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Examining user thermal comfort in spaces between buildings: Exploring parametric solutions for BIPVs for Luleå, Sweden, and Limassol, Cyprus

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ABSTRACT

The global concern over the interplay between climate mitigation, urban structures, and city energy usage underscores a pressing need for innovative solutions. This research delves into the relationship between urban layouts, energy dynamics, and the thermal comfort of public spaces between buildings. Focusing on the contrasting climates of Luleå, Sweden, and Limassol, Cyprus, the study employs ENVI-met, a microscale urban climate simulation tool, for a parametric exploration at the city block scale. Assessing eight distinct scenarios across morning, noon, and afternoon timeframes, the research considers the impact of Building-Integrated Photovoltaics (BIPVs) on user thermal comfort. Contrary to expectations, the study reveals that BIPV integration alone may not be the primary driver of improved thermal comfort during peak heat periods. Instead, factors like urban density and urban morphology emerge as influential contributors. For instance, increasing the urban fabric density by doubling the building height resulted in greater PET fluctuations ranging from −3 to +3 degrees, compared to the modest PET fluctuations ranging from 0 to +3 degrees observed with the simple integration of PVs onto buildings. These findings offer valuable insights for urban planners and policymakers, guiding decisions in considering the issue of thermal comfort in public spaces between buildings, while optimizing energy consumption in urban areas.

1. Introduction

The current climate situation poses significant challenges for urban environments, with increasing temperatures and higher energy demands for cooling and heating (Filho et al., 2019). Urban areas account for a substantial portion of global energy consumption and greenhouse gas emissions, thus contributing to the ongoing climate crisis (Savvides et al., 2019). Furthermore, the aging building stock in Europe presents additional challenges, as the bulk of the building stock in many countries was built with lower standards than today. s (Theokli et al., 2021; Italos et al., 2022; Lidelöw et al., 2019). Addressing the energy performance of buildings erected in the 1960 s, 1970 s, and 1980 s is paramount in reducing carbon emissions.

To address these issues, the European Union has proposed measures to promote the energy renovation of buildings, through a number of ambitious sustainability targets in urban areas, which aim to reduce greenhouse gas emissions and to improve energy efficiency in buildings (Bertoldi et al., 2021). These targets, such as the Energy Performance of Buildings Directive (EPBD) and the Nearly Zero-Energy Buildings (NZEB) standard, aim to augment the sustainability outlook of the existing building stock. However, achieving these targets requires substantial renovations and infrastructural upgrades to the existing building stock (Vardopoulos et al., 2020), which can be both complex and costly (Karytsas et al., 2019; Michael et al., 2020). This investigation looks at the potential effects in the integration of active solar systems, such as building integrated photovoltaics (BIPVs), as a response to these energy usage directives driving building renovation strategies. It is believed that BIPVs may have a positive contribution by reducing the carbon footprint of buildings, improving their overall energy performance (Saretta et al., 2019; Barone et al., 2023) and positively affecting user thermal comfort in the open spaces between them.

Improving thermal comfort in these interstitial spaces requires a balance between various parameters, such as building design, urban morphology, and solar system integration (Lai et al., 2020). This requires a thorough understanding of the local climate and energy demands, since geometry, morphology and the height of buildings, all have a significant impact on the microclimatic properties of the open space

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Nomenclatures

BIPV	Building-Integrated Photovoltaics
EPBD	Energy Performance of Buildings Directive
NZEB	Nearly Zero-Energy Buildings
UHI	Urban Heat Island
PET	Physiological Equivalent Temperature
ES	Ecosystem Services
PV	Photovoltaics
MEMI	Munich Energy Balance Model for Individuals
UTCI	Universal Thermal Climate Index

between buildings (Chatzidimitriou and Yannas, 2016). The shape and layout of buildings can also affect the flow paths of air currents through urban breezeways. Failure to address these aspects of building design may cause near air stagnation of hot or cold air at the two ends of the spectrum of possible outcomes. High-rise buildings can also create canyon-like streets, where air movement is restricted, and temperatures may significantly rise. Thus, the siting, height, and massing of buildings must be considered, to positively affect airflow (Al-Kodmany, 2013). Beyond the siting and massing considerations and especially in locations experiencing long periods of hot weather, integration of green spaces and the use of green roofs and walls can also help to mitigate the impact of urban heat and to improve thermal comfort in the open spaces between buildings. It is also crucial to carefully consider how building cladding materials are employed in these urban blocks, and how their collective effect on the thermal well-being in communal areas between structures may significantly contribute to sustainable urban development (Vassiliades et al., 2022).

In evaluating new building proposals or renovations of existing structures in the context of the challenges outlined above require a multi-faceted approach, one that encompasses innovative building technologies, policy frameworks, financial incentives and public awareness campaigns (Gallego-Schmid et al., 2020).This research paper endeavours to examine one aspect of climate mitigation in urban areas by focusing on thermal comfort in the open spaces between buildings, in two contrasting regions of Europe, Luleå, Sweden, and Limassol, Cyprus. These two cities are roughly located in the northern and southern edges of Europe, respectively, and thus offer unique climatic and morphological characteristics for comparative analysis. Informed by the dynamic approach outlined above, the research question is: what is the impact of BIPV – coupled to material and planting choices – with regards to user-comfort in the open spaces between buildings in the areas under study? The article is structured as follows: in Section 2, we summarize relevant BIPV literature, while in Section 3 we present the case studies and methodology. In Section 4, we present the results which will be used to answer our research question in Section 5.

2. Literature review

The impact of the urban building massing on the microclimatic conditions in the open spaces between buildings has been of major concern in recent years. The role of urban design and planning, in creating a comfortable and sustainable built environment, has also received much attention. In order then to address aspects of microclimate mitigation in the open spaces between buildings in urban areas, a number of different strategies have been proposed, including that of the integration of Building-Integrated Photovoltaics (BIPVs) in building shells. Research has shown that the materiality changes brought about by BIPVs – coupled to street landscaping and to the material palette of existing building facades – can affect user thermal comfort in interstitial environments (Vassiliades et al., 2022, 2023). The literature review, as organized in the subheadings below, aims to present a broad understanding of the various factors that may affect user thermal comfort in the interstitial open spaces between buildings, so that the decision to examine Building Integrated Photovoltaics as a cladding option is better understood in this context of investigation.

2.1. Thermal comfort in open spaces

While there have been numerous studies examining the effects of built environment characteristics, such as materiality and morphology, ones addressing the microclimate and thermal comfort in open spaces between buildings, and specifically on the influence therein of building-integrated solar energy systems, is limited. A notable example of such research is the investigation conducted by Freitas et al (Freitas et al., 2019)., which assessed the impact of photovoltaic (PV) integrated systems on façades and rooftops to public space user comfort in a Lisbon neighbourhood. According to their preliminary findings, PV integration had a negligible impact on the average outdoor temperature. Another work, by Vassiliades et al (Vassiliades et al., 2022). used the Physiological Equivalent Temperature (PET), to examine the impacts on thermal comfort in public areas brought on by the integration of active solar energy systems on existing facades in two coastal Mediterranean cities. The findings indicated that there is a limited impact on the thermal comfort at street level resulting from active building integrated solar energy systems.

Hence, as already mentioned above, there is a number of parameters that may affect thermal comfort in urban open spaces, namely: building geometry, building height and the urban morphology in general, in the way in which they form the urban street wall (Lai et al., 2020). These design aspects must be considered in the context of the specific location and climate parameters in order to optimize results for specific situations. The review of relevant literature, as it develops below, will cover specific topics that inform the methodological approach to this investigation, as it touches upon more specific fields of knowledge.

2.2. Siting according to environmental design principles

The rapid pace of urbanization has led to significant changes in the local climate. These changes occur due to the absorption and retention of heat by the built environment, leading to increased energy consumption for cooling and to reduced air quality. It is vital to explore the connection between the built environment and climate dynamics in the quest for sustainable urban development, especially in terms of surface texture, albedo, thermal storage capacity, and integration of blue and green elements in urban infrastructure (Gunawardena et al., 2019; Oke, 1982). High urban temperatures result from these factors, which are coupled to the deterioration of air quality caused by human activity (Oke, 2002; Taha et al., 1988; Gunawardena et al., 2017). Consequently, as these outcomes worsen there is a reciprocal increase in energy demand for cooling and heating in buildings (Taha et al., 1988; Grimmond et al., 2010), leading to further challenges in the management of user thermal comfort (Oke, 2002; Calì et al., 2016; Steemers, 2003). Therefore, research into these environmental design parameters is both timely and essential for addressing the energy load of buildings. It is also important in finding ways for alleviating issues that might emerge from less-than-optimal selections in the material qualities of the built fabric, along with their impact on publicly accessed spaces between buildings. Various studies have shown that these challenges can be mitigated by revising urban planning and design strategies, with Taslim et al (Taslim et al., 2015). and Aiko et al (Nakano et al., 2015). proposing guidelines that mitigate these effects and provide climate specific advice for rethinking urban morphology and land use. On the other hand, Ronchi et al (Ronchi et al., 2020). used Ecosystem Services (ES) to show how various urban planning strategies (including the incorporation of green spaces, surface permeability, built-up footprint, and tree density and cover) have influenced the cooling capacity of the urban open space system.

2.3. Material choices – thermal massing characteristics

The thermal experience in public spaces can be markedly influenced by the materiality, geometry, morphology, and height of structures. Instances include the potential of high thermal mass materials to modulate indoor temperatures and the capacity of light-coloured and reflective surfaces to mitigate heat absorption. It is recognized that the thermal characteristics of building elements, encompassing building shells, roofing components, and paving surfaces, constitute a factor that could exacerbate user discomfort in urban settings (Jannat et al., 2020; Larsen et al., 2009; Sahnoune and Benhassine, 2017; Mohajerani et al., 2017) by negatively affecting the microclimate. Factors like transportation infrastructure, greenery, and plantings further contribute to shaping the overall urban comfort experience (Wonorahardjo, 2012; Alves and Lopes, 2017; Louiza et al., 2015). Additionally, research has shown that the height and density of building stock can affect wind flow patterns in urban environments, which in itself may then have an impact on thermal comfort (Bajšanski et al., 2015; Wai et al., 2020; Sharmin et al., 2015; Li et al., 2020).

2.4. Material choices – building shells

Examining various height options and materiality alternatives for building facades is crucial since these elements constitute a significant portion of the building envelope, which may directly affect the outdoor thermal environment. Previous studies (Wonorahardjo et al., 2022; Wonorahardjo and Sutjahja, 2018) have indicated that opting for inappropriate building materials and unsuitable choices in the paving of open spaces can worsen these impacts when contrasted with the use of "lighter alternatives," such as sandwich panels and double-skinned facades, which dissipate heat more appropriately.

