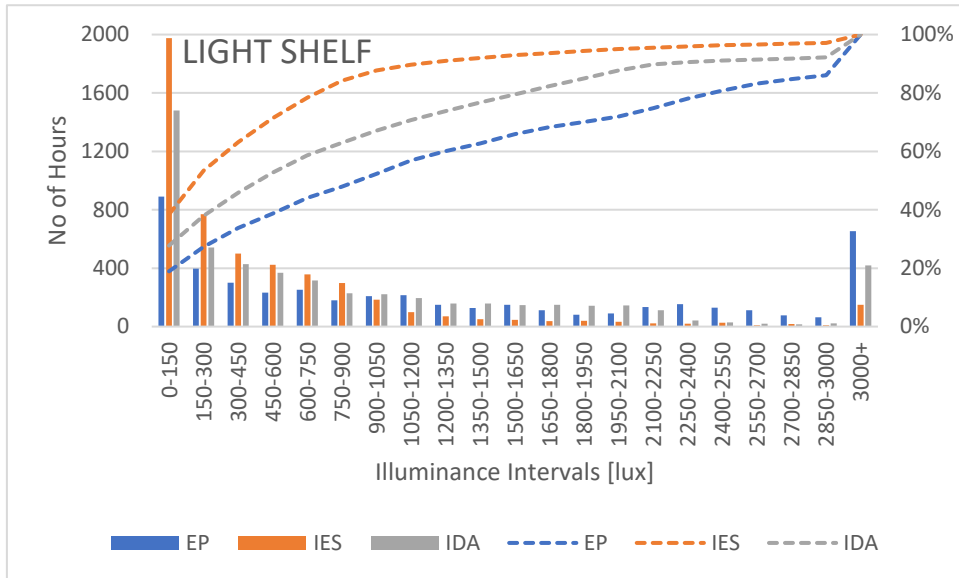


Table 31: Light Shelf

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 an overhang-like shading system rather than a system which aims to increase the daylighting within the zone.

It is also 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. [41] 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 thesis 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. Yet, the significant difference in the results show that the light-self shading calculations are considered differently.

4.1.2.2 Daily Analysis

4.1.2.2.1 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.

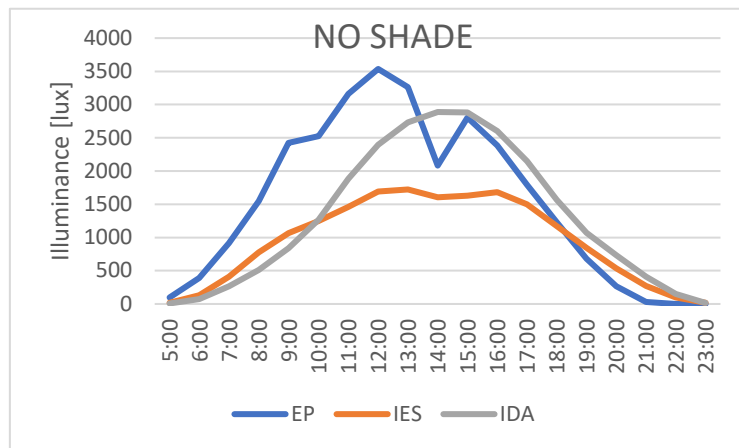


Table 32: No Shade

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.

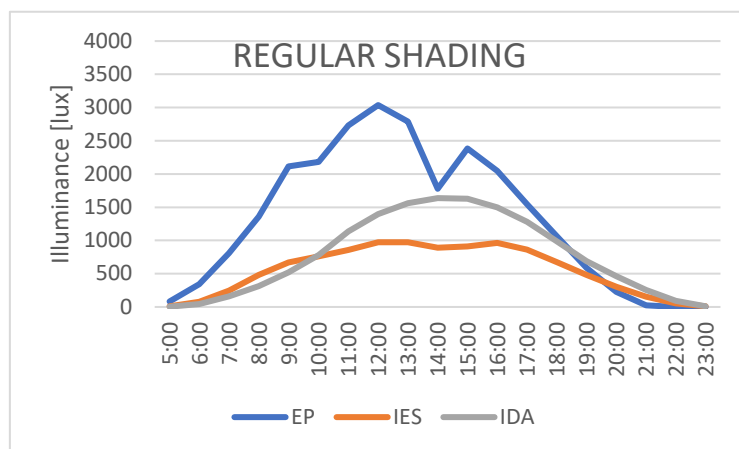


Table 33: Regular Shade

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

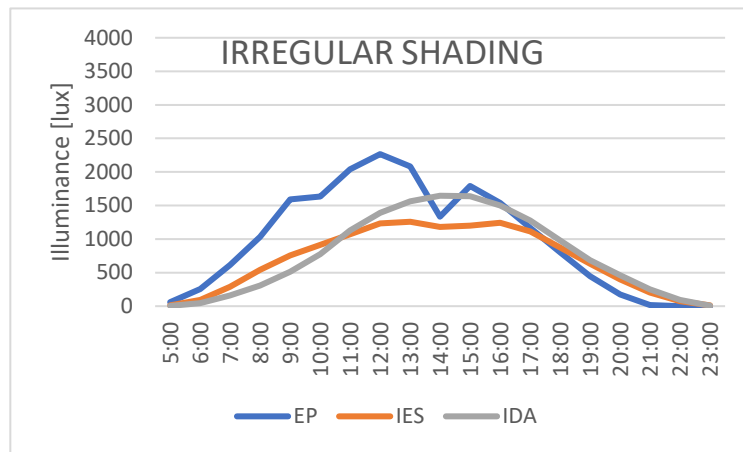


Table 34: Irregular Shade

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.

