EARLY DESIGN EVALUATION OF SCHOOL BUILDING MORPHOLOGY ON ENERGY PERFORMANCE: CLIMATIC CONTEXTS OF SOUTHEAST EUROPE

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **"Early design evaluation of school building morphology on energy performance: climatic contexts of Southeast Europe"** and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

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Contemporary societies have shifted their focus towards sustainable and resilient public buildings, transcending the institutional and functional role of the physical structures. School buildings, despite the high impact on setting everyday standards of comfort, remain the second highest expenditure of municipalities' total running costs. The impact on well-being and improved knowledge along with the average lifespan of school buildings, imply the necessity to pay special attention to its expected performance since the early design phase, as the main influencer on the building performance. The building geometry, the most salient design characteristic in a building, has substantial influence on its energy performance. Studies on the impact of school buildings morphology are rare but present. However, there is a literature gap regarding the influence of specific climate contexts on the performance of open-schools. Hence, the present research aims to contribute to estimating the impact of early design evaluation of open-school building morphology on energy performance in the climatic contexts of Southeast Europe. Design variables including building shape and orientation are selected for a comprehensive whole-building energy performance analysis. The results highlight the efficiency of the method in reducing a maximum of 33.7 % of the annual energy demand and in increasing a maximum of 1.15 °C the thermal comfort in classrooms by means of geometry optimization. Suggestions are made on the appropriateness level of each typology for each studied climatic context. The Design Builder interface version 6 for Energy Plus is selected to develop the simulations in different climate contexts of Southeast Europe. A

fundamental framework towards early design decision-making stages is generated through the performed simulation results.

Keywords: *Simulation, morphology, open-school buildings, energy optimization, early design evaluation, climate*

ABSTRAKT

VLERËSIMI I HERSHËM I MODELIT TË MORFOLOGJISË SË SHKOLLAVE MBI PERFORMANCËN E ENERGJISË NË KONTEKSTET KLIMATIKE TË EVROPËS JUGLINDORE

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Shoqëritë bashkëkohore kanë zhvendosur fokusin e tyre drejt ndërtesave publike të qëndrueshme dhe elastike, duke tejkaluar rolin institucional dhe funksional të strukturave te tyre fizike. Ndërtesat shkollore, përkundër ndikimit të lartë në vendosjen e standardeve të përditshme të komfortit, mbeten shpenzimi i dytë më i lartë i fondeve të bashkive. Ndikimi në mirëqenien dhe njohuritë e përmirësuara nxënësve së bashku me jetëgjatësinë mesatare të ndërtesave shkollore, nënkuptojnë nevojën për t'i kushtuar vëmendje të veçantë performancës së saj të pritur që nga faza e hershme e projektimit, si ndikuesi kryesor në performancën e ndërtesës. Gjeometria e ndërtesës, karakteristika më e spikatur e projektimit në një ndërtesë, ka ndikim thelbësor në performancën e saj të energjisë. Studimet mbi ndikimin e morfologjisë së ndërtesave shkollore janë të rralla, por të pranishme. Sidoqoftë, ekziston një hendek i literaturës në lidhje me ndikimin e konteksteve specifike të klimës në performancën e shkollave të hapura per komunitetin. Prandaj, hulumtimi i tanishëm synon të kontribuojë në vlerësimin e ndikimit të morfologjisë së ndërtesës së ketyre shkollave në performancën e energjisë në kontekstet klimatike të Evropës Juglindore. Variablat e projektimit duke përfshirë formën dhe orientimin e ndërtesës janë zgjedhur për një analizë gjithëpërfshirëse të performancës së energjisë të tërë ndërtesës. Rezultatet nxjerrin në pah efikasitetin e metodës në zvogëlimin e një maksimumi prej 33.7% të kërkesës vjetore të energjisë dhe në rritjen maksimale prej 1.15 ° C te komoditetit termik në klasa me anë të optimizimit të gjeometrisë. Sugjerime bëhen në nivelin e

përshtatshmërisë së secilës tipologji për secilin kontekst klimatik të studiuar. Versioni 6 i Design Builder për Energy Plus është zgjedhur për të zhvilluar simulimet në kontekste të ndryshme klimatike të Evropës Juglindore. Një kornizë themelore drejt fazave të hershme të vendimmarrjes së dizajnit gjenerohet përmes rezultateve të simulimeve të kryera.

Fjalët kyçe: *simulimi, morfologjia, ndërtesat e shkollave të hapura per komunitetin, optimizimi i energjisë, vlerësimi i hershëm i dizajnit, klima*

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Contemporary societies have shifted their focus towards sustainable and resilient public buildings, transcending the institutional and functional role of the physical structures. Public buildings nowadays are perceived as model buildings which serve as good practice examples in envisioning the immediate and long-term advantages of green building principles. This is evident in the recent changes of demand for public entities; among them schools, offices and other public institutions. A tendency of reducing primary energy demands by 25% every 5 years is noticeable. (Ramboll, 2010) By addressing the youngest population during the years of their formation, the role of schools as a good practice example becomes greater when confronted to that of other public institutions. Building users are engaged with environmental issues in buildings, under the concept of “School as a teaching tool”. Students adopt the design and operation features of the facility as an everyday norm, and expect the same design and operational models, as well as comfort levels in their future living and working places.

Still, despite the tendency to set new norms and standards, energy consumption in public schools remains the second highest expenditure of municipalities' total running costs. The high energy consumption does not necessarily mean that thermal comfort is provided in classrooms, as studies reveal otherwise. (Duarte et al., 2017; Corgnati et al., 2009) With more than 64 million European school children and 4.5 million teachers spending around 200 days in school per year, any efficient building design is necessary to improve the situation. Children spend around 70% of their time indoors corresponding to almost 1 year indoor throughout primary school years and researches show that a well-designed indoor school environment will promote improved knowledge and learning, as well as children’s health and well-being.

The impact on energy consumption, student well-being and improved knowledge, along with the average lifespan of school buildings, imply the necessity to pay special attention to its expected performance since the early design phase, as the early stage of building design is the major influencer on the building performance. (Granadeiro, Duarte, Leal, & Correia, 2013) The complexity of the design process often shifts attention away from energy consumption and efficiency into other aspects a designer may consider of a greater importance or has the capability and tools to deal with. To address this issue, practitioners of the field should be provided with enough guiding information in order to deal with contrasting objectives during the early design process.

The majority of existing studies on building performance state the importance of materials, façade solutions and ventilation system while geometry is nonchanging in the whole life cycle of a building and its impact substantial on energy consumption. Some stress the impact of form on buildings of different functions (Al-Anzi et al., 2007; Parasonis et al., 2012; Premrov et al., 2017; Ciardiello et al. 2020), but their outcomes are not applicable due to particularity in the usage pattern that school buildings have. Among the ones addressing the impact of form, there is a limited number of studies aimed at energy evaluation of schools of different morphologies (Zhang et al., 2017; Montenegro et al., 2012; Zomorodian et al., 2013; Perez et al. 2009). Still, the climatic impact on the results and suggested geometries, justifies the need for further studies.

1.2 Thesis Objective

Even though the influence of building morphology on energy performance of schools has been clearly stated, a literature gap on the impact of specific climatic contexts on energy and thermal performance exists. Therefore, the present research aims to estimate the climatic influence on the early energy evaluation of 21st century open-school buildings morphology in Southeastern Europe, a region with a high climatic variance. Through simulations, the impact of morphology on energy performance can be measured and used as parameters and guidelines for the design of new school buildings in Southeast Europe and in locations displaying similar climatic patterns with those found in the studied region. An improved thermal comfort of the occupants and economic benefits for governments or private entities of those regions are ensured.

1.3 Structure

This thesis is divided in 5 chapters. The organization is done as follows:
In Chapter 1, the problem statement and thesis objective are presented. Chapter 2, includes the literature review. Chapter 3, consists of the methodology followed in this study. In Chapter 4, the simulated results are presented. Chapter 5 consists of the discussion session where main results are evaluated. In Chapter 6, conclusions and recommendations for further research are stated.

CHAPTER 2

LITERATURE REVIEW

2.1. Theoretical background

2.1.1. Environmental comfort and student learning

The importance of environmental comfort in student learning, was recognized since the mid-19th century in the books of Barnard (1854). Later studies revealed a link between performance and indoor air quality, temperature and humidity, ventilation and lighting conditions as well as acoustics. (Schneider, 2002; Wargocki et al., 2017; Jiang et al., 2018) These parameters are set and strongly influenced by building design and its adjustments to user activities. As a highly complex process, architectural design integrates building, occupant demands and environmental conditions. For specific buildings user behavior should be assessed in more detail, to enable the optimization of building for the actual user and its peculiarities. (Hoes et al., 2009) Due to the particular needs of students in learning and growth, school design process requires focusing on user comfort and on student-teacher performance while limiting energy use to extents.

2.1.2. Energy consumption and influencing parameters

Energy consumption in public schools is estimated to be the second highest expenditure of municipalities' total running costs. Still, despite the high energy consumption, studies reveal that thermal comfort is usually not provided in classrooms. (Duarte et al., 2017; Corgnati et al. 2009) In Europe students spend more than one third of their time inside school. (Mendes et al., 2014; Annesi-Maesano et al. 2013) Any efficient building design is necessary to improve the situation. Several architectural and construction parameters are influential on building energy performance. The majority of them can be modified along a building operational phase and so can their performance. Morphology and other variables with a lifespan impact on energy expenses need to be carefully considered since the early design phase.

2.1.2.1. Shape factor

Building energy performance standards account for reliable semantic and quantitative indicators of building morphology. As a nonchanging element in the whole life cycle of a building, shape factor has been previously studied and its effects on energy consumption mostly for dwellings and office buildings, has been addressed.

In a study done on office buildings in Kuwait, several building shapes and forms including rectangular, L-shape, U-shape, and H-shape were considered through a comprehensive whole building energy simulation analysis and WWR, RC and glazing materials were found to have a considerable influence in total energy use. In low WWR buildings, the total energy use is found to be inversely proportional to the building RC independent of its form (Al-Anzi et al., 2007)

Parasonis et al. (2012) found a different demand for energy at buildings of similar areas but of different geometries and envelopes. Building with an approximate internal area of 3000 m2 and various proportions showed a geometric efficiency range of 20%. (Parasonis, J., Keizikas, A., and Kalibatiene, D., 2012).

Premov et al. (2017) put an emphasis on climate context conditions while determining the influence morphology has on building energy performance. In their research on timber glass-buildings, warm climate conditions are found to generate almost opposite findings when compared to cold climates. A higher aspect ratio is recommended in cold climates for a reduced energy use. (Premrov et al., 2017).

Passive volume ratio, sum of roofs and best oriented surfaces were the parameters Camporeale et al. (2019) studied while morphologically optimizing high-rise housing typologies and studying the influence on energy use. The optimization process of the performance-driven building shapes was based on local climate requirements. The passive strategies were applied at the concept stage of the architectural design and the workflow they introduce is suitable for different building typologies and climate locations. (Camporeale et al., 2019)

In a recent study of Ciardiello et al. (2020), a multi-objective optimization approach was developed based on a genetic algorithm to optimize energy consumption of a case study building in the Mediterranean climate. By means of geometry optimization 60% of the annual energy demand could be saved and once the geometry was fixed, by means of passive and active strategies 23% of the annual energy cost was reduced. (Ciardiello et al. 2020)

2.1.2.2. Relative compactness

Depecker et al. (2001) studied 14 buildings conceived from the same basic cell to find that the energy consumption and compactness (the ratio between the external skin surfaces and the inner volume of the building) were inversely proportionate in case of cold severe and scarcely sunny winters. Still the findings are not applicable in case of mild climates, where compactness is not recommended. (Depecker et al., 2001)

Given that buildings with the same compactness attribute may differ in orientation, morphology and enclosure transparence, Werner et al. (2003) used extensive parametric thermal simulations to study the reliability of compactness indicators for energy-related evaluative assessments. A significant association was found between RC and simulated heating loads of buildings with a variance in shape, glazing percentage, glazing distribution and orientation. (Werner et al., 2003)

The need to introduce and consider other parameters besides shape coefficient or relative compactness, was also introduced in a study of Albatici et al. (2010) that strongly suggested a strict consideration of orientation, openings, exposition to atmospheric agents and natural elements in the optimization process. The results of the study laid in the Italian territory recommend a bioclimatic approach in the early design phase for better results to be obtained. (Albatici et al., 2010)

Muhaisen et al. (2013) found an increase of same rate in both energy consumption and RC of housing units in the Mediterranean climate of the Gaza Strip. The study further recommends the application of passive solar design strategies, as residential apartments having a horizontal arrangement were found to perform better thermally than the ones having a vertical arrangement of the same RC. (Muhaisen et al., 2013)

Similar studies in different climatic contexts display dissimilar results. This leads to adopting design methods with proper regard of climate issues in order to obtain an enhanced energy performance of buildings. Boubekri et al. (2017) studied the case of small, medium and tall office buildings of different morphologies in U.S.A to find that heating loads decreased with the increase in RC. (Boubekri et al., 2017)

Hassan et al. (2020) found different building morphologies with varying relative compactness (RC) to have a substantial impact even on the dispersion of pollutants. The results of the study show an approximate reduction of 30%–90% at specific points in the studied time sequence, thus proving the significance morphology in the improvement of outdoor air quality (Hassan et al., 2020)

2.1.2.3. Window-to-wall ratio

Among the components of a public building's envelope, the transfer coefficients of the outside windows are the ones with the greatest impact on indoor thermal load, this according to a study done in Beijing by Hu et al. (2015). Simulations with DeST-c software on the building envelope with components of different thermal property, have shown the roof to be secondary and the exterior walls the weakest influencers on thermal performance. (Hu et al., 2015)

A workflow considering both daylighting and energy consumption in the optimization process of WWR with sunshades is proposed by Xue et al. (2019) The minimum WWR is suggested to be set considering daylighting requirements, while the maximum WWR is determined according to energy consumption. The study done in

China low latitude region displays standards verified to be applicable in a variety of buildings and climates. (Xue et al., 2019)

Persson et al. (2006) studied the impact WWR has on energy efficiency in different seasons of the year. 20 terraced houses built in Gothenburg, Sweden were modelled and simulated to show that WWR has a major influence on the cooling demand in summer, but is not relevant for the heating demand in winter. An increase on WWR of north-facing walls is highly recommended for better lighting conditions, thus providing architects with a variance in possibilities while designing façades. (Persson et al., 2006)

2.1.2.4. Courtyards

Salameh et al. (2017) while studying the impact of a closed courtyard with different proportions on school building in UAE, emphasized the private outdoor space, improved thermal comfort, ventilation properties and the minimized energy consumption courtyards have to offer. Furthermore, safer inner playgrounds and learning scientific atmosphere for the students are promoted through the integration of courtyards in school morphologies. Still, the study suggests a correlation between the courtyard proportions and the height and function of the building (Salameh et al., 2017) as it has a direct impact on ventilation, lighting and thermal performance of the adjacent interior spaces. (Guedouh et al., 2017) In the cold climates of China, an integrated school and schoolyard design approach can mitigate school heat stress reducing by 25% the outdoor discomfort time and improve energy performance by decreasing 5% building cooling demand. (Zhang et al., 2017)

Zamani et al. (2018) studies length-to-height courtyard proportion as one of parameters with the greatest influence on courtyard climatic function. Results claim that a length to height ratio less than 5 can easily manage airflows. Vegetation cooling effect is found to be higher than that of water basins. (Zamani et al., 2018)

Yaşa et al. (2014) goes further, associating the courtyard proportions even with the features of the climatic region. 7 courtyard forms in different climatic regions in

Turkey were studied and air movements, sun-shadow, length-depth ratio relations were observed to determine their effect on thermal performance. The inter-courtyard shadowy areas were increased the closer to the square shape the courtyard got and shadowing showed a higher influence on heating loads than on cooling loads. Influenced by the direction of prevailing wind, the annual energy consumption increased with the increase in courtyard length. (Yaşa et al., 2014) It is long known that courtyards have the ability to change wind pressure coefficients due to their surfaces, vegetation and their wind shadowing effects. (Safarzadeh et al., 2005)

Covered courtyard edifices display a dissimilar behavior. A study on annual energy performance of covered-courtyard hotel buildings in Belgrade showed a significant contribution of the atrium on heating and cooling energy savings in the rest of the building. Still the high demand of the atrium itself for air-conditioning cast doubts on the efficiency of its integration in building plans. Certain parameters were studied and varied (orientation, building structure..) to observe the influence on energy performance. (Vujošević et al., 2017)

Table 1. *Reviewed scientific literature concerning early-design evaluation (please, note that WWR is window-to-wall ratio, RC is relative compactness)*

Contribution area	Authors	Description
Shape factor	Premrov et al. (2017)	The increasing aspect ratio shows a positive influence on the energy need reduction. In the case of warm climate conditions the findings are almost opposite to those for cold climates.
	Parasonis et al. (2012)	Buildings of similar areas but different external envelope areas have different demand for energy at their operation stage and different demand for building materials at the construction stage.
	Camporeale et al. (2019)	Primary energy consumption (PE)1 of slab and high-rise housing typologies is reduced through the optimization of their building shapes. The process considered applies passive strategies at the concept stage of the architectural design
	Al-Anzi et al. (2007)	Energy use of office buildings is mostly affected by three factors: WWR, RC, and glazing materials. Total energy use in buildings with RC independent of its form, were found inversely proportional in low WWR buildings.
Relative compactness	Werner et al. (2003)	A significant association was found between RC and simulated heating loads of buildings with a variance in shape, glazing percentage, glazing distribution and orientation. given that buildings with the same compactness attribute could differ in enclosure transparence, orientation, and morphology
	Depecker et al. (2001)	The energetic consumption is inversely proportional to the compactness (weak shape coefficient) in case of cold severe and scarcely sunny winters. However, it can't be applied in case of mild climates, which leads to no recommendation of compactness
	Albatici et al. (2010)	Shape coefficient is not the only parameter to be considered in the first stage of the design process, but better results can be achieve considering a bioclimatic

		(even if simplified) approach by the very beginning. Some aspects such as orientation, openings, exposition to atmospheric agents and natural elements must be strictly considered.
	Muhaisen et al. (2013)	The surface to volume ratio is the main responsible for the thermal response in different geometric shapes. Increasing the depth ratio in convex shapes has the ability to increase the percentage of the shaded facades which help to reduce heating and cooling energy.
	Boubekri et al. (2017)	Designing with proper regard of climate issues leads to enhanced energy performance. Heating loads decrease with the increase in RC of office buildings in three different cases.
	Hassan et al. (2020)	Different designs of building morphology with varying Relative compactness (RC) indicator highlight the importance of considering morphological factors to improve outdoor air quality
WWR	Hu et al. (2015)	The transfer coefficients of the outside windows have largest effect on indoor thermal load, the roof is secondary, and exterior walls are weakest.
	Persson et al. (2006)	The size of the energy efficient windows does not have a major influence on the heating demand in the winter, but is relevant for the cooling need in the summer. It is possible to enlarge the window area facing north and get better lighting conditions.
	Xue et al. (2019)	The minimum WWR is set considering daylighting requirements, while the maximum WWR is determined according to energy consumption.
Courtyards	Yaşa et al. (2014)	A courtyard should be applied in a form compatible with the features of the climatic region it is used.
	Safarzadeh et al. (2005)	Wind pressure coefficients change in buildings with courtyards in comparison with the buildings without courtyards, due to the courtyard surfaces, vegetation and its wind shadowing effects.
	Zamani et al (2018)	The courtyard length-to-height ratio is one of the most influential factors on courtyard climatic function. Airflows can be managed through keeping the right ratio of courtyard`s length to height (less than 5).Vegetation cooling effect is greater than water basins.
	Zhang et al. (2017)	The integrated school and schoolyard design approach is effective for mitigating school heat stress reducing the outdoor discomfort time by 25% and energy saving decreasing building cooling demand by 5%.
	Guedouh et al. (2017)	Findings are related to the high potential for natural lighting and thermal control that, and later, discovered the relationship between the morphological indicators and the qualities of thermal and luminous environments of adjacent spaces,
Environmental comfort	Hoes et al.(2009)	For specific buildings, user behavior should be assessed in more detail, to allow the building design to be optimized for the actual user and its peculiarities.
	Zomorodian et al. (2016)	Students′ thermal preferences are not in the comfort range provided in the standards. Ventilation as an essential determinant of indoor air quality and thermal comfort has been highlighted in most studies. The wide disparity in thermal neutralities underlines the need for micro-level thermal comfort studies.
	Jiang et al. (2018) Schneider (2002) Wargocki et al. (2017)	Thermal discomfort caused by high or low temperatures has a negative impact on pupil learning performance. The temperature variation affected not only thermal comfort, but also pupil well-being.