Moreover, research has also indicated that opting for lightweight materials, like gypsum walls, plywood boards, and even glass-fibre-reinforced-concrete with appropriate wool insulation, can decrease fluctuations in the temperature of adjacent spaces by improving infrared emissivity (Wonorahardjo et al., 2020; Khadraoui and Sriti, 2018). However, incorporating high thermal inertia materials in buildings has been shown to have mixed effects on outdoor thermal comfort – depending on the time of day – as this is partly influenced by building shell material choices and facade modifications (Khadraoui and Sriti, 2018; Kandya and Mohan, 2018).

The choice of building facade materials and their impact on neighbouring buildings and open public areas has also been of research interest. Several studies have investigated the effects of reflectivity on both outdoor and indoor temperatures (Wen et al., 2020; Guo et al., 2017). The use of lighter colours on facades and roofs has been shown to reduce interior temperatures, while darker colours tend to increase heat absorption, resulting in higher exterior ambient temperatures (Hoffmann et al., 2021).

These results underscore the breadth of factors to consider when evaluating the influence of material selections and construction techniques of facade systems on building associated temperatures in the interstitial space between buildings.

2.5. A further look at building integrated photovoltaics

In the context of reviewing relevant literature above, with regards to design parameter choices and their effect on user thermal comfort in the open spaces between buildings, a further examination of Building Integrated Photovoltaics as an alternative cladding choice may be warranted. BIPVs are an interesting consideration because in addition to providing the option of acting as a building shell they also offer a promising technology for the production of renewable energy in buildings. However, the integration of BIPVs can also have a significant impact on the thermal comfort of the surrounding environment. Research has shown that BIPVs can increase the surface temperature of buildings (Zhang et al., 2017), which can lead to a temperature increase in the surrounding spaces. On the other hand, BIPVs can also provide shading that may reduce solar radiation reaching the ground.

2.6. The usefulness of a parametric investigation

The variety of inputs affecting outdoor user thermal comfort, suggests the use of a parametric investigation, as this allows researchers to systematically explore the effects of various design parameters (Lai et al., 2019). Several works have shown that the variation of parameters, such as, building orientation, landscaping and vegetation, shading devices, and material and colour choices, can help researchers determine which factors have the greatest impact on thermal comfort and to identify the most effective design strategies for improving it (Morakinyo et al., 2017, 2018; Morakinyo and Lam, 2016). This approach is especially useful in complex urban environments and it can help designers to optimize their proposals and to ensure that they are achieving desired thermal performances. Additionally, a parametric investigation can help to reduce the costs associated with designing and testing multiple prototypes, by allowing researchers the opportunity to simulate and evaluate different options digitally, before proceeding to physical prototyping and testing (Eltaweel and SU, 2017), and as such it is an approach that significantly informs the methodological approach to this investigation as it unfolds in the next section.

3. Case studies and methodology

3.1. The cities

Luleå (65°35′4″N 22°9′14″E) is characterised by a small and dense urban core that sits on the tip of a peninsula, surrounded by low-rise hinterland. Even though it is located in an Arctic/Sub-Arctic zone, prevalent temperatures and winds may differ significantly between areas located by the shore and those in the hinterland. The city is one of a handful of medium size urban centres (approx. population 80,000 inhabitants) in northern Sweden that are affected by an investment spree to convert local, national strategic industries (natural resources, steel, batteries, etc.) to a carbon neutral business. This means that urban development is expected to accelerate substantially and with this trend, questions related to sustainability and comfort are central in creating the conditions to attract a new work force to the country's north (Rizzo et al., 2023).

Limassol (34°42'25.6680''N 33°1′21.4212'' E) is the second largest metropolitan area on the island of Cyprus and the largest in terms of municipal area. It lies in the southern coastline of the island and is spatially characterized by a small and compact medieval urban core that quickly sprawls outwards radially – like a fan – around this central core and along major commercial arterials. The city has seen a tremendous wave of real estate investment and development in the last decade, leading to an influx of both affluent investor-migrants as well as of migrants and immigrants – primarily from SE.ME.NA. countries of origin – engaged in professional and service sectors. The main port of the island is located at the western sdge of the city, and whose significance has been rising due to its location close to the outlet from the Red Sea to the Mediterranean – at the Suez Canal – and along major trade routes to Sothern European destinations. As a result of the above, the income sectors based on service industries, tourism and shipping have been significantly augmented and are of strategic economic importance to Limassol and by extension to Cyprus (Geddes, 2020).

3.2. Simulations

Following the review of existing literature, in the knowledge sectors described above, particular elements were identified as potential influencers on the thermal comfort in public spaces between buildings, thereby forming the basis for a subsequent parametric analysis. To determine these thermal conditions, the Physiological Equivalent Temperature (PET) output from the Munich Energy Balance Model for Individuals (MEMI) was utilized (Esmaili and Montazeri, 2013), which is one of the most widely used indices for evaluating heat stress in outdoor environments. This approach has been validated multiple times in previous research (Zare et al., 2018), with studies demonstrating a strong correlation between PET and other widely used indices for determining heat stress, such as the Universal Thermal Climate Index (UTCI) (Błażejczyk, 1994). In this study, the levels of physiological and thermal perception stress were analysed in PET, as detailed in Table 1 (Matzarakis et al., 1999).

The simulations in this study were conducted using ENVI-Met, a software specifically designed for simulating environmental conditions in urban areas and evaluating the impacts of various factors such as atmosphere, vegetation, structures and materiality (GmbH, 2021). ENVI-Met has been extensively utilized in previous studies and has been validated against observed data for multiple environmental parameters (Vassiliades et al., 2022; Freitas et al., 2019; Morakinyo and Lam, 2016; Perini et al., 2017; Acero and Herranz-Pascual, 2015; Yang et al., 2012; Lobaccaro and Acero, 2015; Carfan et al., 2012; Acero and Arrizabalaga, 2018). It is widely recognized and accepted as a reliable tool for urban planners and architects. A comprehensive description of ENVI-Met, including all the equations involved, can be found in the work of Bruse and Fleer (Bruse and Fleer, 1998).

The simulations were specifically carried out for the summer solstice at 9:00, 12:00, and 15:00, chosen for their significance in terms of thermal stress induced by insolation, which is relevant to both locations. In Limassol, the convergence of high incident radiation and elevated temperatures directly influences both the buildings and the thermal well-being of individuals in public spaces. Meanwhile, in Luleå, the interplay of high incident radiation values and the low angle of incidence directly affects individual thermal comfort. The study aimed at identifying the optimal combination of parameters that may help establish design guidelines applicable to similar urban contexts in both the Mediterranean south and the Arctic north.

The research process began with the choice of a typical, simplified example of the urban organizational layout of Limassol, Cyprus and Luleå, Sweden. The "pavilion" layout was used for Limassol, while the "patio" layout was used for Luleå, following the taxonomy provided by Martin and March (March and Martin, 1972) (Fig. 1). The current thermal comfort conditions were simulated in both cities for a 9-meter--high building, and then the simulation was repeated with double that value. Additionally, and in the context of an urban investigation, a scenario was simulated where the urban development type was changed

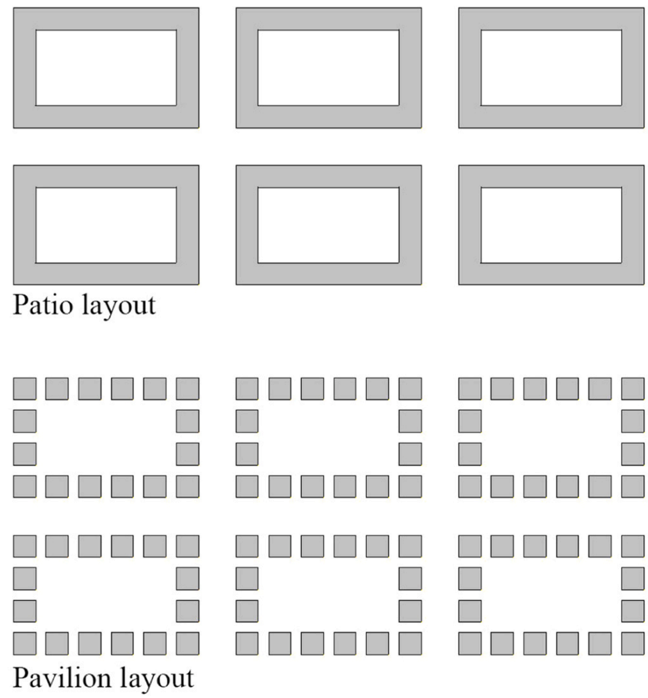

Fig. 1. The patio layout as used in Luleå, Sweden (Top) and the pavilion layout as used for Limassol, Cyprus (Bottom). The building block size for both cases is 66 ×108 m, and the width of the roads is 21 m.

from "pavilion" to "patio" for Limassol and from "patio" to "pavilion" for Luleå. Another parameter was the incorporation of building-integrated photovoltaics, which were also added to the simulations for all the scenarios.

Regarding the scenario involving the integration of photovoltaics onto building facades for both cities in question, the approach utilized to determine appropriate positions for building integration was based on the methodology outlined by Vassiliades et al (Vassiliades et al., 2022). To pinpoint surfaces with the maximum solar energy input, an assessment of incident radiation on the buildings was carried out using PVSites (Sites, 2019). While this offers an initial insight into geometries suitable for incorporating active solar systems on to buildings, it does not offer a complete evaluation of integration feasibility. A building might exhibit a high average incident radiation value, yet specific facades could possess architectural characteristics leading to significantly lower values, rendering the integration of an active solar system impractical (Savvides et al., 2019). Therefore, Eq. (1) was employed to calculate the minimum required incident radiation for each surface to ensure viable building integration:

$$ISR\left(\frac{kWh}{m^2 \cdot yr}\right) = \frac{IC\left(\frac{€}{m^2}\right)}{\eta \times Ce\left(\frac{€}{kWh}\right) \quad \times YR} \tag{1}$$

Where ISR (kWh/m^2/yr) represents the annual incident solar radiation for the specific location, while IC denotes the cost of system installation (€/m^2). The parameter η signifies the system's performance, and Ce represents the energy cost (€/kWh). YR indicates the number of years required for repayment (yr). Considering current technological data, such as the approximate performance of photovoltaics (PV) at 19% and an investment depreciation period of 9 years, it was determined that a minimum of 650 (kWh/m^2/yr) of incident radiation on a façade surface is necessary for the viability of integrating an active solar system into the building. This criterion applies to both cities. As expected, the integration of photovoltaics was primarily focused on the southern facades, with partial integration on the western and eastern facades in the case of

Table 1
The thermal scale measured by the Physiological Equivalent Temperature (PET) which accounts for different levels of human thermal perception and physiological strain (Matzarakis et al., 1999; Jendritzky et al., 1990; Matzarakis and Mayer, 1997).