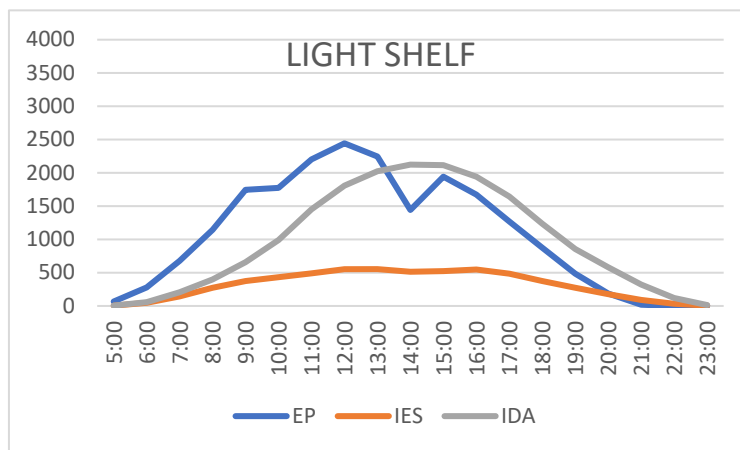


Table 35: Light Shelf

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.

4.1.2.2.2 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.

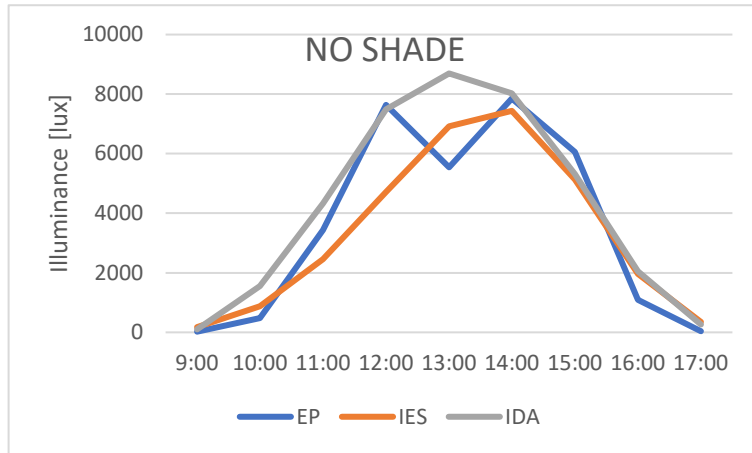


Table 36: No Shade

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.

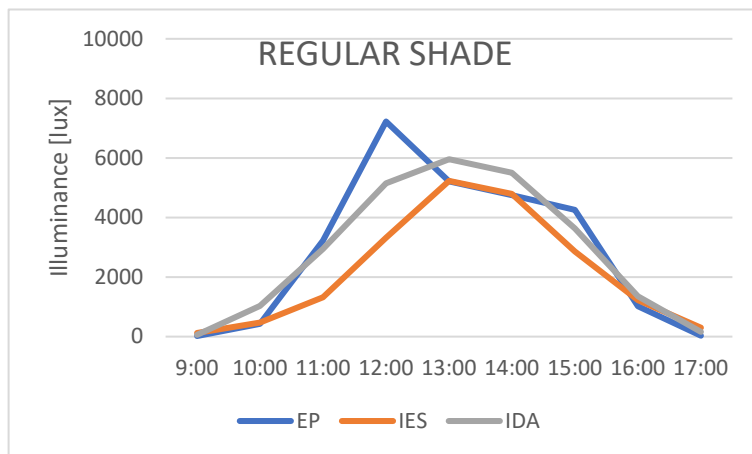


Table 37: Regular Shade

The correlation still 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.

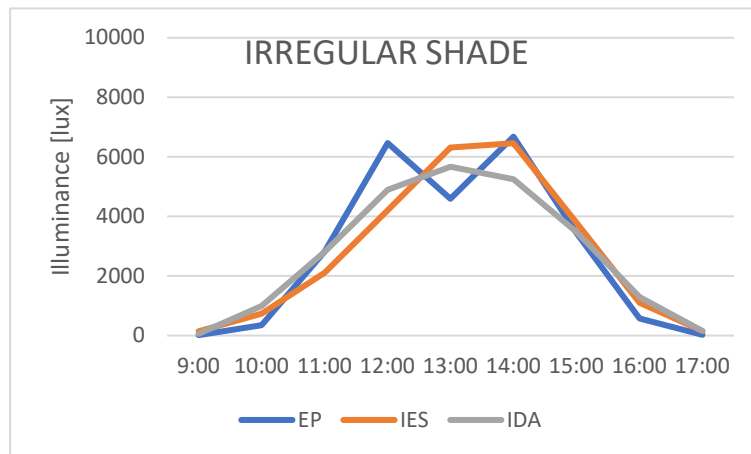


Table 38: Irregular Shade

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.

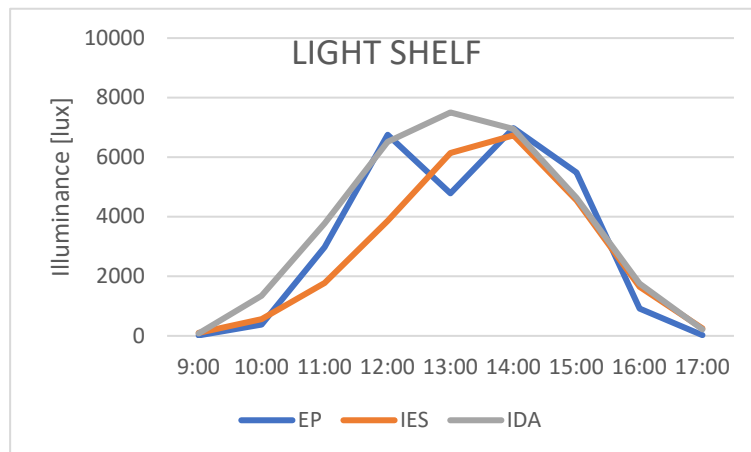


Table 39: Light Shelf

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.

4.2 Comparative Study within the BPS tools (User-built vs In-built Shading)

The following chapter investigates the correlation between the user-built and in-built regular external louvres shading system within each analyzed BPS tool. The findings of the two design approaches have been displayed in a way to also enable a comparison between the correlations of the BPS tools. The checks for correlation are done to investigate the reliability of the offered in-built shading modelling options of the tools, in comparison to the in-built shading modelling.