2.2. Previously related studies

To develop a better predictive framework for early-design evaluation of school building morphology, scientific literature is reviewed.

Da Graça et al. (2007) presented fuzzy set theory as a method for the evaluation and optimization of parameters of seven school building morphologies in São Paulo, Brazil. In the optimization process, four aspects of comfort were analyzed: thermal, acoustic, natural lighting, and functionality. The maximization of various comfort aspects was shown to be improbable; however, compromises could still be found. (Da Graça et al., 2007)

The influence of different design variables on the energy consumption of school buildings was assessed in a study conducted by Perez and Capeluto (2009)in the hot–humid climatic zone of Israel. In order to determine the variables with the greatest impact on energy consumption and thermal comfort in the classroom, comparative tests were undertaken. The results highlight the presence of a complex interdependence among design variables, and recommend values for each variable required to achieve a high-performance classroom. (Perez et al., 2009)

Dimoudi et al. (2009) did a summary of school morphologies in terms of building plan in a region displaying the lowest air temperature during the winter period- the C' climatic zone of Greece. As the most abundant in the region, 'ATHINA' type in 5 different classroom openings' orientation was selected for a thorough thermal performance study through data monitoring. A combination of different energy saving measures was suggested. (Dimoudi et al., 2009)

Montenegro et al. (2012) analyzed nine spatial typologies of school buildings modelled through 3 recurring classroom proportions for cold (Montreal, QC, Canada) and temperate (Santiago, Chile) climates. Their visual, thermal, and energy performance study found a consistent relation between an improved performance and linear typologies under both climates. The research casts doubt on the compactness of form as the best solution for energy saving. (Montenegro et al., 2012)

Zomorodian et al. (2013) selected, modeled and analyzed a typical elementary school in the hot and dry climate of Iran by varying geometry parameters such as building shape, space organization and WWR. A decrease by 31% in the primary energy demand of the studied case was found by solely applying optimum architectural strategies while simulating, without any change in construction parameters and building materials. (Zomorodian et al., 2013)

Su (2013) with a focus on winter thermal performance in Auckland, New Zealand showed that the high ratio of building surface to volume of conventional school designs in Auckland was not appropriate for the local climate. Therefore, a minimization in the number of isolated buildings and an increase in the height and volume of school buildings was suggested to improve the thermal and energy performance. (Su, 2013)

Zhang et al. (2017) simulated and compared three kinds of plan layouts with a variance in glazing materials, shading types, WWR interface, room and corridor depths. A multi-objective genetic algorithm was utilized to optimize both the thermal and daylight performance of schools in the cold climate of China. The best performance was obtained by the double-sided corridor school, as the most suitable for the cold climate as it manages reduce summer thermal discomfort by 9–23%, lighting and heating demand by 24–28% and increase UDIavg (100–2000 lx) by 15–63%. A careful consideration of the passive design parameters is recommended as each spatial configuration has its own optimal passive design parameters. . (Zhang et al., 2017)

In a later study, Zhang et al. (2017) through simulations and questionnaires observed the thermal and energy performance of 7 different school building morphologies to conclude that the best performance was shown by H shape building. When compared to the base case scenario, 13.6% of energy savings and 3.8% of thermal comfort improvement could be achieved through a variance in building shape, WWR, room depth and orientation. A reduced proportion of west-oriented rooms, a WWR of 20–40% and rooms with a depth smaller than 8m had more possibilities to achieve energy savings. Still, students’ preference for rooms of a greater depth needs to be considered during the early design phase. (Zhang et al., 2017)

Table 2. *Data available in scientific literature for early-design evaluation of school building morphology (please, note that WWR is window-to-wall ratio)*

Authors	Year	Climate	Aspects of comfort studied	Variables	Method/Program	Model	Location
da Graça et al.	2007	Oceanic (Cfb)	Thermal, acoustic, natural lighting, functionality.	Position of the openings, form, orientation, location of functions	fuzzy set theory	7 school building morphologies	Sao Paolo, Brazil
Perez et al.	2009	Hot humid Mediterranean (Csa)	Thermal, visual, energy performance	Orientation, light control, shading, window size, infiltration, night ventilation, glazing, roof insulation, wall insulation	ENERGY, SHADING, RADIANCE	base-case classroom	Israel
Dimoudi et al.	2009	C' climatic zone of Greece	Energy performance	thickness of the wall, thermal insulation, airtightness, shading devices	SUMMER-BUILDING	ATHINA school building morphology in 5 different classroom openings' orientation.	Greece
Montenegro et al.	2012	cold (Dfb) in Montreal and cool semi-arid climate (Csb) in Santiago	visual, thermal, indoor air quality, energy performance	3 classroom types (2:3, 1:1 and 3:2)	IES-VE	9 school building morphologies	Montreal, Canada Santiago, Chile
Zomorodian et al.	2013	hot and dry climate of Iran	visual, thermal, energy performance	orientation, WWR, space organization, sun shading, and building shape	Energy Plus	a three story prototype elementary school building	Iran
Su	2013	oceanic	Energy performance	ratio of : building surface to volume, roof surface area to building volume, wall surface area to building volume, roof space volume to building volume, WWR, window area to building volume, window to floor area, north wall and total wall area	real data collection		Auckland, New Zealand
Zhang et al.	2017	Cold climates of China	thermal, energy performance	building shape, WWR, room depth, orientation	Energy Plus questionnaire-based survey	7 school building morphologies	China
Zhang et al.	2017	Cold climates of China	energy use, summer discomfort time, Useful Daylight Illuminance	orientation, room depth and corridor depth, WWR of different interfaces, glazing materials and shading types	Octopus, Radiance, Energy Plus, Rhinoceros, plug-ins: Grasshopper , Ladybug Honeybee	single-sided open corridor type, a single-sided enclosed corridor type and a double-sided corridor type school	China
Heracleous et al.	2020	Csa	thermal comfort	Ventilation strategies	monitoring of physical parameters a questionnaire-based survey	a secondary school	Nicosia, Cyprus.

2.3. Aim and originality of the study

The abovementioned studies show that geometry parameters can have a significant impact in the energy performance of school buildings. However, the high complexity of morphology-based energy performance optimization of schools due to the impact of numerous variables, makes the study a valuable contributor to the existing body of knowledge as it addresses the knowledge gaps identified below.

• No simulation-assisted study has an occupancy schedule in accordance to the current need and aim to create a spread network of schools open to community, even though schools nowadays are being designed as core social activity environments for their corresponding neighborhoods opening up auditoriums and sports facilities all year round.

• No previous simulation-assisted study has selected and developed school morphologies that involve innovative spaces for learning and socializing or are in compliance with the latest pedagogical thinking. The current change in learning methods is being reflected in the internal layouts of schools designed nowadays. By analyzing the most common morphologies in the studied context (Da Graça et al., 2007; Dimoudi et al., 2009; Montenegro et al., 2012; Zhang et al., 2017) whose abundance may be an expression of economic costs or accordant with former pedagogies, a full and useful guideline for the design of new school buildings in the studied region cannot be obtained. In this regard, the proposed approach of this research is studying and optimizing the typologies which respond to the general rethinking of school building layout and to the major challenges of designing today's and tomorrow's schools.

• Eight different locations are identified in the papers reviewed; Sao Paolo, Brazil (da Graça et al., 2007) Israel (Perez et al., 2009) Greece (Dimoudi et al., 2009) Montreal, Canada ; Santiago, Chile (Montenegro et al., 2012) Iran (Zomorodian et al., 2013) Auckland, New Zealand (Su, 2013) China (Zhang et al., 2017). The climate region induces changes in the heating, ventilation and air conditioning (HVAC) pattern of buildings. In this regard, only two simulation studies (Perez et al., 2009; Montenegro et al., 2012) are conducted in a Mediterranean climate. Perez et al. (2009)

provides results for a base-case classroom only, addressing the need for further research in this context. In addition, evaluating results for the whole building represents an original contribution of the study. Even though the study of Montenegro et al. (2012) analyzed nine spatial typologies of school buildings modelled through 3 recurring classroom proportions, it did not consider some other important variables such as orientation. No previous simulation-assisted study is conducted in an oceanic climate. The studies conducted in such a climate (Su, 2013; da Graça et al., 2007) introduce other methods based on real data collection only. No previous researcher studies the impact of a humid subtropical climate context.

Therefore, in this paper a new comprehensive framework is proposed aiming to initiate an analytical and quantitative approach towards evaluating the thermal and energy performance of open-school building morphologies in various climatic contexts. The study is based on an energy performance analysis, taking into account different design variables: shape, orientation. The main novelty and significance consists in evaluating and optimizing the energy and thermal performance of diverse morphologies of 21st century open-schools, thus contributing to the increment of the climatic awareness of designers and architects in the decision-making process. The proposed approach is an enhancement of methodologies proposed by authors (Zhang et al., 2017; Montenegro et al., 2012; Zomorodian et al., 2013; Perez et al. 2009) and provides novel and worthy contributions compared to the mentioned studies.

CHAPTER 3

METHODOLOGY

3.1 Overview

Among many other parameters, the morphology of a building has a predominant effect on energy consumption of a building. As such, the main focus of this research is to point out its impact on energy performance of open-school buildings. The methodological framework of the study is illustrated in ***Figure 1***. Alternative hypothetical school morphologies are proposed in a variety of climates within Southeast Europe. By achieving precise, accurate, comparative data and results, it provides guides that can easily be used from architects in preliminary design stages of schools, not only in Southeast Europe, but in regions displaying similar climates to those found in the studied region as well. Computational evaluations will depict how shape parameter affects indoor thermal and energy performance of school buildings in diverse climatic contexts.

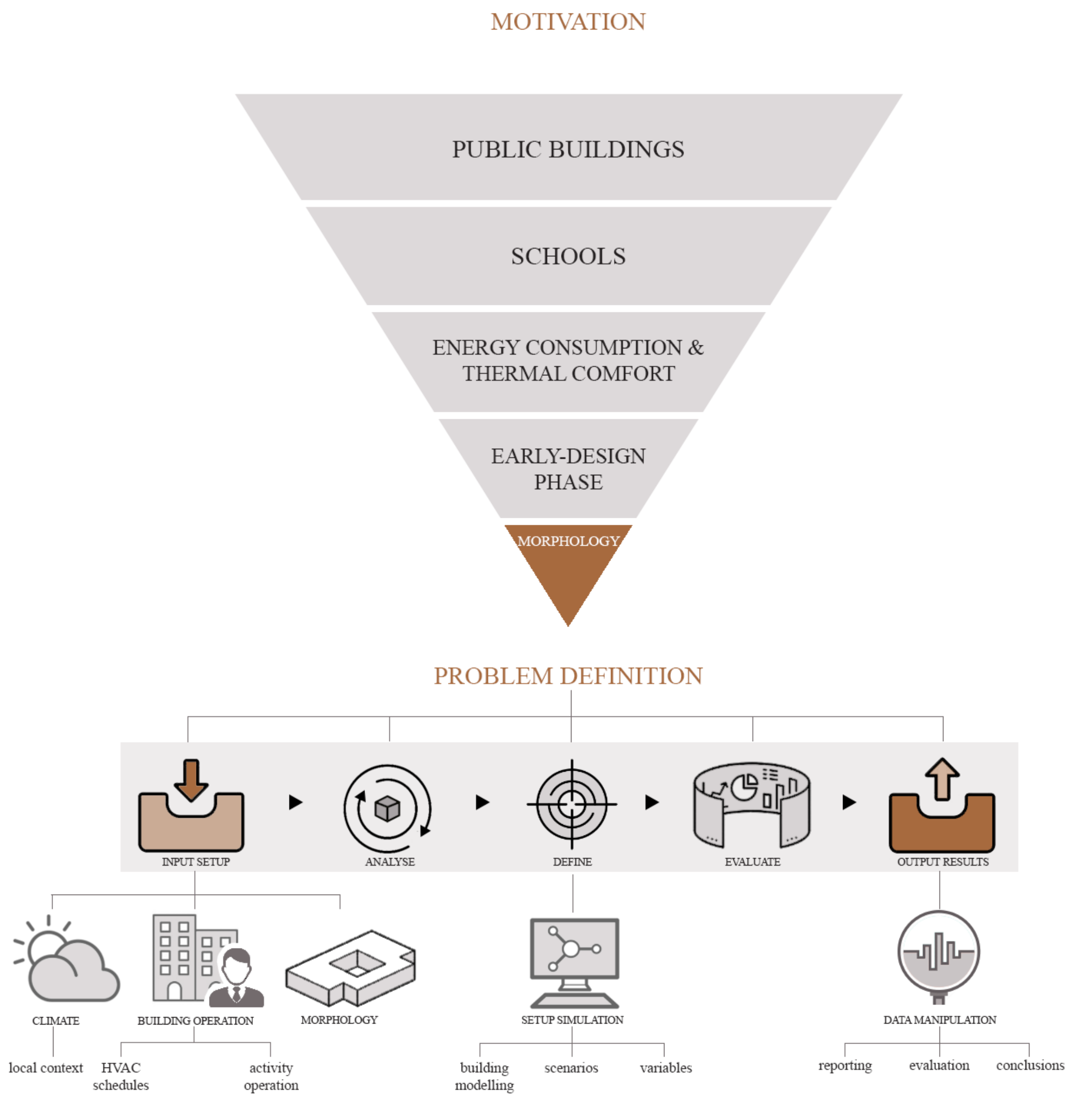

Figure 1. *Methodological framework of the study*

2.2. Climate characterization

In Southeast Europe a wide variety of climates is encountered due to the proximity of water bodies and its latitude. On the Adriatic and Aegean coasts the climate is Mediterranean, on the Black Sea coast the climate is humid subtropical and oceanic, and inland it is humid continental. Towards having a broader understanding and with the aim of constituting more accurate evaluations of energy performance of schools in this region, four contrasting climates are selected. The locations shown in ***Figure 2*** are chosen based on the variance in temperatures, solar radiation and other different attributes possessed by each of them. The climate data inputs are taken from “Meteonorm 7.3”. ***Figure 3*** illustrates the mean temperatures for the case of Tirana, Zagreb, Sarajevo and Athens.

Figure 2. *The selected locations*

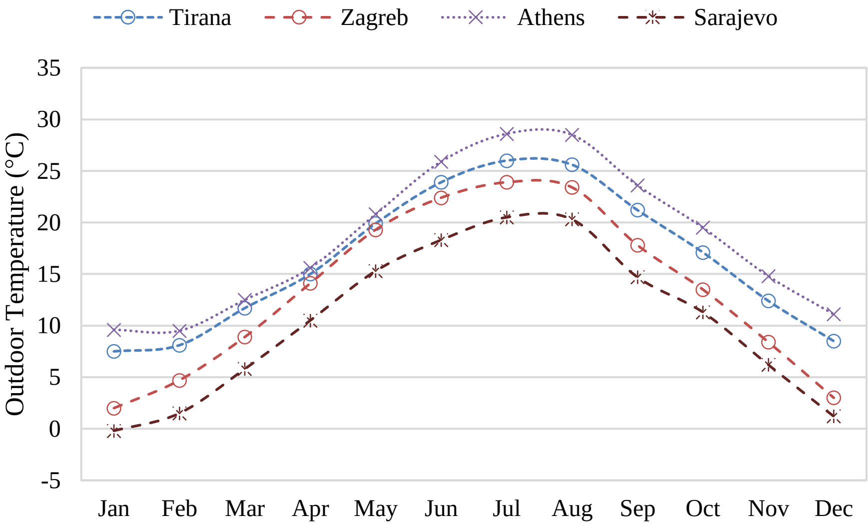

Figure 3. *Mean outdoor temperatures for the selected locations*

2.2.1. Tirana, Albania

Tirana enjoys a humid subtropical climate, defined by the Köppen climate classification as Cfa, receiving a considerable amount of precipitation throughout the summer. It avoids the classification under Mediterranean climate (Csa) category, since each summer month receives more than 40 mm of rainfall, with hot and fairly dry summers and cool and wet winters. The average precipitation in Tirana is about 1,266 millimeters per year. The majority of precipitation is received in winter months, from November to March, and less in summer months, from June to September. In terms of precipitation, both rain and snow, the city is ranked third among the wettest cities in Europe. Temperatures vary throughout the year from an average of 6.7 °C in January to 24 °C in July. ***Figure 4*** illustrates the annual temperature of Tirana. The city receives approximately 2500 hours of sun, thus becoming one of the sunniest cities in the European Continent. The duration of sunny hours is 198.6 h in January, and 394.56 h in July. The total amount of solar radiation per year is 1574.7 kWh*m^{-2}.

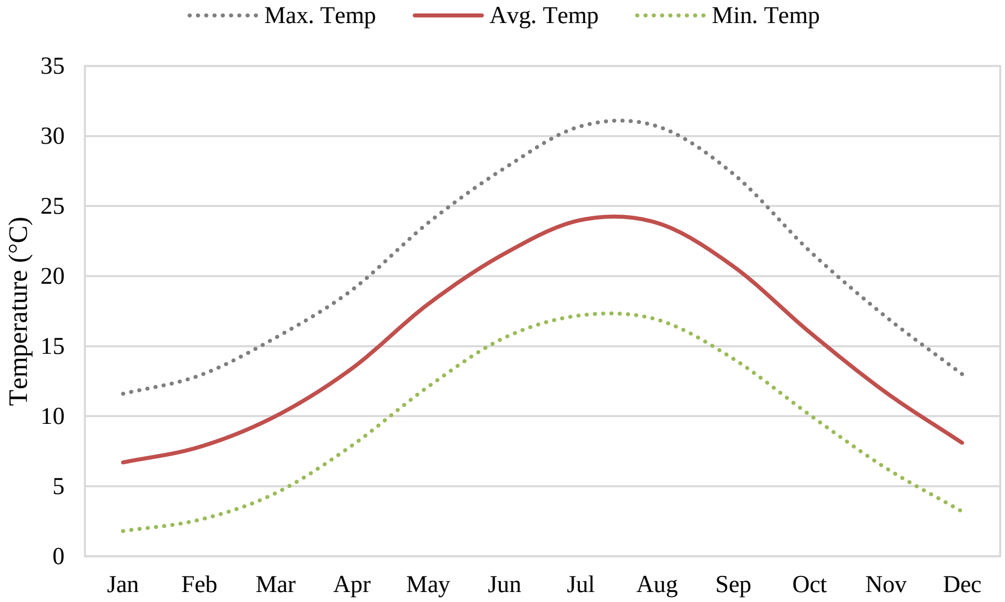

Figure 4. *Annual temperatures for the city of Tirana*

2.2.2. Zagreb, Croatia

Zagreb's climate is categorized as oceanic (Köppen climate classification Cfb), but with substantial continental influences and extremely close proximity to a humid continental climate (Dfb) and a humid subtropical climate (Cfa). Zagreb has four distinct seasons. Summers are typically warm. The average annual temperature is 11.6 °C. July has the greatest average temperature, which is about 22.5 °C. January is the coldest month of the year, with an average temperature of 0.5 °C. ***Figure 5****Error! Reference source not found.* illustrates the annual temperature of Zagreb. The rainfall in Zagreb is significant, with precipitation even during the driest month, making it Europe's ninth wettest capital, receiving less precipitation than Luxembourg but more than Brussels, Paris or London. The least amount of rainfall occurs in January. The average in this month is 54 mm. In September, the precipitation reaches its peak, with an average of 98 mm. On average there are 29 days with snowfall, with the first snow usually falling in early December. The duration of sunny hours is 127.02 h in January, and 365.93 h in July. The total amount of solar radiation per year is 1288.3 kWh*m^{-2}.