PET (°C)	Thermal Grade of physiological perception	Grade of physiological perception stress
< 4.0	Very cold	Extreme cold stress
4.1 – 8.0	Cold	Strong cold stress
8.1 – 13.0	Cool	Moderate cold stress
13.1 – 18.0	Slightly cool	Slight cold stress
18.1 – 23.0	Comfortable	No thermal stress
23.1 – 29.0	Slightly warm	Slight heat stress
29.1 – 35.0	Warm	Moderate heat stress
35.1 – 41.0	Hot	Strong heat stress
> 41.1	Very Hot	Extreme heat stress

Limassol.

It is noted that an 8-digit coding has been specified for easier understanding of the simulated parameters, which is broken down as follows:

Digit No.:	1	2	3	4	5	6	7	8
Code:								

Where:

- Digit 1–3: “LIM” = Limassol, “LLA” = Luleå
- Digit 4: “O” = Original, single height, “D” = Double-height
- Digit 5–6: “BS” = Base case, “PV” = BIPV
- Digit 7–8: “09” = Time 09:00, “12” = Time 12:00, “15” = Time 15:00

For example, the code LIMOBS09, stands for Limassol, original single height, Base case at 09:00.

3.3. Materials

3.3.1. Limassol, Cyprus

By conducting on-site observations together with an extensive review of existing literature, it was noted that a predominant construction approach in the surveyed region involves the use of reinforced concrete and non-load-bearing masonry brick walls, typically with an average thickness of approximately 20–30 cm. Standard finishes include a cement mortar layer of around 3–4 cm. For flooring, reinforced concrete is a common choice, often topped by a layer of concrete and mortar measuring 25–30 cm in thickness. The materials utilized in Limassol are summarized in Table 2, which also provides information on the optical and thermophysical properties of the PV layer. These properties are chosen in accordance with typical monocrystalline silicon solar panels (Freitas et al., 2019), whose optical and thermophysical characteristics are well-documented.

3.3.2. Luleå, Sweden

Upon on-site assessment and insights from pertinent literature, it is discernible that the predominant construction method in the designated region involves the use of reinforced concrete slabs and structural systems, complemented by non-bearing walls constructed with drywall-timber frames, insulation, and metal cladding. These walls typically boast an approximate thickness of 30 cm. Flooring comprises reinforced concrete, layered with concrete and mortar, measuring 25–30 cm in thickness. The selection of these construction materials for buildings in Luleå is deliberate, and their specifics can be referenced in Table 3. Additionally, the table furnishes details on the optical and thermophysical properties of the photovoltaic (PV) layer. It’s noteworthy that these properties are chosen based on typical monocrystalline silicon solar panels (Freitas et al., 2019), with their respective optical and thermophysical attributes duly reported.

3.4. Climate analysis

European countries exhibit diverse climate and energy characteristics along the North-South gradient. Countries in the Mediterranean, like Cyprus, experience relatively consistent daylight throughout the seasons (Fig. 2), but exhibit hot summers (Fig. 3). Conversely, northern countries, such as Sweden, have darker winters (Fig. 2), colder temperatures (Fig. 3), and exceptionally long summer days (Ebrahimabadi et al., 2018; Rizzo, 2017; Chapman et al., 2018). This highlights the interest for a comparative investigation of several parameters that may affect thermal comfort in public spaces between the North and South regions of Europe.

3.5. Assumptions

The chosen software for assessing outdoor thermal comfort, ENVI-met, restricts the representation of PV panels as a cladding material, preventing accurate estimation of photovoltaic and photothermal conversions, as well as the effective PV temperature. Consequently, the outdoor comfort evaluation is influenced slightly by an overestimation of the PV panel temperature. This assumption of PV panels as cladding material, while conservative for this study, aligns with ENVI-met’s designation of PV panels with their optical and thermophysical properties, as outlined in Table 1 and Table 2. Due to the scale of the investigated areas and aforementioned limitations, experimental validation of the findings is challenging. Therefore, the current work adopts a more abstract and comprehensive approach to provide essential design guidelines.

4. Results

This section contains the presentation of the results and the related discussion based on each sub-theme of the research goals.

4.1. Limassol, Cyprus

In the initial stage, a simulation was conducted within a simplified urban fabric for Limassol to determine the PET for the summer solstice at three different times: 09:00, 12:00, and 15:00. Subsequently, photovoltaic panels were integrated onto the buildings, within the same urban fabric and time periods, to assess their impact on the thermal comfort of public space users. Furthermore, the influence of the urban fabric density on thermal comfort was investigated by doubling the height of the buildings while maintaining their original geometry, followed by another iteration of simulations. Lastly, in these double-height building scenarios, photovoltaic systems were integrated, and the simulations were repeated. To analyse the specific impact of each parameter variation mentioned above, each scenario was compared against the base case.

4.1.1. LIMOBS09

The simulations start with LIMOBS09, representing Limassol’s original single-height configuration at 09:00. The simulations and comparisons with LIMOPV09, LIMDBS09, and LIMDPV09 performed for this stage, are presented in Fig. 4.

The simulations at this point demonstrate that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Limassol at 09:00 during the summer solstice, as the variations in PET range from 0 to −3 degrees. Conversely, increasing the urban fabric density by doubling the building height leads to greater PET fluctuations ranging from −3 to +3 degrees, creating slightly less favourable conditions for public space users at that specific hour. Finally, the integration of photovoltaics into

Table 2
Limassol: Material characteristics.

Name	Absorption	Transmission	Reflection	Emissivity	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Density (kg/m^3)
Cement plaster	0.50	0.00	0.50	0.90	1000.00	1.00	1800.00
Brick Masonry	0.60	0.00	0.40	0.90	1000.00	0.40	1000.00
Clear Float Glass	0.05	0.90	0.05	0.90	750.00	1.05	2500.00
PV Panel	1.00	0.00	0.00	0.84	700.00	0.15	3000.00

Table 3
Luleå: Material characteristics.

Name	Absorption	Transmission	Reflection	Emissivity	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Density (kg/m^3)
Cement plaster	0.50	0.00	0.50	0.90	1000.00	1.00	1800.00
Metal cladding	0.10	0.00	0.90	0.18	880.00	203.00	2700.00
Dry wall	0.29	0.00	0.50	0.85	1000.00	0.25	900.00
Clear Float Glass	0.05	0.90	0.05	0.90	750.00	1.05	2500.00
PV Panel	1.00	0.00	0.00	0.84	700.00	0.15	3000.00

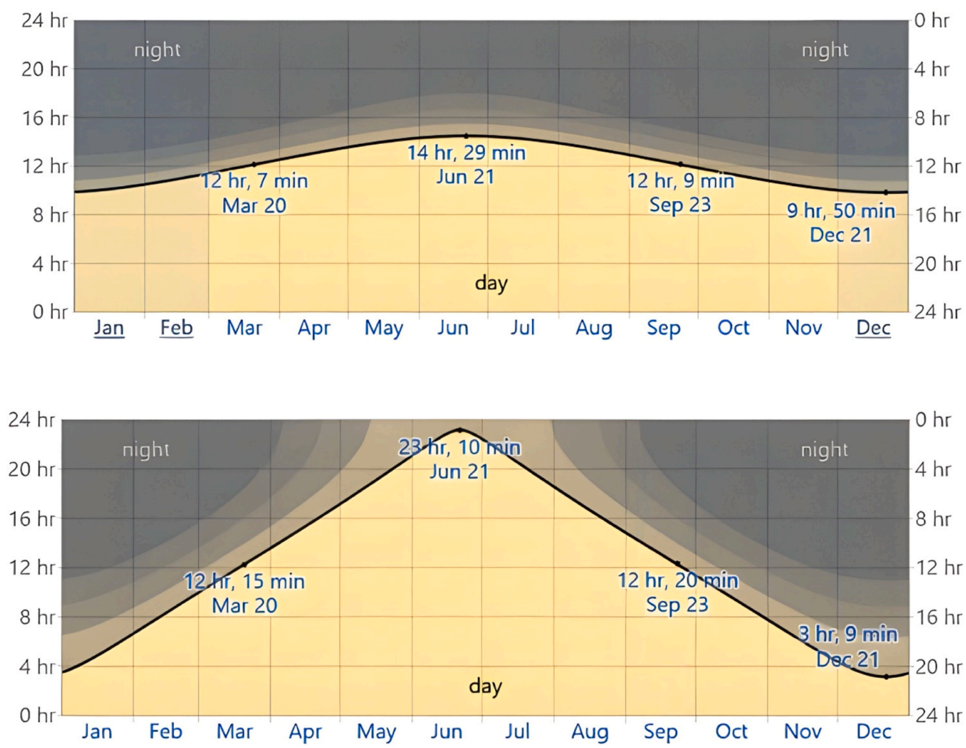

Fig. 2. The graphical representation illustrates the duration of daylight and twilight in two cities, Limassol (top) and Luleå (bottom). The black line represents the hours when the Sun is visible. Moving from the bottom (more yellow) to the top (more gray), the color bands represent various phases: full daylight, different levels of twilight (civil, nautical, and astronomical), and complete darkness (Climate and Average Weather Year Round, 2022).

double-height buildings mitigates this fluctuation to some extent, as it reduces the area where increasing trends in PET apply.

At this stage, the influence of the urban organizational layout in the city of Limassol on the thermal comfort of users was investigated based on the same parameters. Thus, the urban organizational layout of the city was changed from pavilion to patio, a commonly used urban organizational layout in European city centres, in order to assess whether it could be a solution to thermal comfort issues in public spaces. The results of the simulations and the comparisons of parameters for the LIMOBS09 case in a patio urban organizational type are presented in Fig. 5.

As previously noted, it was shown that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Limassol, given a patio type layout, at 09:00 during the summer solstice, as the variations in PET range from 0 to −3 degrees. Conversely, the simulations at this point demonstrate that the change of the urban organizational layout in Limassol, can have a slightly bigger impact on the thermal comfort of users of the public spaces, since the increased urban fabric density, resulting from doubling the building height, leads to greater PET fluctuations, ranging mostly from 0 to +3 degrees, and creating less favourable conditions for public space users at that specific hour, especially when compared to the pavilion layout scenario. Finally, the integration of photovoltaics on to double-height buildings mitigates this fluctuation slightly, as it reduces the area of surfaces exhibiting increasing trends in PET. However, this fluctuation is not limited as much as in the pavilion layout scenario.

4.1.2. LIMOBS12

The simulations progressed, with LIMOBS12, representing Limassol's original single-height configuration at 12:00. The comparisons with LIMOPV12, LIMDBS12 and LIMDPV12, performed at this stage, are presented in Fig. 6.