4.2.1 Thermal Analysis

4.2.1.1 Free Floating (Indoor Mean Air Temperature)

The hourly indoor mean air temperature values together with their monthly averages have been plotted in the following graphs. Below the graphs, tables containing RMSE values for yearly, monthly, and daily timeframes exist. The graphs illustrate a more general visualization of the correlation, whereas the RMSE values provide a more precise, numerical understanding of the results. The color scaling of the RMSE values have been defined for all the RMSE values for the 3 tools, to better illustrate the difference in their correlations.

4.2.1.1.1 EnergyPlus

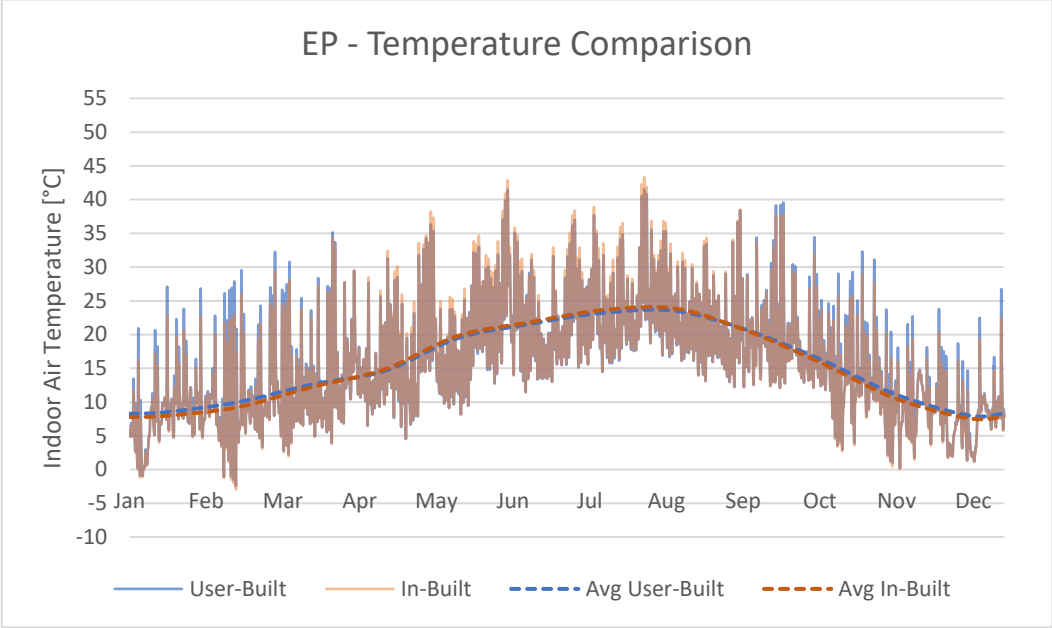


Table 40: EP Hourly Annual Temperature Graph

Table 40 illustrates the high correlation of the user-built and in-built shading implementation methods. The hourly temperature values are coinciding with each other almost perfectly except for some small seasonal differences. The average indoor air temperature lines (dashed) also indicate that in cold seasons the user-built shading method values show slightly higher values, as opposed to its lower values in hotter seasons.

	YEARLY	MONTHLY				DAILY	
	Year	January	April	July	October	Jun-21	Dec-21
RMSE (°C)	0.76	0.98	0.40	0.66	0.79	0.17	1.52

Table 41: EP Temperature RMSE

The most noticeable difference with the RMSE values in Table 41 is that the lowest and highest discrepancies are both in the daily RMSE values. The overall values are considerably low compared to the other tools, as also the greenish tone of the cells indicate. EP can be said to have strong correlation between the temperature results in its in-built shading implementation and the user-built one.

4.2.1.1.2 IES-VE

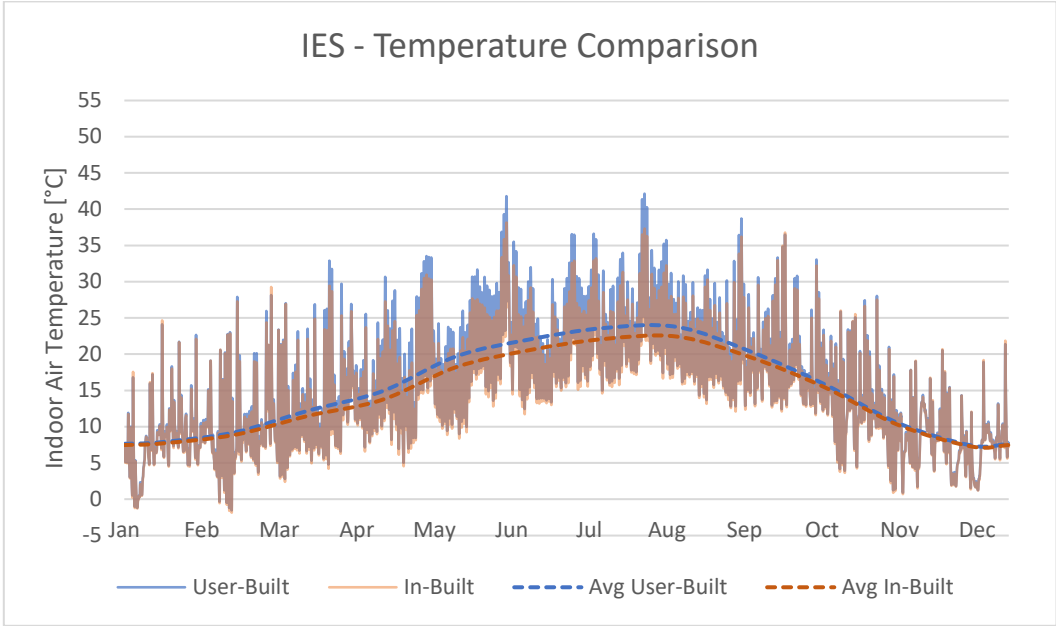


Table 42: IES Hourly Annual Temperature Graph

At first sight, Table 42 illustrates a good correlation of the temperature results for colder seasons, whereas their trends start to differ in March until September. The difference between the results of the two different shading implementations differ slightly more in the presence of higher solar radiation.

