Thermal Comfort and Energy-Use in Urban Transitional Spaces

Bus stop in Slovenia

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

Lund University

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

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

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Abstract

Transportation plays an essential role in the European economy. The European Transport Policy aims to establish a sustainable means of transportation system to provide the social, economic and environmental needs of society contributing to an integrated society. Major reasons for people to choose private cars over public transport are infrequent connections, inadequate infrastructure and low thermal comfort while waiting for their transport. This thesis is a research on the adaptive approach to thermal comfort in bus stops in Slovenia. It provides an innovative opportunity to assess thermal comfort by using the Universal Thermal Climate Index (UTCI) method. The UTCI was compared with the operating/room temperature inside the bus stop to assess the total number of comfortable hours during an entire year. The role of climate on the architectural design was investigated. Subsequently, passive design measures such as triple glazing, insulated walls and green roof were included in the bus stop design to achieve maximum thermal comfort. A conventional and a climate-based bus stop design were tested and the thermal comfort and energy-use in both these bus stops were analysed. An iterative parametric study analysis resulted in the climate-based bus stop performing better than the conventional bus stop. Addition of an active measure comprising of an electrical floor heating powered by solar photovoltaic cells was also investigated. It was found that active floor heating could increase thermal comfort substantially, but it was necessary to investigate the feasibility and costs to determine if an active measure would be profitable in reality. In the end, it was deduced that whether or not, an active measure was included in the design, it was nevertheless, important to incorporate passive design measures to be able to achieve a holistic, sustainable design.

Acknowledgement

Writing a thesis is never easy: nothing ever seems to go quite as planned, and while 4 months sounds like a long time, most of it goes up on encountering crisis after crisis, each appearing more disastrous than the last. This thesis, unfortunately, was no exception: whether it was inexplicable simulation results, malfunctioning software or faulty building designs, problems never failed to surface at the least convenient of times.

That probably explains why anyone in academics needs a strong support group around them, and I was lucky enough to have just that. Firstly, I want to thank my supervisor, Petter Wallentén for somehow always making me feel as if all was under control, where several minutes before a meeting, I still believed I was doomed. I want to thank my family and friends, in India, in Sweden and in Slovenia, for always listening to my thesis stories, and above all, reminding me that there is a life beyond it. And I want to thank everyone at Ofis Arhitekti, especially Špela Videčnik and Andrej Gregorič, for the support they gave me in the making of this thesis, and the opportunity they gave me to write it in a country as beautiful as Slovenia in the first place.

All in all, I think I can confidently say that the making of this thesis has been little less than a disaster, and that I could not have completed it without the people around me. But it has above all been a very educational disaster, and with that, I do believe I could call it a rather typical Master thesis: a disaster, but an educational one, and ultimately one I am proud of.

Terminology

BIPV – Building integrated photovoltaic cells

EU – European Union

GDP – Gross domestic product

GHG – Greenhouse gases

LED – Light emitting diode

MRT – Mean radiant temperature

PRH – Public rental housing

PV – Photovoltaic solar panel

SA – Sensitivity analysis

SGHC – Solar heat gain coefficient

UTCI- Universal thermal climate index

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1 Introduction

Transportation plays an essential role in the European economy. The transport sector accounts for *7 %* of the GDP and over *5 %* of employment in the European Union (EU). The European Transport Policy aims to establish a sustainable means of transportation system to provide the social, economic and environmental needs of society contributing to an integrated society. (Hocevar M, & Novak A. 2013) There is a pressing need to mitigate the negative environmental impact of transport. The EU has adopted a recent policy to reduce greenhouse gas (GHG) emissions by *20 %* since the *1990s*. The transport sector is a key component in achieving this target. (European Community 2009).

1.1 Background

Slovenia, a country in central Europe with a population of *2* million is known for its mountains, ski resorts and lakes. Figure 1 shows that in the year *2016*, Slovenia had a very high motorway density of more than *35 km / 1000* km^2, making it a country with one of the densest motorways in the EU. (Eurostat, 2019) According to the website of the Slovenian statistical office *2.3* million passengers were transported by buses in the public scheduled transport in December *2018* which was *8 %* fewer than in December *2017*. Seasonally adjusted data on the website also indicates that in December *2018*, the registered number of new cars was *2 %* higher than in November *2018*. (RSSO 2018) Major reasons for people to choose private cars over public transport are infrequent connections, inadequate infrastructure and low thermal comfort while waiting for their transport.

1.2 Context

According to the AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS. (2004), p4 - *“Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment. Because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space. The environmental conditions required for comfort are not the same for everyone.”*

In the last decade, due to climate change and heat stress in urban cities, several studies have been conducted on indoor thermal comfort. On the other hand, relatively few studies have been carried out for thermal comfort in an outdoor environment. (Honjo, T. 2009) Considerable attention to human satisfaction in outdoor and semi-outdoor thermal comfort is a duty of architects and urban planners. Thermal comfort provides a significant framework for sustainability and plays a key role in urban zones along with air contamination, noise level and aesthetics. (Goshayeshi, Danial, Shahidan, et al. 2013)

Air temperature, relative humidity, wind speed and mean radiant temperature (MRT) are four parameters that are essential in determining thermal comfort. (Park, S., Tuller, S. E., & JO, M. 2014) Amongst several other factors which affect thermal comfort in semi-outdoor spaces, the local microclimate has a strong impact. In comparison with car users, pedestrians and commuters by bus are directly exposed to the outdoor environment in terms of temperature, relative humidity, wind speed and other characteristics. (Chen, L., & NG, E. 2012)

1.3 Aim/Purpose

Since the thermal satisfaction of human beings is greatly dependant on microclimatic parameters, good microclimatic conditions result in higher usability of the semi-outdoor space. The harsh, cold climate in the Julian Alps in Slovenia combined with high wind speeds can make it a very uncomfortable wait for the bus for commuters. The main goal of this thesis is to provide a suitable thermal environment at bus stops located in this region. The paper aims to answer the following research questions –

"Does the climate play any role on the architectural design to achieve better thermal comfort?

"How can a simple bus stop design be made energy-efficient and self-reliant on renewable sources of energy, whilst keeping in mind the thermal comfort of the users?"

By assessing the energy use and thermal comfort of two different bus stop designs, the paper endeavours to assess the importance of climate-based design to be able to achieve an energy efficient bus stop model which would provide a good thermal comfort for the users.

1.4 Significance, scope and limitations

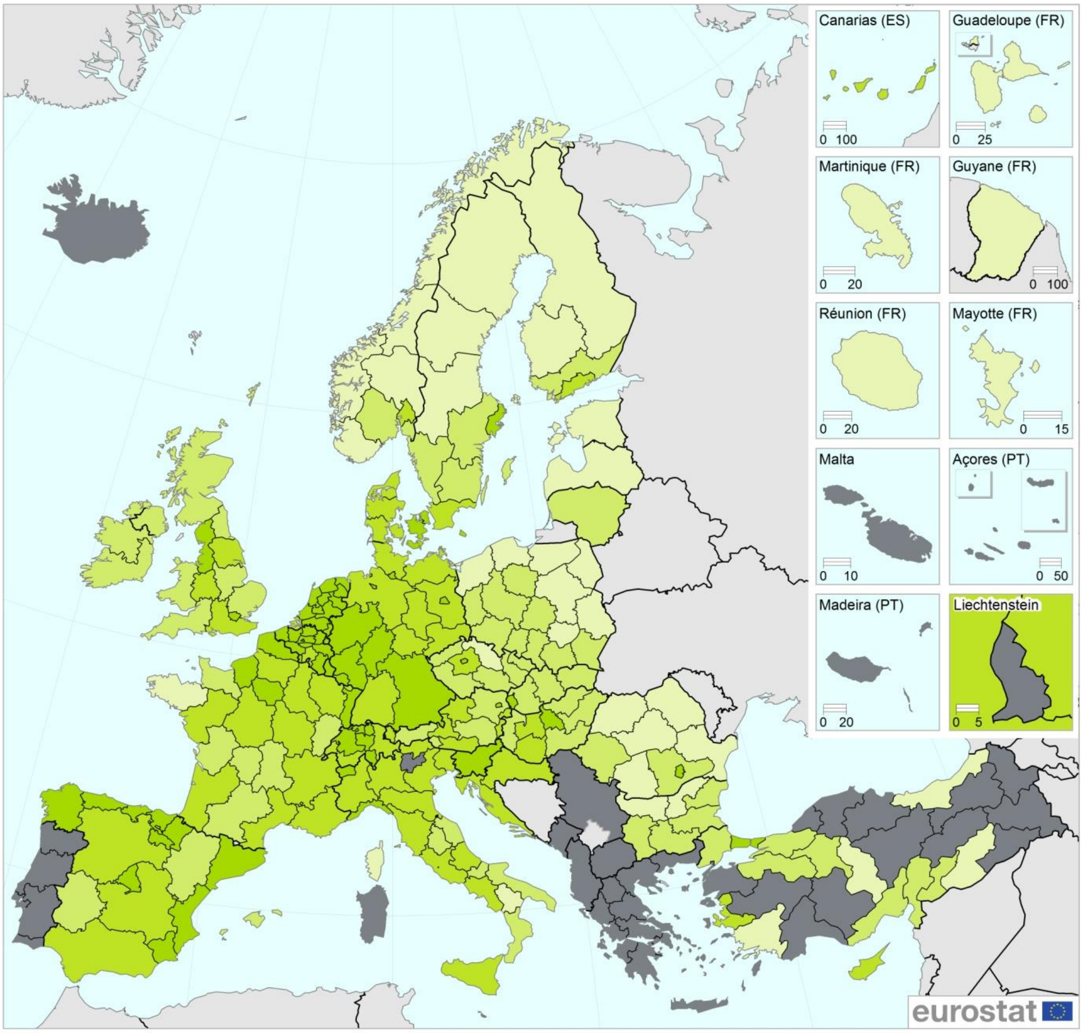
Human beings have a natural inclination to adapt themselves to the constantly changing outdoor environment. This thesis is a research on the adaptive approach to thermal comfort. It provides an innovative opportunity to assess thermal comfort by using the Universal Thermal Climate Index (UTCI) method. (UTCI 2019) The UTCI is compared with the operating/room temperature inside the bus stop to assess the total number of comfortable hours during an entire year.

The developed prototype could not only be used as a bus stop model in Slovenia, but also in other places with a similar climatic condition. Since bus stops are widespread and have different orientations and shading contexts based on the road orientation and location, it was not possible to assess the design for all orientations. Therefore, a fixed site was chosen, and the analysis was carried out for it.

1.5 Overall method

The thesis begins with problem formulation where the main problem or issue is laid out and the aims and objectives of this thesis along with the scope are stated. This is followed by a literature review on self-sufficient buildings built with passive measures. The design work is carried out next where different design options are investigated to combine function and aesthetics. An iterative, qualitative energy comfort investigation is further done to determine two designs which provide an enhanced thermal comfort by using passive measures. A detailed energy and comfort analysis are finally done for both the chosen designs and one particular design with low energy-use and maximum thermal comfort is selected. The results are then compared with the outdoor thermal comfort condition in order to determine the increase in thermal comfort compared to the harsh outdoor condition. The paper finally ends with generalisations and discussions about further improvements that could be made for the design.

Motorway density, by NUTS 2 regions, 2016
(km/1000 km²)



(km/1000 km²)

Administrative Boundaries: © EuroGeographics © UN-FAO © Turkstat
Cartography: Eurostat — IMAGE, 17-05-18

- **< 5**
- **5 – < 20**
- **20 – < 35**
- **>= 35**
- **Data not available**

0 200 400 600 800 km

Note: Croatia and Italy: 2015. Germany, Portugal, Slovenia and United Kingdom: NUTS level 1.
Source: Eurostat (online data code: tran_r_net)

Figure 1 Motorway map of Slovenia

2 Literature Review

In their paper "An exhaustive parametric study on major passive design strategies of a typical high-rise residential building in Hong Kong" Xi Chen and Hongxing Yang present a comprehensive sensitivity analysis of a high-rise residential building in Hong Kong. A public rental housing (PRH) building is studied with the ground and top floors acting as service areas with negligible energy consumption as compared to the *30* to *40* floors of domestic floors in between. The sensitivity analysis (SA) determines how much influence a certain architectural parameter has on the specified output of the generic building model. The following various architectural design parameters inputs are considered in the study:

- Infiltration air mass flowrate
- Overhang projection ratio
- Window to ground ratio (WGR)
- Window SHGC
- External wall specific heat
- External wall thermal resistance
- External Obstruction angle
- Building orientation

From the results of the SA on cooling energy it was found that all input parameters influenced the lighting energy except the building orientation. Another SA was carried out for the yearly operative temperature inside the building. It was observed that WGR, window SGHC, external obstruction angle, building orientation and overhang projection ratio has a significant impact on the operative temperature inside the building. In the end, it could be concluded that passive architectural design strategies such as building layout, building envelope, building geometry and infiltration and airtightness have a significant impact on the building energy consumption. Architects and engineers should identify such passive strategies in the building design phase in order to reduce the energy consumption of such high-rise buildings. (Chen X., & Yang H. 2016)

Another study on the use of Building Integrated Photovoltaic Cells (BI*PV*) in an existing institutional building and a hypothetical residential building with a pre-thought BIPV design in the western state of Gujarat, India was conducted by Joshi et al (2014). The results show that a building designed with passive solar measures and integrated with BIPV in the planning stage performs better than when BIPV is added as a retrofit in an existing building. A BIPV retrofit in the institutional building was concluded to be more expensive since it provided restricted potential for positioning the panels while a new design would allow integration of BIPV at the building stage. A new design would also be able to provide a suitable building orientation which was not possible in a building retrofit. The BIPV was integrated into the sunshades, skylights, rooftops, windows and façades of the building. The study is conducted for a period of one year from July *2011* to June *2012*. In the case of the building retrofit, it was found that BIPV in sunshades had a reduction potential of *17.29 %*, BIPV in adjacent walls had a reduction potential of *16.43 %* and BIPV in the windows had a reduction potential of *11.99 %*. It was also found that although the installation area of the BIPV panel was only *36.17 %* of the total built-up area, it replaced *45.71 %* of the total energy consumption of the building. In the second case, BIPV was integrated into a hypothetical residential building of ground area of *100* m^2. For the building design in the planning stage, the prime consideration was the orientation of the building. Passive solar measures such as optimal positioning of window openings was integrated into the building design. The verandah was proposed to be covered with outdoor plantation in order to reduce ground reflectance, resulting in a comfortable indoor condition with ample of daylight inside the building. It was found that sunshades had a reduction potential of *80.84 %*, skylights had a reduction potential of *38.65 %*, rooftop had a reduction potential of *29.76 %* and the façade had a reduction potential of *35.40 %*. The installations yielded to completely satisfying the energy demand throughout the year while also having some surplus. The surplus energy generated could be fed to the grid or could be used for a secondary or communal use. The BIPV provided exact energy for the month of June and the maximum surplus energy was in the month of January. It was found that if BIPV was installed in only *40 %* of the total built-up area in the design stage, it could result in covering the entire energy demand throughout the year. (Joshi, R., Pathak, M., & Singh, A. K. 2014)

3 Thermal comfort

Outdoor thermal comfort plays an important role to determine the microclimate in an urban setting. Considerations regarding outdoor thermal comfort in the design stage can lead to a comprehensive, sustainable design, providing maximum thermal comfort for users. Thermal comfort studies have begun in the recent past. In the *1930's*, *Gagge* developed the 'two node model' for evaluation of thermal comfort. Thermodynamics was applied for the first time in evaluation of body heat exchange with the thermal environment. Additionally, in *1963 Givoni* developed the *'Thermal stress index'* followed by *Fanger* developing the *'Predicted Mean Vote' (PMV)* in *1970's*. PMV is recognized as an internationally accepted standard for the evaluation of thermal comfort in indoor spaces. Although there have been various studies on indoor thermal comfort with steady state conditions inside a room, relatively few studies have been performed on outdoor thermal comfort because of the dynamic state of outdoor conditions. An important factor to be considered in outdoor thermal comfort is the variable exposure time, lasting from a few minutes and up to a couple of hours for users spending time outdoors. This leads to the need of a non-steady state model to assess thermal comfort in outdoor conditions. (Coccolo, S., Kämpf, J., et al. 2016)

Peter Hoppe in his paper "Different aspects of assessing indoor and outdoor thermal comfort" describes that because people in industrialised cities spend less than 1 hour of their time in outdoor settings, hence, it is difficult to reach outdoor steady conditions in such short periods of time. When indoor standards for thermal comfort are applied to outdoor settings, the models tend to overestimate discomfort especially in cool conditions as compared to warmer conditions. Similarly, thermal indices such as 'Perceived Temperature' (PT), 'Outdoor Standard Effective Temperature' (OUT_SET) and 'Physiological Equivalent Temperature (PET) are established on steady state energy balance models on the human body and are relevant for people who spend a long time outdoors. To assess thermal comfort in outdoor conditions for shorter periods of time, a new multi-nodal model called the 'Universal Thermal Climate Index'(UTCI) has been recently developed. (Hoppe, P. 2002)

3.1 UTCI thermal index

UTCI was developed following the concept of equivalent temperature. A reference environment with *50 %* relative humidity (vapour pressure not exceeding *20 hPa*) along with calm wind and MRT equal to the air temperature is defined and all other climatic conditions are compared to this. An equal physiological response is based on the dynamic physiological response anticipated by the model for both the reference and the chosen climate. Since the dynamic physiological response is multidimensional (temperature, sweat rate etc at different exposure times), a strain index was calculated. The UTCI equivalent temperature for the chosen climatic condition is therefore defined as an equivalent temperature of the reference climate with the same strain index value. (Jendritzky, G., De Dear, R., & Havenith, G. 2012)

In simpler terms, UTCI can also be defined as the perceived temperature or the 'real feel' by humans, taking in to account the air temperature, relative humidity, wind speed and mean radiant temperature. The UTCI thermal index assesses thermal comfort in a bio-meteorological environment and is based on dynamic model of physiological responses of human body thermal regulation along with an adaptive clothing model for shorter periods of time. For a better understanding of UTCI for the general public, the UTCI index is listed on a temperature scale (°*C*). Table 1 shows the thermal categories of the UTCI index. (Mansoureh Tahbaz., Sharbanoo Djalilian., Fatemeh Mousavi., 2014).