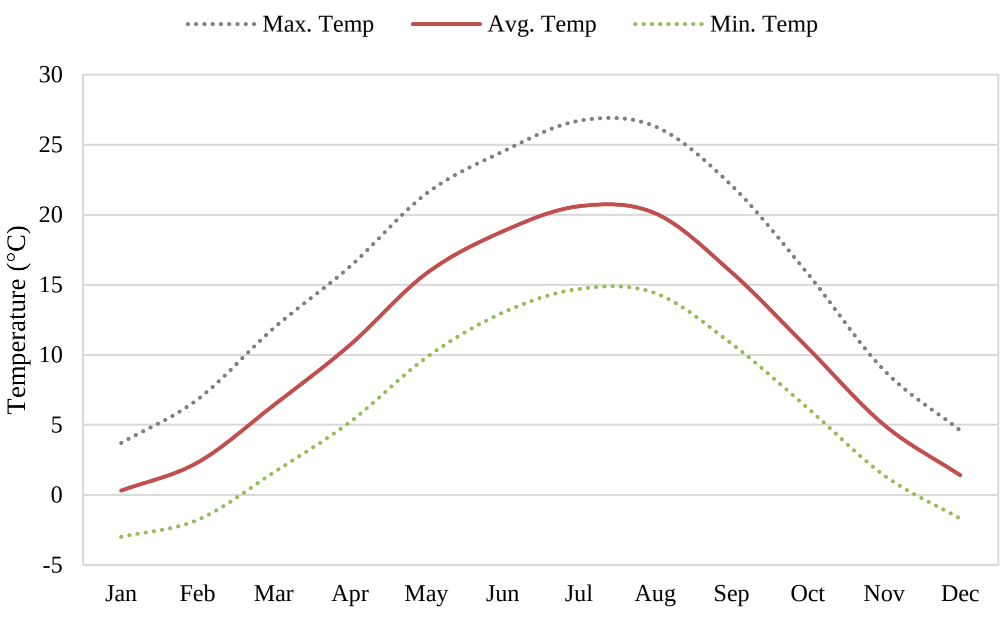

Figure 5. *Annual temperatures for the city of Zagreb*

2.2.3. Sarajevo, Bosnia and Herzegovina

Sarajevo has a humid continental climate (Köppen climate classification: Dfb). Its climate exhibits four seasons and uniformly spread precipitation. Precipitation is the lowest in August, with an average of 79 mm and highest in May, with an average of 120 mm. The Adriatic Sea's presence moderates Sarajevo's climate slightly, however the mountains to the south of the city significantly limit this maritime impact. The average yearly temperature is 10 °C, with January (−0.5 °C on average) being the coldest month of the year and July (19.7 °C on average) the warmest. ***Figure 6*** illustrates the annual temperature of Sarajevo. The duration of sunny hours is 115.77 h in January, and 296.42 h in July. The total amount of solar radiation per year is 1334.5 kWh*m^{-2}.

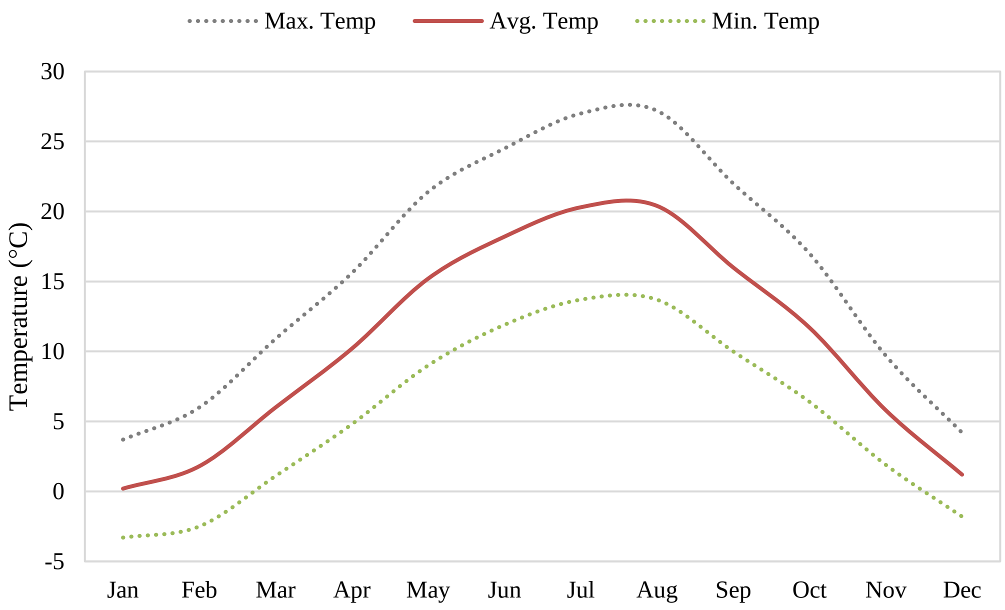

Figure 6. *Annual temperatures for the city of Sarajevo*

2.2.4. Athens, Greece

Athens has a hot-summer Mediterranean climate (Köppen climate classification: Csa). The predominant feature of Athens' climate is the alternation of extended hot and dry summers caused by dry and hot winds blowing from the Sahara and warm, wet winters with moderate rainfall caused by westerly winds. Rainfall occurs mostly between the months of October and April, with an average annual precipitation of 451 mm. July and August are the driest months. The average annual temperature is 17.5 °C. At an average temperature of 27.7 °C, July is the hottest month of the year. The lowest average temperatures in the year occur in January, when it is around 8.2 °C. ***Figure 7*** illustrates the annual temperature of Athens. The duration of sunny hours is 171.23 h in January, and 397.42 h in June. The total amount of solar radiation per year is 1751.5 kWh*m^{-2}.

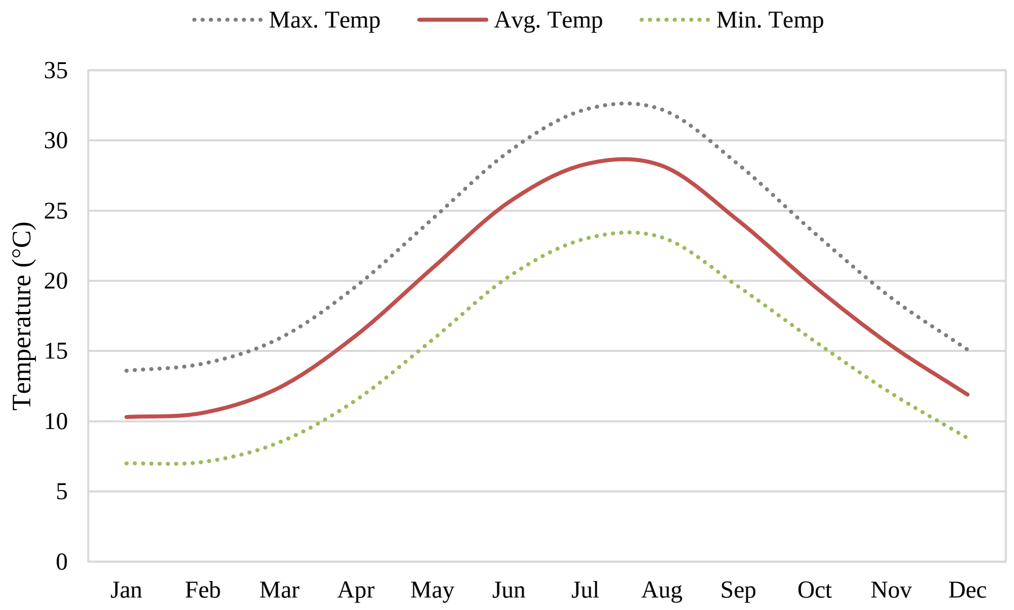

Figure 7. *Annual temperatures for the city of Athens*

2.3. School morphologies

The level of education, number of pupils, the school's educational philosophy, the climatic region or the context (urban, suburban, rural) may be detrimental in selecting the morphology during the early-design phase. The selection criteria for the developed morphologies in this study is the presence of innovative spaces that fulfill didactic and social needs (Rigolon, 2010). Four main design types are identified: the courtyard plan, block plan, cluster plan and town-like plan as shown in ***Figure 8***. These types are elaborated due to their morphology and internal layout. These latter factors have a significant impact on the characteristics of certain spatial patterns that are essential to the school building planning process. They determine the hierarchy between functions within the facility and the co-existence of classrooms and the semi-private areas nearby. (Rigolon, 2010). Due to morphological variations, WWR of the envelope and the quantity of space dedicated to circulation and socialization differs as depicted in ***Table 3***.

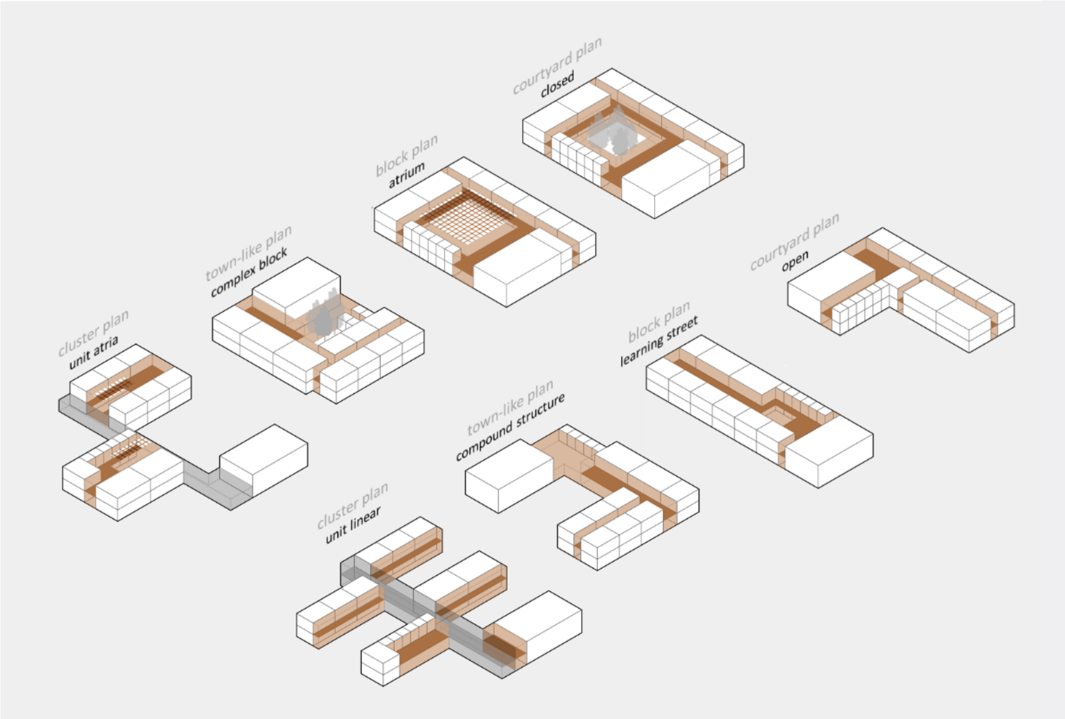

Figure 8. *School morphologies*

Table 3. *Features of each open-school morphology*

Morphologies	Envelope WWR (%)				Circulation (%)	Skylight roof ratio (%)
	N	E	S	W		
BA	36.84	13.87	22.19	30.99	39	21.7
BL	26.02	31.48	11.43	27.69	29	0
CC	30.16	37.05	22.37	26.60	26	0
CO	36.80	21.55	23.99	20.11	21	0
UA	23.79	30.66	20.15	23.41	35	6.88
UL	28.86	29.31	20.43	32.86	35	0
TB	19.75	16.92	27.72	28.70	21	0
TS	25.77	28.60	18.99	17.42	24	0

2.3.1. Block plan

The first two morphologies are blocks, characterized by simple internal layouts and compact volumes. The circulation area is optimized and the layout highly flexible. A large single space for socializing leads directly to the didactical spaces.

The first morphology, BA, is shaped around a central atrium with single loaded corridors and north-oriented classrooms. The effectiveness of this layout is dependent on the key socializing space being actually used by students: if this space did not provide many and diverse options for activities, it would merely become a circulation area, and therefore a "serving space". The second morphology shown in ***Figure 9*** which falls under block plan category, BL, is organized around a double loaded central hall with north-oriented classrooms. The circulation scheme's simplicity, consisting of a winding internal street, is intended to aid orientation. All of the school's learning and service areas are centered on a huge hall that serves as the school's social hub.

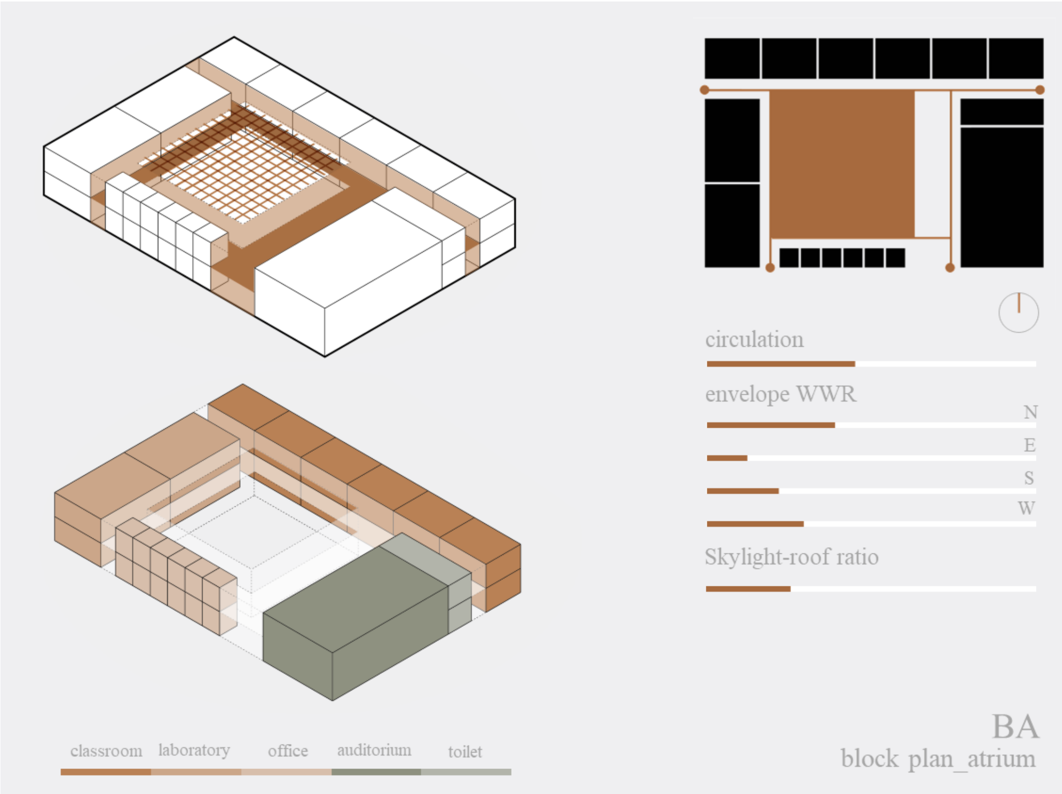

Figure 9. *BA morphology*

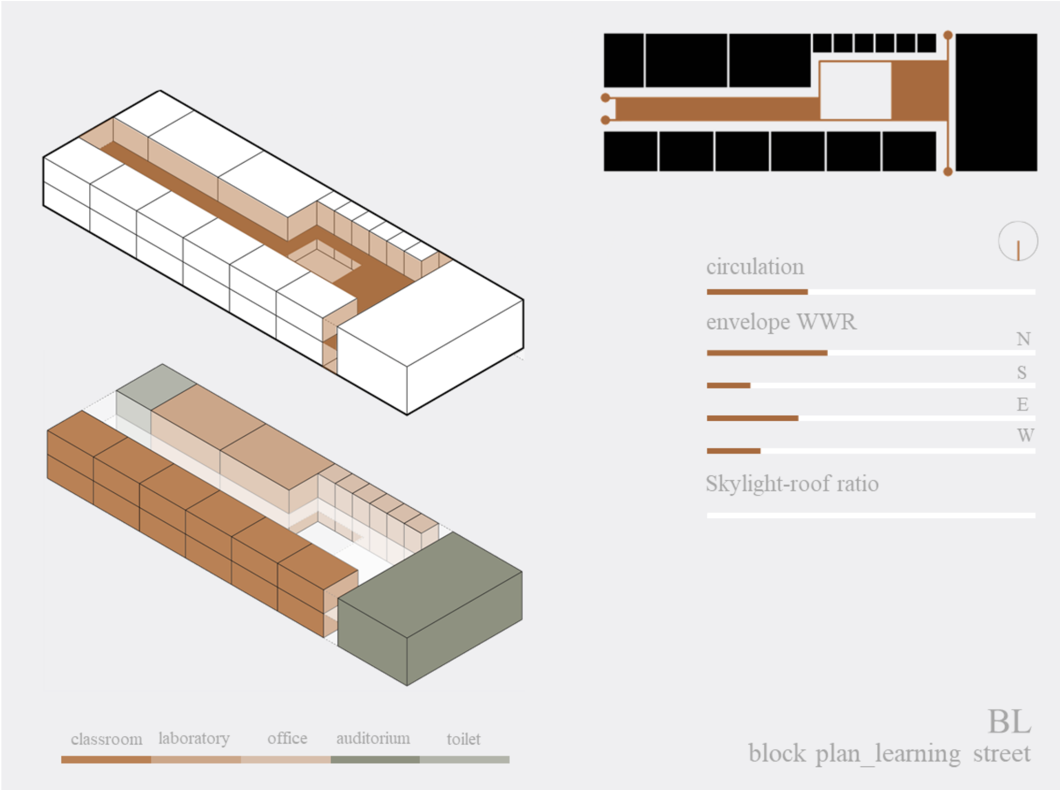

Figure 10. *BL morphology*

2.3.2. Courtyard plan

Two of the morphologies are organized around a central courtyard. Whether open or closed, it contributes to the creation of a sense of ownership, of an improved visual focus and sense of wellbeing (Rigolon, 2010) Since the school grounds are the primary gathering place for students, the internal commons are typically built as merely circulating areas: the obsolete conventional layout is adopted, with a hallway leading to the classrooms.

CC portrays a single, enclosed courtyard plan, with single loaded corridors and north-oriented classrooms. CO morphology has a single, open courtyard plan, with double loaded corridors and north-oriented classrooms.

Figure 11. *CC morphology*

Figure 12. *CO morphology*

2.3.3. Cluster plan

Cluster type morphologies enhance sense of belongingness through the 'small learning communities' arranged either in a longitudinal or a central atria layout (Rigolon, 2010) In contrast to the block type, the transition from the private to public areas is done gradually through common areas acting as buffers. This layout play a vital psychological function for pupils allowing them to locate themselves in a small group, eventually transiting into the rest of the building. The individual volumes are linked by a general gathering place, thus defining the building's public character. A broad covered hall serves as the unifying feature in the proposed typologies, connecting all of the educational units. UA is the first subtype of cluster plan, fragmented in units organized around atriums, with double loaded corridors and classrooms both north and south oriented. The other subtype of cluster plan morphologies, UL, is fragmented in units organized around single loaded corridors, with north-oriented classrooms.