	YEARLY	MONTHLY				DAILY	
	Year	January	April	July	October	Jun-21	Dec-21
RMSE (°C)	1.36	0.56	1.62	1.90	0.86	1.32	0.80

Table 43: IES Temperature RMSE

From a numerical approach, Table 43 confirms the relatively stronger correlation of the temperature values in winter. The RMSE value of 0.56 in January, increases up to a value of 1.9 °C, which indicates higher differences as the solar effect starts to be pre-dominant. After the cooling season, the correlation starts to increase between the results of the two design methodologies.

4.2.1.1.3 IDA-ICE

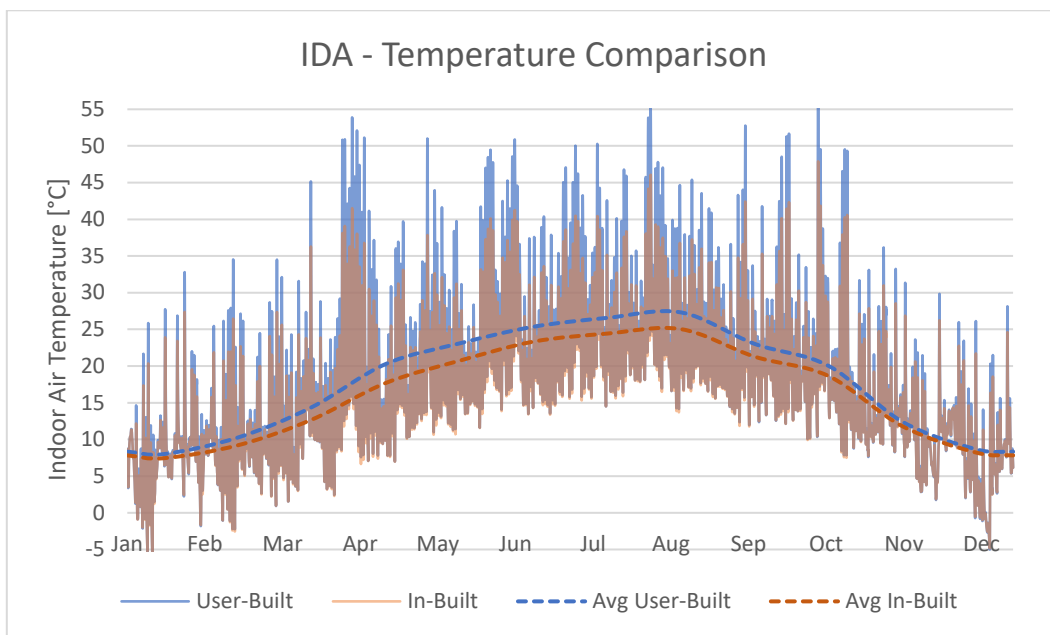


Table 44: IDA Hourly Annual Temperature Graph

A noticeable difference of the temperature graph of IDA is the bigger swings in temperature and the higher peaks they cause. A significant difference of the results is noticeable in both the hourly values and the monthly average values. The correlation is much weaker in comparison to the other two BPS tools.

	YEARLY	MONTHLY				DAILY	
	Year	January	April	July	October	Jun-21	Dec-21
RMSE (°C)	2.61	1.11	3.89	3.05	2.31	3.75	0.08

Table 45: IDA Temperature RMSE

The dominant red coloring of the RMSE values indicate that the RMSE values of IDA are the upper limits of all the numerical results. Discrepancies up to almost 4°C is visible in both June 21 and the month of April. January and December show very little difference in results, both in Table 44 and Table 45, yet when the solar effect becomes more dominant the discrepancies grow drastically. The correlation of IDA’s 2 different shading modelling approaches are considerably weaker.

4.2.1.2 Conditioned (Ideal Heating / Cooling)

As one of the most important aspects of a BPS tool is to be able to determine a building’s energy demands, it is critical to assess their capabilities. The chapter investigates the differences in heating and cooling needs, as well as the peak loads of the 2 studied shading implementation methods.

4.2.1.2.1 Annual Heating / Cooling Needs

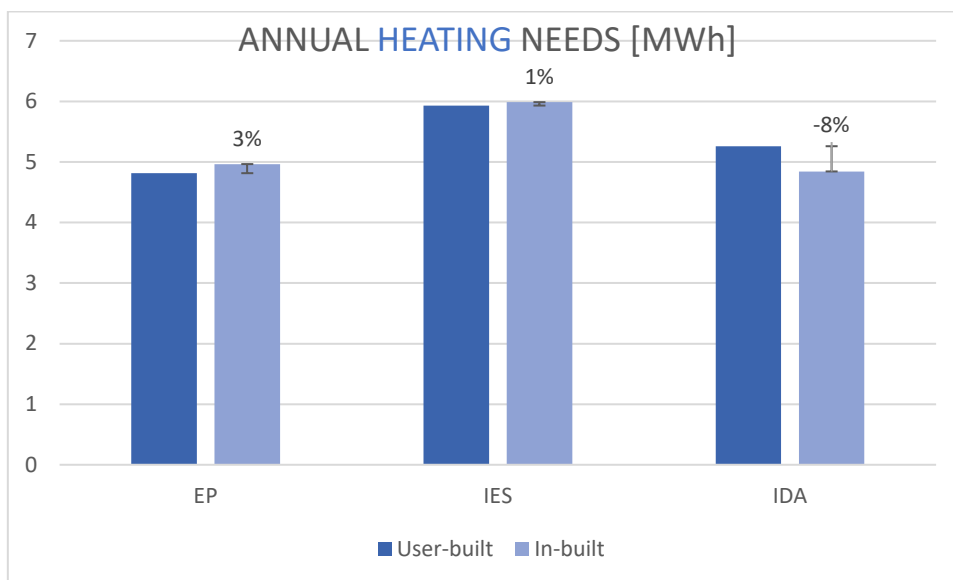


Table 46: Annual Heating Needs Chart

As the shading has lesser effect on the heating needs of a building in Amsterdam, the differences in results are relatively low. In Table 46, IES, with a difference of 1% shows high correlation in the annual heating needs, followed by IDA with a 3% difference, and IDA with 8%.