Table 1 UTCI index

UTCI / °C	**Thermal category**
Below - 40	Extreme cold stress
-40 to -27	Very strong cold stress
-27 to -13	Strong cold stress
-13 to 0	Moderate cold stress
0 to +9	Slight cold stress
+9 to +26	No thermal stress
+26 to +32	Moderate heat stress
+32 to +38	Strong heat stress
+38 to +46	Very strong heat stress
Above +46	Extreme heat stress

4 The site

4.1 Site selection

The first and foremost thing to begin the research was to select a suitable location for the bus stop. In order to do so, the *TMYx WMO Region 6 (Europe)* weather data for Rateče region located in the Julian Alps in the north-west of Slovenia was obtained from the climate one building website. (One building, 2019) Subsequently, as shown in Figure 2, the existing bus stop locations were marked in the region on Google maps. (Google maps, 2019) It was found that the towns - Kranjska Gora and Podkoren boast of hosting the annual Pokal Vitranc FIS Ski World Cup. (Pokal Vitranc, 2019) During this event people from all over Europe visit the area and there is a high demand for buses. The ski race start point is at Kranjska Gora whereas the finish point is located in Podkoren. As no suitable locations were found in Kranjska Gora, the new energy-efficient bus stop was therefore, decided to replace the existing bus stop at Podkoren. Figure 3 shows the images of the existing bus stop in Podkoren.

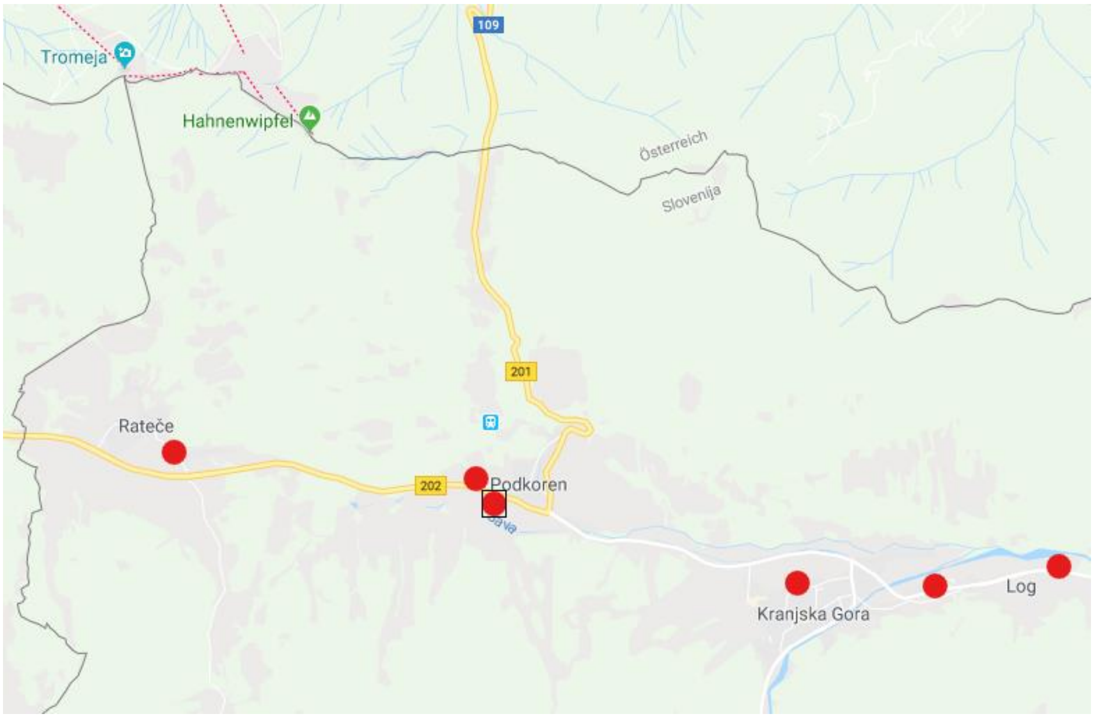


Figure 2 Existing bus stop locations in the north-west of Slovenia

Figure 3 Front and side views of existing bus stop in Podkoren

4.2 Site analysis

4.2.1 Location and surroundings

The co-ordinates for the site location in Podkoren are *46°29’31” N* and *13°45’20” E.* The road runs along the east-west direction and is approximately oriented *105 °E* from the true north. The bus stop is located in a valley with an extensive open area on the eastern and western sides. On the southern end, the vast Alpine mountains surround the bus stop while the access to the stop is from the northern side.

4.2.2 Climate analysis

Rateče weather data was used to analyse the weather conditions in the area. From Figure 4, it can be seen that the annual temperatures range between *-30 °C* in winter and *30 °C* in summer. The hottest day of the year is on the *5th* of August when the temperature is at a maximum of *30.2 °C* at *12 noon* whereas the coldest day of the year is on the *24th* of February when the temperature is at a minimum of *-29.3 °C* at *3 AM* in the morning. The total solar radiation received in Wh/ m^2 can be seen in Figure 5. The month of June experiences a highest total solar radiation of *330 Wh/ m²* comprising of direct solar radiation of *184 Wh/ m²* and diffused solar radiation of *104 Wh/ m²*. The lowest total solar radiation of only *75 Wh/ m²* is experienced in December which comprises of direct solar radiation of *46 Wh/m²* and diffused solar radiation of *29 Wh/ m²*. Figure 6 shows the wind rose of Rateče. The wind speed does not exceed *3 m/s* throughout the year and is described as 'Light breeze' which can be described as wind felt on faces, with leaves rustling. (Stathopoulos, T. 2009)

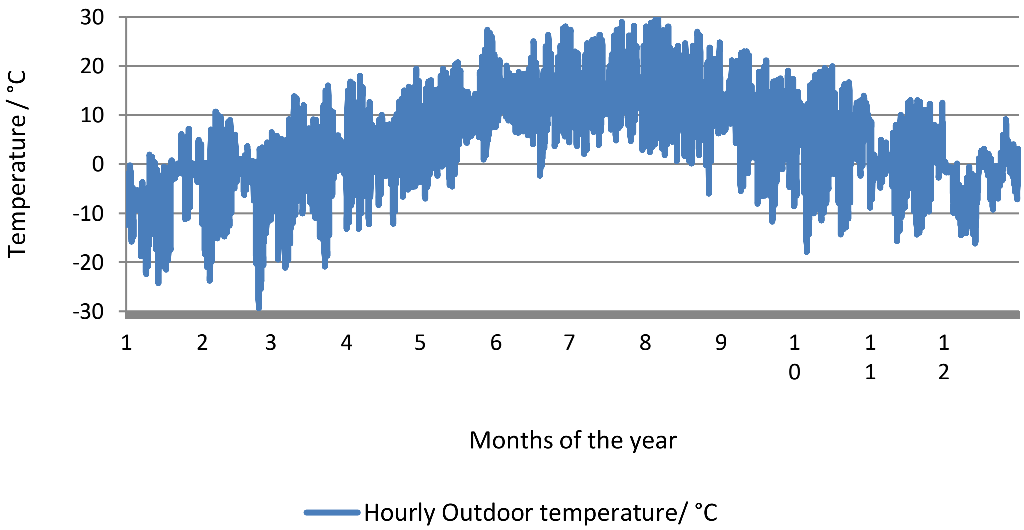


Figure 4 Average hourly outdoor temperature in a year in Ratece

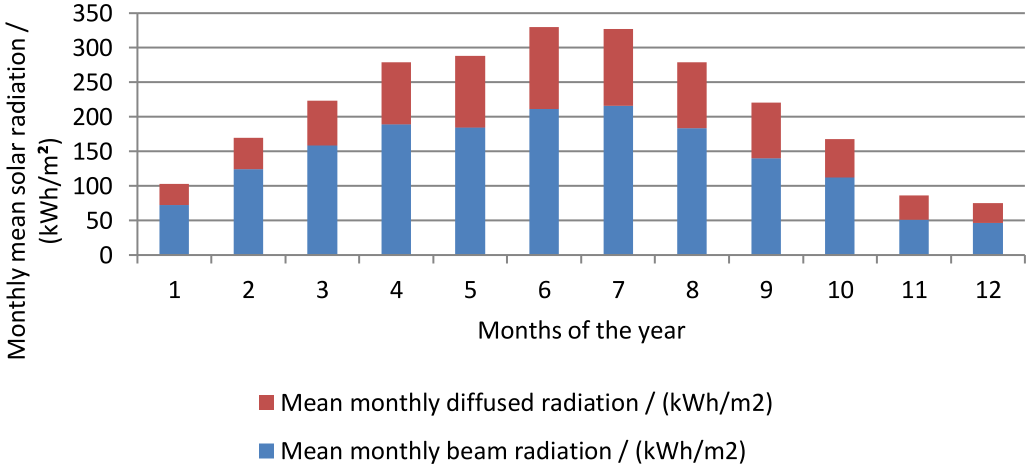


Figure 5 Yearly solar radiation in Ratece

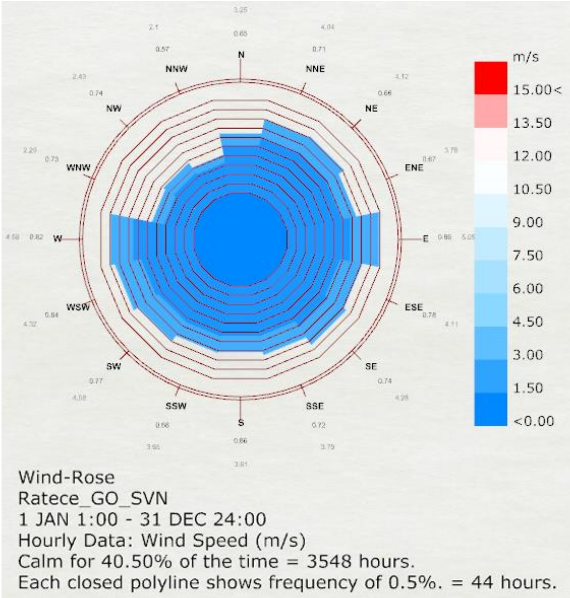


Figure 6 Annual wind rose of Ratece

By observing the above results, the climate of Rateče could be described as:

- Very cold and dry climate with a yearly mean outdoor dry bulb temperature of *4.6 °C.*
- The wind blows from all directions.
- The area also experiences high precipitation mostly in the form of snow.
- Although the wind speed throughout the year can be described as a ‘light breeze’, the presence of wind in low temperatures can make the temperature feel like much lower than what it is.

5 Architectural design

5.1 Architectural design methods

From the results of the site analysis, it was observed that in order to be able to develop a good architecture design, the following questions had to answered:

- How can one provide protection from wind and snow?
- How to deal with very cold temperatures?
- What kind of materials should be used for the construction?

5.1.1 Existing examples

To begin designing, a bus stop, seven existing examples of bus stops across Europe were studied. The requirement criteria for a suitable bus stop design are listed in Table 2. From the table, it can be observed that the most important criteria for each bus shelter was a roof covering, followed by seating. It was also important to have prototypes that were easy to install. The shelters usually almost always had a digital display for real time traffic information, which could be single- or double-sided display, depending on the availability of space and the number of commuters using the bus stop. Another feature integrated into the bus stop design was USB chargers for mobile phones. To lower the energy consumption of the shelter, it was essential to install LED lights for illumination and activity-based LED panels for advertisements and display. To make the shelter self-reliant, solar energy was harnessed using *PV* panels on the roof. It was observed that in all cases, the shelters were either covered with solar panels or had a vegetation cover on the roof. Subsequently, it would be interesting to consider a design integrating both – the solar panels and a vegetation cover on the roof. Radiant heating and cooling, rainwater harvesting and the use of recyclable materials for construction were also some measures that could be adopted. In order to make shelters more user-friendly, garbage bins, ticketing offices, postal delivery, mobile charging and other such facilities could be integrated in the design. Emergency equipment such as fire extinguishers and defibrillators could also be installed.

Table 2 Existing bus stops in Europe with fulfillment of design criteria

Criteria for design	Bus shelter in Paris	Osmose shelter in Paris	Vegetal bus stop	Bird bus stop	Eyestop	Prototype in Slovenia	Prototype in Hungary
Covered area	x	x	x	x	x	x	x
Advertisement panels	x	x		x	x		x
Digital display signs (single or double sided)	x	x			x	x	x
Garbage bin	x	x				x	x
Rainwater harvesting			x	x			
Seating		x	x	x	x	x	x
LED lighting equipment	x	x	x		x	x	x
Mobile charging	x	x			x	x	x
Extra services (postal service, library, noise sensors etc)		x		x	x		x
Vegetation			x	x			
Recyclable materials				x			
Easy installation	x			x	x	x	x
Solar energy	x	x			x	x	x
Radiant heating or cooling		x				x	
Emergency equipment (fire and medical aid)		x				x	

5.1.2 Protection against wind and snow

Since wind at low temperature can cause a higher discomfort level and the wind blows from all directions in the region, it was imperative to have an enclosed bus stop to be able to provide protection from wind and snow. Radiant floor heating could also be incorporated into the design to enhance thermal comfort of the users.

5.1.3 Modular design

The fact that this design would be a prototype for bus stops in the region, it was necessary to develop a modular design where one or more units of the bus stop could be installed based on the number of people using that particular stop. Moreover, a modular bus stop design would also help facilitate a rapid and easy construction.

5.1.4 Choice of materials

As it was favourable to use prefabricated components for the bus stop to achieve a modular design, the chosen materials for the construction were primarily wood and glass. As wood is an abundantly available material in the alpine areas, it could be locally sourced. Being a lightweight material, transportation of pre-fabricated wooden walls would be the most convenient and cost-effective choice. Furthermore, glass provided an opportunity to have an uninterrupted view of the alpine mountains surrounding the bus stop. An insulation material could also be incorporated in the walls and roof to increase the thermal mass in order to be able to retain maximum heat inside the enclosure. An inclined roof design would be most suitable for a region with high precipitation in the form of snow.

5.1.5 Green roof

Green roofs facilitate in improving the building energy performance and provide an alternative to conventional roofs with regard to sustainability. The vegetation on the roof helps to reduce the maximum indoor temperature during summer, thereby, improving the building thermal comfort. Although, the vegetation itself does not have any impact on the minimum indoor temperature during winters, an increased soil thickness can lead to an increase in the minimum indoor temperature. (Rakotondramiarana, H., Ranaivoarisioa, T., & Morau, D. 2015)

5.2 Architectural design development

5.2.1 Open bus stop design

Figure 7 shows different open bus stop designs that were investigated for thermal comfort. It was found that open designs with only a roof covering and a partial glass partition provided little protection from the rain and snow and the design provided almost no protection against the cold wind. As the design was an open type, the thermal conditions inside the bus stop remained virtually the same as the thermal condition outdoors. As a result, it was deduced that in order to achieve an enhanced thermal comfort, with protection against wind and snow inside the bus stop, the bus stop design had to be an enclosed one.

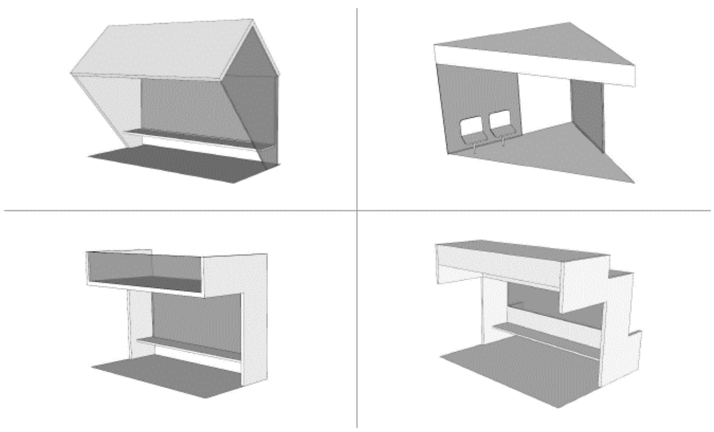


Figure 7 Different types of open designs for bus stops

5.2.2 Covered bus stop design

To improve the thermal conditions inside the bus stop, a covered, enclosed design was developed. Keeping future energy-use in mind, insulated walls and roofs were also incorporated into the design. The architectural design was then divided into two different types - the first design was based on a conventional flat roof, box shaped bus stop design whereas the second design was influenced by the traditional, vernacular alpine architectural of Slovenia. In order to facilitate cleaning of the bus stops, there is a gap of about *5 cm* between the floor surface and the lower edge of the glass façade. Both the designs were modelled in the software Google SketchUp, a 3D modelling software. (Google SketchUp PRO version 2018)

5.2.3 Conventional bus stop design

Figure 8 shows a 3D view of the first design developed. The bus stop has a total area of *13.5* m^2 and can accommodate 5 people inside it at any given time. The stop is covered by glass on the north and west facades to provide a better vision of the oncoming bus for passengers and an enhanced vision of the waiting passengers for bus drivers simultaneously. The eastern façade is a wooden wall with a screen providing real time traffic information.