The simulations at this point, demonstrate that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Limassol, at 12:00 during the summer solstice, as the variations in PET range from 0 to −3 degrees. Conversely, increasing the urban fabric density by doubling the building height leads to greater PET fluctuations ranging from 0 to +3 degrees, creating less favourable conditions for public space users at that specific hour. Finally, the integration of photovoltaics onto buildings of double that of the base height, mitigates this fluctuation to some extent, as it reduces the area where increasing trends in PET appear.

Similar to the above, the influence of the urban organizational layout for this timeframe was also investigated. The results of the simulations and the comparisons of parameters for the LIMOBS12 case, in a patio urban organizational type, are presented in Fig. 7.

Here too, it was shown that the simple integration of photovoltaics

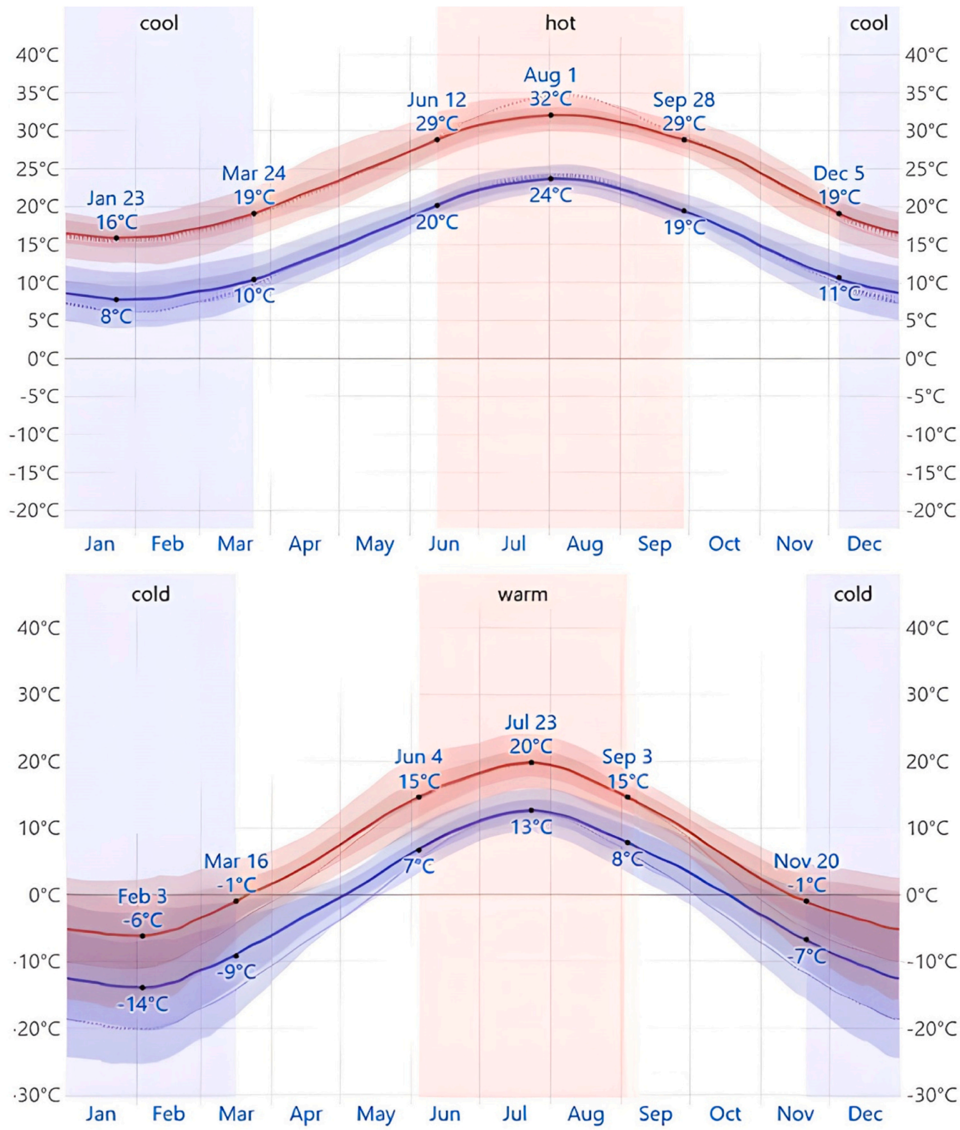

Fig. 3. The temperature patterns in Limassol (top) and Luleå (bottom) are depicted in the following graph. The red line represents the daily average high temperature, while the blue line represents the daily average low temperature. The shaded areas between the 25th and 75th percentiles and between the 10th and 90th percentiles provide additional temperature variation insights. The graph also includes thin dotted lines illustrating the corresponding average perceived temperatures (Climate and Average Weather Year Round, 2022).

on to buildings in their current state has negligible positive influence on the thermal comfort of users in Limassol, with a patio type layout, at 12:00 during the summer solstice, as the variations in PET once again range from 0 to −3 degrees. Conversely, the simulations at this point demonstrate that the change of the urban organizational layout in Limassol, has a bigger impact on the thermal comfort of the users of the public spaces, since the increase in urban fabric density, by doubling the building height, leads to greater PET fluctuations, mostly ranging from 0 to +9 degrees, creating less favourable conditions for public space users at that specific hour, especially when juxtaposed to the pavilion layout. Finally, the integration of photovoltaics into buildings twice as high, does not affect performance at this time slot and with this building geometry, and the situation remains the same as before.

4.1.3. *LIMOBS15*

The simulations continue with LIMOBS15, representing Limassol's original single-height configuration at 15:00. The simulations and comparisons with LIMOPV15, LIMDBS15 and LIMDPV15 performed for this stage, are presented in Fig. 8.

As previously, the simulations at this point demonstrate that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Limassol at 15:00 during the summer solstice, as the variations in PET range from 0 to −3 degrees. Conversely, increasing the urban fabric density by doubling the building height leads to greater PET fluctuations ranging from 0 to +3 degrees, creating less favourable conditions for public space users at that specific hour, with some small exceptions created by the geometry of the buildings. Finally, the integration of photovoltaics into buildings twice as high, mitigates this fluctuation to a small extent, as it slightly reduces the area where increasing trends in PET apply.

Similarly to above, the influence of the urban organizational layout at this time was also investigated. The results of the simulations and the comparisons of parameters for the LIMOBS15 case, in a patio urban organizational type, are presented in Fig. 9.

At this point, it was once again proven that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Limassol, using a patio

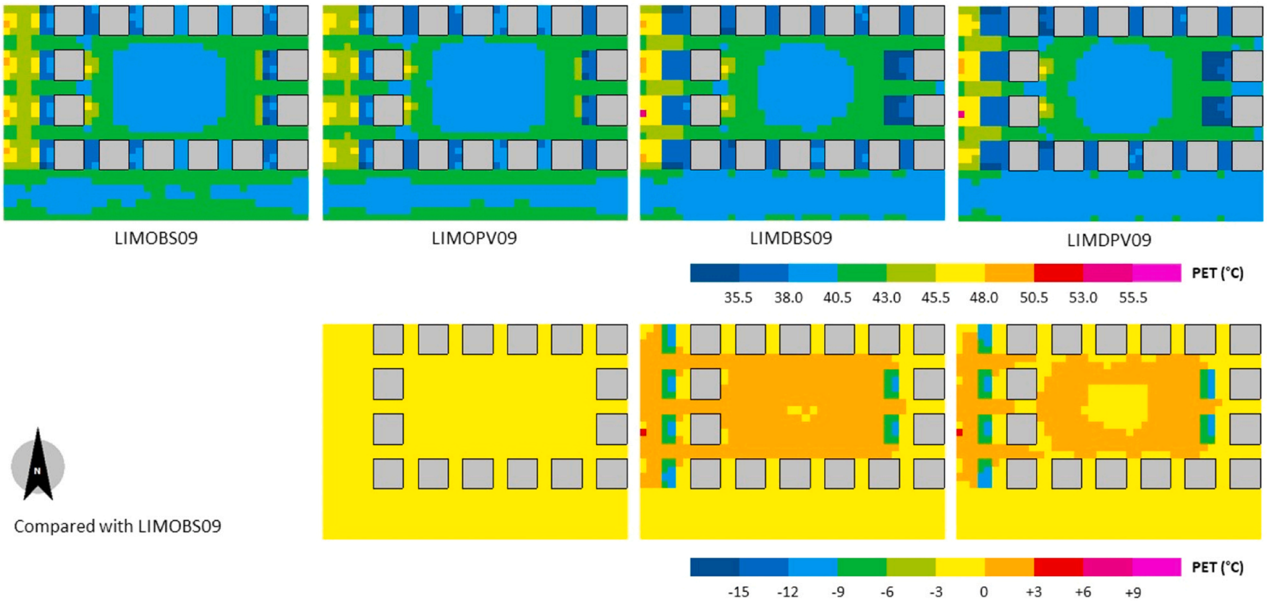

Fig. 4. The results of the simulations for LIMOBS09 on top, compared to the base case at bottom.

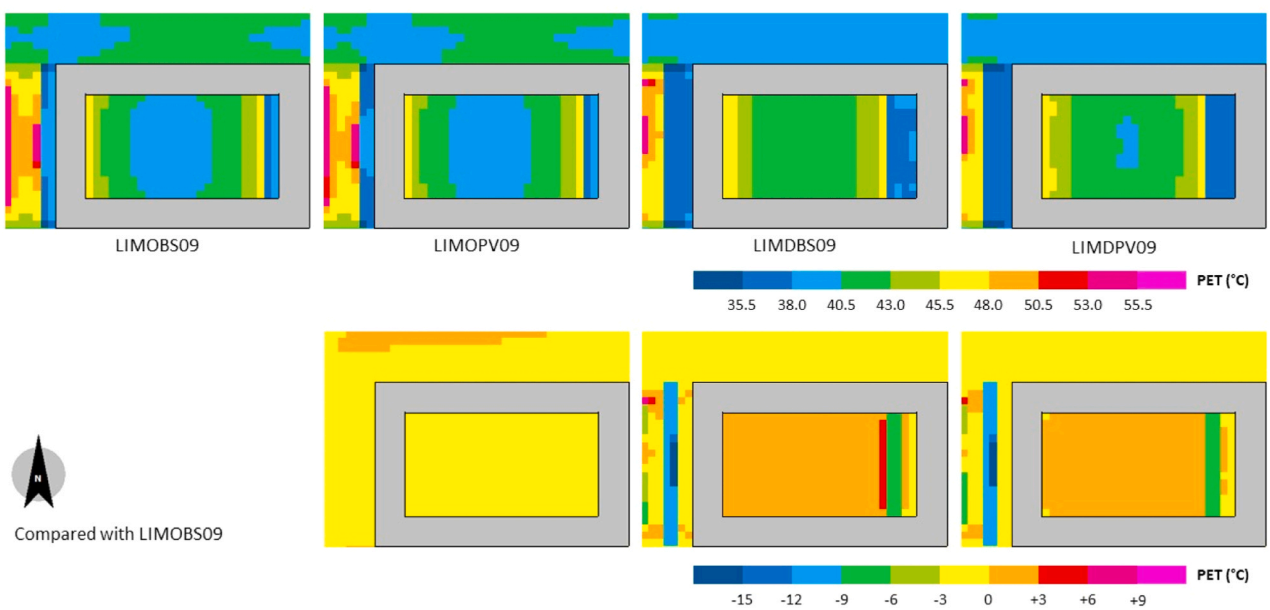

Fig. 5. The results of the simulations for LIMOBS09 patio type on top, compared to the base case at bottom.

type layout, at 15:00 during the summer solstice, as the variations in PET once again range from 0 to −3 degrees. Conversely, the simulations at this point demonstrate that the change of the urban organizational layout in Limassol, has a bigger impact on the thermal comfort of the users of the public space, since increasing of the urban fabric density by doubling the building height, leads to greater PET fluctuations, mostly ranging from −6 to +9 degrees, creating less favourable conditions for public space users for that specific timeframe, especially when compared to the pavilion layout. Finally, the integration of photovoltaics into buildings twice as high does not affect performance for this time slot and for this building geometry, and the situation remains the same as before.