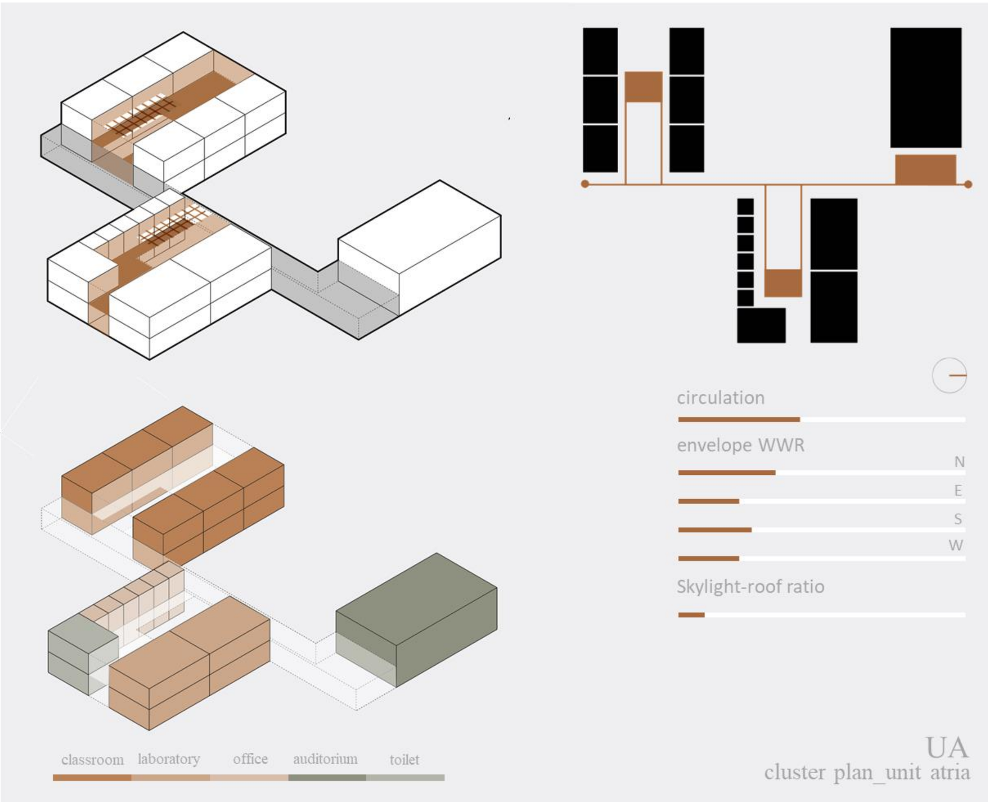

Figure 13. *UA morphology*

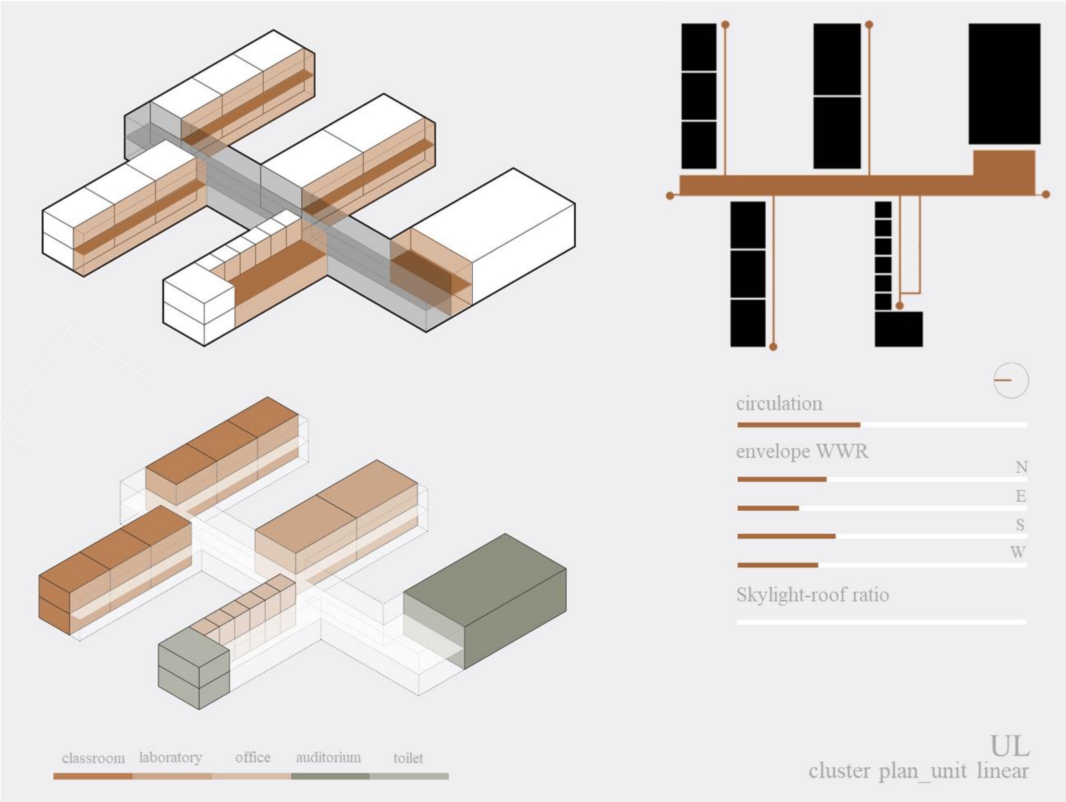

Figure 14. *UL morphology*

2.3.4. Town-like plan

The morphologies which fall under town-like category promote a multiplicity of spaces and functions, thus the metaphor of the town. (Rigolon, 2010). The most important ”buildings” (auditorium etc.) surround the most public space; the “town hall square”. From here, a sequence of roads leads to increasingly "private" spaces, mimicking an organic pattern different from the cluster type.

TB subtype has a town-like plan with hierarchical series of double loaded corridors giving access to classrooms both north and south oriented. TS subtype of this category has a town-like plan and is formed formed by a variety of freely arranged volumes. Corridors are double loaded and classrooms both north and south oriented.

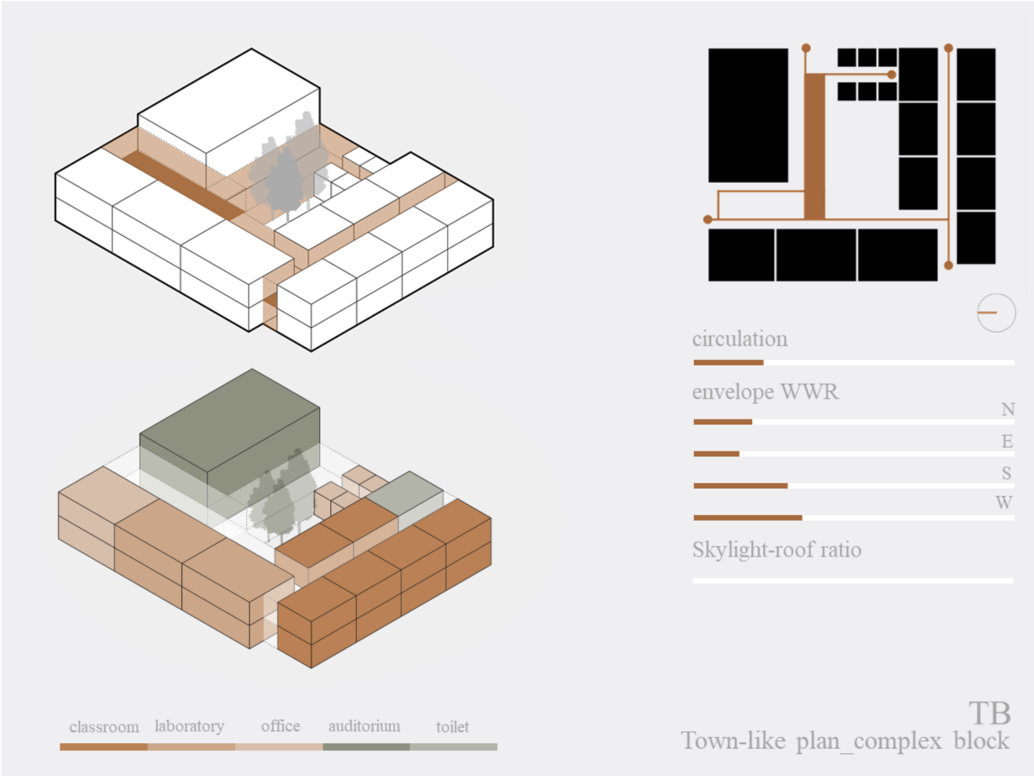

Figure 15. *TB morphology*

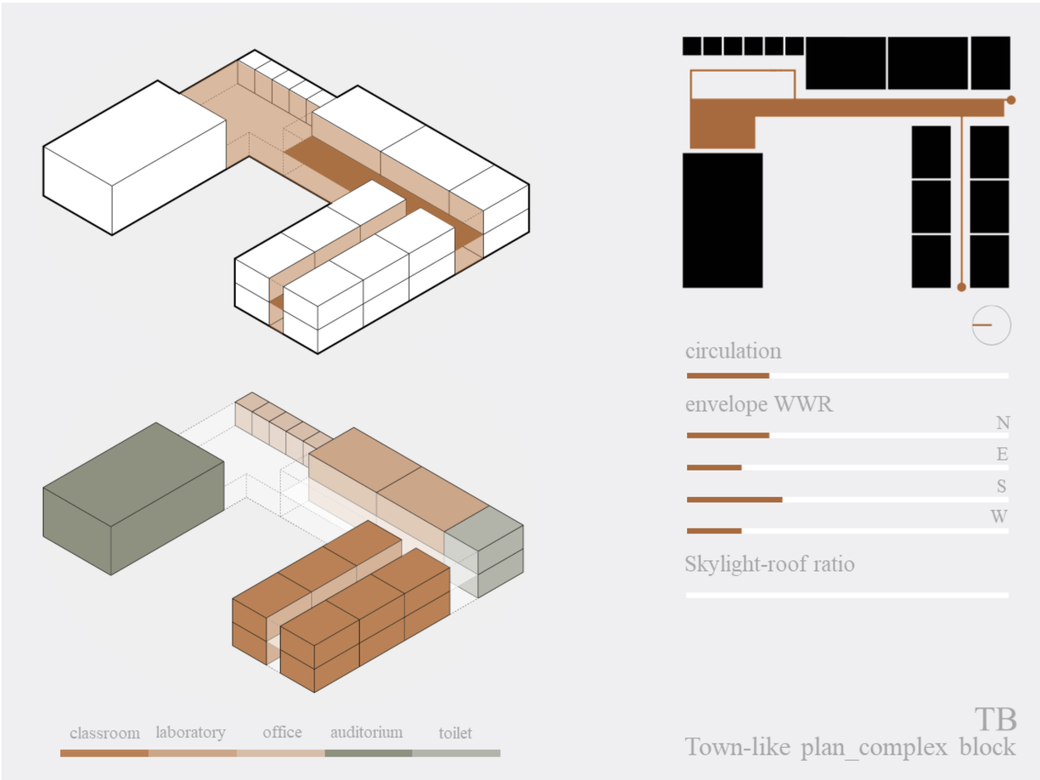

Figure 16. *TS morphology*

2.4. Modelling and simulation

2.4.1. Building models

For the research purpose of evaluating the performance of various morphologies of 21st century open schools, a prototypical 2 stories secondary school building with a 3.5m floor-to floor height and an approximate footprint of 1300 ± 200 m^2 is selected. Eight school building models with the same spatial composition, but of different morphologies are first designed and then built in Design Builder. The layout is comprised of classrooms, laboratories, offices, toilets, auditorium and circulation space with identical size and numbers of rooms in each configuration. The distribution of functions is shown in ***Figure 17***. For all models, the width of the corridor is set at a constant of 2.5 m when single-loaded.

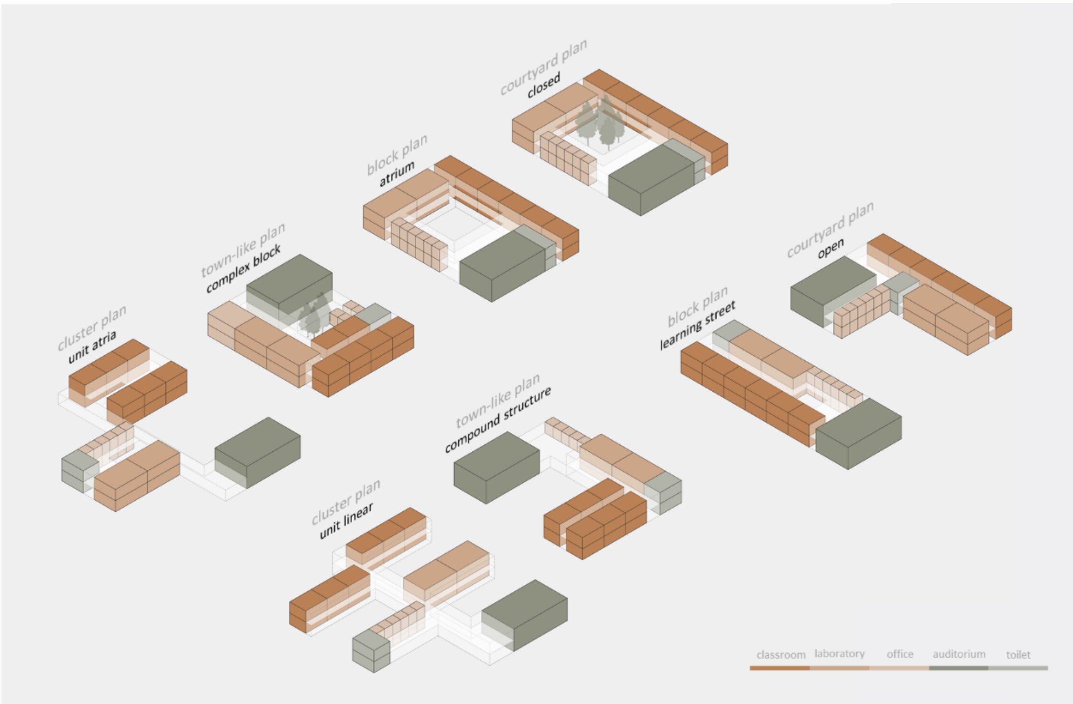

Figure 17. *Functional distribution*

Occupancy schedules as shown in ***Figure 18*** respond to the current need and aim to create a spread network of open schools which will serve to their community as central spaces and core social activity environments for their neighborhood.

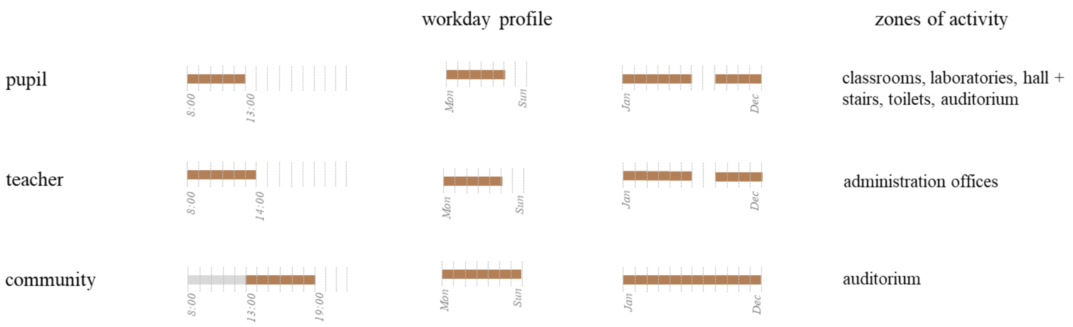

Figure 18. *Occupancy schedules*

The construction parameters, glazing type, lighting, HVAC template and internal loads are kept same as shown in ***Table 4, Table 5*** and ***Table 6***. Construction properties are shown in ***Figure 19***.

Table 4. *Construction properties*

		Density [kg/m³]	Conductivity [W/m °C]	Specific heat [J/kg °C]	Thickness [m]
External wall	Stone - hard stone	2750	2.9	840	0.03
U-value= 0.389	Air gap 30mm				0.03
[W/m^2.K]	MW Stone Wool (standard board)	40	0.038	840	0.07
	Brickwork	1920	0.72	840	0.25
	Cement plaster	1760	0.72	840	0.02
Internal wall					
U-value= 0.516	Cement plaster	1760	0.72	840	0.01
[W/m^2.K]	Brickwork	1920	0.72	840	0.12
	MW Stone Wool (standard board)	40	0.038	840	0.05
	Brickwork	1920	0.72	840	0.12
	Cement plaster	1760	0.72	840	0.01
Insulated roof					
U-value= 0.35	Asphalt - reflective coat	2300	1.2	1700	0.005
[W/m^2.K]	Roof Screed	1200	0.41	840	0.05
	XPS Extruded Polystyrene - CO2 Blowing	35	0.034	1400	0.08
	Cast Concrete (Lightweight)	1200	0.38	1000	0.10
Ground floor					
U-value= 0.5	Timber Flooring	650	0.14	1200	0.02
[W/m^2.K]	Floor Screed	1200	0.41	840	0.07
	Cast Concrete	2000	1.13	1000	0.30
	XPS Extruded Polystyrene - CO2 Blowing	35	0.034	1400	0.04

Table 5. *Input parameters for HVAC operation*

Input parameters	
Fan coil unit	(4 pipe) water cooled chiller, waterside economizer
Heating/cooling system	Electricity from grid
Heating system seasonal [CoP]	1.8
Cooling system seasonal [CoP]	1.8
Heating set back [°C]	12
Cooling set back [°C]	28
Natural ventilation setpoint [°C]	15

Table 6. *Brief for spatial program*

Areas	Size m^2	Number	Fresh Air (L/S-Person)	Air Exchange Rate (Ac/h)	Power density (W/m^2-100 lux)	Heating temperature set points °C	Cooling temperature set points °C	Occupancy density [P/m^2]
Classroom	48	12	8	6	5.0	22	26	0.67
Laboratory	96	4	10	10	5.0	22	26	0.35
Auditorium	240	1	10	10	4.0	22	26	0.2183
Offices	9	12	8	6	5.0	22	26	0.103
Hall	-	-	0.5	4	4.0	20	27	0.11
Toilet	48	2	2.5	8	2.5	24	-	0.11

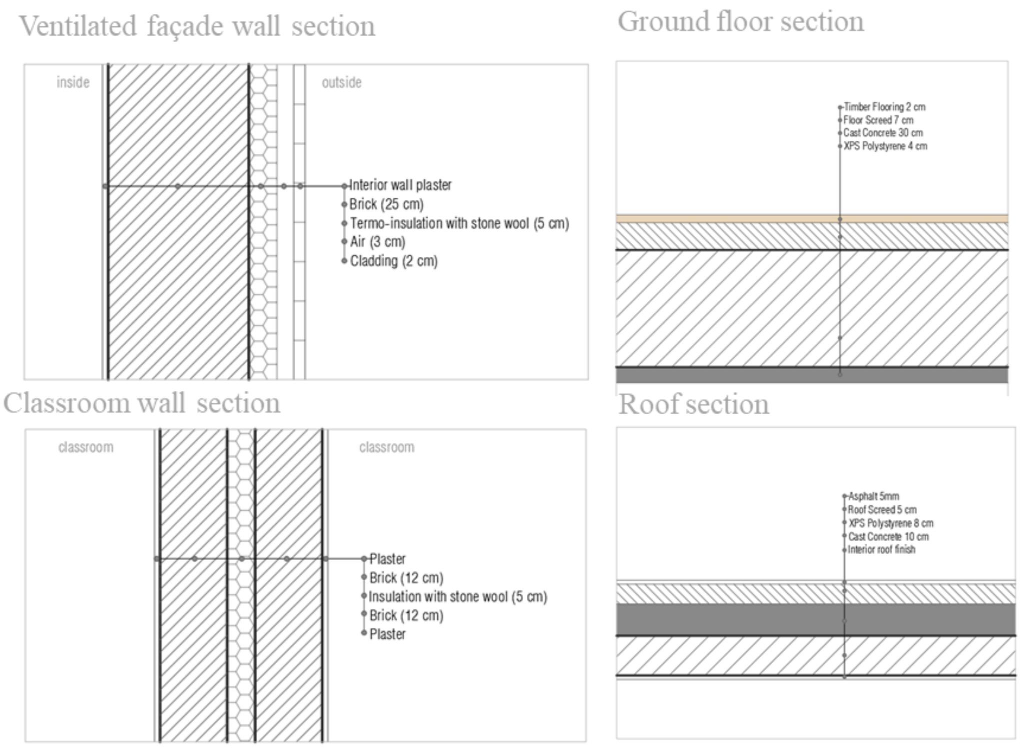

Figure 19. *Section details of the simulation models*

Window to wall ratio (WWR), which indicates the percentage of an exterior wall area occupied by glazing material, is set at a constant of 40%. This value is set at a minimum considering daylighting requirements and at a maximum according to energy efficiency (Xue et al., 2019). Glazing properties are shown in ***Table 7***. The natural ventilation schedule regime illustrated in ***Table 8*** is set based on surveying.