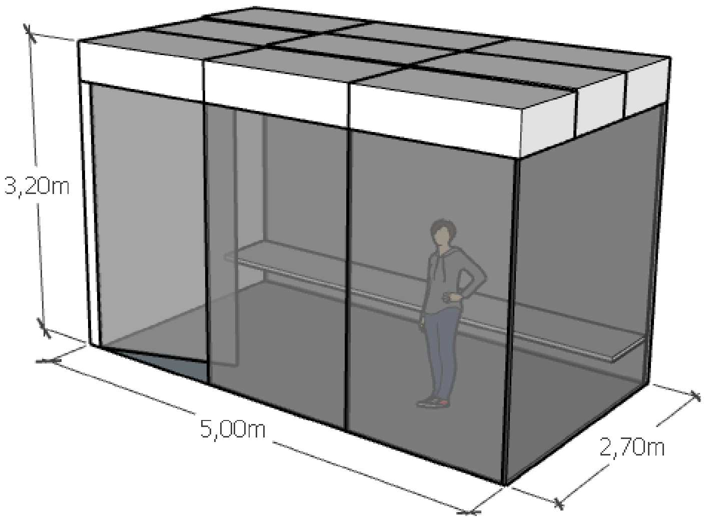


Figure 8 View of the conventional bus stop design

5.2.4 Climate-based bus stop design

A 3D view of the second bus stop design can be seen in Figure 9. The total floor area is *10* m^2 and the bus stop can accommodate *4* people in it. The design has a sloped roof with an inclination angle of *45°*. Similar to the previous design, this bus stop is also covered by glass on the northern, southern and western facades with the only exception being that the southern glass wall is inclined at an angle of *60°*. This was done in order to reduce overheating by minimising solar gains in the summer while maintaining an uninterrupted view of the landscape behind. Just as the previous case, the eastern façade is made up of a wooden wall equipped with a screen to provide real time traffic information.

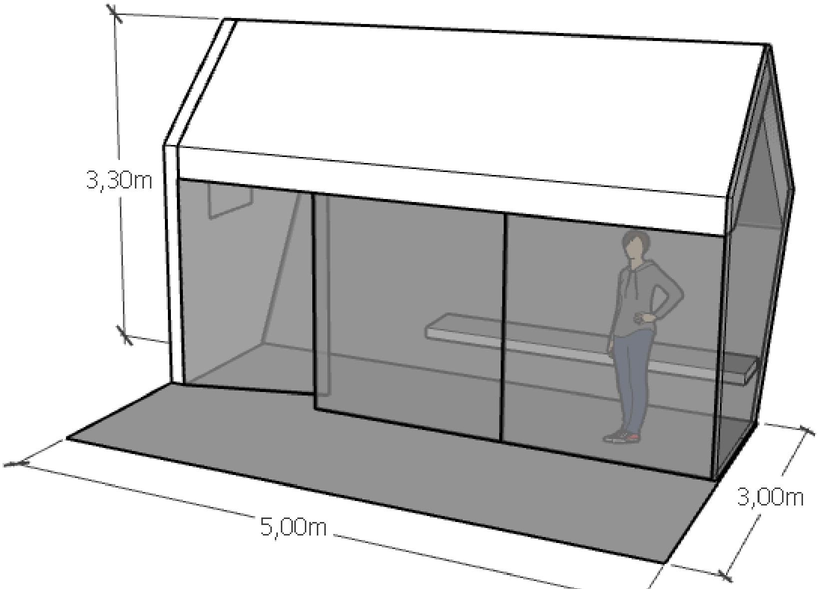


Figure 9 View of the climate-based bus stop design

6 Construction detail

The wall, roof and floor construction details are described below for both- the conventional bus stop design as well as the climate-based bus stop design.

6.1 Conventional bus stop design

6.1.1 External wall

The wall construction used was a wooden wall made up of *94 mm* cross laminated timber (CLT) panels on the inside followed by *150 mm* wood fibre insulation and *22 mm* of impregnated wood fibre insulation board. This is then followed by a *30 mm* vertical air gap and is finally covered by an external timber panel cladding. It is displayed in Figure 10. (Greenspec, 2019a)

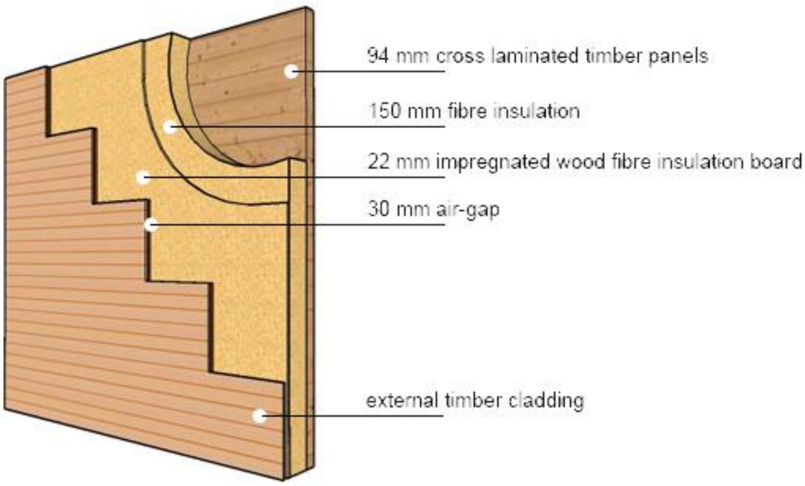


Figure 10 View of the external wall construction detail

6.1.2 Flat roof

The flat roof construction was also made up of *145 mm* CLT followed by a vapour control membrane and *150 mm* wood fibre insulation. The insulation layer is then covered with a polymer bitumen membrane and is topped with a gravel ballast. The construction detail can be seen in the following Figure 11. (Greenspec, 2019b)

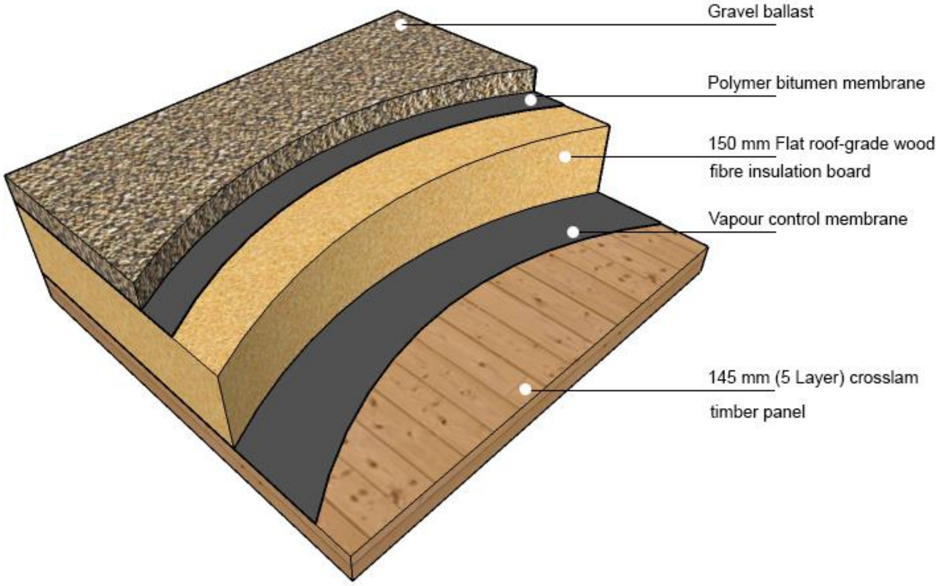


Figure 11 View of the flat roof construction detail

6.1.3 Flat green roof

As shown in Figure 12, the flat green roof had a *70 mm* precast concrete slabs as base with *5 mm* sloping lightweight concrete layer. This was followed by a vapour barrier membrane and *160 mm* of extruded polystyrene (XPS) *Styrodur 3035 CS* insulation. (BASF, 2019) A weather resistant barrier is placed on top of the insulation which is followed by a water soaking felt layer (*XEROflor XF 159*) and topped by a vegetative soil layer (*XEROflor XF 301*).

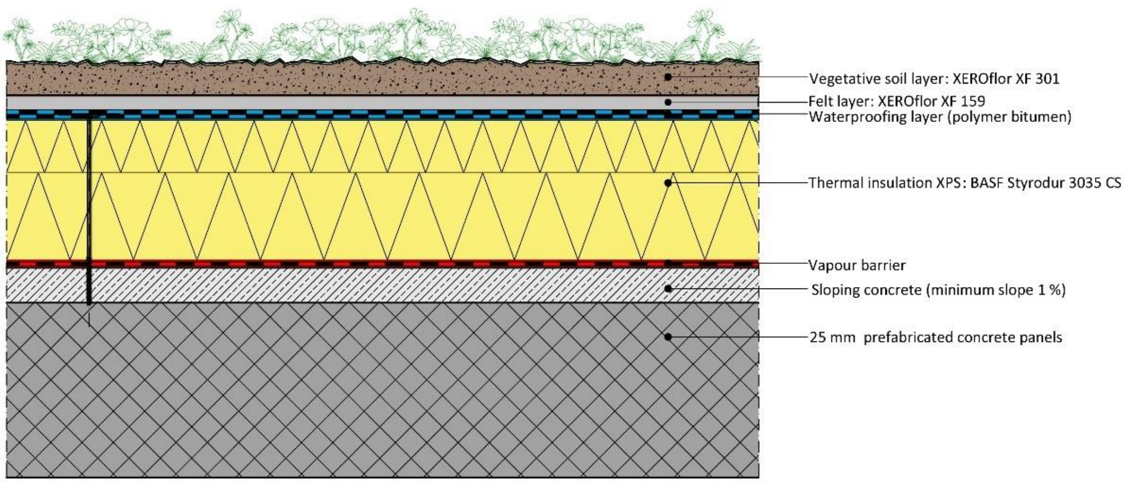


Figure 12 Sectional view of the flat green roof

6.1.4 External floor

The external floor construction was a *250 mm* concrete floor with a *5 mm* dark floor coating to facilitate absorption of solar heat.

6.2 Climate-based bus stop design

6.2.1 External wall

The same external wall construction as the conventional bus stop design was used for the climate-based design. (Figure 10).

6.2.2 Sloped roof construction

The sloped roof comprised of *100 mm* CLT panels followed by a vapour control membrane, *250 mm* wood fibre insulation, *25 mm* sarking grade wood fibre board with slat tiles mounted on battens and counter battens at the top. It is demonstrated in Figure 13. (Greenspec, 2019a)

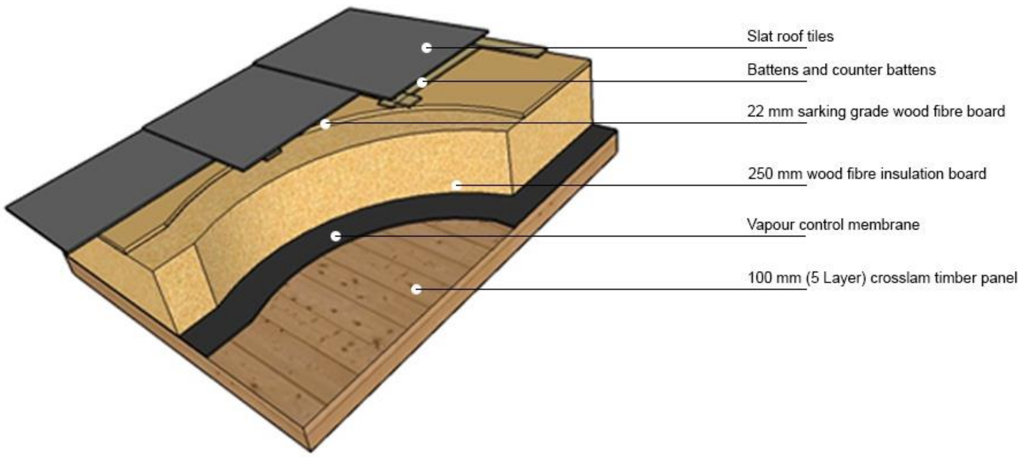


Figure 13 View of the sloping roof construction detail

6.2.3 Sloped green roof

Figure 14 displays the sloped green roof construction. The construction is made up of *60 mm* CLT topped with a PE foil layer, followed by *150 mm* of wood fibre insulation and *25 mm* of impregnated wood fibre insulation boards. This is covered by a water soaking felt layer (*XEROflor XF 159*). A vegetative soil layer tops the exterior surface of the roof (*XEROflor XF 301*).

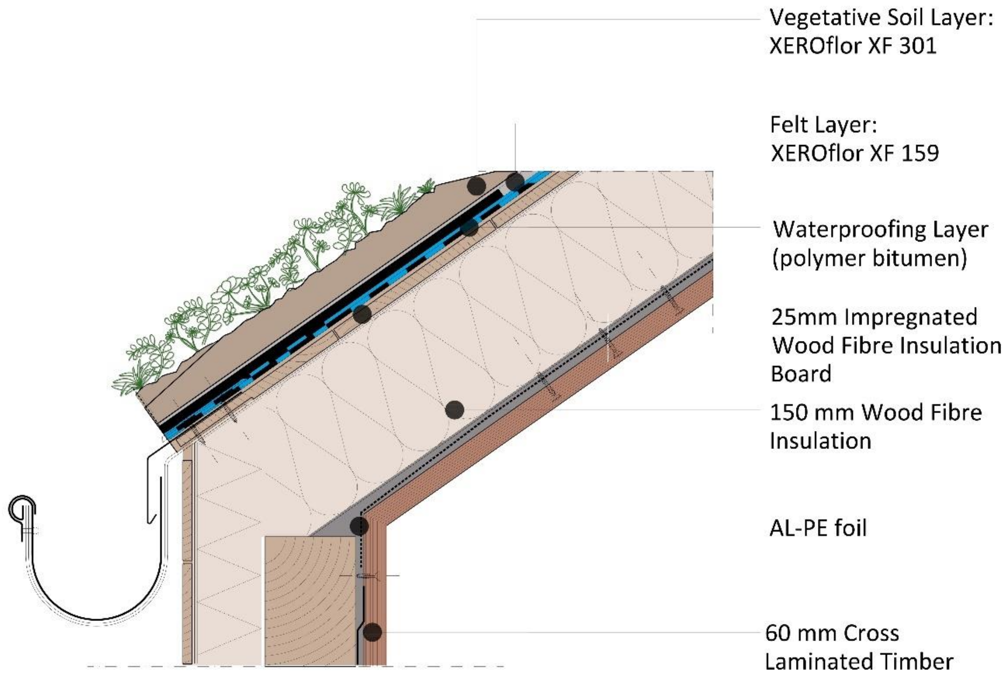


Figure 14 Sectional view of the sloped green roof

6.2.4 External floor

The external floor construction was the same as in the previous design.

7 Thermal comfort and energy performance

The methods for the thermal comfort and energy performance analysis is described in 7.2 while the results of the analysis are displayed in 7.3.
Different parameters such as type of glazing, wall insulation thickness, type of roof, integrated shading, door opening schedule and electrical floor heating were tested and the best performing result in each step was used as an input for the following step to obtain the final design.

7.1 Outdoor UTCI thermal index

To assess the thermal comfort inside the bus stop, the first step was to analyse the UTCI according to the UTCI thermal index. The annual hourly UTCI temperatures were obtained from the Rateče weather file by using the Ladybug plugin in Grasshopper (Grasshopper version 2014) The software MS Excel was used to categorise the working hours (*6205* hours) from the *8760* hours in a year according to the UTCI temperature values based on the UTCI index. (Table 1)

7.2 Thermal comfort and energy performance simulations

The annual, hourly operating temperature inside the bus stop was calculated by running a simulation of the bus stop model in the energy simulating software IDA ICE. (Equa, IDA ICE version 4.5) In order to assess the thermal comfort of users inside the bus stop, the operating/room temperature inside the bus stop was then categorised according to the UTCI thermal category index. The total number of hours in a year during which a user experiences both cold stress and heat stress as well the total number of comfortable hours in a year were listed. A step-by-step parametric analysis was carried out and the results of each step were recorded.
Subsequently, energy simulations were carried out for both, conventional bus stop design as well as climate-based design and the results were compared to establish the design, which was better suited for the region, had a lower energy demand and provided a better user thermal comfort.

7.2.1 Common parameter settings in IDA ICE for both designs

Location, weather file and wind profile

The location was chosen from the IDA ICE (Equa, IDA ICE version 4.5) database and was set to *Ljubljana/Bezigrad_140150 (ASHRAE 2013)* and the climate file chosen was *SVN_GO_Ratece.140070_TMYx*. The wind profile was set to *open country (ASHRAE 1993)*.