4.2. Luleå, Sweden

The same methodology was applied in Luleå, Sweden. Specifically, the simulations were conducted within a simplified urban fabric of Luleå to determine the PET for the summer solstice at three different time points: 09:00, 12:00, and 15:00. Subsequently, photovoltaic panels were integrated on to the buildings within the same urban fabric and time periods. Furthermore, the influence of urban fabric density on thermal comfort was once again investigated by doubling the height of the buildings while maintaining their original geometry, followed by further iterations of simulations. Lastly, in these double height building scenarios, photovoltaic systems were integrated, and the simulations were repeated. Similar to Limassol, and in order to analyse the specific impact of each parameter variation mentioned above, each scenario was compared against the base case.

4.2.1. LLAOBS09

The simulations start with LLAOBS09, representing Luleå's original single-height configuration at 09:00. The simulations and comparisons

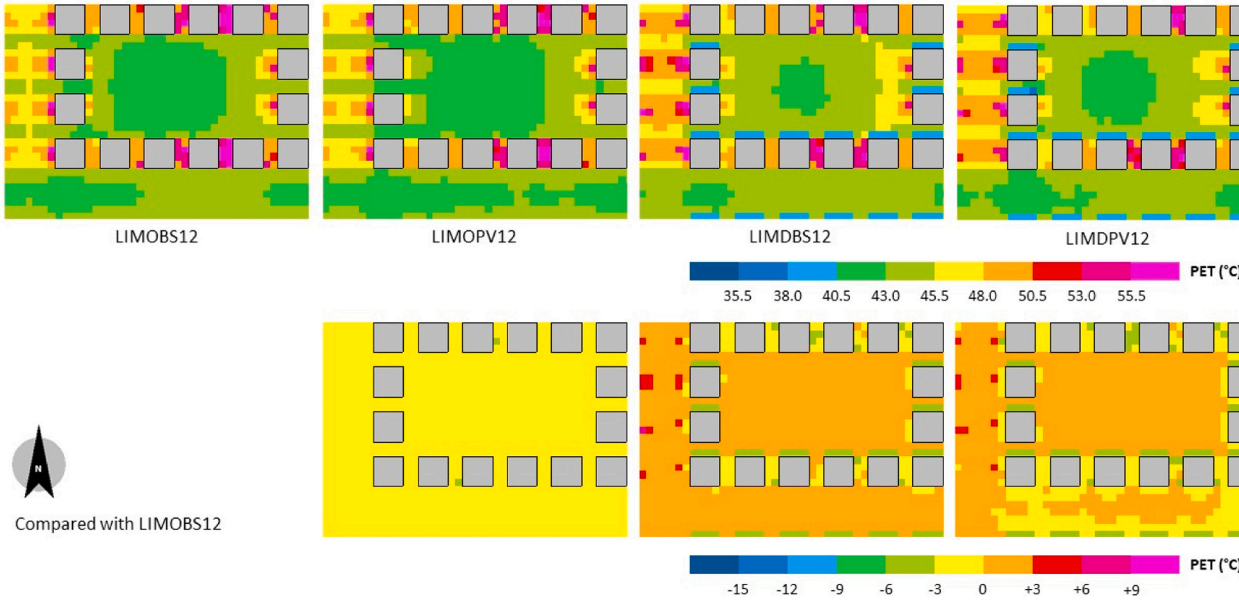

Fig. 6. The results of the simulations for LIMOBS12 on top, compared to the base case at bottom.

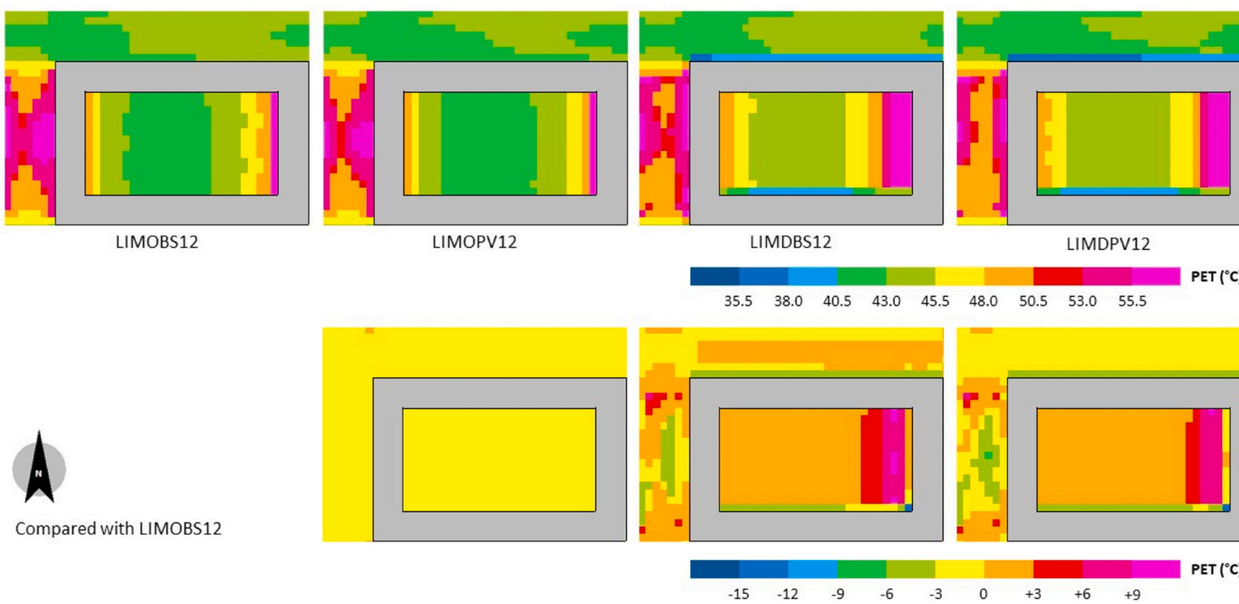

Fig. 7. The results of the simulations for LIMOBS12 patio type on top, compared to the base case at bottom.

with LLAOPV09, LLADBS09, and LLADPV09 performed for this stage, are presented in Fig. 10.

The simulations at this point demonstrate that the simple integration of photovoltaics on to buildings in their current state has a negligible positive influence on the thermal comfort of users in Luleå at 09:00 during the summer solstice, as the variations in PET range from 0 to −2,5 degrees. Conversely, increasing the urban fabric density by doubling the building height leads to greater PET fluctuations ranging from −7,5 to +5 degrees, creating slightly less favourable conditions for public space users at that specific hour. Finally, the integration of photovoltaics into buildings twice as high does not affect the results in this time slot and this building geometry, and the situation remains the same as before.

Similar to Limassol, the influence of the urban organizational layout in the city of Luleå on the thermal comfort of users was investigated based on the same parameters. Thus, the urban organizational layout of the city was changed from patio to pavilion, in order to assess whether it could be a solution to thermal comfort issues in public spaces. The results of the simulations and the comparisons of parameters for the LLAOBS09 case, in a pavilion urban organizational type, are presented in Fig. 11.

As previously, it was proven that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Luleå with a patio type layout, at 09:00 during the summer solstice, as the variations in PET range from 0 to −2,5 degrees. Conversely, the simulations at this point demonstrate that an increase of the urban fabric density by doubling the building height leads to greater PET fluctuations, ranging mostly from −7,5 to +5 degrees, creating less favourable conditions for public space users at that specific hour. On the other hand, the change of the urban organizational layout in Luleå for this date, time and configuration, leads to slightly better results if it is compared to the patio layout.

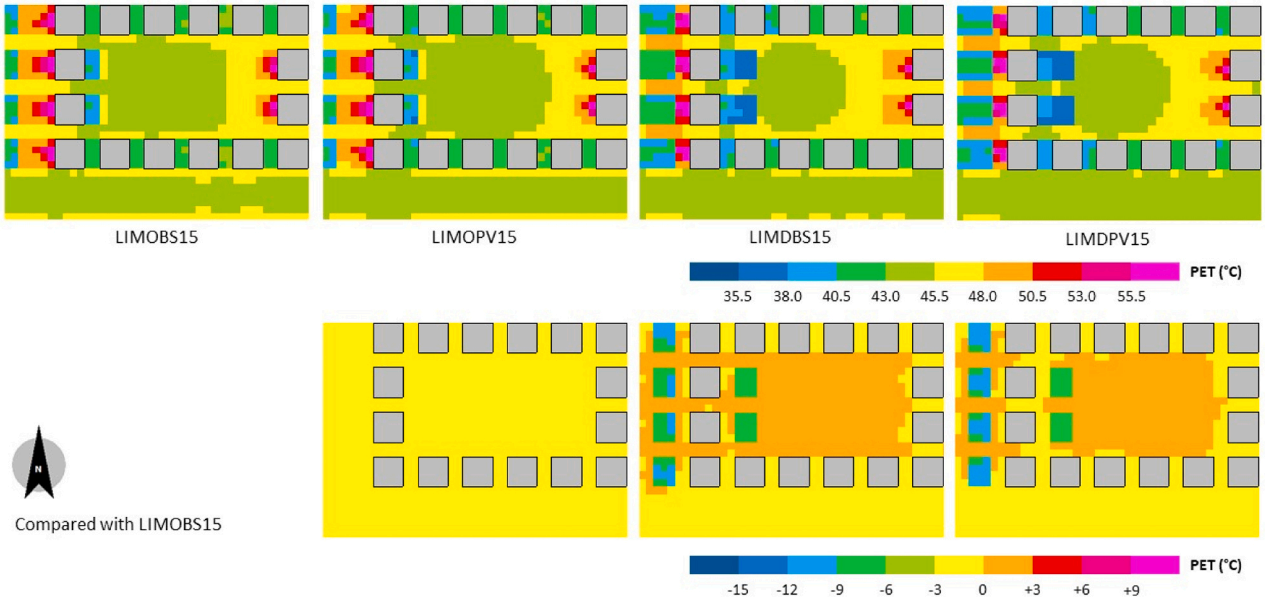

Fig. 8. The results of the simulations for LIMOBS15 on top, compared to the base case at bottom.