Table 7. *Glazing properties for window to wall ratio 40%*

Glazing properties	
Glazing type	Double LoE (e2=1) clear 6mm/13mm Air
Frame properties	Aluminum window frame with thermal break
SHGC (Total solar transmission)	0.568
U-value of glass [W/m^2.K]	1.761
Opening position	middle
Glazing area opens [%]	30
Airtightness [ac/h]	0.5

Table 8. *The natural ventilation schedule regime*

Ventilation	Warm months	Intensity (%)	Cold months	Intensity (%)
Natural	8:00-8:40	50	8:00-8:40	5
	8:40-8:50	50	8:40-:8:50	50
	8:50-9:30	10	8:50-9:30	5
	9:30-9:40	50	9:30-9:40	50
	9:40-10:20	5	9:40-10:20	5
	10:20-10:40	50	10:20-10:40	50
	10:40-11:20	5	10:40-11:20	5
	11:20-11:30	50	11:20-11:30	50
	11:30-12:10	5	11:30-12:10	5
	12:10-12:20	50	12:10-12:20	50
	12:20-13:00	5	12:20-13:00	5

2.4.2. Scenarios of the proposed design strategies

Several related design parameters are varied in the energy and thermal comfort calculation of the eight building shapes. To test the impact of orientation, the building models are rotated by 90, 180, and 270 representing east, south, and west, respectively. The process is repeated for various climatic contexts as illustrated in ***Figure 20***. ***Table 9*** describes the simulation scenarios.

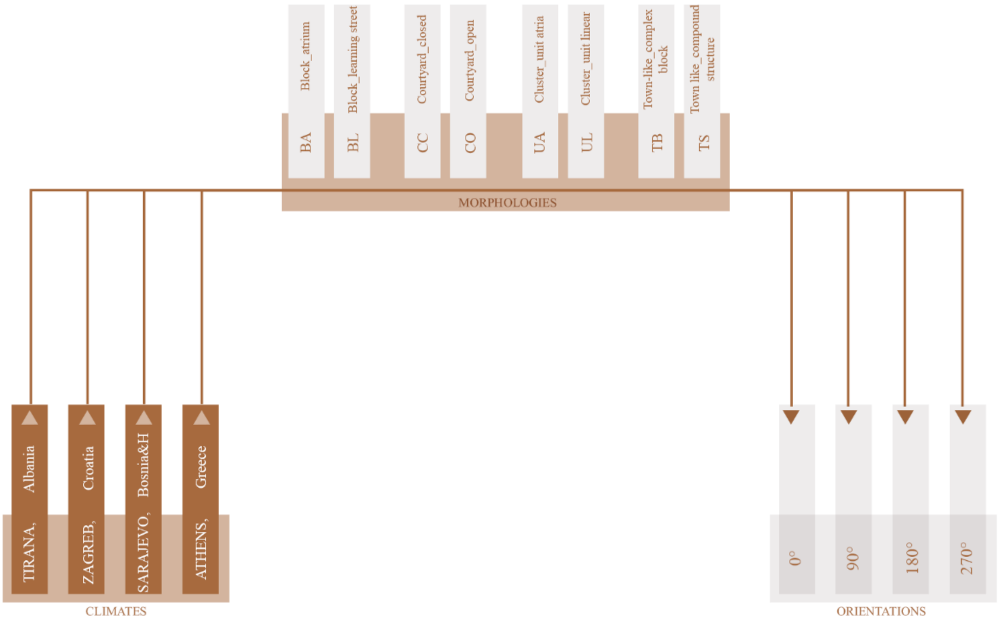

Figure 20. *Simulation scenarios*

Table 9. *Description of the simulation scenarios*

	Code	Scenario	Description
B	BA	Block plan, central atrium, north-oriented classrooms	Block plan organized around a central atrium, with single loaded corridors and north-oriented classrooms
	BL	Block plan, learning street, north-oriented classrooms	Block plan organized around a double loaded central hall with north-oriented classrooms
C	CC	Closed courtyard plan, north-oriented classrooms	A single, enclosed courtyard plan, with single loaded corridors and north-oriented classrooms
	CO	Open courtyard plan, north-oriented classrooms	A single, open courtyard plan, with double loaded corridors and north-oriented classrooms
U	UA	Cluster plan, unit atria, north-oriented	Cluster plan fragmented in units organized around atriums, with double loaded corridors and classrooms both north and south oriented.
	UL	Cluster plan, unit linear, north-oriented classrooms	Cluster plan fragmented in units organized around single loaded corridors, with north-oriented classrooms
T	TB	Town-like plan, complex block, north-oriented	Town-like plan with hierarchical series of double loaded corridors giving access to classrooms both north and south oriented.
	TS	Town-like plan, compound structure, north-oriented	Town-like plan formed by a variety of freely arranged volumes. with double loaded halls and classrooms both north and south oriented

For the evaluation of the impact of the morphologies on the thermal performance, the classrooms illustrated in ***Figure 21*** are selected.

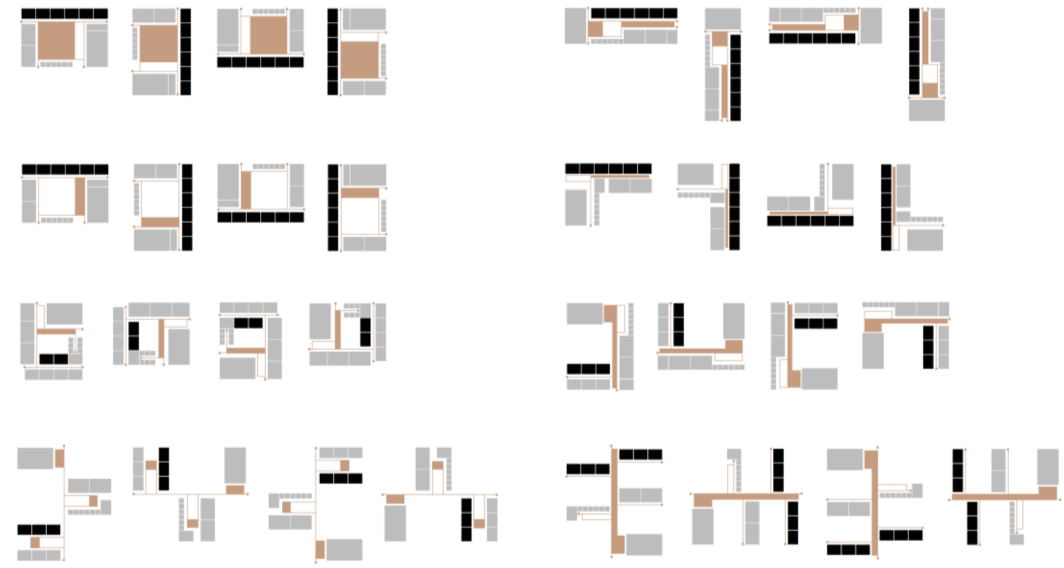

Figure 21. *Scenarios of the thermal comfort analysis*

2.4.3. Output variables

In order to evaluate the impact of the selected morphologies on the thermal performance of a classroom, the hourly indoor air temperature for 2 reference days in summer (12th and 13th of September) and 2 reference days in winter (6th and 7th of January) are analyzed for each scenario; north, west, east and south-oriented. The cooling, heating and energy loads for all the selected scenarios are further compared to measure the influence on energy consumption. The input parameters for the energy simulation process are used as an essential part of the model development process, based on an in-depth assessment of the importance of input parameters specified or implemented in previous research studies.

2.4.4. Simulation Software

The DesignBuilder interface version 6 for EnergyPlus is chosen to develop the simulations in different climatic contexts of Southeast Europe. The selection is based on the validated accuracy of the DesignBuilder software through BESTest (Building

Energy Simulation TEST) procedure developed by the International Energy Agency. The software has previously been adopted to simulate the thermal comfort level and energy balance of school buildings in several countries (Zhang & Bokel, 2017) (Montenegro, Potvin, & Demers, 2012). The local weather file of the various climatic contexts in Southeast Europe is generated through Meteonorm 7.3 software.

CHAPTER 4

RESULTS

The results generated by computer software, are first evaluated and then interpreted into charts. Computer simulations, combining eight school buildings morphologies, having each 4 different orientations, in 4 dissimilar climatic contexts, are computationally calculated. The achieved values clarify the correlation and interaction of building morphology and performance of school buildings.

4.1. Climate of Tirana

A comparison between annual energy consumption and thermal comfort inside classrooms is illustrated in the figures below to determine the impact of the humid subtropical climate of Tirana in the recommended morphologies.

4.1.1. Energy performance

The figures below illustrate the correlation of annual consumption for heating and cooling loads of the school building model in its eight morphology scenarios.

Figure 22 illustrates the monthly heating demand for all typologies with north-oriented classrooms. Induced by its relatively high S_e (surface of the envelope including ground floor slab), TB displays a poor performance in a humid subtropical climate. The best performance is obtained by BA due to the significant contribution of the atrium on heating energy savings. ***Figure 23*** illustrates the monthly cooling demand for all typologies with north-oriented classrooms. The high demand of the atrium itself for air-conditioning increases the cooling demand of BA significantly, thus casting doubts on the efficiency of its integration in building plans for this specific context.

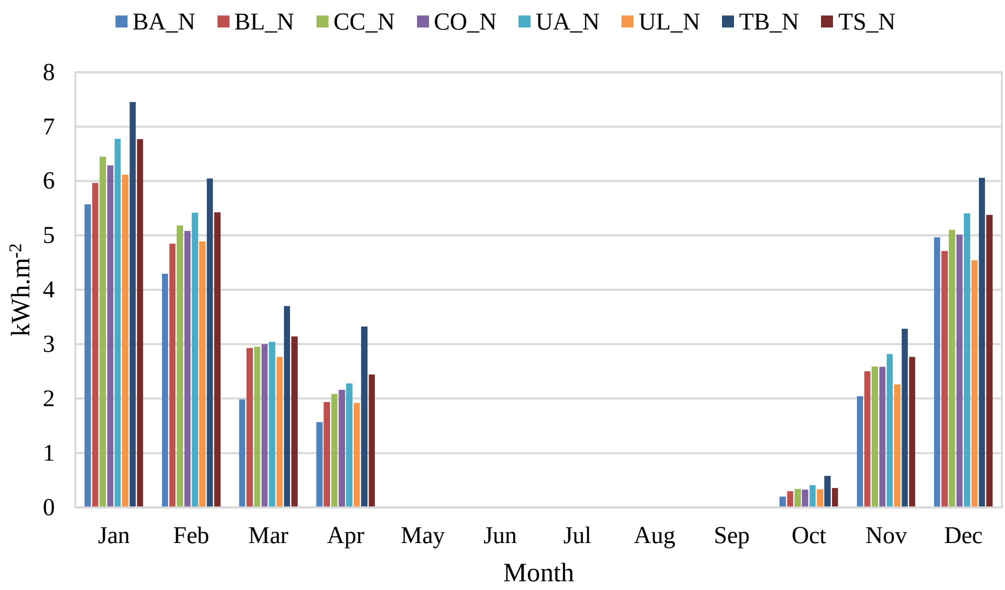

Figure 22. *Comparison of simulated heating demand (kWh.m^{-2}) of north-oriented typologies*

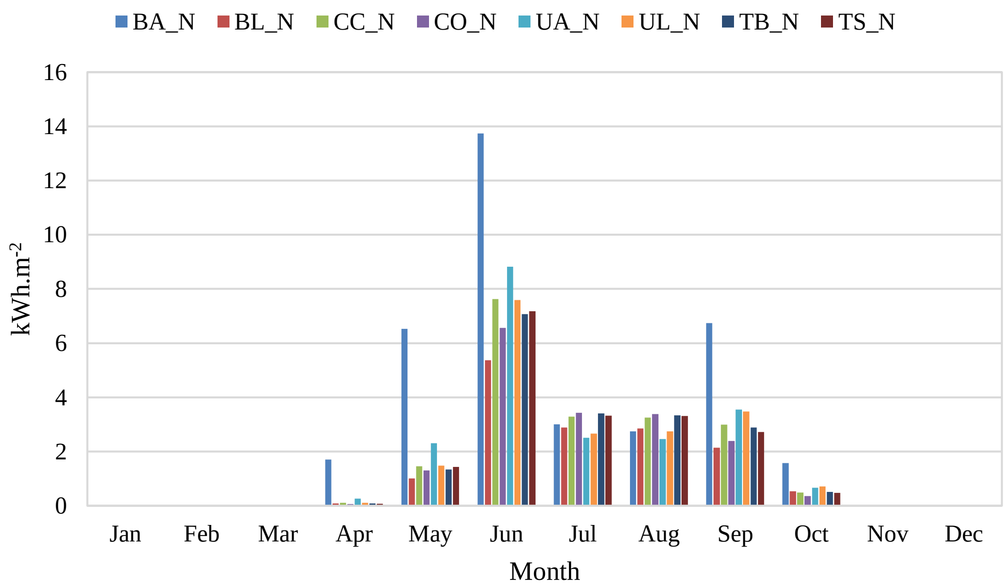

Figure 23. *Comparison of simulated cooling demand (kWh.m^{-2}) of north-oriented typologies*

Figure 24 illustrates the monthly heating demand for all typologies with east-oriented classrooms. ***Figure 25*** illustrates the monthly cooling demand for all typologies with east-oriented classrooms. There is a low demand for both heating and cooling in October and a low cooling demand in April for the climate of Tirana. In July and August not all school premises are open to the community, thus lowering the cooling demand in BA morphology compared to September and June when the school is fully occupied, along with the circulation and socializing area featuring an atrium/covered courtyard.

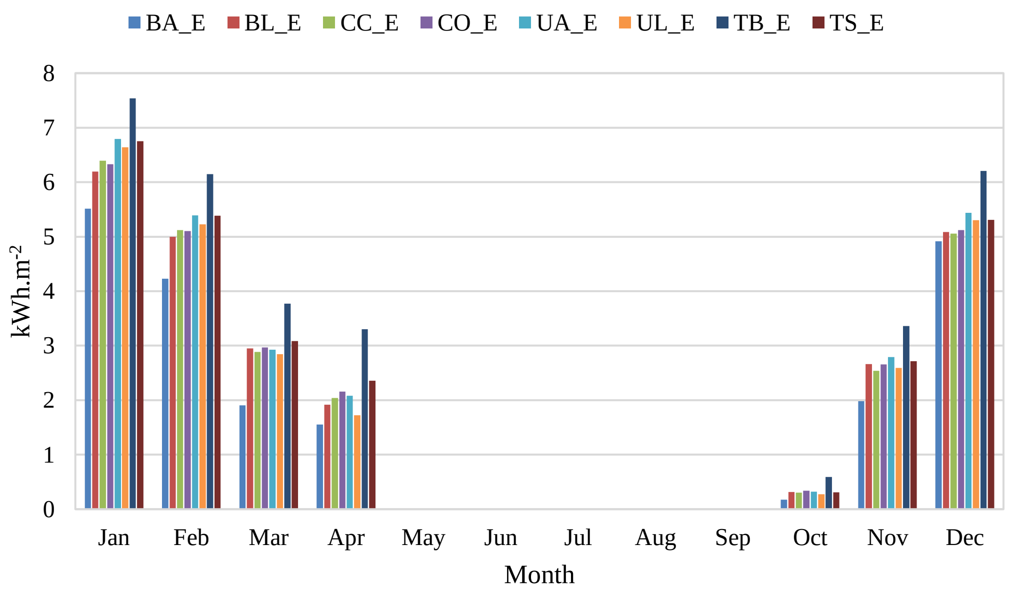

Figure 24. *Comparison of simulated heating demand (kWh.m^{-2}) of east-oriented typologies*

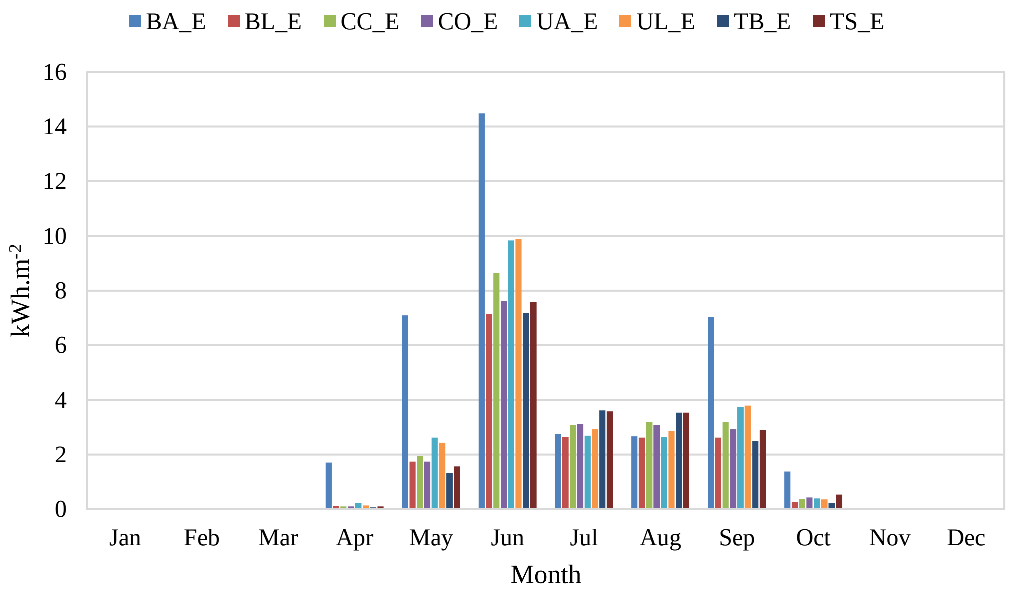

Figure 25. *Comparison of simulated cooling demand (kWh.m^{-2}) of east-oriented typologies*

Figure 26 illustrates the monthly heating demand for all typologies with south-oriented classrooms. ***Figure 27*** illustrates the monthly cooling demand for all typologies with east-oriented classrooms.