HVAC systems

As the bus stop does not have any air handling unit, the air side effectiveness of the heating and cooling coil was set to *0* in the standard air handling unit and the standard plant was used for the simulations.

Site shading and orientation

The site orientation was set to *210°* and no shading was modelled as the site is located in an open area.

Thermal bridges

The thermal bridges were set to typical values provided in IDA ICE (Equa, IDA ICE version 4.5) and can be seen in Table 3 below.

Table 3 Thermal bridge input in IDA ICE

Thermal bridge type	Thermal bridge value
External wall / external wall	0.08 W/K/(m joint)
External door perimeter	0.1 W/K/(m perimeter)
Roof / external walls	0.1781 W/K/(m joint)
External walls, inner corner	-0.1 W/K/(m joint)
External slab / external walls, inner corner	-0.05 W/K/(m joint)
Roof / external walls, inner corner	-0.08 W/K/(m joint)

Infiltration and pressure coefficients

As the bus stop is considered to be a 'leaky building', the infiltration rate was set to *2 l/(s.m^2 ext. surf)* at *50 Pascal* and the pressure coefficient was set to *AIVC "sheltered"*.

Ground properties, extra energy and losses and system parameters

Ground properties, extra energy and losses and system parameters were set to default values.

Heating and cooling set points

As the bus stop did not have any additional heating and cooling in the initial stage, the heating and cooling set point values were kept at default values of *18° C* and *26° C* respectively. With an addition of an active heating measure in the later stages, the heating set point was lowered to *12° C* while the cooling set point remained the same.

Internal gains

Occupant's schedule

The occupant schedule was set according to the *occupants per m^2 per day*. To be able to do this, the number of occupants per m^2 of the total floor area was calculated by dividing the number of occupants with the total floor area. The working hours of the bus stop was from *5 AM* in the morning to *11 PM* at night which makes it *18 hours* per day. The working hours were then divided by *24 hours* in a day and finally this value was multiplied with the number of occupants per m^2 of the total floor area to be able to calculate *occupants per m^2 per day*. Table 4 shows occupant schedules for both conventional bus stop design and climate-based bus stop design.

Table 4 Occupant's schedule

	Conventional bus stop design	**Climate-based bus stop design**
Number of occupants	5	4
Floor area / m^2	13.5	10
Number of occupants per m^2	**0.37**	**0.4**
Occupant presence per day/ hours	18	
Evenly distribute hours over 24 hours	**0.75**	
Occupants per m^2 per day	**0.28**	**0.3**

Equipment schedule

The equipment schedule was set to always off since there was no equipment present inside the bus stop.

Lighting schedule

The bus stop was considered to be equipped with one *60 W* LED light bulb. The lighting schedule was divided in to three parts based on the seasons. From the *1st* of November to the *28th* of February, the light is on according to the winter schedule and it follows the summer schedule from the *1st* of May to the *31st* of August. The periods between the *1st* of March and the *30th* of April and between the *1st* of September and the *31st* of October, the lighting schedule is according to the equinox schedule. The winter, summer and equinox schedules can be seen in Table 5 below:

Table 5 Lighting schedule

Schedules	**Morning hours**	**Evening hours**
Winter (1st Nov- 28th Feb)	4:45 – 7:15	18:30 – 23:15
Summer (1st May- 31st Aug)	–	20:00 – 23:15
Equinox (1st Mar- 30th Apr and 1st Sep-31st Oct)	–	18:30 – 23:15

Door opening schedule

There are buses at an interval of one hour staring from *5:15 AM* in the morning until *11:15 PM* every day. It is assumed that the door is open for *5 %* of the time every hour during this period throughout the year.

7.2.2 Conventional bus stop design

Zone model

Figure 15 shows the 3D energy model modelled in IDA ICE. (Equa, IDA ICE version 4.5) The model has a floor area of *13.5* m^2 and a zone volume of *37.8* m^3. The model comprises of four external walls, a flat roof and an external floor. The north-eastern façade is a wooden wall while the other three sides are covered with glazing. The glazed walls were modelled in the software as detailed windows with a frame fraction of *0.1* for the whole window and a frame U-value of *2 W/ (m² °C)*.

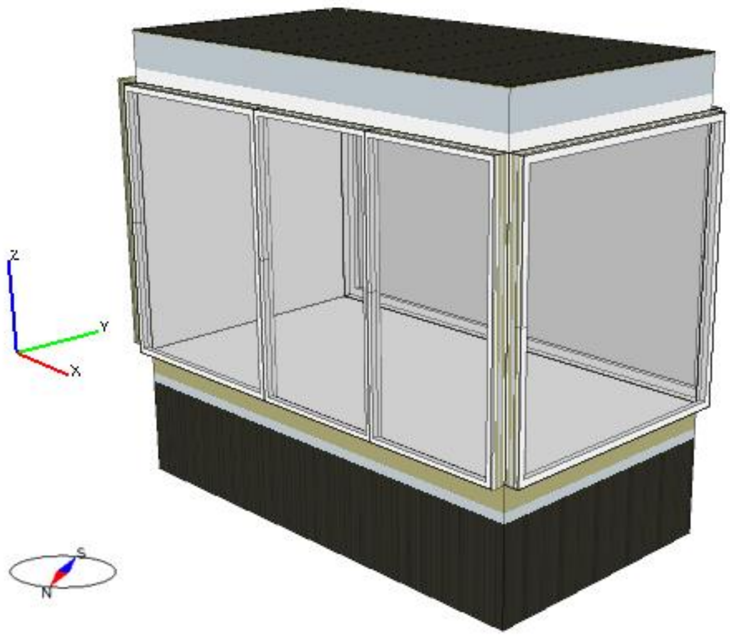


Figure 15 Zone model in IDA ICE for conventional bus stop design

Wall, roof and floor construction

The detail of each material used in the external wall, flat roof, flat green roof and external floor construction is described in Table 6, Table 7, Table 8 and Table 9 respectively. The total thickness and the corresponding U-values of the wall, roof and floor is displayed in Table 10.

Table 6 External wall construction in IDA ICE

Material	Thickness / mm	Thermal conductivity / (W/ m K)	Density / (kg/ m^3)	Specific heat capacity / (J / kg K)
Internal CLT panel	94	0.13	500	2100
Wood fibre insulation	150	0.04	170	2100
Impregnated wood fibre insulation	22	0.04	170	2100
Vertical air gap	300	0,17	1,2	1006
External timber cladding	20	0.14	500	2300

Table 7 Flat roof construction in IDA ICE

Material	**Thickness / mm**	**Thermal conductivity / (W/ m K)**	**Density / (kg/ m^3)**	**Specific heat capacity / (J / kg K)**
Internal CLT panel	145	0.13	500	2100
Wood fibre insulation	150	0.04	170	2100
Polymer bitumen layer	10	0.5	1700	1000
Roof/gravel slag	15	1.4	1674	881

Table 8 Flat green roof construction in IDA ICE

Material	**Thickness / mm**	**Thermal conductivity / (W/ m K)**	**Density / (kg/ m^3)**	**Specific heat capacity / (J / kg K)**
Precast concrete slab	75	1.7	2300	880
Sloping LW concrete	5	0.15	500	1050
Styrodur 3035 CS	160	0.041	20	1200
Polymer bitumen layer	10	0.5	1700	1000
Felt layer	10	0.19	960	837
Cultivated clay soil	40	1.6	2000	1550

Table 9 External floor construction in IDA ICE

Material	**Thickness / mm**	**Thermal conductivity / (W/ m K)**	**Density / (kg/ m^3)**	**Specific heat capacity / (J / kg K)**
Drainage layer	150	0.5	1700	1000
Concrete slab	250	1.7	2300	880
Floor coating	5	0.18	1100	920

Table 10 Total thickness and U-value of components

Component	**Total thickness / mm**	**U-Value / (W/ m^2 K)**
External wall	320	0.18
Flat roof	300	0.19
Flat green roof	300	0.24
External floor	255	2.9[1]

[1] This is not the true U-value of the external floor. Soil resistance is added later.

7.2.3 Climate-based bus stop design

Zone model

Figure 16 shows the 3D energy model modelled in IDA ICE. (Equa, IDA ICE version 4.5) The model has a floor area of *10* m^2 and a zone volume of *28* m^3. In order to simplify the geometry of the building, the sloped roof was modelled as a flat roof in the simulation software keeping the same area and volume as the original design. The model comprises of four external walls, a flat roof and an external floor. The north-eastern façade is a wooden wall while the other three sides are covered with glazing. The glazed walls were created in the software with the same area as in the original design and the glazing was modelled as detailed windows with a frame fraction of *0.1* for the whole window and a frame U-value of *2 W/ (*m^2 *°C)*.

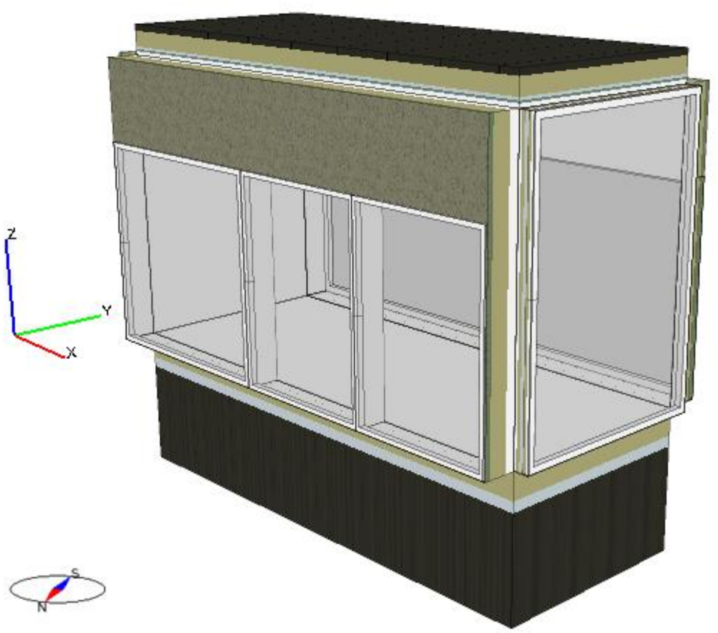


Figure 16 Zone model in IDA ICE for climate-based bus stop design

Wall, roof and floor construction

The external wall and external floor construction used in this design is the same as the previous design. (Table 6, Table 9). The detail of each material used in the sloping roof and the sloping green roof construction is described in Table 11 and Table 12 respectively. The total thickness and the corresponding U-values of the roofs are displayed in Table 13.

Table 11 Sloping roof construction in IDA ICE

Material	Thickness / mm	Thermal conductivity / (W/ m K)	Density / (kg/ m^3)	Specific heat capacity / (J / kg K)
Internal CLT panel	100	0.13	500	2100
Wood fibre insulation	250	0.04	170	2100
Sarking grade wood fibre board	25	0.14	500	2300
Air gap	10	0.11	1.2	1006
Slat tiles	15	2.0	2700	753

Table 12 Sloping green roof construction in IDA ICE

Material	Thickness / mm	Thermal conductivity / (W/ m K)	Density / (kg/ m^3)	Specific heat capacity / (J / kg K)
Internal CLT panel	60	0.13	500	2100
Styrodur 3035 CS	150	0.041	20	1200
Impregnated wood fibre board	25	0.14	500	2300
Polymer bitumen layer	10	0.5	1700	1000
Felt layer	10	0.19	960	837
Cultivated clay soil	35	1.6	2000	1550

Table 13 Total thickness and U-value of components

Component	Total thickness / mm	U-Value / (W/ m^2 K)
External wall	320	0.18
Sloped roof	400	0.13
Sloped green roof	290	0.22
External floor	255	2.9[2]

7.2.4 Parametric framework of energy simulations

The step-by-step framework for the energy simulation analysis is shown in Figure 17.

[2] This is not the true U-value of the external floor. Soil resistance is added later.

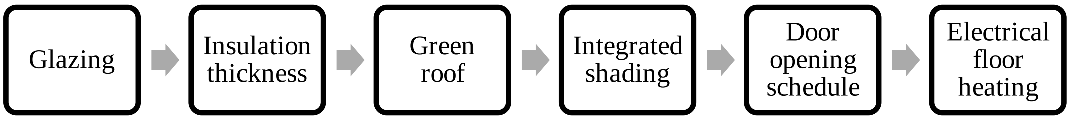


Figure 17 Step-by-step framework for energy simulations

Glazing

A clear air-filled glazing along with a medium and high solar heat gain coefficient (SGHC) were investigated. The three different types of glazing were as follows:

- Simple glazing with air filling in between panes.
- SunGuard 40/23 from Guardian glass. (Guardian glass, 2019a)
- SunGuard 70/37 from Guardian glass. (Guardian glass, 2019b)

Both double pane and triple glazing were tested for each of the glazing category. In case of the first type, the default IDA ICE double clear air and triple clear air window types were chosen while a window construction similar to Guardian glass windows was modelled in IDA ICE for the second and third cases. (Figure 18) Details of all the different types of windows can be found in Table 14.

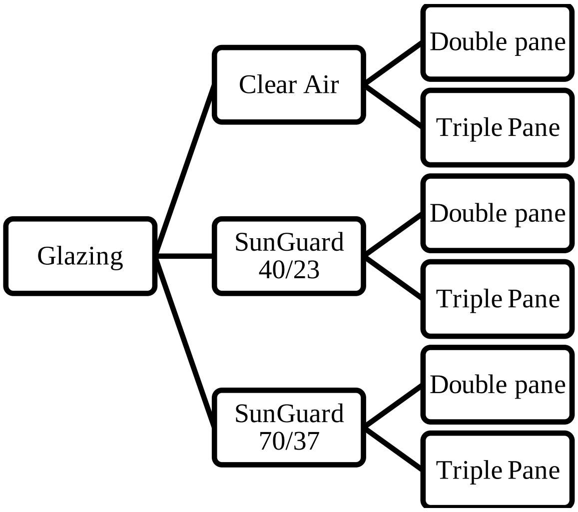


Figure 18 Figure showing glazing categories used in simulations

Table 14 Window specifications

Glazing Type	Solar heat gain coefficient (g-value)	Solar transmittance	Visible transmittance	U-Value / (W/ m^2 K)
Clear air windows				
Double Pane	0,71	0,60	0,79	2,86
Triple Pane	0,62	0,46	0,70	1,90
SunGuard 40/23				
Double Pane	0,23	0,19	0,43	1,18

Triple Pane	0,18	0,12	0,38	0,72
SunGuard 70/37				
Double Pane	0,38	0,33	0,69	1,18
Triple Pane	0,30	0,22	0,61	0,72

Insulation thickness

The wood fibre insulation thickness in the external wall was varied in order to find the most suitable thickness to be able to achieve the maximum number of comfortable hours inside the bus stop. The three different thicknesses tested were *100 mm*, *150 mm* and *200 mm* thick wood fibre insulation.

Green roof

The conventional roof construction was replaced with a green roof and the thermal comfort of the bus was analysed. The flat green roof construction (as mentioned in 6.1.3) was used for the conventional bus stop whereas the sloped green roof construction (as mentioned in 6.2.3) was used for the other bus stop. The moisture content of the green roof has not been taken into consideration for the design

Integrated shading

An integrated micro lamella shading (Microshade MS-A) was added on the south glazing as well as the west glazing to assess the impact on the uncomfortable hours during the summer and the winter. Simulations were carried out for shading only on the southern façade, shading only on the western façade and shading both on the southern and the western façade.

Door opening schedule

In the initial simulations, the door was considered to be open *5 %* of every hour during working hours of the bus stop. In order to combat overheating in the summer, an investigation was carried out with the door always open during work hours between May and August and *5 %* of every hour during work hours between September and April. Monthly hourly temperatures were analysed from the month of May to September as seen in *Appendix 1* and it was concluded that the ideal time for the door to always be open during working hours would be from the *28th* of May to the *15th* of September.

Electrical floor heating

Lastly, as an active heating measure, an electrical heating device was added in the floor to provide radiant floor heating. Simulations were run with the heating device covering *25 %*, *50 %*, *75 %* and *100 %* of the total floor area.

7.3 Thermal comfort and energy performance analysis

7.3.1 Outdoor UTCI thermal index

The 6205 working hours of the bus stop segregated from the annual hourly *8760* UTCI values and categorised according to the UTCI index, can be seen in Figure 19. It can be observed that there is no thermal stress for only *1023* hours from the *6205* working hours in a year which accounts for *19 %* of the time in a year. A slight cold stress is experienced most of the time, during a year, corresponding to *3476* hours and accounting for *56 %* of the working time. Moderate cold stress where the temperature ranges between *-13 °C* and *-27 °C* is also experienced for *1530* hours, accounting for *25 %* of the time in a year. A strong cold stress is experienced for *109* hours from the working hours followed by a very strong cold stress experienced for *3* hours from *6205* hours in a year. A slight heat stress can be experienced for *64* hours, comprising of *1 %* of the time in a year, when the temperature is between *26 °C* and *32 °C*.