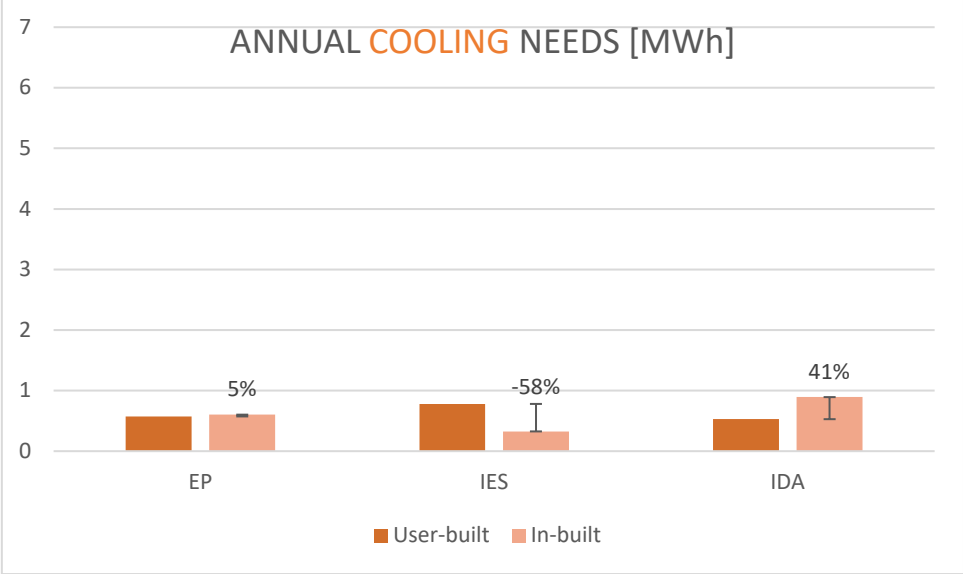


Table 47: Annual Cooling Needs Chart

The shading strategies, having more impact on the cooling needs, show significantly higher differences. This indicates that the 2 different shading implementations are considered differently in the simulation calculations, except for EP. Table 47 illustrates the strong correlation of EP in the annual cooling needs, as opposed to the high discrepancies within IES and IDA’s results.

4.2.1.2.2 Peak Heating / Cooling Loads

The peak loads are important indicators for building performance, as the mechanical equipment for heating and cooling applications will be sized accordingly. The differences in results of the different shading implementations may cause varying choices of the mechanical systems.

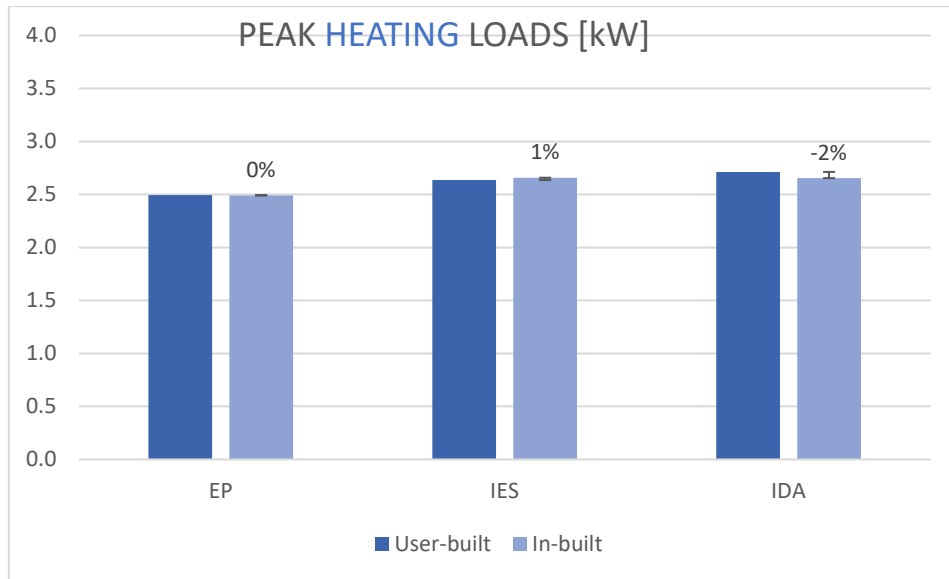


Table 48: Peak Heating Loads Chart

No significant difference between the results from the user-built and in-built shading implementations can be observed from Table 48, the peak heating loads chart. The shading is not the determinant in the case of peak heating loads; thus, the differences are very low.

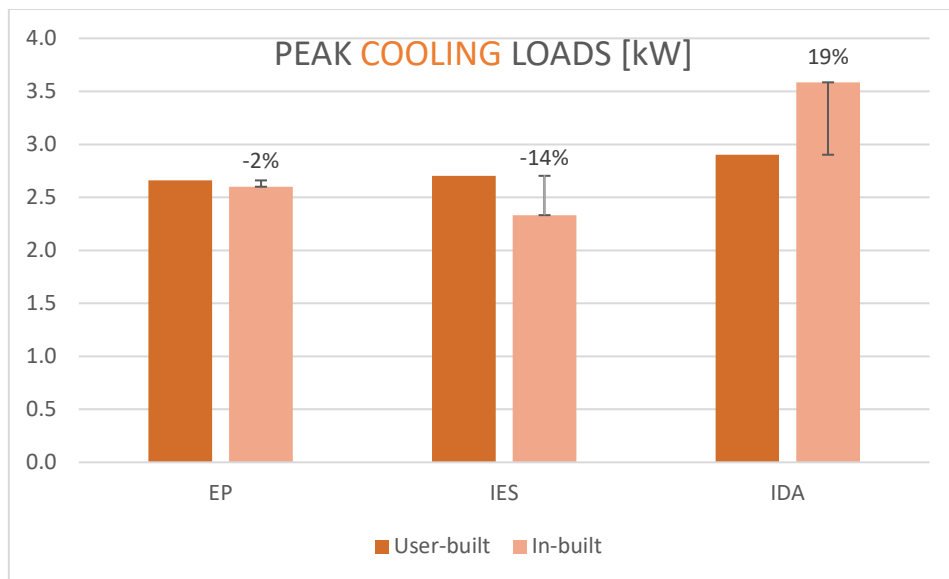


Table 49: Peak Cooling Loads Chart

Table 49 illustrates the peak cooling loads for the user-built and in-built shading implementations. The differences between the 2 methods go up to almost 20% in IDA, and to 14% in IES. These varying results, just because of the different shading implementations, might cause different cooling system choices.