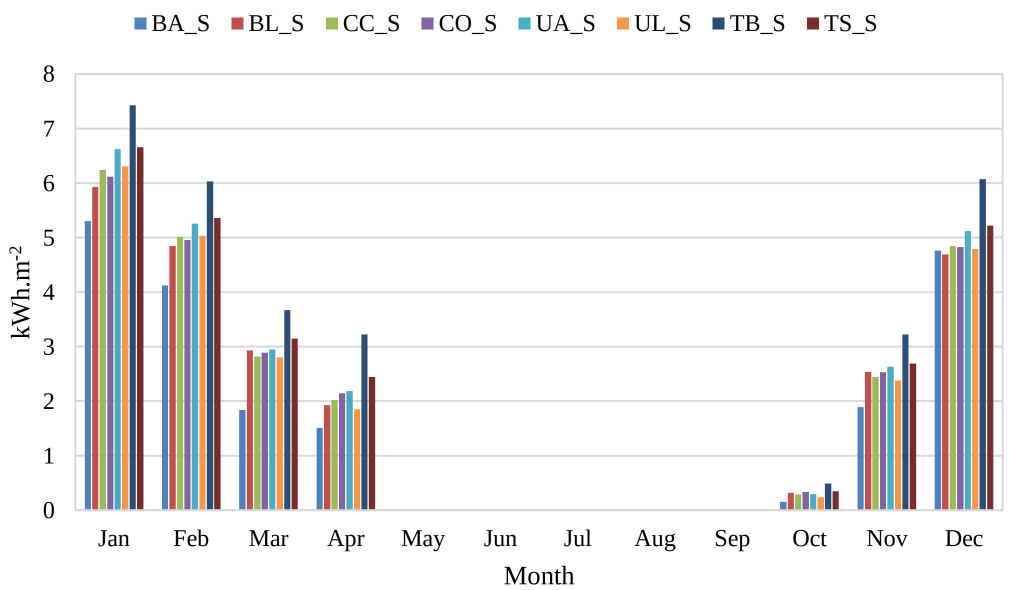

Figure 26. *Comparison of simulated heating demand (kWh.m^{-2}) of south-oriented typologies*

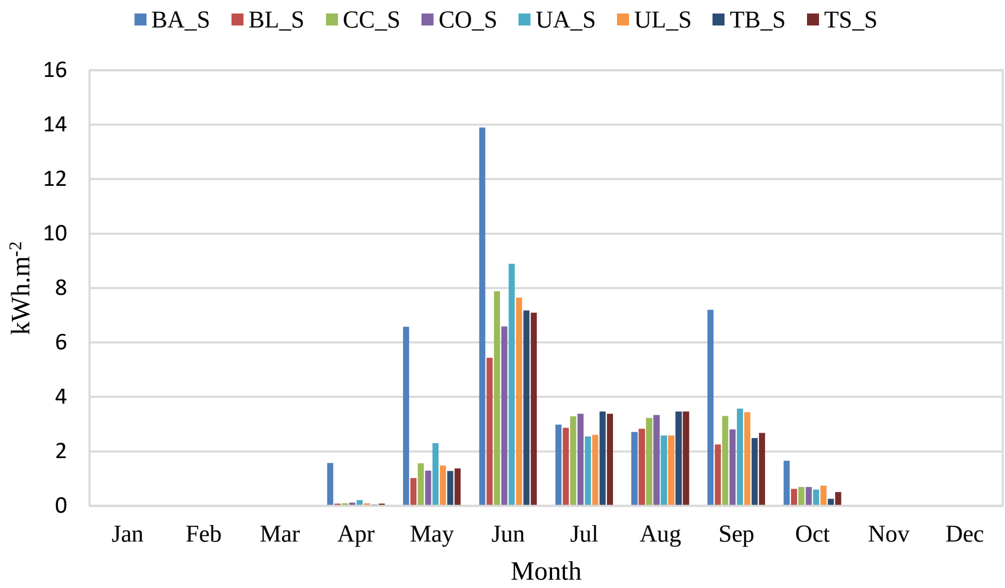

Figure 27. *Comparison of simulated cooling demand (kWh.m^{-2}) of south-oriented typologies*

Figure 28 illustrates the monthly heating demand for all typologies with west-oriented classrooms***. Figure 29*** illustrates the monthly cooling demand for all typologies with west-oriented classrooms.

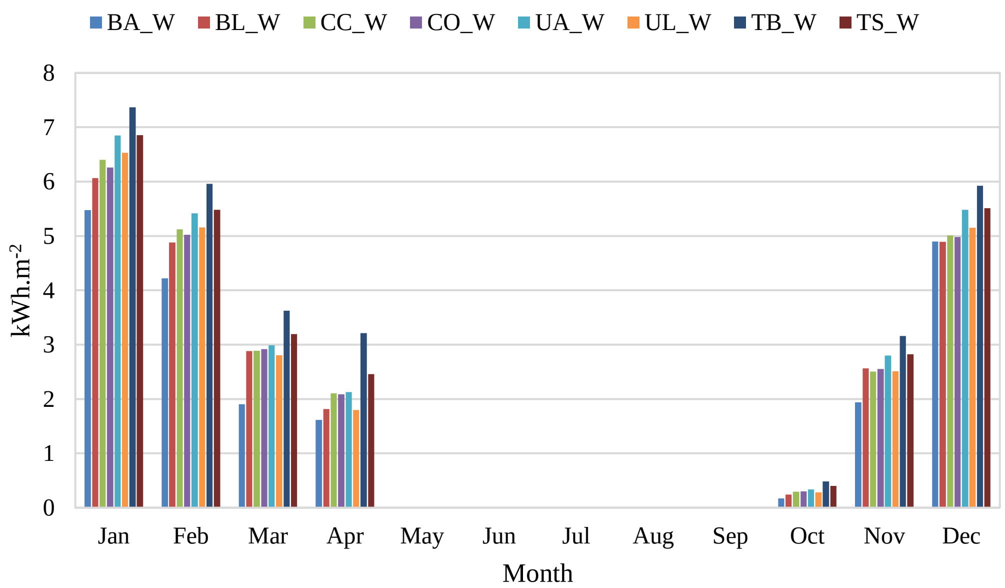

Figure 28. *Comparison of simulated heating demand (kWh.m^{-2}) of west-oriented typologies*

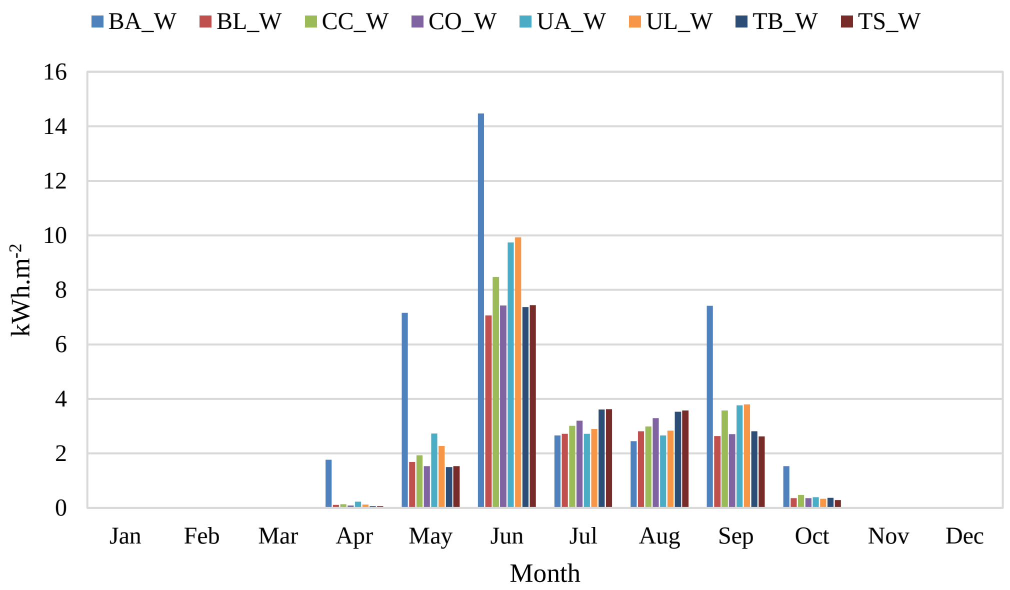

Figure 29. *Comparison of simulated cooling demand (kWh.m^{-2}) of west-oriented typologies*

4.1.2. Thermal performance

The figures below illustrate the correlation of thermal comfort inside classrooms and eight morphology scenarios. Indoor air temperatures are measured during two winter typical days and two summer typical days when the school is occupied.

Figure 30 displays simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September. The courtyard-facing classrooms of TB and TS typologies manage to maintain air temperatures closer to the comfort temperature. ***Figure 31*** provides a comparison between simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January. The courtyard impact, being it closed or open, is still apparent on the increased thermal comfort of TB and UL, but still marginal when compared to the impact it has on summer months.

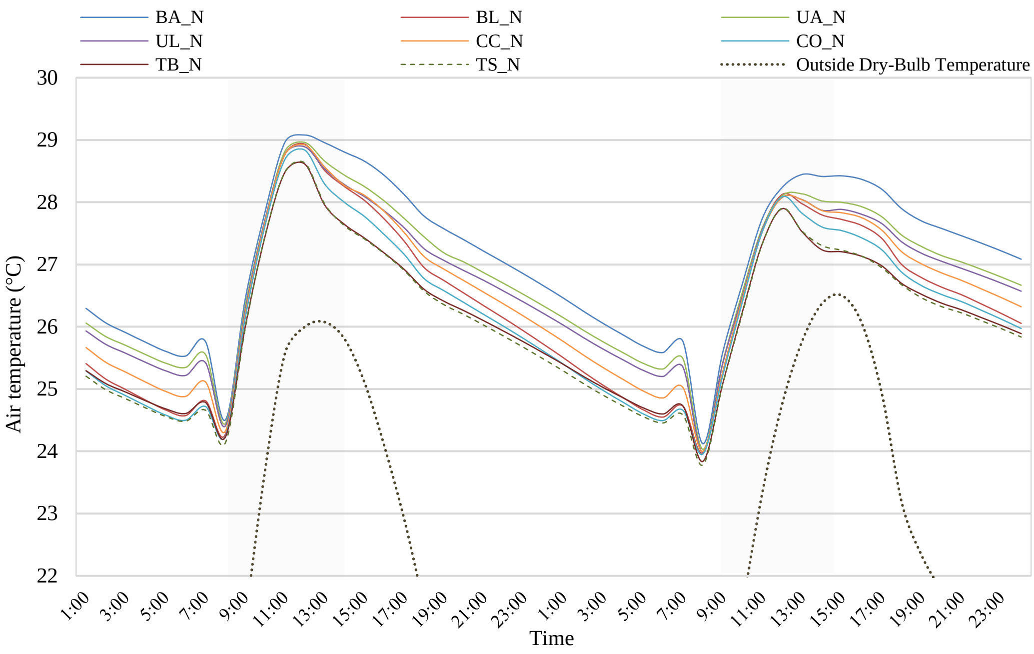

Figure 30. *Simulated indoor air temperatures for north-oriented scenrios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September*

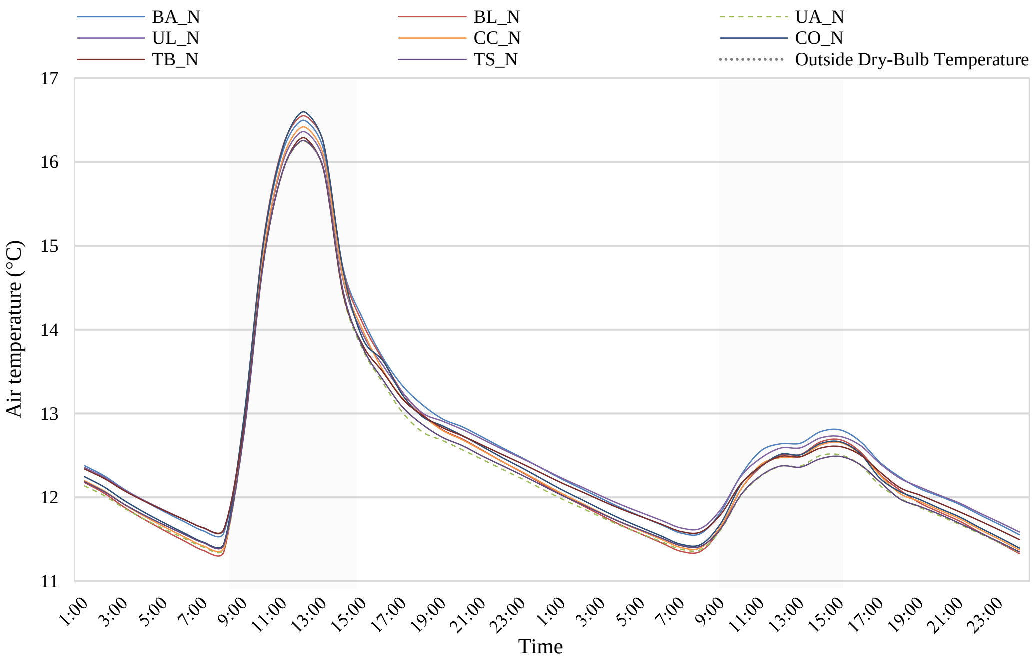

Figure 31. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 6th and 7th of January*

Figure 32 provides a comparison between simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September. The worst performance is obtained by BA, with the atrium increasing air temperatures of the adjacent spaces beyond the comfort temperature. ***Figure 33*** illustrates the **s**imulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 6th and 7th of January. Their relatively low S_e improves the thermal performance of classrooms in block typologies, BL and BA, reducing heat loss.

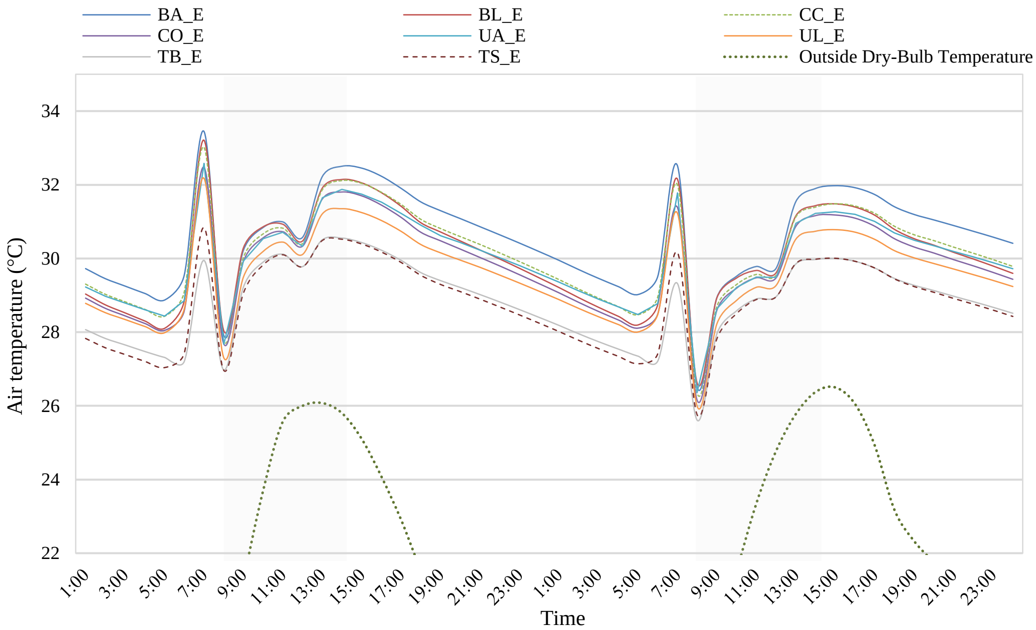

Figure 32. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September*

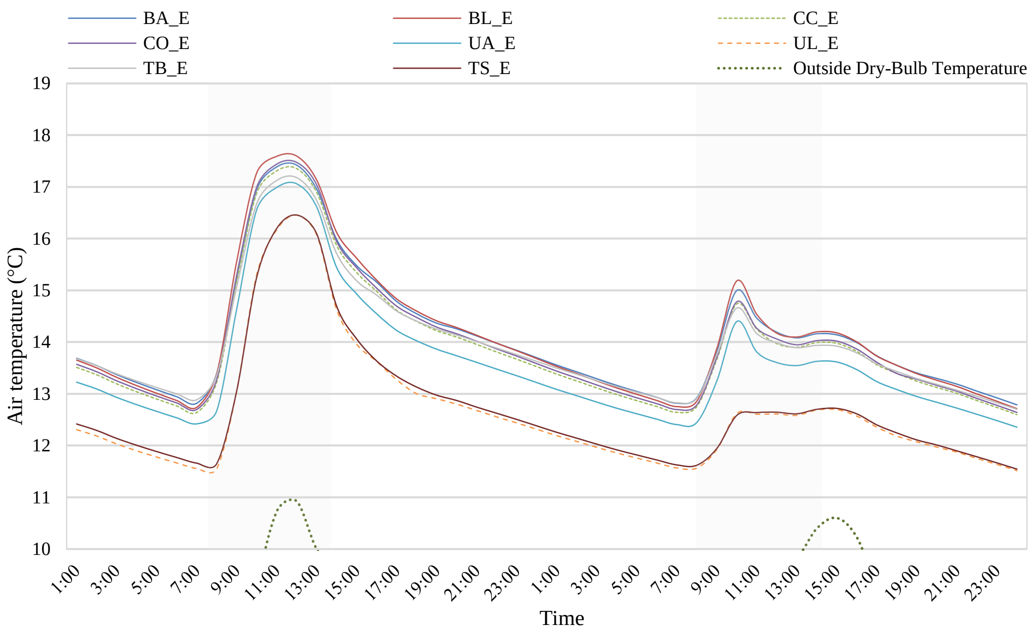

Figure 33. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 6th and 7th of January*

Figure 34 provides a comparison between the simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September. The curves drop significantly during the break as set in the natural ventilation schedule regime. This links thermal performance of buildings to their operational and space utilization characteristics and the behavior of their occupants. The influence of the occupant is due to his presence and activities in the building and due to his control actions aiming to ameliorate indoor environmental conditions. ***Figure 35*** illustrates the simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January.