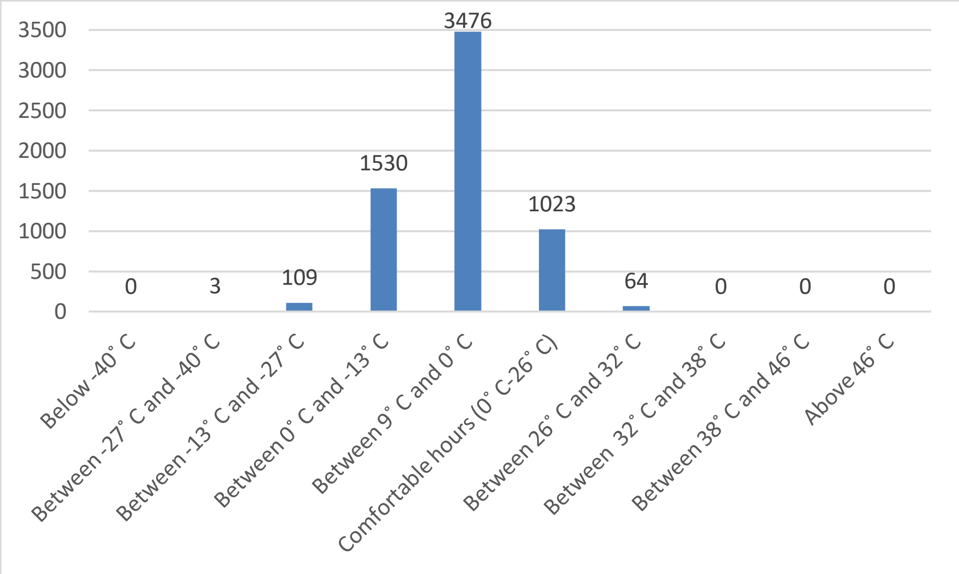


Figure 19 Outdoor UTCI index

7.3.2 Conventional bus stop design

7.3.2.1 Glazing

The results for the number of comfortable hours in a year by using different glazing types are shown in Figure 20. In nearly all cases except for the clear air-filled glazing, triple pane glass performs better than double pane glass. In case of the air-filled glazing, there are *12* hours per year and *34* hours per year when the operative temperature exceeds *38 °C* for double pane and triple pane glazing respectively. In all cases, triple pane glazing has about *1 %* increase in the total number of comfortable hours (*9 °C – 26 °C*) per year as compared to a double pane glass of the same type.

Although, by using *SunGuard 40/23* glass, the number of comfortable hours (*9 °C – 26 °C*) increases by *10 %* as compared to clear, air-filled glass, the percentage of hours below *0 °C* increases by *2 %* and *4 %* as compared to double paned clear air-filled and triple paned clear air-filled glass respectively. There are no hours above *32 °C* as there is no overheating. This is because of the low g-value of *SunGuard 40/23.*

The best performing glass is *SunGuard 70/37* triple paned glass which provides a maximum number of comfortable hours (*9 °C – 26 °C*) at *2349* hours accounting for *38 %* of the time in a year. The high g-value along with selective low e allows maximum heat gains in the winter (*675* hours below *0 °C* per year) and the selective *ClimaGuard* coating reduces overheating in the summer (*84* hours above *32 °C* per year).

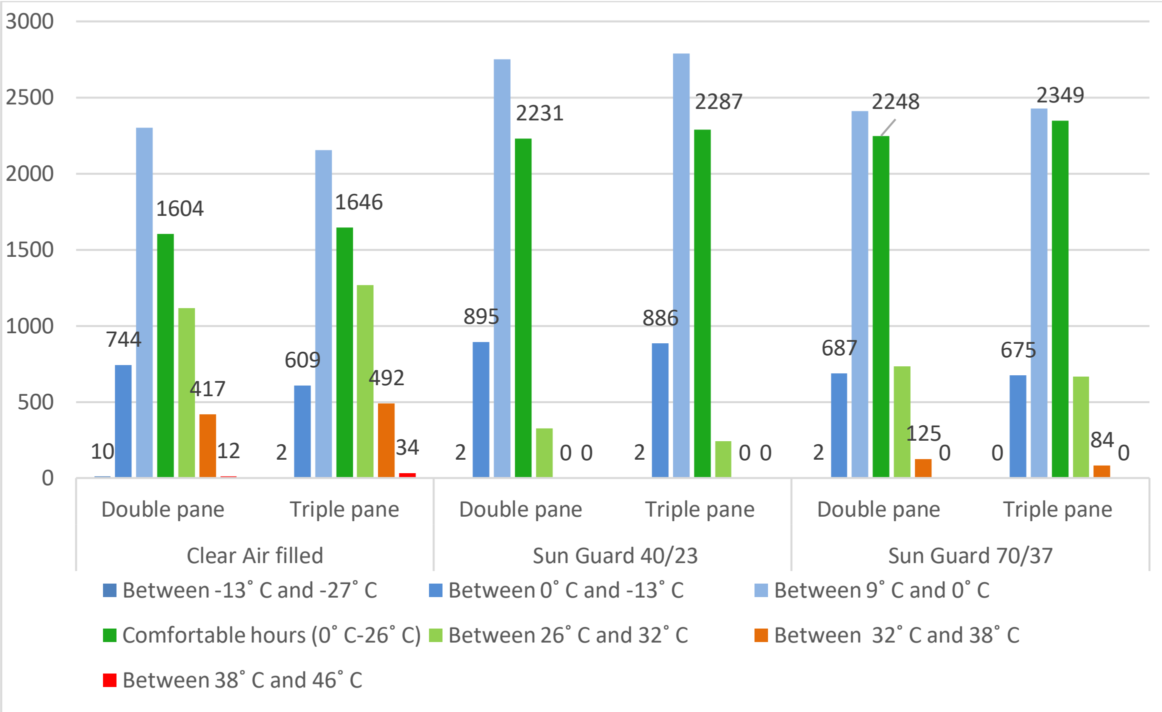


Figure 20 Comparison of UTCI index for different glazing types

7.3.2.2 Insulation thickness

Figure 21 provides results for wood fibre insulation thicknesses of *100 mm*, *150 mm* and *200 mm* with the eastern and rear facade of the bus stop considered as walls and the other two facades as glazing, and wood fibre insulation thicknesses of *100 mm*, *150 mm* and *200 mm* with only the eastern façade of the bus stop considered as a wall while the other three facades are covered by glazing.

It was found that thermal comfort inside the bus stop when only the eastern façade is a wall is higher as compared to when both the eastern and southern facades are walls. This is because the southern glazing allows heat gains during winters, lowering the percentage of hours when the temperature falls below *0 °C* from *15.7 %* of the time in a year in the first case to *10.8 %* of the time in a year for the second case and increasing the percentage of comfortable hours (*9 °C – 26 °C*) from *33.5 %* in the first case to *37.9 %* in the second case.

Among the three insulation thicknesses in the second case, it was observed that the percentage of comfortable hours remained the same at *37.9 %* for all thicknesses of the insulating material. The percentage of hours below *0 °C* was also equal in all three cases and accounted for *10.8 %* of the time in a year. An insulation thickness of *150 mm* was chosen since it balanced both, thermal comfort and the amount of material used.

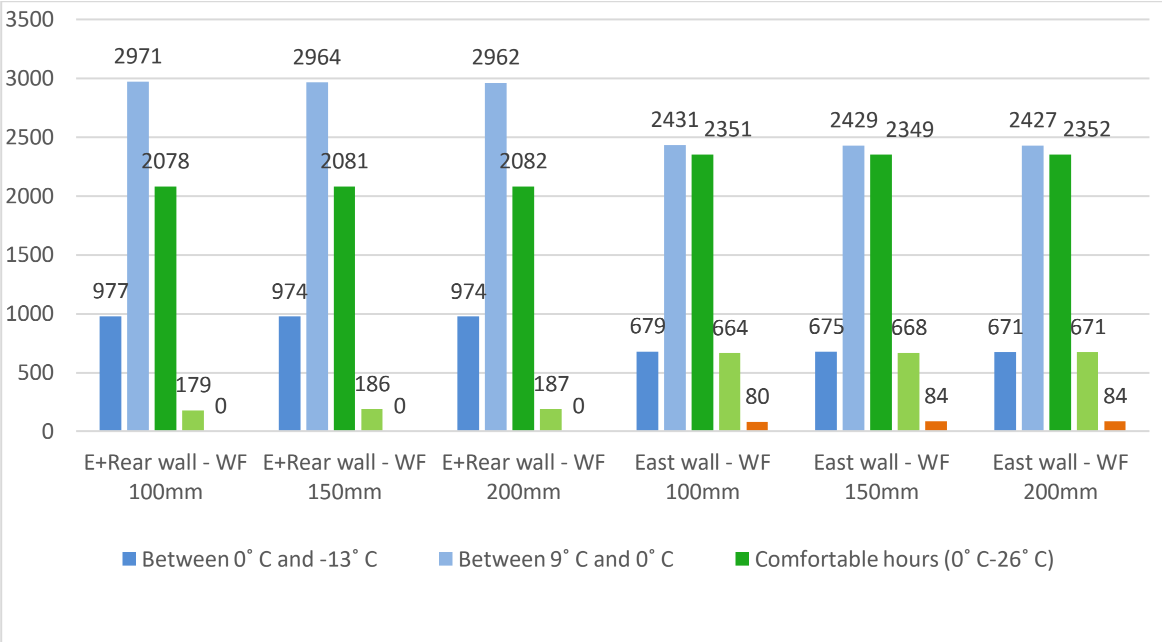


Figure 21 Comparison of UTCI index for walls with different insulation thicknesses

7.3.2.3 Green roof

As seen in Figure 22, with a replacement of the conventional flat roof with a green one, it was found that there was an increase in the number of comfortable hours per year from *2349* hours in the first case to *2535* hours in the second case. The green roof also reduced the number of hours below *0 °C* from *675* hours per year to *656* hours per year. Due to a slightly higher thermal mass of the green roof as compared to the conventional flat roof, the number of hours above *26 °C* decreased from *668* hours per year to *540* hours per year. The most significant change was in the reduction of the of the number of hours above *32 °C* from *84* hours per year accounting for *1.4 %* to *11* hours per year accounting to only *0.2 %* of the total time.

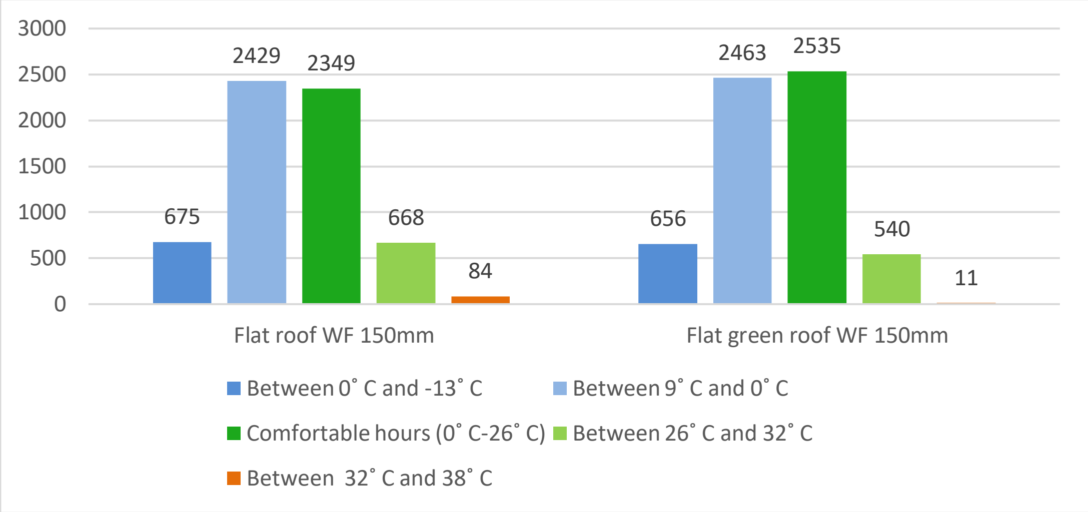


Figure 22 Comparison of UTCI index for flat roof and flat green roof

7.3.2.4 Integrated shading

The results for integrated microshading in the southern glazing, western glazing and both the southern glazing and western glazing is shown in Figure 23 below. The thermal comfort inside the bus stop was the worst when both the southern glazing and western glazing were shaded due to very low solar heat gains in the winter. The best performing result was provided when only the western glazing was shaded. The percentage of comfortable hours in a year was only *35.4 %* in the worst case as compared to *40 %* in the best case and the percentage of hours below *0 °C* was *15.6 %* in the worst case as compared to *11.9 %* in the best case. The microshading helped to reduce the number of hours above *32 °C* to *0* in all three cases.

When comparing the results of thermal comfort for the best performing (shaded western glazing) in Figure 21 with the results of thermal comfort with no shading in Figure 22, it was noticed that although the percentage of comfortable hours (*9 °C – 26 °C*) remained similar at *40.9 %* when there was no shading to *40.4 %* with shaded western glazing, the percentage of hours below *0 °C* varied considerably. There were *656* hours below *0 °C* accounting for *10.6 %* in the case of no shading whereas, there were *740* hours below *0 °C* accounting for *11.9 %* when the western glazing was shaded. Due to this, it was decided to omit shading in the further steps of the analysis.

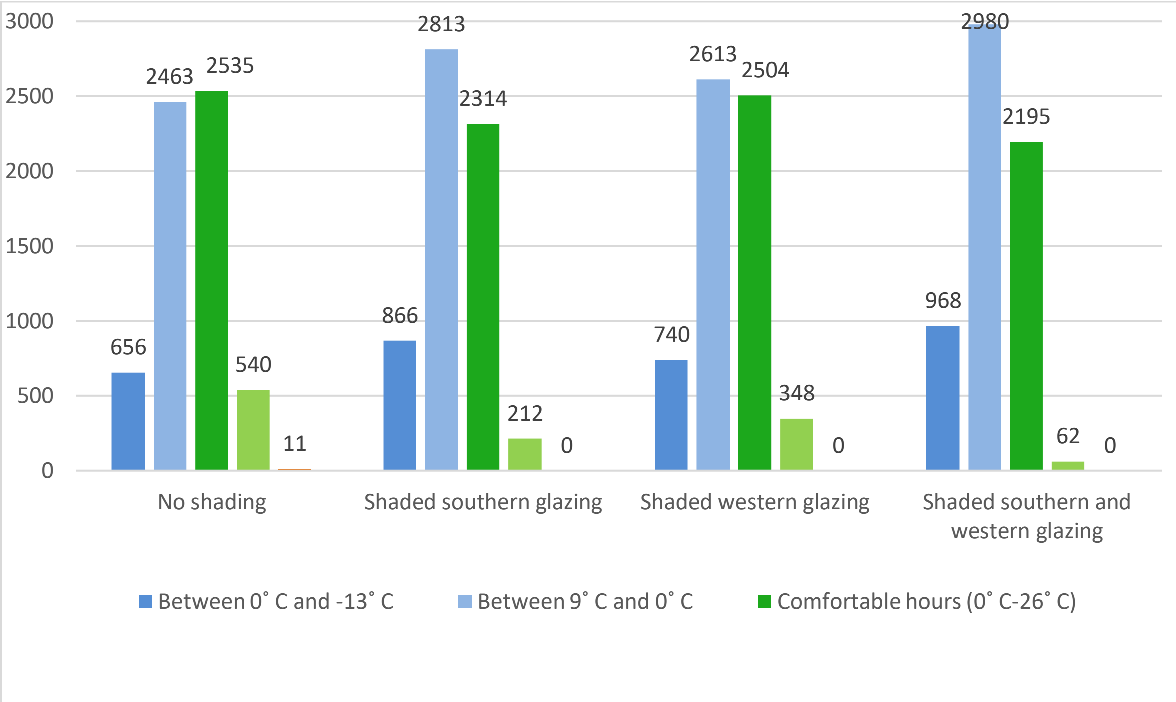


Figure 23 Comparison of UTCI index for integrated shading

7.3.2.5 Door opening schedule

Figure 24 below shows a comparison between the operative temperature inside the bus stop when the door is open only for *5 %* of every hour for working hours throughout the year and when the door is always open between the *28th* of May to the *13th* of September and *5 %* of every hour for working hours throughout the year. It can be seen that the operative temperature inside the bus stop is significantly lowered in the second case as compared to the first case.

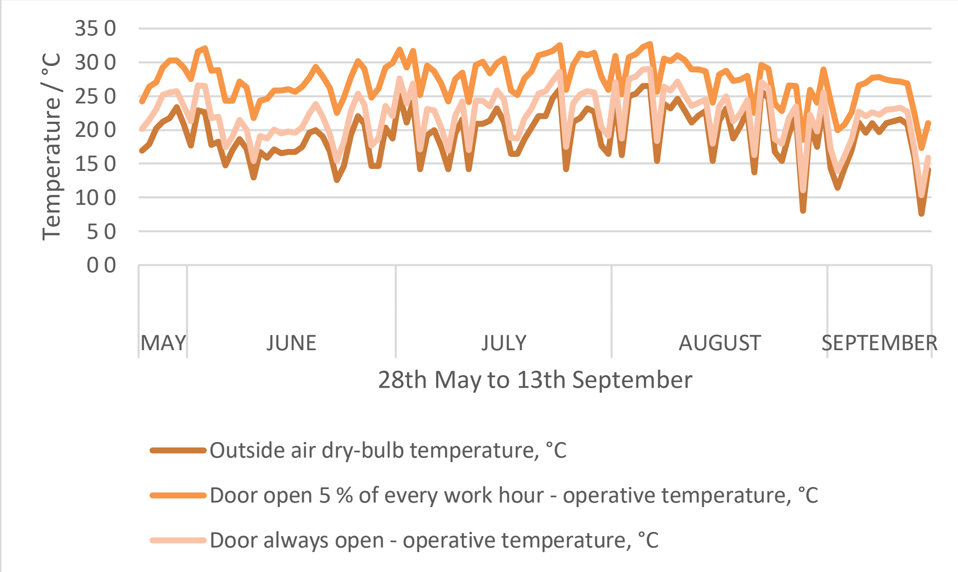


Figure 24 The effect of door opening on the operative temperature inside the conventional bus stop

From Figure 25, it can be observed that the number of comfortable hours (*9 °C – 26 °C*) increased from *2535* hours per year corresponding to *40.9 %* of the time in a year to *2913* hours per year corresponding to *46.9 %* of the time in a year in the first and second case respectively. There was a significant *7 %* reduction in the number of hours above *26 °C* from *540* hours in the first case to only *97* hours in the second case and the number of hours above *32 °C* was reduced to from *11* hours per year to *0* hours per year from the first to the second case respectively.