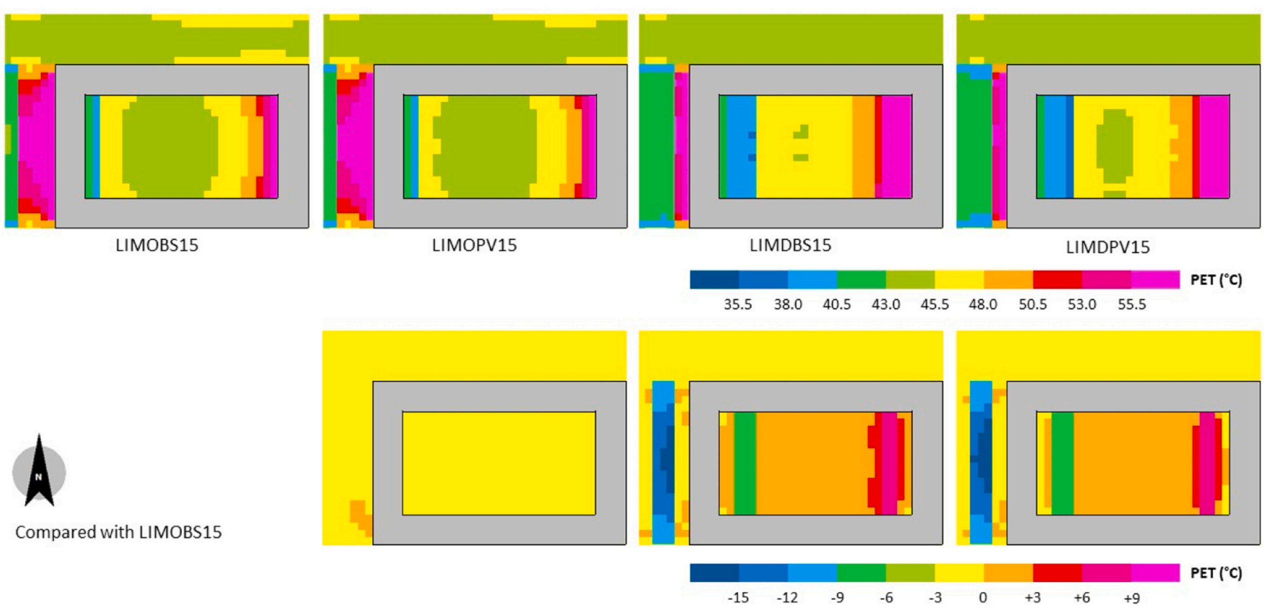

Fig. 9. The results of the simulations for the LIMOBS15 patio type on top, compared to the base case at bottom.

Finally, the integration of photovoltaics into buildings twice as high does not affect results for this time slot and building geometry, and the situation remains the same as before.

4.2.2. LLAOBS12

The simulations continue with LLAOBS12, representing Luleå's original single-height configuration at 12:00. The simulations and comparisons with LLAOPV12, LLADBS12 and LLADPV12 performed for this stage, are presented in Fig. 12.

Once again, the simulations show that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Luleå at 12:00 during the summer solstice, as the variations in PET range from 0 to −2,5 degrees. Conversely, increasing the urban fabric density by doubling the building height leads to greater PET fluctuations ranging from −7,5 to +5 degrees, creating less favourable conditions for public space users at that specific hour. Finally, the integration of photovoltaics on to buildings twice as high, does not have an impact on PET values.

Similar to above, the influence of the urban organizational layout was also investigated at this time. The results of the simulations and the comparisons of parameters for the LLAOBS12 case exhibiting a pavilion urban organizational type characteristics, are presented in Fig. 13.

Here, it was once again proven that the simple integration of photovoltaics on to buildings in their current state has a negligible positive influence on the thermal comfort of users in Luleå, given a pavilion type layout, at 12:00 during the summer solstice, as the variations in PET once again range from 0 to −2,5 degrees. Conversely, the simulations at this point demonstrate that the increase in urban fabric density, by doubling the building height, leads to greater PET fluctuations ranging mostly from −7,5 to +5 degrees, creating less favourable conditions for public space users at that specific hour. On the other hand, the change of the urban organizational layout in Luleå for this date, time and

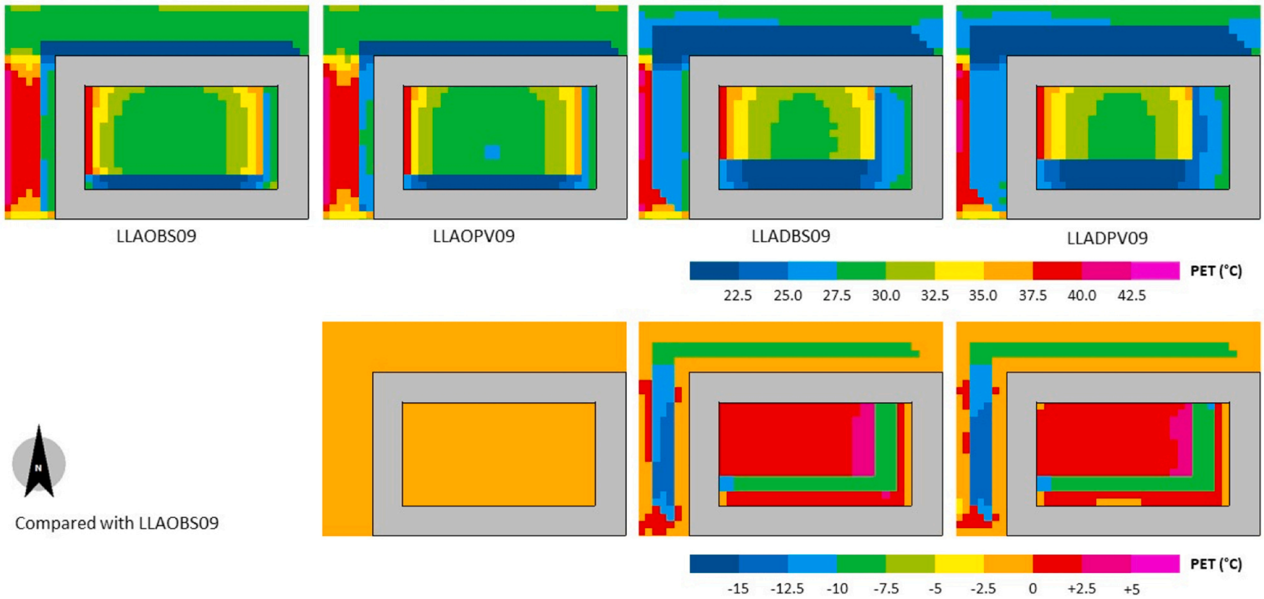

Fig. 10. The results of the simulations for LLAOBS09 on top, compared to the base case at bottom.

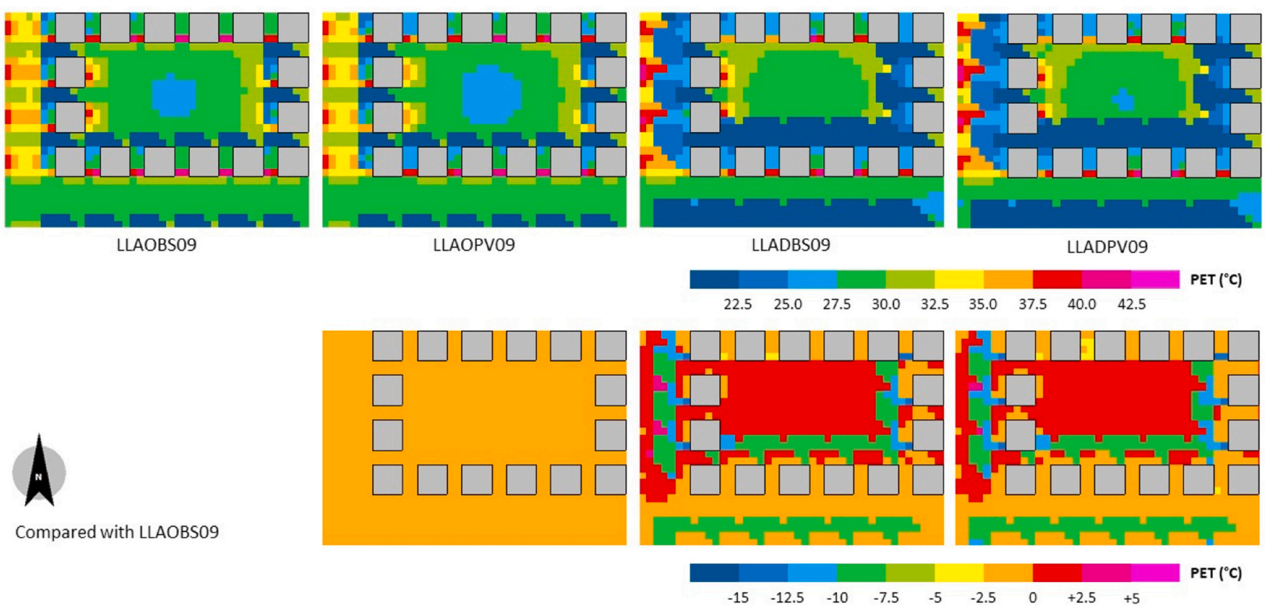

Fig. 11. The results of the simulations for LLAOBS09 pavilion type on top, compared the base case at bottom.

configuration, leads to slightly better results, if it is compared to the patio layout. Finally, the integration of photovoltaics on to double-height buildings does not affect the results for this time slot and building geometry, and the situation remains the same as before.

4.2.3. LLAOBS15

The simulations continue with LLAOBS15, representing Luleå's original single-height configuration at 15:00. The simulations and comparisons with LLAOPV15, LLADBS15 and LLADPV15 performed for this stage, are presented in Fig. 14.