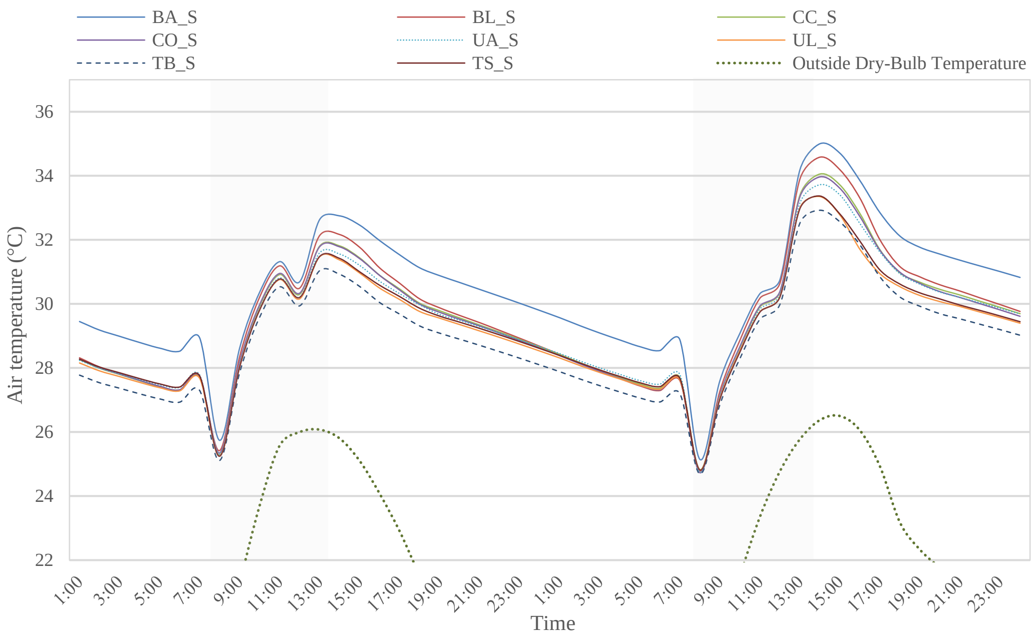

Figure 34. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September*

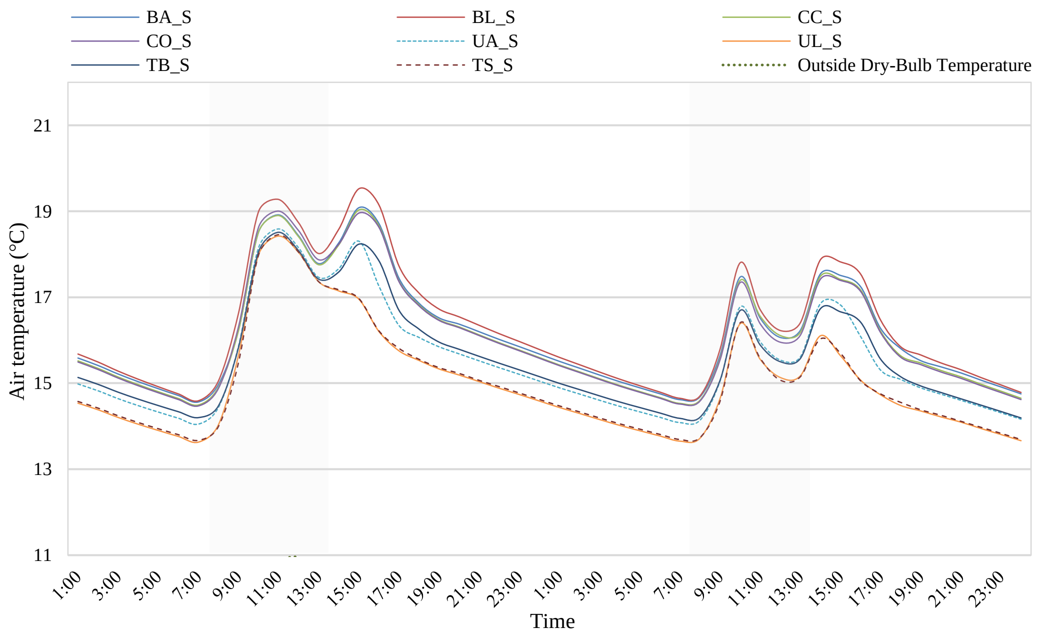

Figure 35. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 6th and 7th of January*

Figure 36 shows the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September. More noticeable differences are those on the second part of the day which corresponds to the warmest time of the day in a west-oriented room. ***Figure 37*** compares the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 6th and 7th of January.

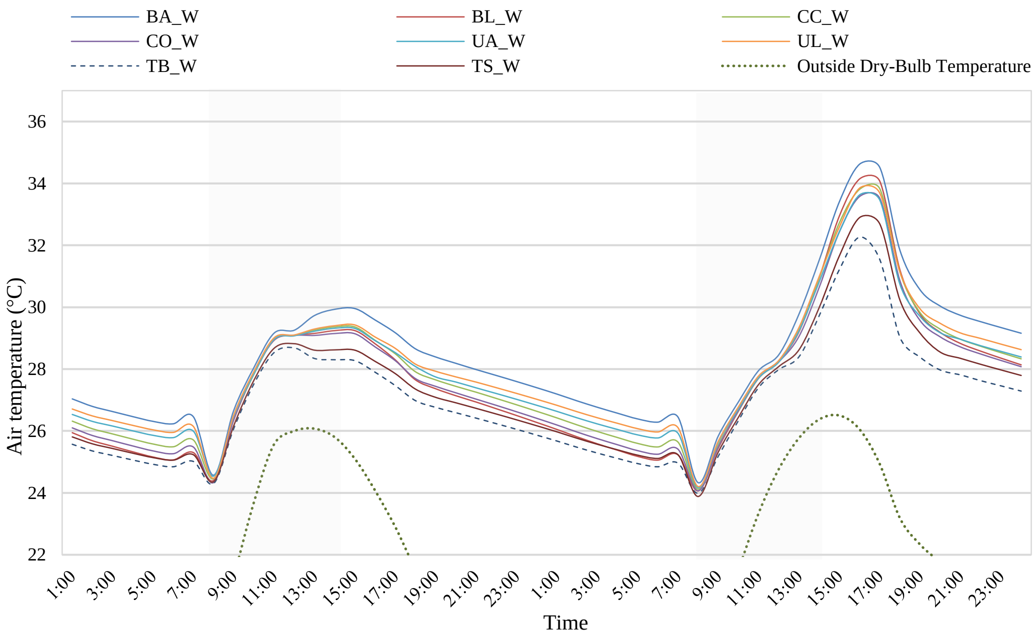

Figure 36. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 12th and 13th of September*

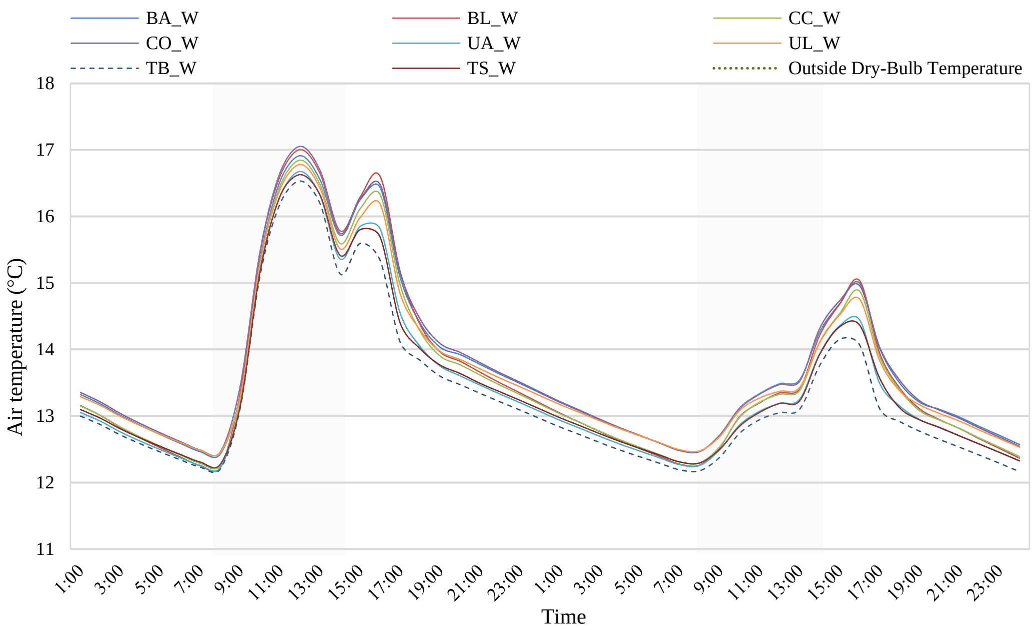

Figure 37. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Tirana weather file for 6th and 7th of January*

4.2. Climate of Zagreb

A comparison between annual energy consumption and thermal comfort inside classrooms is illustrated in the figures below to determine the impact of the oceanic climate of Zagreb in the recommended morphologies.

4.2.1. Energy performance

The figures below illustrate the correlation of annual consumption for heating and cooling of the school building model in its eight morphology scenarios. ***Figure 38*** provides a comparison of the monthly heating demand for all typologies with north-oriented classrooms. ***Figure 39*** illustrates the monthly cooling demand for all typologies with north-oriented classrooms. There is a low cooling demand in September and no demand in April and October due to climatic context the typologies are located in. In July and August, despite the increase in temperatures, the cooling demand is lower when compared to June due to the partial occupation of open-schools during summer.

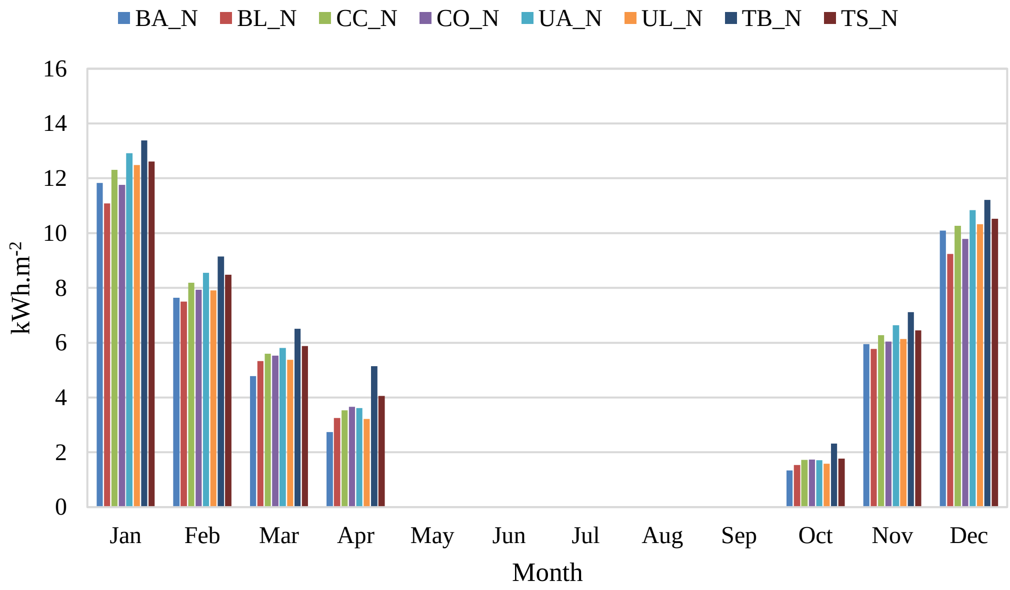

Figure 38. *Comparison of simulated heating demand (kWh.m^{-2}) of north-oriented typologies*

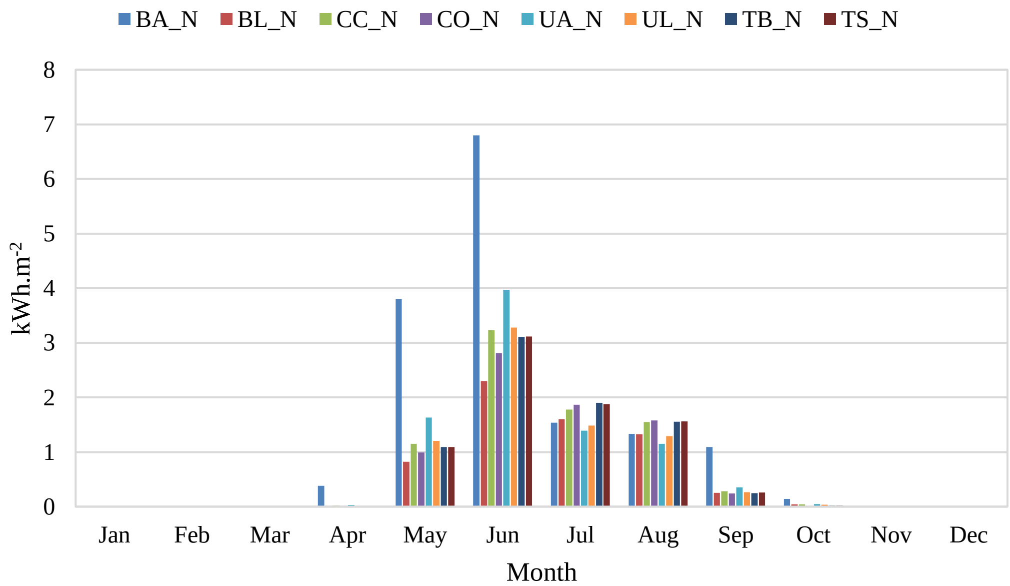

Figure 39. *Comparison of simulated cooling demand (kWh.m^{-2}) of north-oriented typologies*

Figure 40 illustrate***s*** the monthly heating demand for all typologies with east-oriented classrooms. The increase in S_e causes the heating demand to rise. This makes compact typologies which fall under block category perform better for similar climatic contexts with high heating demands. ***Figure 41*** provides a comparison of the monthly cooling demand for all typologies with east-oriented classrooms.

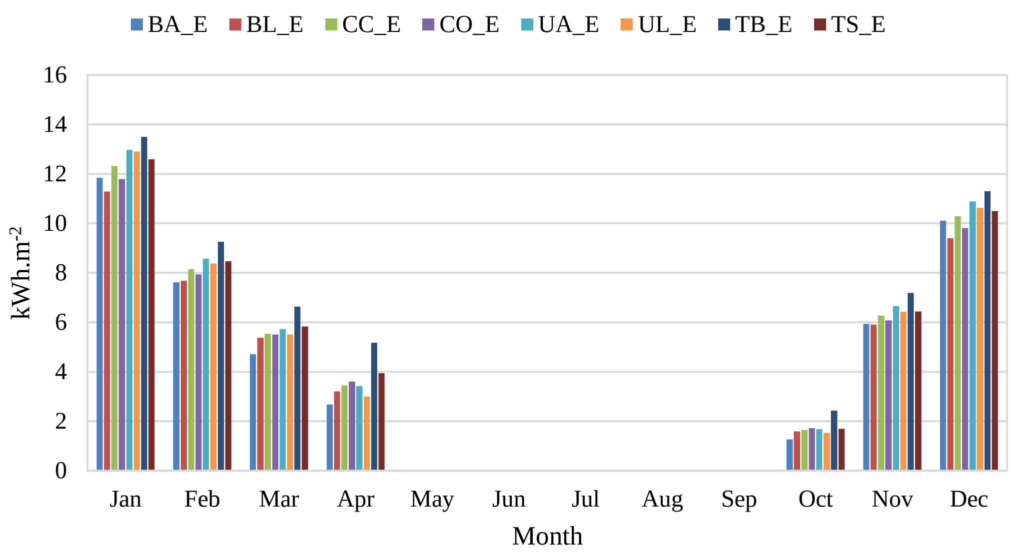

Figure 40. *Comparison of simulated heating demand (kWh.m^{-2}) of east-oriented typologies*

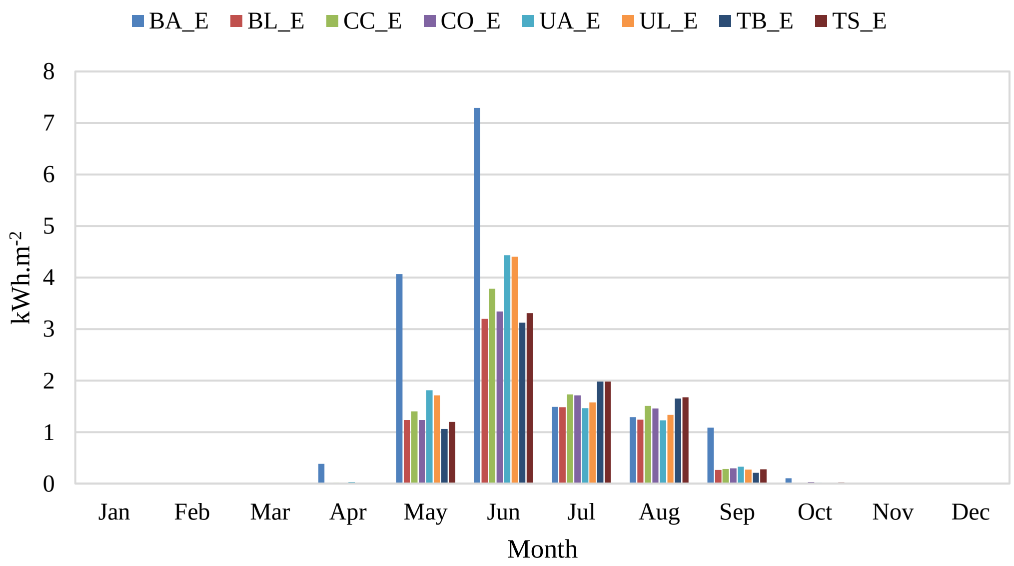

Figure 41. *Comparison of simulated heating demand (kWh.m^{-2}) of east-oriented typologies*

Figure 42 illustrate**s** the monthly heating demand for all typologies with south-oriented classrooms. The worst performance is obtained from TB, a morphology with an organic layout and high S_e causing high heat loss in cold climates. ***Figure 43*** provides a comparison of the monthly cooling demand for all typologies with south-oriented classrooms. The performance of BA is worse due to the atrium's self-need for cooling.

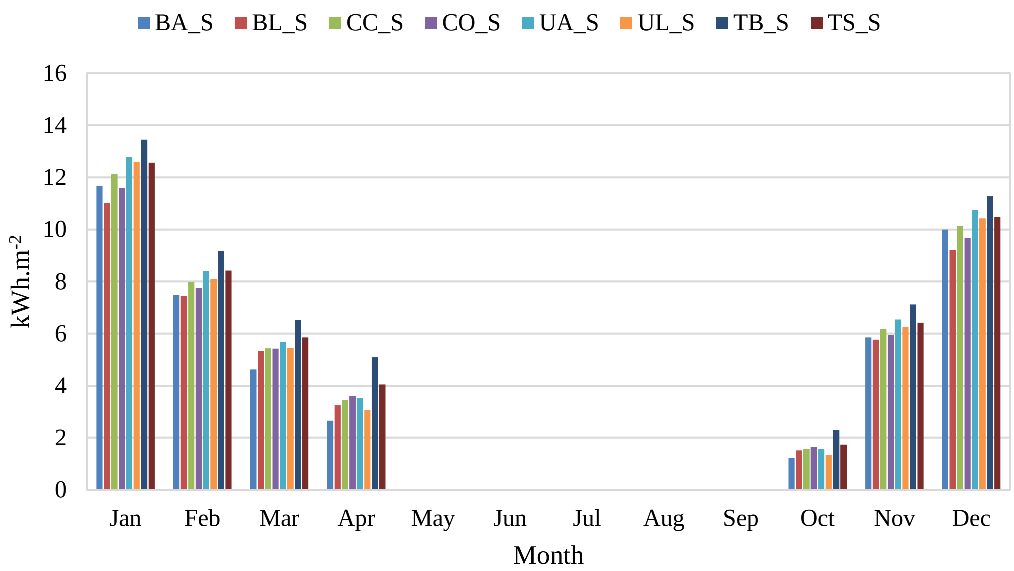

Figure 42. *Comparison of simulated heating demand (kWh.m^{-2}) of south-oriented typologies*

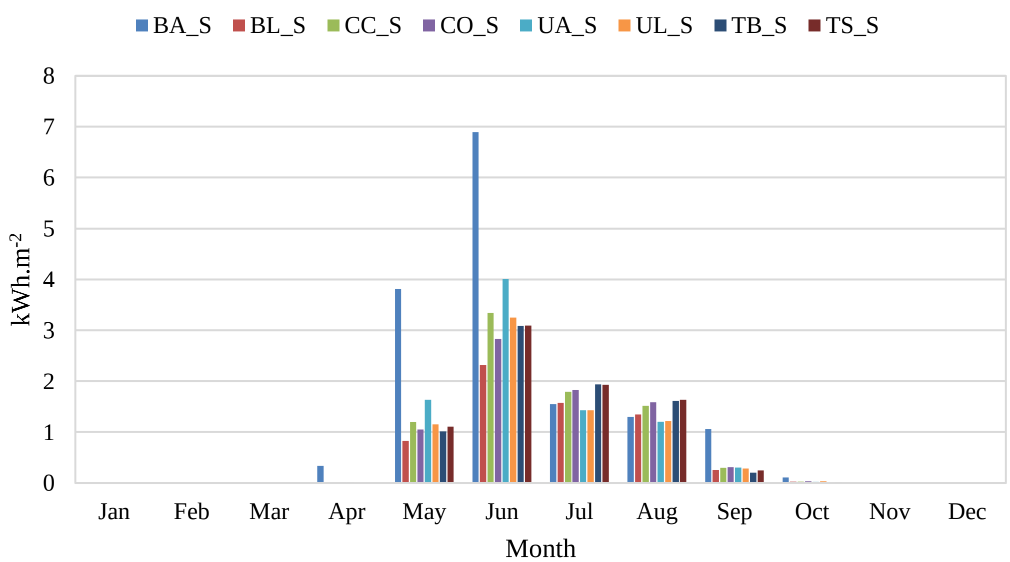

Figure 43. *Comparison of simulated cooling demand (kWh.m^{-2}) of south-oriented typologies*

Figure 44 provides a comparison of the monthly heating demand for all typologies with west-oriented classrooms. ***Figure 45*** illustrates the monthly cooling demand for all typologies with west-oriented classrooms. A ranking similar to the previous orientations is obtained, but with a variance in the amount of energy consumed (kWh.m^{-2}).