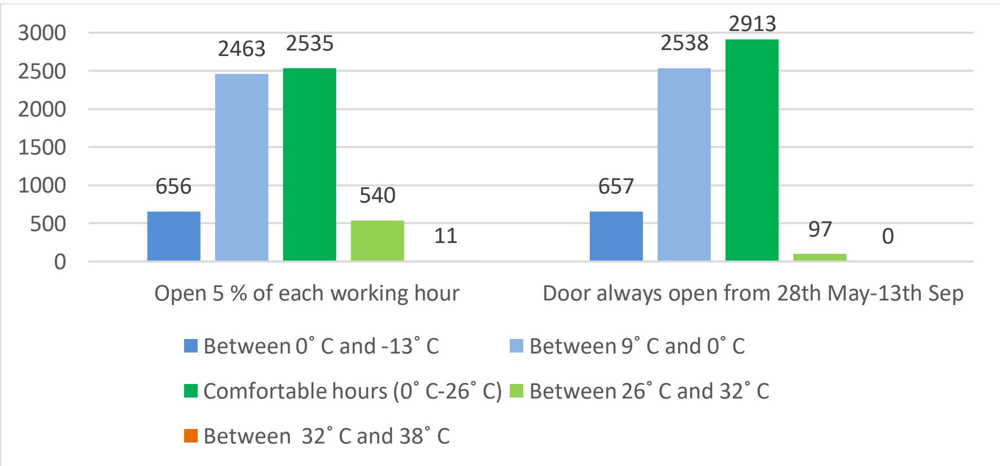


Figure 25 Comparison of UTCI index for door opening schedule

7.3.2.6 Electrical floor heating

Figure 26 exhibits a comparison of thermal comfort inside the bus stop when the floor area is heated to *25 %*, *50 %*, *75 %* and *100 %* respectively. In all four cases, the percentage of comfortable hours in a year is above *50 %* with the addition of an electrical floor heating ranging from *52.8 %* when *25 %* of the floor area is heated to *67.5 %* when *100 %* of the floor area is heated. The percentage of hours below *0 °C* is under *10 %* in all cases and reduces by almost *2 %* with every *25 %* increase in the heated floor area and the percentage of hours above *26 °C* remains constant at *1.6 %* for all cases.

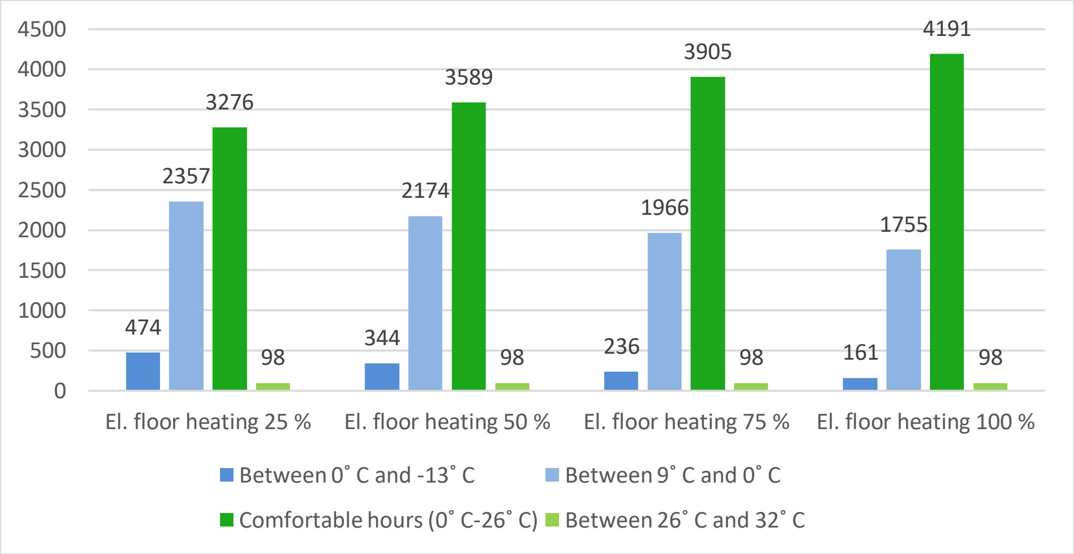


Figure 26 Comparison UTCI index for electrical heated floor area

Table 15 shows the annual energy demand for the bus stop with electrical floor heating for the working hours (*6205* hours per year). All the months of the year require some heating due to cold temperatures in the region. The months of January and December required maximum heating while the least amount of heating was required in the month of July. It was interesting to note that a larger heated floor area required less energy as compared to a smaller heated floor area. When the floor area was heated to *100 %*, the energy demand was only *1726.9 kWh* as compared to *472.4 kWh* when *25 %* of the floor area was heated. This suggested that covering *100 %* of the floor area with electrical heating would prove to be the most cost-effective measure amongst all the four cases.

Table 15 Monthly zone heating for conventional design

Month	**Zone heating / kWh**			
	25 % heating	**50 % heating**	**75 % heating**	**100 % heating**
January	70.3	139.9	208.3	275.2
February	61.4	121.3	179.8	236.7
March	60.6	116.8	169.1	217.6
April	38.6	72.7	102.1	125.2
May	11.6	20.3	27.4	33.7
June	11.7	22.8	32.9	42.7
July	7.2	13.8	20.0	26.2
August	15.7	30.3	44.3	57.9
September	23.4	44.1	62.0	76.9
October	38.2	70.4	99.6	125.5
November	63.8	123.3	178.8	230.6
December	70.2	140.1	209.7	278.7
Yearly	**472.4**	**915.6**	**1334.0**	**1726.9**

7.3.3 Climate-based bus stop design

7.3.3.1 Glazing

The results for the number of comfortable hours in a year by using different glazing types are exhibited in Figure 27 and follow a similar pattern to the previous design. *SunGuard 70/37* triple pane glazing performs the best and provides the maximum number of comfortable hours (*9 °C – 26 °C*) at *2461 hours* in a year accounting to *40 %* of the time. This means that the number of comfortable hours (*9 °C – 26 °C*) for the second design exceeds the first design by *112 hours* per year and corresponds to a *2 %* increase.

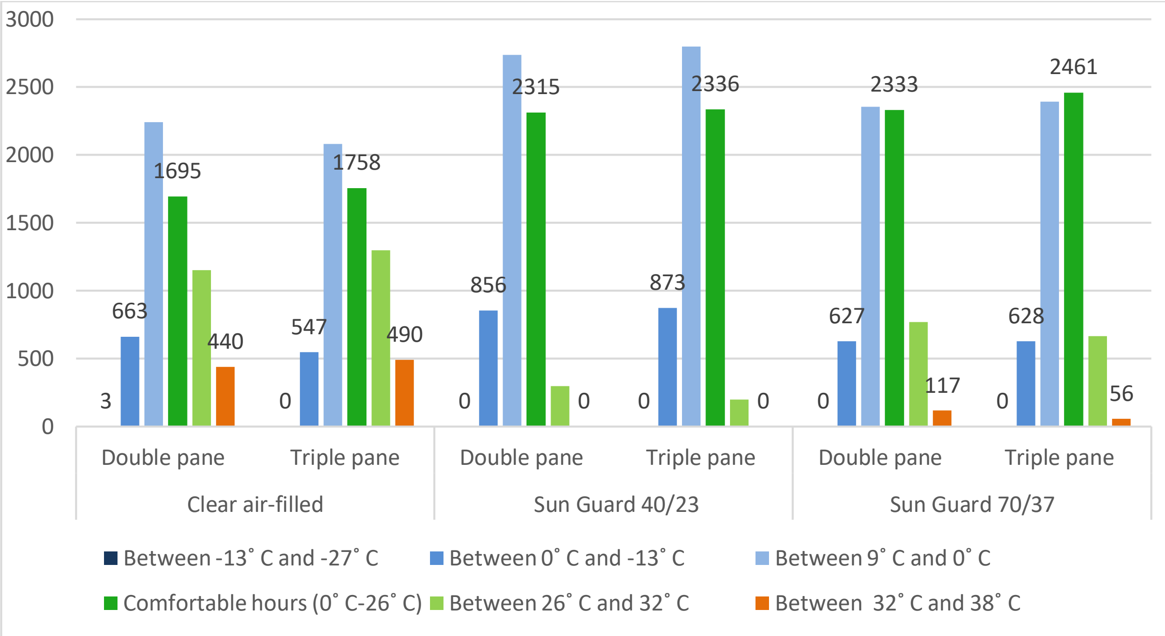


Figure 27 Comparison of UTCI index for different types of glazing

7.3.3.2 Insulation thickness

As seen in the previous case, the thermal comfort inside the bus stop when only the eastern façade was a wall appeared to be better than when both the eastern and southern facades are walls (Figure 28). An insulation thickness of *150 mm* and an eastern wall façade accounts for 39*.7 %* of the comfortable hours in a year, which is the same as the previous design. Although, there was only a slight difference between the operating temperature below *0 °C* for an insulation thickness of *150 mm* and *200 mm*, there was a difference of *10 hours* for operating temperature below *0 °C*, between *100 mm* and *150 mm* of insulation thickness. There was also a reduction of *47 hours* for operating temperature below *0 °C* and a reduction of *28 hours* for operating temperature exceeding *32 °C* in this design as compared to the previous one.

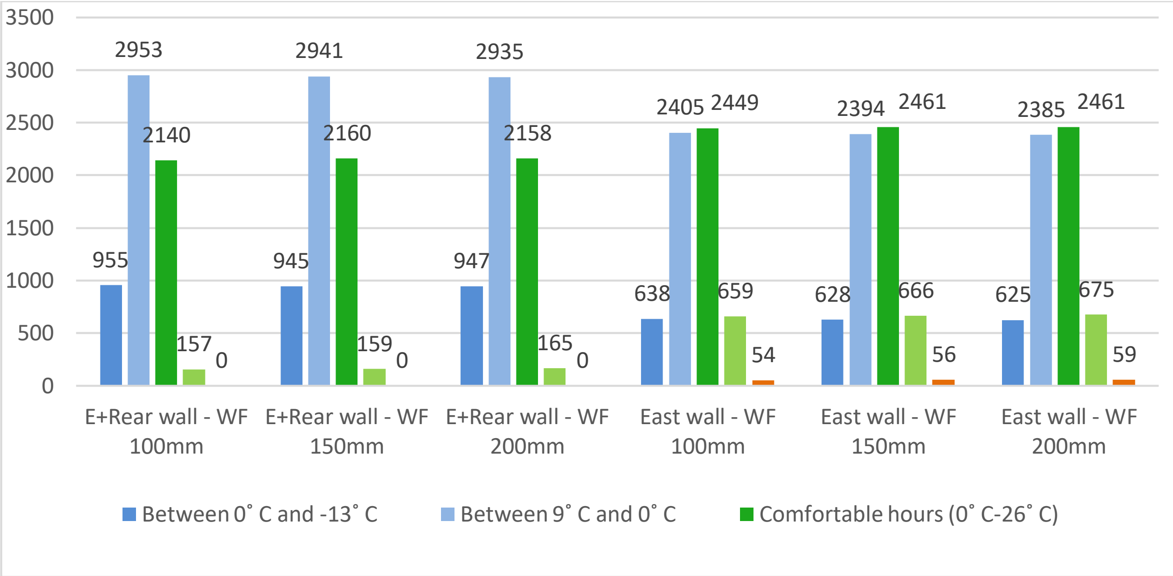


Figure 28 Comparison of UTCI index for walls with different insulation thicknesses

7.3.3.3 Green roof

As seen in Figure 29, the replacement of the sloped roof with a green sloped roof resulted similar to the first design with an increase in the number of comfortable hours per year from *2461 hours* in the sloped roof to *2600 hours* in the sloped green roof. The most significant reduction was a reduction from *56 hours* in the first case to *5 hours* in the second case for the number of hours when the operating temperature exceeds *32 °C*. There was a total reduction of *6 hours* when the operating temperature exceeds *32 °C* between the first and second design.

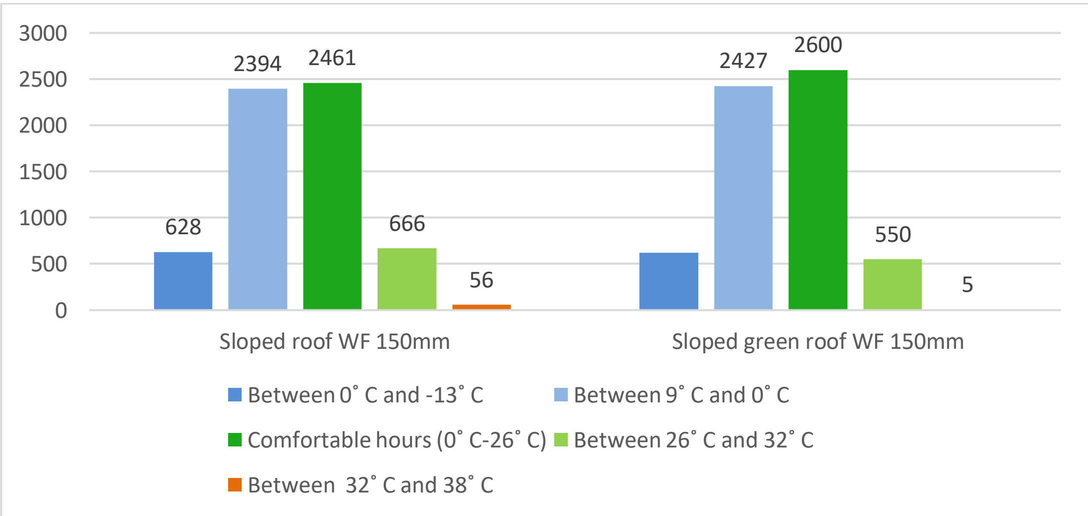


Figure 29 Comparison of UTCI index between sloped roof and sloped green roof

7.3.3.4 Integrated shading

The results from the integrated shading as shown in Figure 30, follow the same pattern as the previous design. The highest thermal discomfort is felt when both the southern glazing and western glazing are shaded, making the users feel moderate cold stress for *942 hours* in a year. With an integrated shading only in the western glazing, users feel a moderate cold stress for *721 hours* in a year which is *1.6 %* higher than without any integrated shading. Hence, it was decided to omit integrated shading for this design as well.

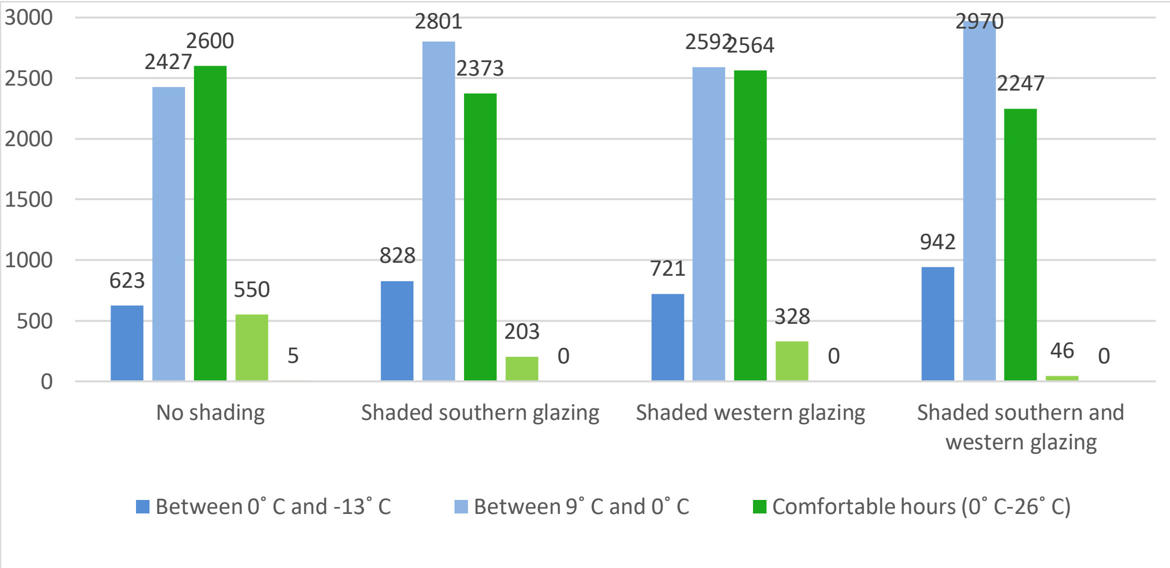


Figure 30 Comparison of UTCI index for integrated shading

7.3.3.5 Door opening schedule

Identical to the previous design, as seen in Figure 31, opening the door from the *28th* of May to the *13th* of September during working hours reduced the operating temperature inside the bus stop resulting in a decrease in overheating.