As previously, the simulations at this point demonstrate that the simple integration of photovoltaics on to buildings in their current state has negligible positive influence on the thermal comfort of users in Luleå at 15:00 during the summer solstice, as the variations in PET range once again from 0 to −2,5 degrees. Conversely, increasing the urban fabric density by doubling the building height, leads to greater PET fluctuations ranging from −15 to +5 degrees, creating less favourable conditions for public space users at that specific hour, with some small exceptions created by the geometry of the buildings. Finally, the integration of photovoltaics into double-height buildings does not have an impact on the PET values.

Similar to above, the influence of the urban organizational layout at this time was also investigated. The results of the simulations and the comparisons of parameters for the LLAOBS15 case exhibiting a pavilion urban organizational type, are presented in Fig. 15.

At this point, it is once again proven that the simple integration of photovoltaics on to buildings in their current state has a negligible positive influence on the thermal comfort of users in Luleå, given a pavilion type layout, at 15:00 during the summer solstice, as the variations in PET once again range from 0 to −2,5 degrees. Conversely, the simulations at this point demonstrate that an increase of the urban fabric density by doubling the building height, leads to greater PET

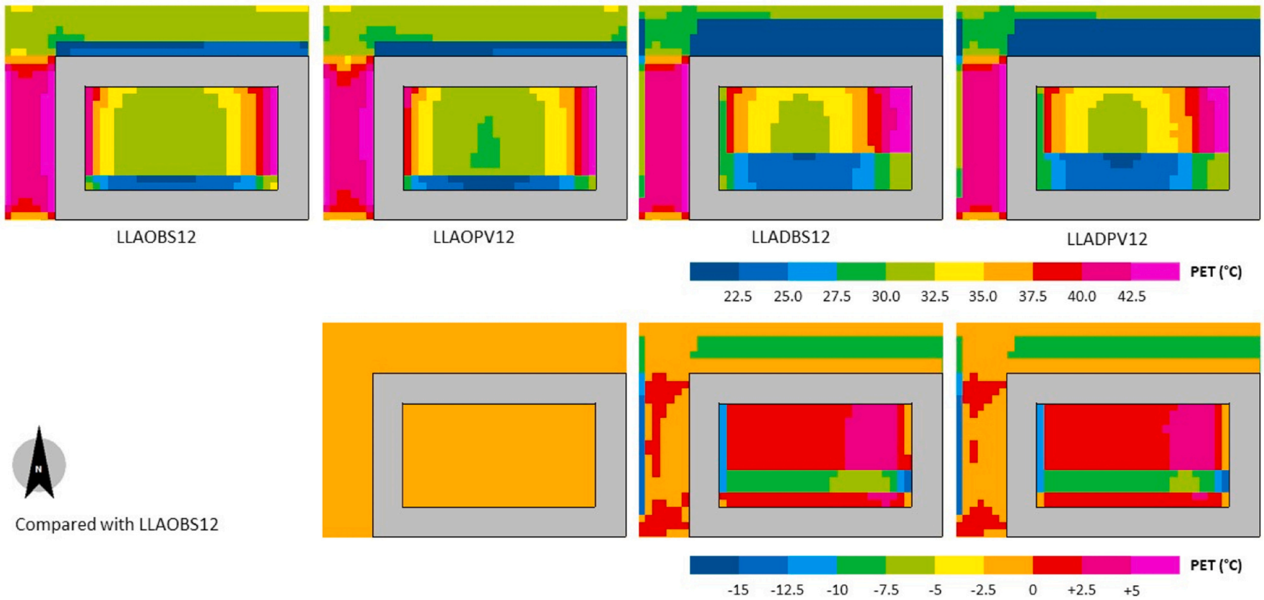

Fig. 12. The results of the simulations for LLAOBS12 on top, compared to the base case on bottom.

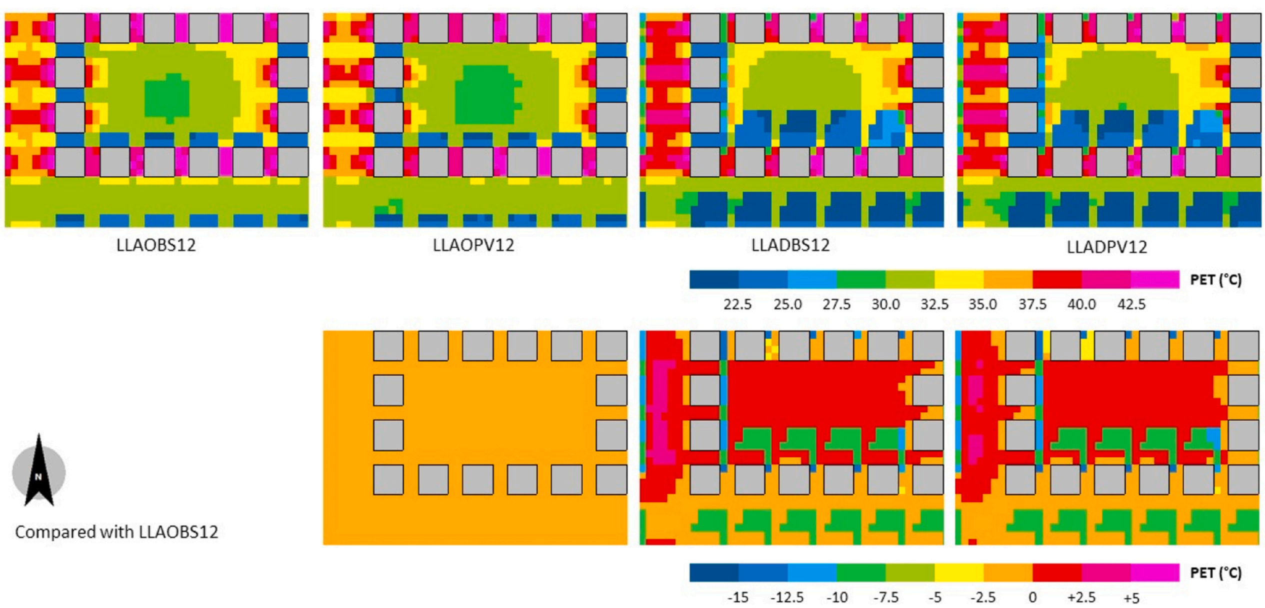

Fig. 13. The results of the simulations for LLAOBS12 pavilion type on top, compared to the base case on bottom.

fluctuations, ranging mostly from −12,5 to +2,5 degrees, creating less favourable conditions for public space users at that specific hour. On the other hand, the change of the urban organizational layout in Luleå for this date, time and configuration, leads to slightly better results if it is compared to the patio layout. Finally, the integration of photovoltaics into buildings twice as high, does not affect the results at this time slot and building geometry, and the situation remains the same as before.

5. Discussion and conclusions

Our research question was: what is the impact of BIPV on user comfort in public spaces between buildings?

The study examined how the materiality, the density and the geometry of building stock layout in typical city blocksin the two extremes of Europe, Limassol, Cyprus, and Luleå, Sweden, affects thermal comfort in the open spaces between buildings. Using ENVI-met, the thermal conditions at street level are simulated for a geometrically simplified representative example of the urban fabric of each city, for a number of parameters, aiming to determine the best combination.

The researchers carried out simulations to assess the impact of photovoltaic panels integration and urban fabric density, on thermal comfort in the public space between buildings in two different cities, Limassol, Cyprus, and Luleå, Sweden. The simulations were performed at three time slots (09:00, 12:00, and 15:00) during the summer solstice, and different scenarios were compared against the base case to discern the specific effects of each parameter variation.

In both cities, the integration of photovoltaic panels on to buildings in their current state showed negligible positive influence on the thermal comfort of public space users. The variations in PET ranged from 0 to −3 degrees at 09:00, indicating minimal improvement. Similarly, at 12:00 and 15:00, the impact remained insignificant, with PET variations ranging from 0 to −3 degrees. These results suggest that photovoltaic

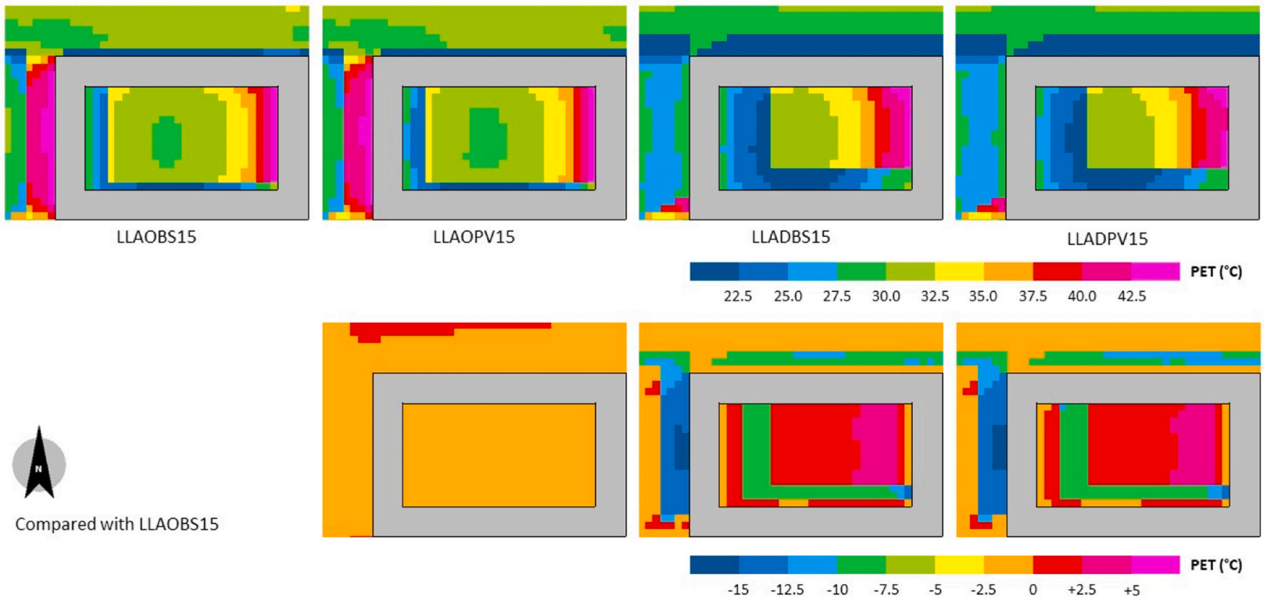

Fig. 14. The results of the simulations for LLAOBS15 on top, compared to the base case on bottom.