The correlation of EP, with its results from the 2 different modelling strategies being only at 2%, is very high compared to the other two BPS tools.

4.2.2 Daylighting Analysis (Illuminance)

Another important aspect of BPS tools is their capability of simulating daylighting performances. The daylighting analysis is crucial for providing the occupants with a healthy and comfortable luminous environment, by also helping to design for energy efficiency [30]. This section of the study investigates the differences of the illuminance results for the user-built and in-built shading implemented models.

4.2.2.1 EnergyPlus

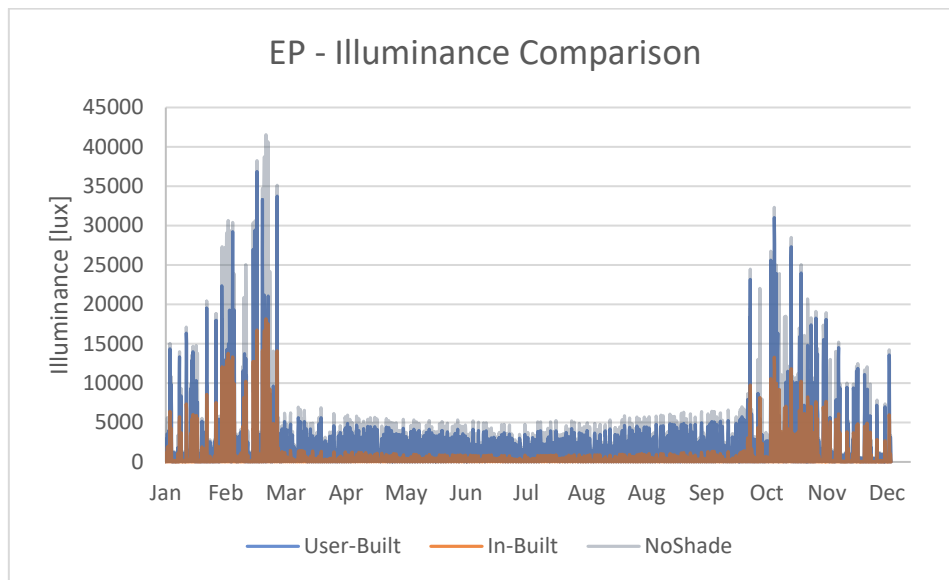


Table 50: EP Hourly Annual Illuminance Graph

Table 50 includes the results for the user-built and in-built shadings, as well as the model without shading. The results for the “no shade” model have been implemented to better illustrate the effect of shading in both scenarios. As seen from the graph, the user-built shading results are not much less than those of the “no shade” results. The difference in the user-built and in-built illuminance results are considerably different. This gives an understanding that the 2 different modelling approaches are not coherent with each other.

	YEARLY	MONTHLY				DAILY	
	Year	January	April	July	October	Jun-21	Dec-21
RMSE (lux)	2299.5	2041.2	1656.2	1431.1	3407.4	1498.6	2207.7

Table 51: EP Illuminance RMSE

A numerical validation of the lack of coherence between the 2 different shading implementations can be made from Table 51. The RMSE results show very high values, which indicate the weak correlation between the results. The daylighting aspect

4.2.2.2 IES-VE

IES's in-built external louvres implementation does not provide any change in the daylighting results in comparison to the model without shading. Thus, the software's in-built shading implementation only works with the thermal aspect of the simulation calculations and does not take effect in the daylighting analyses.

4.2.2.3 IDA-ICE

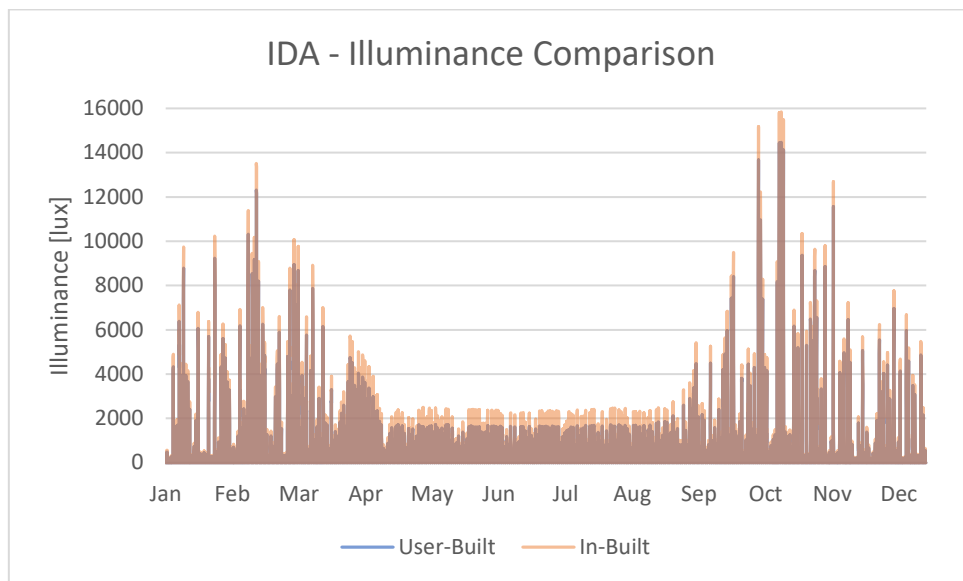


Table 52: IDA Hourly Annual Illuminance Graph

Table 52 displays a strong correlation between the results of the user-built and in-built models, especially compared to EP. The difference in the scale of Table 49 and Table 51 must also be highlighted to have a better understanding of IDA's coherence with its results.