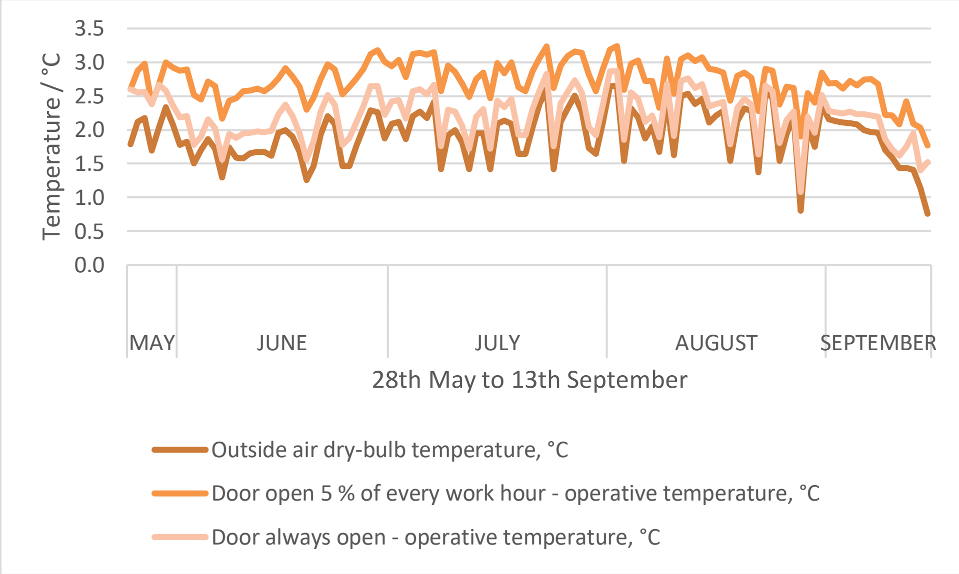


Figure 31 The effect of door opening on the operative temperature inside the conventional bus stop

When the door was kept open during working hours between the *28th* of May and the *13th* of September, it was found that there was no strong heat stress felt by users as compared to *5 hours* of strong heat stress felt by users each year, when the door was kept open for only *5 %* of the each working hour throughout the year. The door opening schedule also resulted in an increase in the number of comfortable hours by *420 hours*. There was also an increase in the number of comfortable hours by *687 hours* between this design and the conventional bus stop design. (Figure 32)

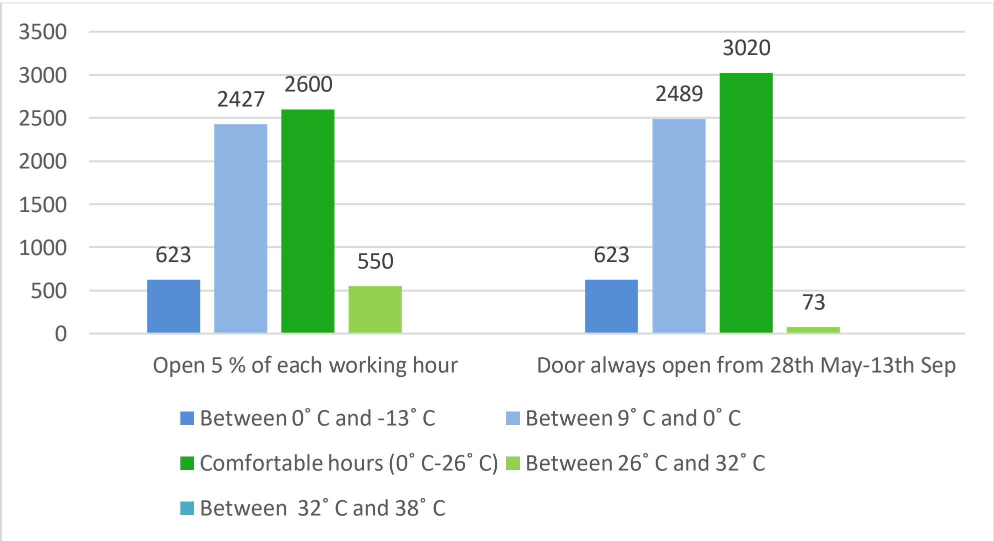


Figure 32 Comparison of UTCI index for door opening schedule

7.3.3.6 Electrical floor heating

A comparison of thermal comfort inside the bus stop when the floor area is heated to *25 %, 50 %, 75 %* and *100 %* is displayed in Figure 33. With a *25 %* increase in the floor area, there is almost an average increase of *315 hours* in the number of comfortable hours experienced by users during a year. A moderate heat stress is experienced by users for about for *1.25 %* in a year, at *75 hours* in all four cases.

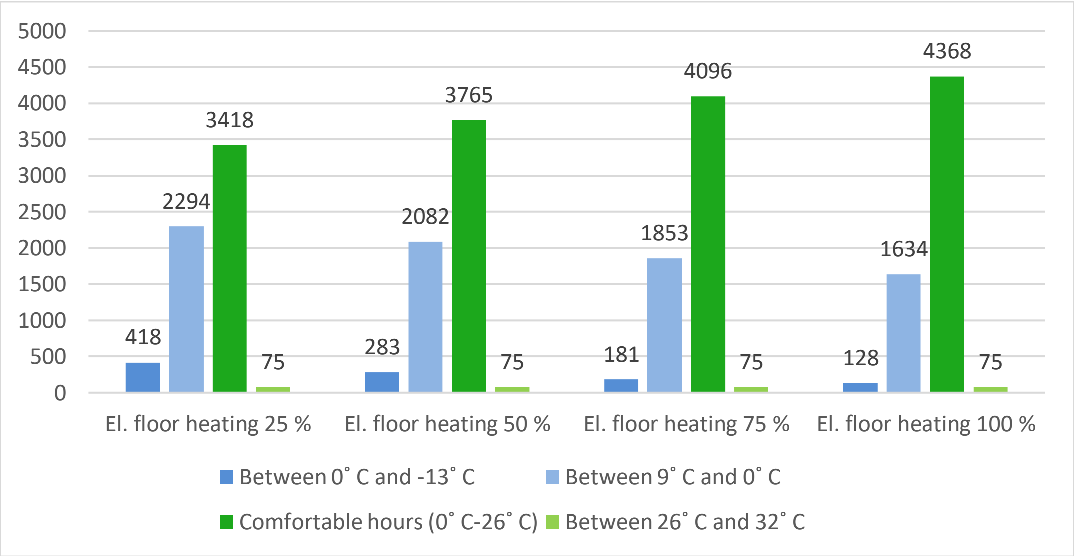


Figure 33 Comparison of UTCI index for electrical heated floor area

Table 16 shows the annual energy demand for the bus stop with electrical floor heating for the working hours (*6205 hours* per year). The climate- based bus stop design requires only *338.9 kWh* of energy when *25 %* of the floor area is heated as compared to the conventional bus stop which required *472.4 kWh* of energy when *25 %* of the floor area was heated. In case of 100 % heated floor area, the climate-based design required *1229.5 kW*h of energy as compared to *1726.9 kWh* in the previous design.

Table 16 Monthly zone heating for climate-based design

Month	**Zone heating / kWh**			
	25 % heating	**50 % heating**	**75 % heating**	**100 % heating**
January	52.1	103.7	154.6	203.7
February	45.6	90.0	133.3	175.0
March	44.7	85.7	122.9	156.8
April	27.2	50.4	69.0	83.3
May	6.2	11.1	15.2	18.7
June	7.1	13.9	20.3	26.5
July	4.1	8.1	11.8	15.5
August	10.4	20.2	29.7	38.6
September	15.3	28.7	39.8	49.1
October	26.7	49.9	69.6	85.8
November	47.5	91.6	132.3	169.9
December	52.1	103.8	155.4	206.5
Yearly	**338.9**	**657.0**	**953.8**	**1229.5**

8 Solar energy integration

8.1 Solar energy calculations

Although covering *100 %* of the floor area would provide maximum thermal comfort, it was necessary to assess the energy that could be generated by solar panels installed on the roof of the bus stops in order to make it self-sufficient. The solar calculation analysis was conducted on the website of photovoltaic geographical information system by the European Commission. (JRC European Commission, 2019)
The solar energy output was calculated to provide electrical floor heating, to light up one *60 W* LED bulb during working hours and to provide energy to run the *32"* display screen inside the bus stop. (Papercast, 2019) The lighting schedules for the year is shown in Table 17. There is a small difference between the maximum lighting load in January and the lighting load in May due to the fact that buses run from *5 AM* to *11 PM* every day. The *32"* display screen load is shown in Table 18.

Table 17 Lighting load

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of hours per day	7.5	7.5	5.5	5.5	3.5	3.5	3.5	3.5	5.5	5.5	7.5	7.5
Energy load per day / kWh	0.45	0.45	0.33	0.33	0.21	0.21	0.21	0.21	0.33	0.33	0.45	0.45
Energy load per month / kWh	**14.0**	**14.0**	**10.2**	**10.2**	**6.5**	**6.5**	**6.5**	**6.5**	**10.2**	**10.2**	**14.0**	**14.0**

Table 18 Display load

Power consumption (1 min data update)/ Amp	0.1
Power consumption (text-to-speech)/ Amp	0.14
Power consumption (user interface) / Amp	0.15
Total power consumption / Amp	0.39
Required voltage / Volts	12
Number of hours per day	18
Energy load per day / kWh	0.1
Energy load per month / kWh	**2.6**

The daily solar energy output per month was obtained for all cases and the average Photovoltaic (*PV)* panel output per month was calculated. Since the month of December received the least amount of solar radiation, the lighting and display loads were deducted from the *PV* output obtained during this month. The remaining *PV* output was then used to calculate the energy demand for a corresponding percentage of heated floor area. To utilise the surplus energy from the *PV*, a *120 V, 5 amp* charging socket was added and the number of functioning hours per month for the socket was calculated.

8.1.1 Conventional bus stop design

As shown in Figure 34 solar energy output was calculated for *3*, *5*, *6* and *9* panels on the roof respectively. Each panel was considered to have an installed peak *PV* power of *300* W_p[3]. A *48 V* battery with a battery capacity of *260 Ah* provides storage for the system and has a discharge cut off limit at *40 %*. The module inclination was set to *0°* and the azimuth angle was set at *+30°* as the panels face the south west direction.

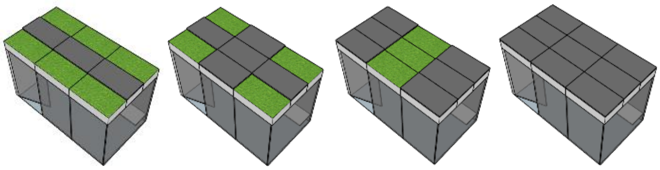


Figure 34 showing 3,5,6 and 9 solar panels on the flat roof

8.1.2 Climate-based bus stop design

In case of the climate-based design, the effect of module inclination for *PV* output was investigated. Module inclination at an angle from *40°* up to *75°* was investigated with increments of *5°*. (Figure 35) The *PV* peak power, the battery voltage, battery capacity and azimuth angle were kept the same as in the previous design.

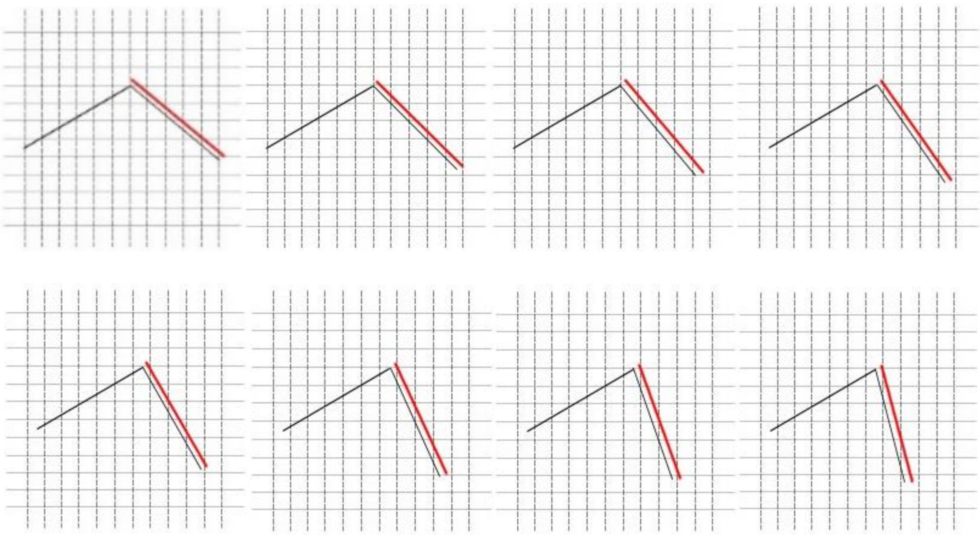


Figure 35 showing module inclination angles of 40°,45°,50°,55°,75°,70°,65°,60° (clockwise from top left)

[3] With inputs provided by Julian Ascencio-Vasquez, currently pursuing his PhD on Modelling and worldwide assessment of performance and aging of photovoltaic modules and systems from the University of Ljubljana, on the 19th of April 2019.

8.2 Solar energy calculations

8.2.1 Conventional bus stop design

The daily solar energy output per month for *3*, *5*, *6* and *9* panels are shown in Table 19. As the panels are laid horizontally on the roof, the *PV* output is significantly low. Due to this, further calculations are done considering that the entire roof is covered with solar panels (*9* panels in total).

Table 19 Monthly average electricity output per day for different number of panels

Month	**3 panels / (average kWh/ day)**	**5 panels / (average kWh/ day)**	**6 panels / (average kWh/ day)**	**9 panels / (average kWh/ day)**
January	0.65	1.08	1.29	1.94
February	1.18	1.97	2.33	2.87
March	1.78	2.71	2.89	2.97
April	2.29	2.90	2.98	3.03
May	2.87	3.00	3.02	3.01
June	2.79	3.01	3.01	3.00
July	2.94	2.99	2.99	3.00
August	2.94	3.00	2.99	2.99
September	2.16	2.89	2.94	3.00
October	1.49	2.39	2.64	2.88
November	0.78	1.30	1.56	2.21
December	0.49	0.81	0.97	1.45
Year	**22.35**	**28.04**	**29.62**	**32.34**

It was found that even when the entire roof was covered with solar panels, the *PV* output per month could cover only *10 %* of the heated floor area along with the lighting and display load in the month of December. (Table 20)

Table 20 PV output per month and surplus energy for conventional bus stop design

Month	Heating 10% / kWh	Lighting per month/ kWh	Display per month/ kWh	*PV* output per month/ kWh	Surplus energy per month/ kWh
January	28.1	14.0	2.6	60.0	15.3
February	25.4	14.0	2.6	80.4	38.4
March	27.0	10.2	2.6	92.0	52.2
April	23.5	10.2	2.6	90.8	54.5
May	17.6	6.5	2.6	93.2	66.5
June	7.5	6.5	2.6	90.1	73.5
July	3.4	6.5	2.6	92.9	80.4
August	8.4	6.5	2.6	92.7	75.2
September	17.3	10.2	2.6	90.0	59.9
October	23.9	10.2	2.6	89.2	52.4
November	27.2	14.0	2.6	66.3	22.5
December	28.1	14.0	2.6	45.0	0.3
Yearly	**237.4**	**122.8**	**31.3**	**982.7**	**591.2**

As seen in Table 21, the charging socket did not function throughout all the working hours in a year. The remaining energy is able to supply power to the charging socket for at most *20 %* of the operating hours in a month, and far less than that in most months.

Table 21 Functional hours of a charging point for the conventional design

Month	1 Charging socket - 120V, 5 Amp	
	Power of 1 socket / kW	Functional hours/ h
January	0.6	26
February	0.6	64
March	0.6	87
April	0.6	91
May	0.6	111
June	0.6	122
July	0.6	134
August	0.6	125
September	0.6	100
October	0.6	87
November	0.6	37
December	0.6	1

8.2.2 Climate-based bus stop design

To evaluate the optimal angle for *PV* output, module inclination angles from *40°* up to *75°* in increments of *5°* was calculated as shown in Table 22. It was found that the yearly *PV* output increases by approximately *0.4 kWh* per year with an increase of *5°* in module inclination. The yearly *PV* output is the maximum at a module inclination of *55°*, above which the total yearly output begins to decline, although the average daily *PV* output in the month of December remains the same from *55°* to *75°*. It was found that *55°* was the optimal *PV* module inclination angle for maximum *PV* output.