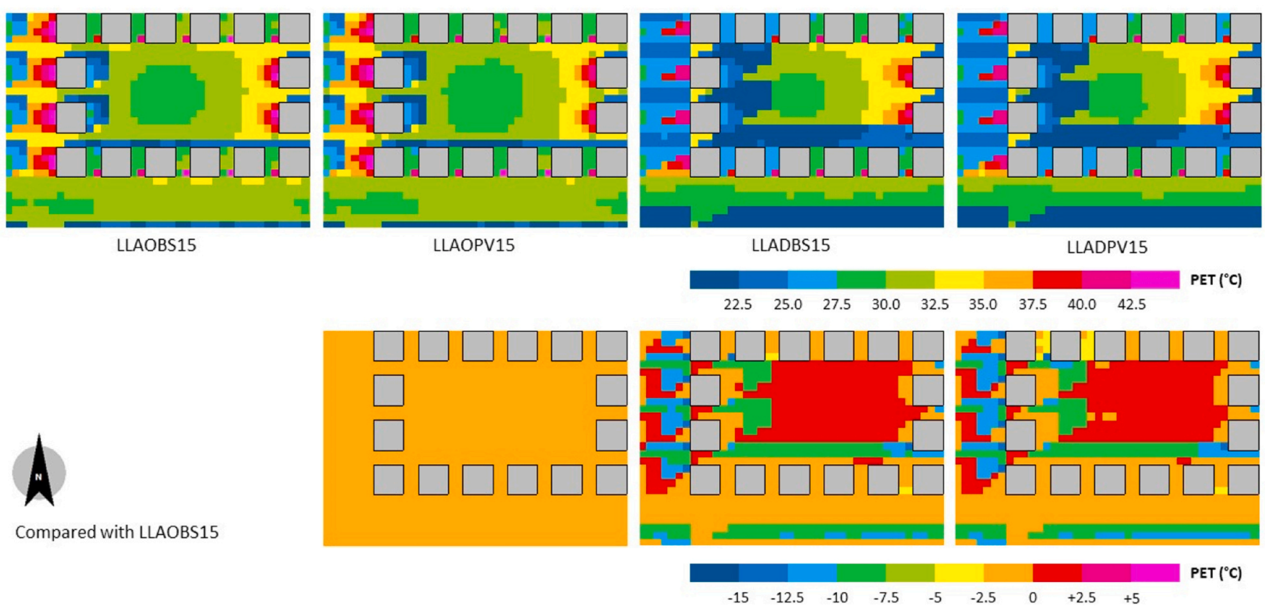

Fig. 15. The results of the simulations for LLAOBS15 pavilion type on top, with the comparisons with the base case on bottom.

integration alone is not sufficient to significantly enhance thermal comfort during the summer solstice in the urban contexts examined.

Increasing the urban fabric density by doubling the building height resulted in greater PET fluctuations, ranging from −3 to +3 degrees. This increased density created slightly less favourable conditions for public space users, particularly during the specific hours analysed. The integration of photovoltaics on to buildings twice as high, partially mitigated this fluctuation, reducing the area exhibiting increasing trends in PET. However, the mitigation effect was not significant compared to the base case, indicating limited benefits in terms of thermal comfort improvement. A summary of all the results is presented in Fig. 16, to provide an overview of the findings.

The influence of an urban organizational layout at the city block scale, was also examined, with the transition from a pavilion to a patio layout in Limassol and vice versa in Luleå. The simulations showed that the change in urban morphology had a slightly bigger impact on thermal comfort compared to the integration of photovoltaics. In Limassol, the pavilion layout demonstrated slightly better thermal comfort results compared to the patio layout, while in Luleå, the pavilion layout provided slightly better conditions compared to the patio layout. However, the differences were not substantial, and the impact of the urban morphology alone on thermal comfort remained limited.

Overall, the findings suggest that solely integrating photovoltaic panels or modifying the urban morphology does not lead to significant improvements in thermal comfort during the summer solstice in the cities examined; thus, it can be inferred that the implementation of BIPVs preserves thermal comfort in outdoor environments across different configurations, indicating potential co-benefits in contributing to renewable energy production while maintaining favourable microclimatic conditions. Other strategies and interventions may need to be considered to effectively enhance thermal comfort in public spaces. Additionally, further research could explore the combination of various

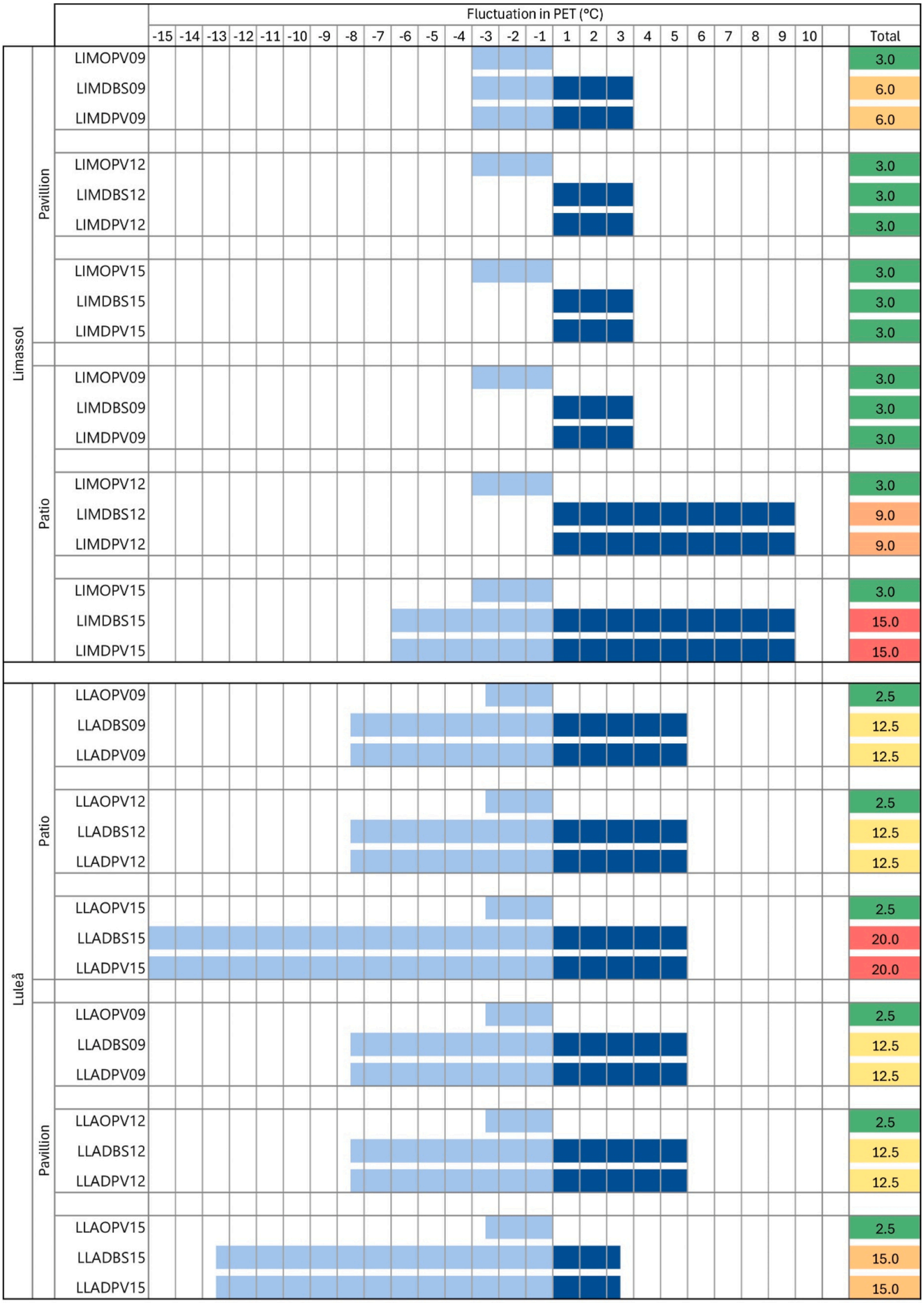

Fig. 16. A summary of all the results. PET fluctuation (as well as the total value of this fluctuation) is presented, showcasing the instances where the difference between the base case to the proposed scenario is minimal.

parameters, such as vegetation, shading devices, and building materials, to identify more effective strategies for improving thermal comfort in urban environments.

In conclusion, the research complements and enriches the current literature by addressing the impact of Building-Integrated Photovoltaics (BIPVs) on the thermal comfort of users of urban environments in general and of public spaces between buildings in particular. While previous studies have explored the effects of various parameters, such as materiality (Wonorahardjo et al., 2022; Wonorahardjo and Sutjahja, 2018), urban morphology, and height of buildings (Bajšanski et al., 2015; Wai et al., 2020; Sharmin et al., 2015; Li et al., 2020), on thermal comfort and urban climate, there is limited research specifically focusing on the influence of BIPVs. This work fills this gap by investigating the thermal effects of BIPVs on building surfaces to user comfort in the spaces between the buildings. Through the findings, valuable insights into the complex relationship between BIPVs and thermal comfort in the interstitial spaces is provided, highlighting the need for careful consideration of design choices when integrating BIPVs into buildings. Furthermore, the current research underscores the importance of a parametric investigation in understanding the optimization of thermal comfort in complex urban environments, offering a systematic approach to evaluate the impact of various design parameters on thermal performance. By bridging this gap in knowledge and providing practical insights, this study contributes to the advancement of sustainable urban development and the design of comfortable built environments. The novelty of this research lies in its comprehensive investigation of various parameters that affect thermal comfort in public spaces, including different scenarios of building integration of active solar systems and changes in urban layout. The findings of this study aim to provide valuable insights for urban planners and policymakers to make informed decisions to improve thermal comfort in public spaces and to achieve sustainable urban development in the face of climate change challenges.

5.1. Future research

In the future research endeavours of the team, the focus will be on delving deeper into the technical aspects of Building-Integrated Photovoltaics (BIPVs) and their impact on thermal comfort in urban environments. One avenue for exploration involves conducting a more detailed analysis of innovative types of BIPVs, including novel materials and technologies, and their potential effects on urban microclimates. Additionally, research will be directed towards investigating the thermal effects associated with different colours of BIPVs and their implications for pedestrian comfort. This future study will adopt a more focused approach, potentially at a smaller scale, allowing for a comprehensive examination of the thermal dynamics of BIPVs within the urban fabric. Furthermore, case studies involving groups of buildings equipped with BIPVs will be conducted to measure their actual effects on pedestrian thermal comfort in real-world scenarios. The findings from this future research endeavour will contribute to a deeper understanding of the role of BIPVs in enhancing thermal comfort in urban environments and inform more innovative approaches to sustainable urban design and energy planning.

Author Statement

All authors have contributed equally.

CRediT authorship contribution statement

Andreas Savvides: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Kevin Lau:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Constantinos Vassiliades:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Agatino Rizzo:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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