	YEARLY	MONTHLY				DAILY	
	Year	January	April	July	October	Jun-21	Dec-21
RMSE (lux)	288.4	246.3	328.6	267.8	365.0	326.0	20.7

Table 53: IDA Illuminance RMSE

Table 53, being predominantly green colored, indicates IDA's high correlation between the in-built and user-built illuminance results in comparison to EP's RMSE values. Another important aspect to be mentioned is the consistency of the RMSE values of IDA. The differences in results do not fluctuate greatly.

5 Discussion

5.1 Comparative Study among the BPS tools (EP v IES v IDA)

5.1.1 Thermal analysis

5.1.1.1 *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 [43]. 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 cannot 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.

5.1.1.2 *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 thesis [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.

5.1.2 Daylighting Analysis

When considering the daylighting analysis conducted in this thesis, it is important to be critical against the methodology of the research. The illuminance value of 1 point of a 48 m² 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].

5.2 Comparative Study within the BPS tools (User-built vs In-built Shading)

5.2.1 Thermal analysis

5.2.1.1 Indoor Mean Air Temperature

The comparative study between the temperature results of each BPS tools' user-built and in-built shading implementations has given interesting findings. The differences in coherence of the BPS tools, in some cases, are not negligible and have to be considered if precise and accurate design is intended.

EP, giving out the most coherent results in terms of indoor mean air temperature values has achieved RMSE values lower than 1°C in almost every timeframe (except for the 21st of December). This means that the user-built and in-built shading calculations are strongly correlated and have very similar significance in calculation, in comparison to the other BPS tools. The designer will acquire very similar thermal results with both shading implementation methods in EP.

The degree of coherence or discrepancy can only be assessed in a comparative way because a limiting value cannot be determined for the RMSE values. This is due to both shading implementation methods representing the same system, thus should be giving the exact same results. The RMSE values from IES are slightly less coherent as opposed to EP's values. The temperature results of IDA's shading implementations give out very high discrepancies as opposed to the other two BPS tools. The discrepancy of IDA might be a result of an extra thermal resistance implemented between the glazing and the shading system within its in-built external louvres system. Yet, further analyses must be carried out to find the exact reasonings of these calculation differences.

5.2.1.2 Heating / Cooling

Determining the heating and cooling needs, as well as the peak loads of a building is fundamental in the assessment of its performance. Therefore, the comparison of these aspects has been evaluated for the questioned BPS tools. The findings of the study on the heating and cooling load calculations give useful insights on the tools.

When the calculation for the peak heating loads take place, it is for the day in which no solar effect is present. That is why there is almost little to no difference in the resulting values. The solar gains are also less impactful, yet not negligible, for the calculation of annual heating needs. So, drawing solid conclusions from this aspect would not be totally precise. Yet, it is worth mentioning that IDA's 8% difference is considerable in comparison to the differences in the other two BPS tools.

The solar irradiance will be much more dominant in the energy calculations of the cooling seasons. As some of the findings also indicate, the differences between the results of the two

shading implementations are considerable. Although the amount of cooling needs is small compared to that of the heating needs, what is important is the amount of change which occurs between the results. The differences of IES and IDA being 58 and 41% for the annual cooling needs, and 14 and 19% for the peak cooling loads respectively, do not represent a viable coherence within the tools. The differences are very large and would therefore result in completely different cooling estimations and choices in cooling equipment. EP, with its relatively small differences, proves its highly coherent cooling calculation estimations within its two different shading implementation methods.

5.2.2 Daylighting Analysis

Even though EP has shown strong correlation between its thermal results from the user-built and in-built shading implemented models, the daylighting aspect proves otherwise. The inconsistency of the correlation of the thermal and daylighting aspects of the tool gives an understanding that a BPS tool consists of a series of functions which may give uncoordinated results. It is therefore important to be aware of this separation of operations.

IES does not consider the effect of its in-built shading for external louvres within its daylighting calculations. If the user desires to investigate the daylighting performance of a building, he or she must construct a user-built shading model.

IDA, with its stronger coherence between the daylighting results of the two different shading implementations, proves that its daylighting calculations are more reliable. Even though RMSE values of 200-300 lux are not negligible differences, it is far more coherent than EP's weak coherence and IES's non-existing in-built daylighting results.

5.3 Interpretation of Results and User-Assessment

Table 54 indicated on the next page is a summary of the findings from the conducted research and a user commentary on the use of the three considered BPS tools. The user experience in constructing the models and navigation through the tools have been outlined from the perspective of a master's student working closely with the tools for a period of about 5 months, with prior knowledge in their use. The aim with the commentary-based part is to give feedback to the community, as it is crucial for raising awareness for certain aspects of the tools and sharing the experience.