Table 22 Monthly average PV output per day for different module inclination angles

Month	**Monthly average *PV* output per day/ kWh**							
	75°	**70°**	**65°**	**60°**	**55°**	**50°**	**45°**	**40°**
January	2.4	2.4	2.4	2.4	2.4	2.4	2.3	2.3
February	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
March	2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.9
April	2.6	2.7	2.7	2.8	2.8	2.9	2.9	2.9
May	2.7	2.9	2.9	2.9	2.9	2.9	3.0	3.0
June	2.5	2.7	2.7	2.8	2.9	2.9	3.0	3.0
July	2.8	2.9	3.0	3.0	3.0	3.0	3.0	3.0
August	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
September	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
October	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9
November	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.4
December	2.1	2.2	2.1	2.1	2.1	2.0	2.0	1.9
Year	**32.0**	**32.5**	**32.8**	**33.0**	**33.1**	**33.1**	**32.6**	**32.2**

With the module inclination angle set at *55*, it was calculated that the *PV* production per month could suffice for *23 %* electrical heating of the floor area, along with lighting and display loads. The surplus energy could be used for a single charging point as shown in Table 23. Similar to the previous case, the surplus energy could provide energy for the charging socket to function for less than *20 %* working hours in June and far less in the other months. (Table 24)

Table 23 PV output and surplus energy for climate-based bus stop design

Month	**Heating 23% / kWh**	**Lighting per month/kWh**	**Display per month /kWh**	***PV* production per month /kWh**	**Surplus energy per month /kWh**
January	45.9	14.0	2.6	74.9	12.5
February	40.3	14.0	2.6	79.5	22.6
March	39.5	10.2	2.6	87.6	35.3
April	24.2	10.2	2.6	84.7	47.7
May	5.5	6.5	2.6	91.0	76.3
June	6.3	6.5	2.6	86.3	70.9
July	3.6	6.5	2.6	93.4	80.6
August	9.1	6.5	2.6	92.9	74.7
September	13.6	10.2	2.6	88.4	62.0
October	23.8	10.2	2.6	89.1	52.5
November	41.9	14.0	2.6	74.5	16.0
December	45.9	14.0	2.6	64.9	2.4
Yearly	**299.5**	**122.8**	**31.3**	**1007.1**	**553.5**

Table 24 Functional hours of a charging point for climate-based design

Month	**1 Charging socket - 120V**	
	Power of 1 socket / W	Functional hours / h
January	0.6	22
February	0.6	38
March	0.6	58
April	0.6	77
May	0.6	127
June	0.6	114
July	0.6	134
August	0.6	125
September	0.6	103
October	0.6	87
November	0.6	27
December	0.6	6

9 Final proposal

9.1 Comparison between conventional and climate-based design

As seen in Figure 36, after the integration of solar energy, a design with *10 %* and a design with *23 %* of heated floor area was chosen for the conventional and the climate-based bus stop respectively. Figure 21 shows a comparison between the conventional design and the climate-based design for all stages of the parametric study performed. Design 1 and design 2 correspond to the conventional bus stop design and climate-based bus stop design respectively. It can be observed that design 2 performs better at every stage of the parametric study.

At the glazing and insulation thickness stage, the design 2 had *112* comfortable hours (no thermal stress) as compared to design 1. There was only a difference of *47* hours in the moderate cold stress and a difference of *2* hours in the moderate heat stress felt by users during the first two stages in both designs. An addition of green roof to the designs, led to an increase in the moderate heat stress felt inside the climate-based bus stop by *10* hours as compared to the other design. However, the climate-based design had *65* more comfortable hours and *33* hours less of moderate cold stress felt by users inside the bus stop as compared to the conventional design.

The door opening schedule from the *28th* of May to the *13th* of September facilitated to increase the number of comfortable hours by about *400* hours from the previous stage. The second design preceded the first design by *107* hours in the number of comfortable hours experienced in the bus stops. While the difference in the number of hours felt for moderate cold stress remained the same in both designs as from the previous stage, the number of hours in which a moderate heat stress was felt by users, was lowered significantly. Design *1* experienced *97* hours of moderate heat stress while design *2* experienced only *73* hours of moderate heat stress felt by users.

The most significant difference in the number of comfortable hours was observed in the last stage, when electrical heating was applied to the floor. With only *10 %* of the floor area heated in design *1* as compared to *23 %* of heated floor area in design *2*, the number of hours with no thermal stress felt by users was *487* hours lesser in design *1* than from design *2*. Consequently, the moderate cold stress experienced by users was reduced by *204* hours in design *2* than in design *1*. The moderate heat stress experienced by users was also reduced by *29* hours in the second design as compared to the first design.

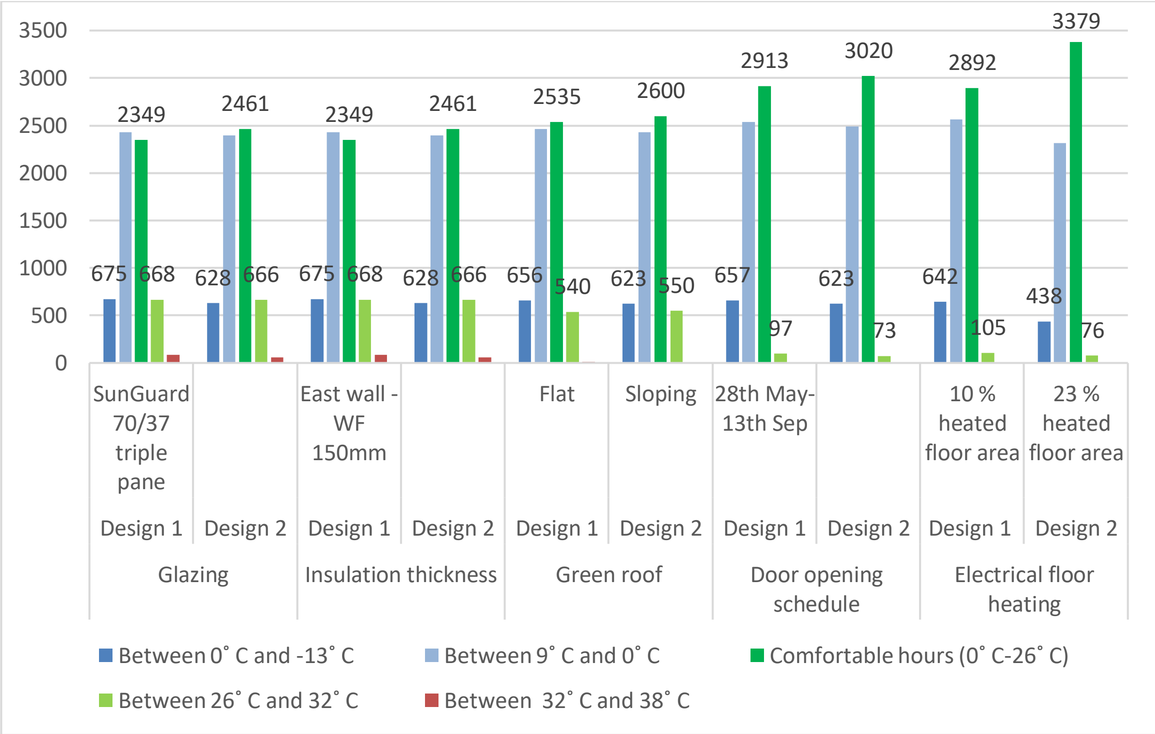


Figure 36 Comparison between conventional bus stop design and climate-based bus stop design

9.2 Final design

From the results of Figure 36, it was found that the climate-based design performed better in terms of thermal comfort of users than the conventional bus stop design. Therefore, the second design was selected as the final design proposal. Figure 37, Figure 38 and Figure 39 show a view of the final bus stop design on the site.

Figure 37 Front view of the climate-based bus stop design

Figure 38 View of the climate-based bus stop design

Figure 39 Side view of the climate-based bus stop design

9.3 Comparison of thermal comfort with outdoor temperature

Figure 40 shows a comparison between the outdoor thermal comfort with the thermal comfort inside the bus stop with and without electrical floor heating. In the outdoor condition, a very strong cold stress is felt for *3* hours, which is completely removed in the final proposal with and without electrical floor heating. In contrary, there is an increase of *9* hours in moderate heat stress experienced by users as compared to the outdoor condition.

In case of the final proposal with no heating, the strong cold stress experienced inside the bus stop decreases by *907* hours accounting for a *14 %* reduction. Similarly, there is also a decrease of *987* hours corresponding to *16 %* reduction, for the number of hours when moderate cold stress is experienced by users. There is an increase in the number of comfortable hours by *1,997* hours accounting for a *33 %* increase from the number of comfortable hours for the outdoor UTCI temperature per year.

With the addition of floor heating inside the bus stop, the number of hours with strong cold stress is reduced by *1,092* hours from the outdoor condition, corresponding to an *18 %* reduction while the number of hours with moderate cold stress is reduced by *1,164* hours accounting for a *19 %* reduction from the outside UTCI temperature. The most significant change was an increase in the number of comfortable hours by *2,359* hours, leading to a *39 %* increase from the outdoor condition.

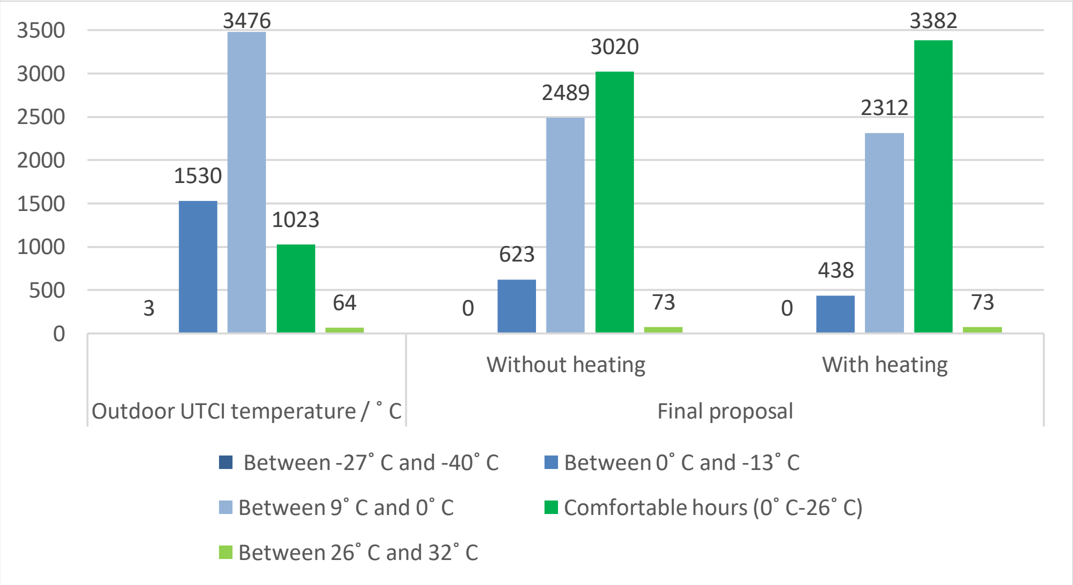


Figure 40 Comparison of thermal comfort of the final proposal with outdoor UTCI

10 Discussion/Conclusion

10.1 Architectural design

Architectural design has a significant role to play in achieving a holistic and sustainable bus stop design in cold climates. In case of the bus stop design in Slovenia, it was found that although an open design did provide comfort in terms of shade from the open sky, it had almost no effect on protection from the wind and snow. Thermal comfort inside an open design bus stop remained essentially similar to the outdoor UTCI temperatures. A significant increase in the comfortable hours with no thermal stress was observed with just an addition of an enclosed bus stop design. Although, both the conventional design and the climate-based design provided a better thermal comfort than the outdoor conditions, the climate-based design had an improved performance on the thermal comfort. Keeping in mind, passive design measures such as snow loads and rain, a sloping roof inspired by the vernacular design in the region proved to be better than a flat roof. A sloping roof also provided better module inclination angle for the solar *PV* panels leading to a higher *PV* output generation which led to an increased percentage of floor heating capacity in the bus stop. The addition of a green roof also facilitated in an increase in the number of comfortable hours, although the moisture content analysis for the sloping roof has not been taken into account during this study. Lastly, even though, the climate-based design functions better than the conventional design, both designs provide an enhanced thermal comfort as compared to the outdoor conditions. The aesthetic aspect of the design is therefore, left on the choice of the architect.

10.2 Passive and active measures

Passive design measures when applied correctly can have a great impact on thermal comfort and energy-use of a building. Although, an enclosed space did provide an increased thermal comfort as compared to the outdoor conditions, it had to be kept in mind, that the type of glass chosen for the enclosure had a high influence on thermal comfort inside the bus stop. The use of clear, double or triple paned glass resulted in a lower moderate cold stress, however, there was a significant increase in the moderate heat stress with strong heat stress experienced by the user for about *7 %* of the time in a year.

Since the variation in insulation thickness in the wall did not have a significant impact on thermal comfort, in order to achieve an optimal thermal comfort, the cost of the constructing wall should be considered. The facades that should be made up of solid walls had to be a design choice made by comparing the results of thermal comfort with different facades as walls for the bus stop and an aesthetic aspect, providing an uninterrupted view of the surroundings.

In order to simplify the model in IDA ICE, the sloping roof model was considered to be a flat roof and the results from the sloping green roof was calculated considering the entire roof to be a green roof, when in reality, only half of the sloping roof is a green roof, whereas the other half is a simple sloping roof, with solar panels incorporated on it. This means that thermal comfort inside the bus stop, after the addition of a green roof would be lower in reality as compared to the simulation results.

Lastly, an addition of an active measure, such as a radiant floor heating can significantly increase the number of hours with no thermal stress. A *100 %* heated floor area could ensure no thermal stress inside the bus stop for *70 %* of the working time in a year while 25 % of heated floor area provided no thermal stress for *55 %* of the working time in a year. To install an active system inside the bus stop, the biggest challenge was to provide electricity for heating whilst also keeping in mind to make the bus stop self-sufficient. Moreover, the effect of other types of active electrical heating such as radiant heat from the ceiling or the walls could also be investigated.

10.3 Conclusion

Although the final proposal provides an enhanced thermal comfort experience inside the bus stop for a user, the step-by-step parametric analysis followed to obtain the final proposal might not be the best possible method to achieve an optimal design. The thesis research has proved that the climate does play an important role on the architectural design in order to achieve passive design measures for thermal comfort. More ways to integrate passive design measures could also be investigated to ensure that there is no overheating inside the bus stop since the current proposal has overheating for *8* hours inside the bus stop.

The integration of the solar *PV* system to provide additional electrical heating inside the bus stop is still questionable since the cost of the system has not been calculated and there is no evidence that the system would be a profitable investment. Moreover, a battery integrated solar *PV* system might not be the most plausible choice since the bus stop has working hours mostly during the day when the sun is shining. A *PV* system with no battery could be used along with materials having a high thermal capacity, which could retain heat for a longer period of time. The fact that the *PV* output generation is not very high in this region, could be another factor to check for an appropriate integration of the solar *PV* system considering the high cost of the system itself. Other ways to provide electricity to the bus stop could also be investigated and the feasibility and cost of such a system should be checked in order to find a most reasonable option.

Even though, an active measure such as electrical heating, if included in the design can provide a significant increase in the thermal comfort of the user, it is still a question of feasibility and costs to determine if an active measure is profitable in reality. Whether or not, an active measure was included in the design, it was nevertheless, important to incorporate passive design measures to be able to achieve a holistic, sustainable design.

11 Summary

Transportation plays an essential role in the European economy. The European Transport Policy aims to establish a sustainable means of transportation system to provide the social, economic and environmental needs of society contributing to an integrated society. Major reasons for people to choose private cars over public transport are infrequent connections, inadequate infrastructure and low thermal comfort while waiting for their transport. This thesis is a research on the adaptive approach to thermal comfort in bus stops in Slovenia. It provides an innovative opportunity to assess thermal comfort by using the Universal Thermal Climate Index (UTCI) method. Amongst several other adaptive models present for thermal comfort, the UTCI model was chosen since it is a multi-nodal model which considers the dynamic conditions of the outdoor climate. Moreover, the UTCI model can be used for people spending shorter periods of time in outdoor conditions which is apt in the case of people waiting at bus stops for their ride.

To begin assessing the thermal comfort inside a bus stop, several types of bus stop designs were developed and tested. Initially, open-design bus stops were tested, but it was found that although such bus stop designs provided some shade and protection from the wind and rain, it did little for thermal comfort. Therefore, it was deemed that in order to enhance thermal comfort inside the bus stop, the designs had to covered. Another objective of the thesis was to determine the role of climate on the architectural design. Subsequently, two types of covered designs were investigated - a conventional box-shaped bus stop design and a climate-based bus stop design.

Assessment of thermal comfort was carried out based on the UTCI index. The operative temperature inside the bus stop was compared to the outdoor UTCI temperature, and the number of comfortable working hours of the bus stop in a year was calculated. A step-by-step, iterative parametric analysis was carried out for both designs. Passive measures such as different types of glazing, different wall insulation thicknesses, addition of green roofs, integrated sun-shading and changes in the door opening schedule were applied to enhance thermal comfort inside the bus stop. In addition, an active measure in the form of electrical floor heating was also included. Solar *PV* panels were installed on the roof of the bus stop and based on the energy generated by the solar panels, it was decided how much of the floor area could be heated.

From the results of the iterative parametric process, it was observed that the climate-based bus stop performed better than the conventional bus stop design. With the addition of an active measure, it was found that active floor heating could increase thermal comfort substantially, but it was necessary to investigate the feasibility and costs to determine if an active measure would be profitable in reality. In the end, it was deduced that whether or not, an active measure was included in the design, it was nevertheless, important to incorporate passive design measures to be able to achieve a holistic, sustainable design.

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