	EP	IES	IDA							
Geometry Construction / Import	<ul style="list-style-type: none"> - User has to also be familiar with software other than Energy-Plus, including SketchUp, OpenStudio (Excel for outputs) - Debugging geometrical errors cause the user to go back-and-forth between software - Easy to use after grasping the "idf Editor" concept of linking inputs and referring to objects 	<ul style="list-style-type: none"> - Simple in-built geometry builder with minor bugs when using some functions - 3D model with color palettes for types of surfaces gives good understanding and visualization - Easy management of constructions and templates for quick changes in design 	<ul style="list-style-type: none"> - Easy to understand geometry builder with a user-friendly, simplistic user-interface - The straightforward editing of the model and its components in 3D space gives high control to the user - The "Palette" tab and the drag-and-drop feature for its objects allows users to model in a fast and efficient way 							
	<table border="1"> <tr> <td rowspan="2">Shading Implementation</td> <td>Regular External Louvers</td> <td> <ul style="list-style-type: none"> - Each blade was built in SketchUp with 6 surfaces and caused "errors", 1 surface per blade could have been sufficient - Detailed input parameters with clear step-by-step guidelines and visualization </td> <td> <ul style="list-style-type: none"> - Quick and easy design within the geometry builder, "ModelIT" - No clear details and insufficient guidelines for detailing (i.e. Transmission Factor) </td> </tr> <tr> <td>In-built</td> <td> <ul style="list-style-type: none"> - Same issue as "regular" shades, no specific problem caused by the irregularities - The edges of the inner shelf not coinciding with the "Daylit Zone" edges causes minor issues </td> <td> <ul style="list-style-type: none"> - Import from SketchUp and easy placement with coordinates in 3D model - Various in-built shading elements exist with their visualizations, implemented from the library - Import from SketchUp and easy placement with coordinates in 3D model - Simple drag-and-drop feature for "horizontal shade" on 3D model makes the design fast and easy </td> </tr> </table>	Shading Implementation	Regular External Louvers	<ul style="list-style-type: none"> - Each blade was built in SketchUp with 6 surfaces and caused "errors", 1 surface per blade could have been sufficient - Detailed input parameters with clear step-by-step guidelines and visualization 	<ul style="list-style-type: none"> - Quick and easy design within the geometry builder, "ModelIT" - No clear details and insufficient guidelines for detailing (i.e. Transmission Factor) 	In-built	<ul style="list-style-type: none"> - Same issue as "regular" shades, no specific problem caused by the irregularities - The edges of the inner shelf not coinciding with the "Daylit Zone" edges causes minor issues 	<ul style="list-style-type: none"> - Import from SketchUp and easy placement with coordinates in 3D model - Various in-built shading elements exist with their visualizations, implemented from the library - Import from SketchUp and easy placement with coordinates in 3D model - Simple drag-and-drop feature for "horizontal shade" on 3D model makes the design fast and easy 	<ul style="list-style-type: none"> - Quick and easy design within the geometry builder, "ModelIT" - Horizontal shading surface created with specific properties, no problems occurred with glazing 	<ul style="list-style-type: none"> - Import from SketchUp and easy placement with coordinates in 3D model - Simple drag-and-drop feature for "horizontal shade" on 3D model makes the design fast and easy
	Shading Implementation		Regular External Louvers	<ul style="list-style-type: none"> - Each blade was built in SketchUp with 6 surfaces and caused "errors", 1 surface per blade could have been sufficient - Detailed input parameters with clear step-by-step guidelines and visualization 	<ul style="list-style-type: none"> - Quick and easy design within the geometry builder, "ModelIT" - No clear details and insufficient guidelines for detailing (i.e. Transmission Factor) 					
In-built		<ul style="list-style-type: none"> - Same issue as "regular" shades, no specific problem caused by the irregularities - The edges of the inner shelf not coinciding with the "Daylit Zone" edges causes minor issues 	<ul style="list-style-type: none"> - Import from SketchUp and easy placement with coordinates in 3D model - Various in-built shading elements exist with their visualizations, implemented from the library - Import from SketchUp and easy placement with coordinates in 3D model - Simple drag-and-drop feature for "horizontal shade" on 3D model makes the design fast and easy 							
Comparison among BPS Tools	<ul style="list-style-type: none"> - Strong correlation with the hourly temperature results of IES (except for Light shelf) - Very high illuminance values were obtained for all models in comparison to the other tools 	<ul style="list-style-type: none"> - The light shelf results show a comparably high barrier for the solar gains - Illuminance values taken from daily analyses were mostly lower 	<ul style="list-style-type: none"> - Relatively high temperature fluctuations and high peak values occurred - Low correlation in temperature values, yet heating and cooling calculations are in correlation - The results for the daily and yearly analyses seemed coherent and in line with at least one of the two tools 							
Comparison within BPS Tools	Thermal Analysis	<ul style="list-style-type: none"> - Strongest correlation for thermal analyses within the two different shading implementations - Very low RMSE values, low differences in heating and cooling calculations 	<ul style="list-style-type: none"> - The hourly indoor temperature values show moderate coherence - The difference in cooling needs went up to 58% 	<ul style="list-style-type: none"> - Weak temperature correlation with RMSE values going up to 3-4°C - Relatively high differences in the cooling calculations 						
	Daylighting Analysis	<ul style="list-style-type: none"> - Very high differences between the daylighting results of the two shading methodologies 	<ul style="list-style-type: none"> - The in-built external louvers shading implementation does not work with the daylighting analyses 	<ul style="list-style-type: none"> - Strongest coherence within the illuminance results of the shading implementations 						

Table 54: Interpretation of Results and User-Assessment

6 Conclusion

The thesis investigated certain aspects of the functioning of BPS tools by looking at the outputs obtained from its simulations. The main comparative aspects were the thermal and daylighting results, from an hourly, monthly, and yearly basis. These results were compared by the addition of complexity with shading implementations and the daylight improvement strategy, the light shelf. The regular external louvres shading was also implemented in the models with two different methods to check the coherence between the modelling approaches. Interesting points have been obtained from the findings.

To conclude on the thermal aspects of the comparative study among the BPS tools, EP and IES showed stronger correlation with the results of the indoor air temperature except for IES's slight differences in light shelf results. IDA's temperature values fluctuated with a higher amplitude, which resulted in higher and lower temperature values. Yet, all three BPS tools had a certain correlation in the heating and cooling calculations. It is not possible to determine the more "correct" results without an experimental implementation to the analyses, which could be further implemented within the research scope in the future. Yet, these kinds of comparative studies are important for input debugging and in improving engineering judgment, which are crucial steps for the progress of the analyses [25].

Even though the models were kept as simple as possible some increments in the complexity of shadings resulted in discrepancies, especially in the daylighting analyses, 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 [24]. 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 [29].

The comparative analyses within the tools resulted in substantial differences between the results of the two different shading implementations. This shows that the user must always be skeptical when making design choices and should have a way to validate the results obtained. The user should also keep in mind that a validation for a certain function of a BPS tool does not necessarily validate another "linked" function. This conclusion is derived from the fact that some of the analyzed BPS tools proved coherent in the thermal analyses, yet tested poorly in the daylighting aspect, and vice versa.

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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