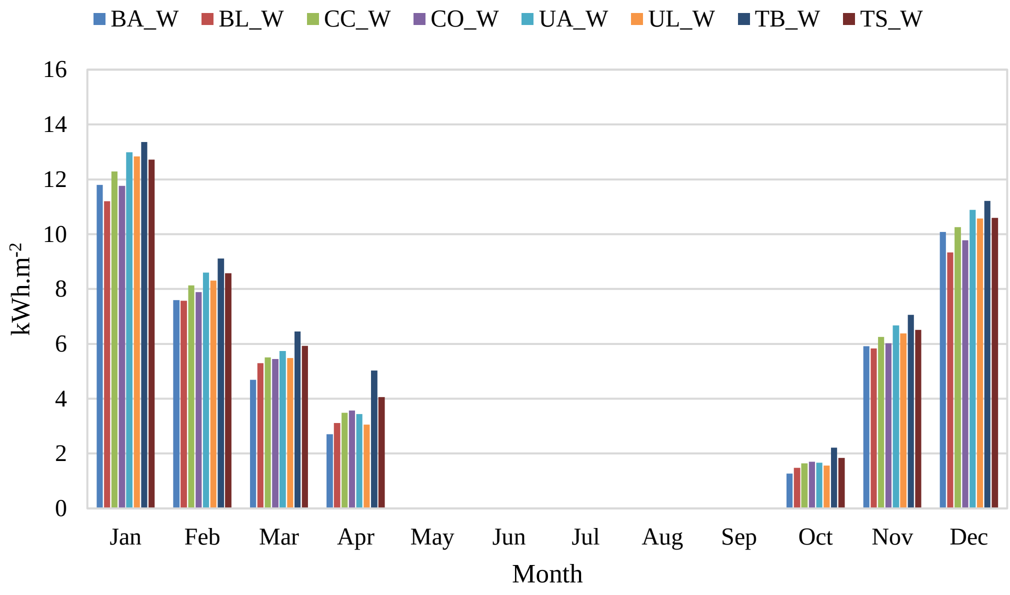

Figure 44. *Comparison of simulated heating demand (kWh.m^{-2}) of west-oriented typologies*

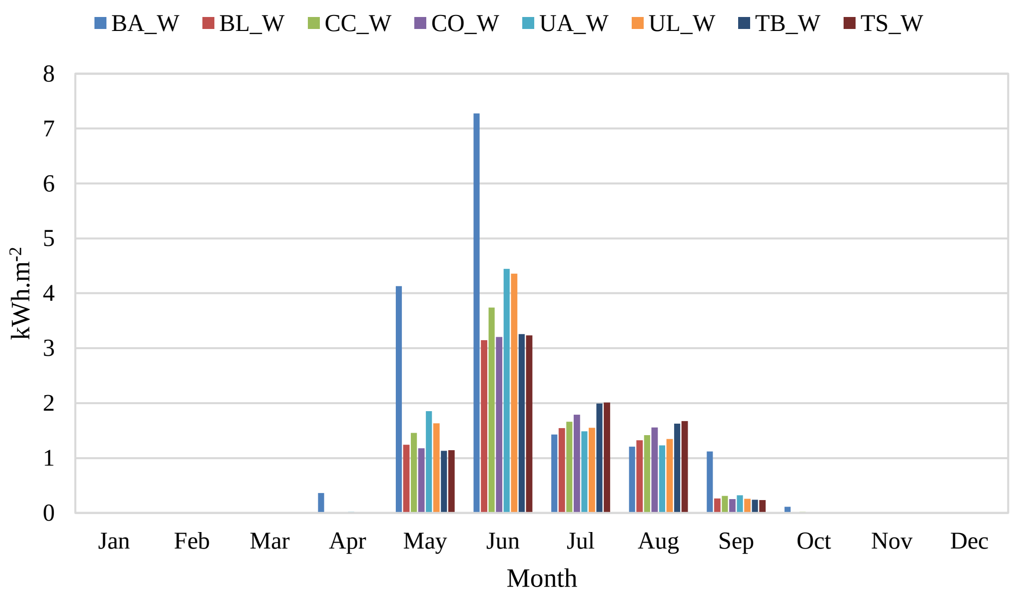

Figure 45. *Comparison of simulated cooling demand (kWh.m^{-2}) of west-oriented typologies*

4.2.2. Thermal performance

The figures below illustrate the correlation of thermal comfort inside classrooms and eight morphology scenarios. Indoor air temperatures are measured during two winter typical days and two summer typical days when the school is occupied.

Figure 46 displays simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September. An air temperature closer to the comfort temperature is observed on the courtyard-facing classrooms of TB and TS typologies. ***Figure 47*** provides a comparison between simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January. The high building compactness of CO and BL induces an increased thermal comfort inside classrooms during winter months. The courtyard impact is still apparent on the relatively higher thermal comfort of TB on the second day studied.

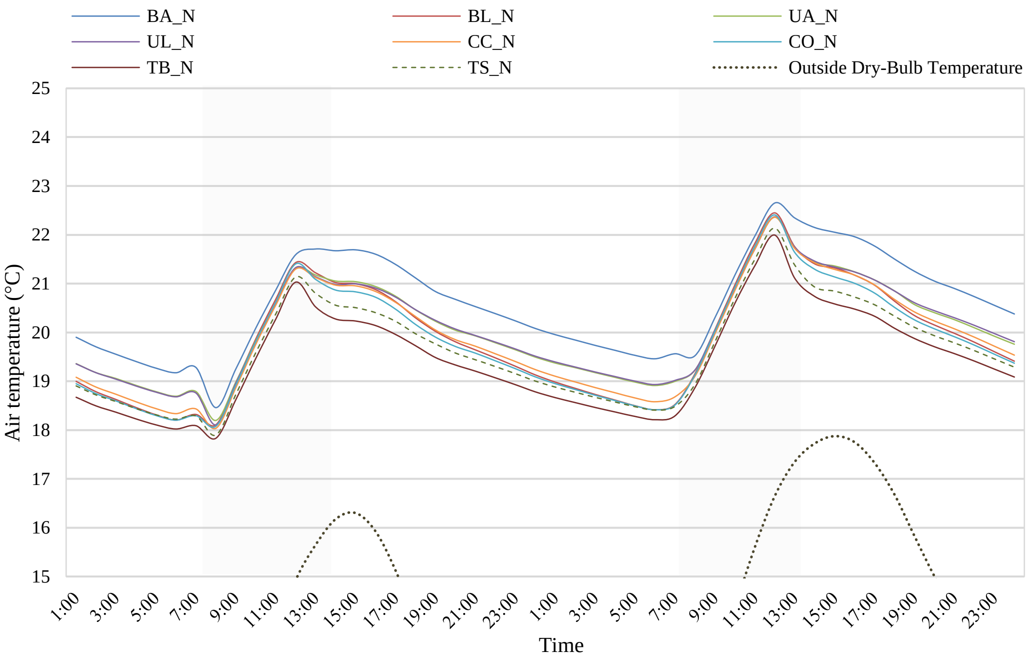

Figure 46. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September*

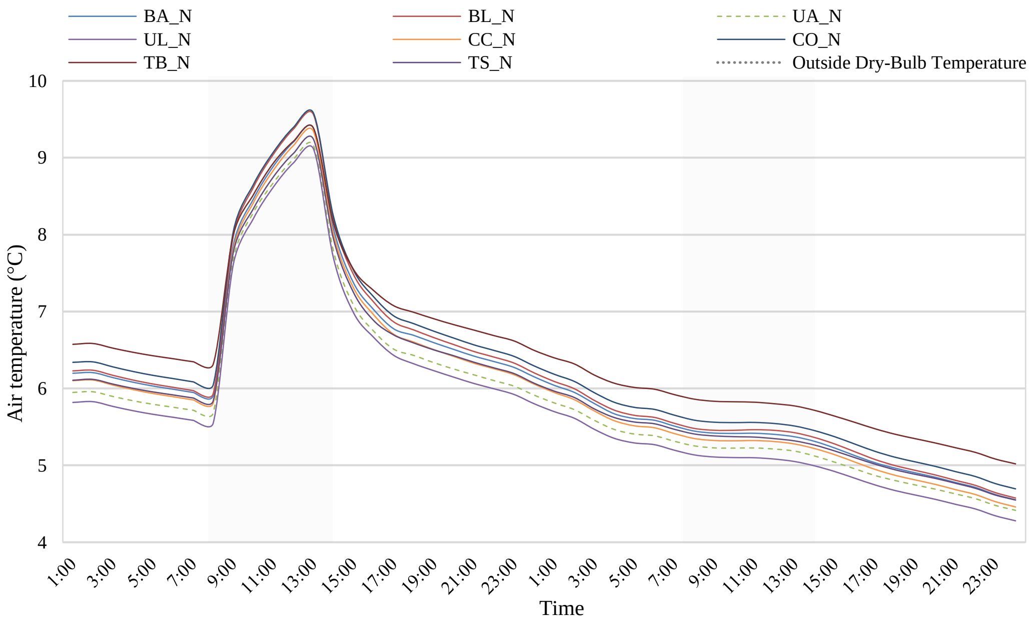

Figure 47. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 6th and 7th of January*

Figure 48 provides a comparison between simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September. The worst performance is obtained from block-type plan, BA and BL induced by their high relative compactness which deteriorates the thermal performance of classrooms during summer months. ***Figure 49*** illustrates the **s**imulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 6th and 7th of January. UL performs worse due to the heat loss caused by its low relative compactness.

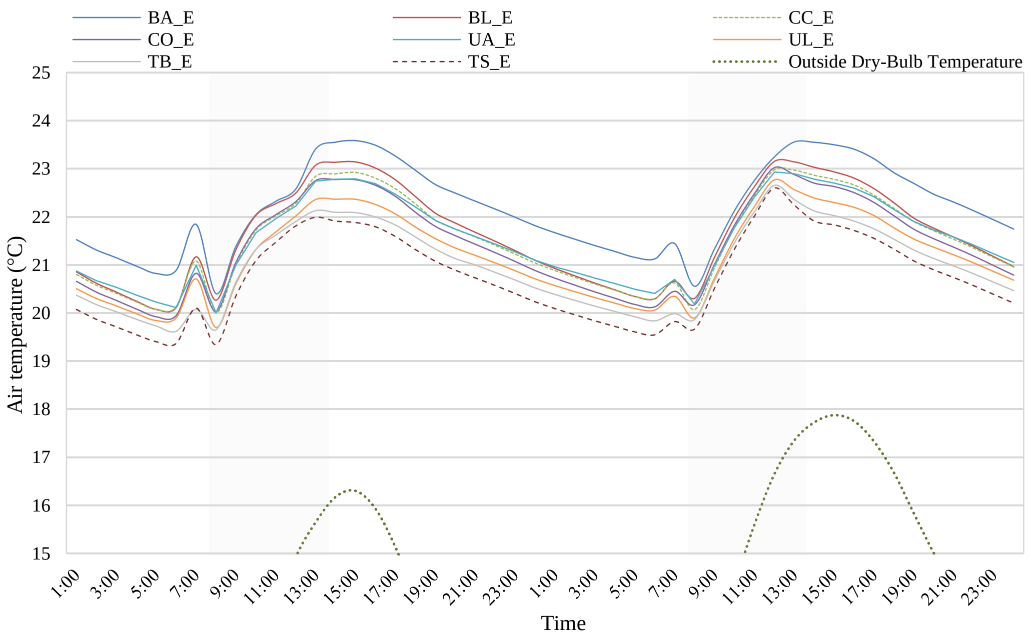

Figure 48. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September*

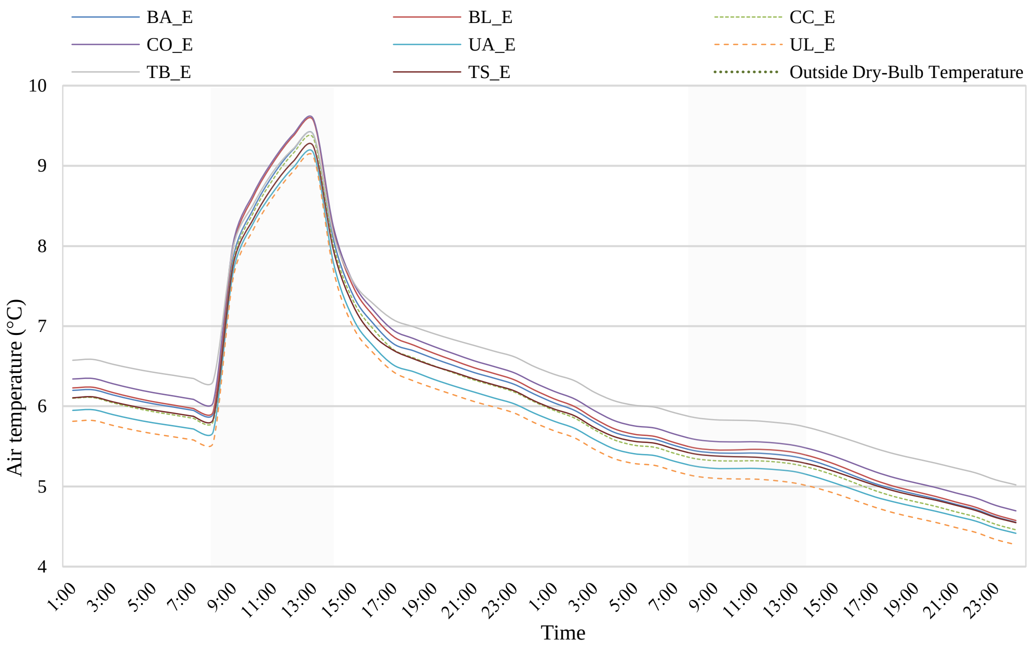

Figure 49. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 6th and 7th of January*

Figure 50 provides a comparison between the simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September. The curves drop slightly during the break due to the natural ventilation schedule regime and the occupants' control actions aiming to improve indoor environmental conditions. It reaches its peak at 14:00. ***Figure 51*** illustrates the simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January.

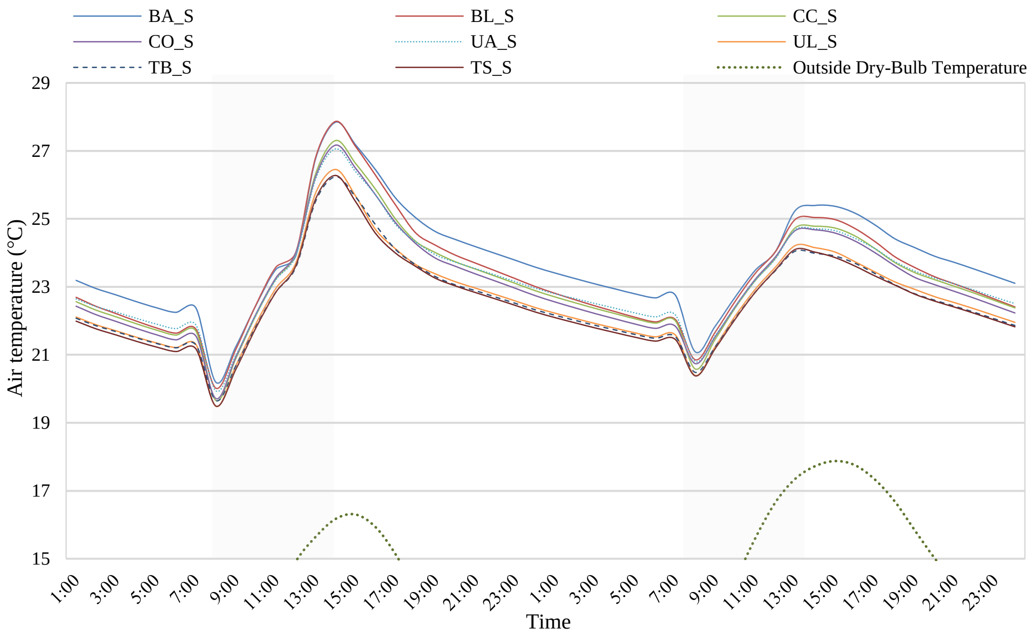

Figure 50. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September*

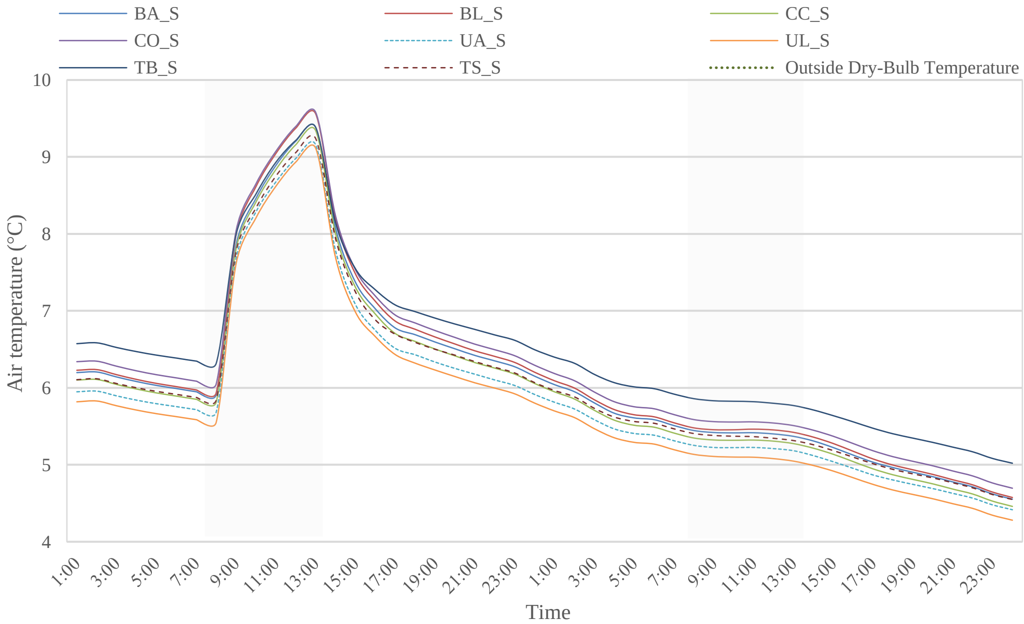

Figure 51. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 6th and 7th of January*

Figure 52 shows the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September. More noticeable differences are those on the second part of the day which corresponds to the warmest time of the day in a west-oriented room. ***Figure 53*** compares the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 6th and 7th of January

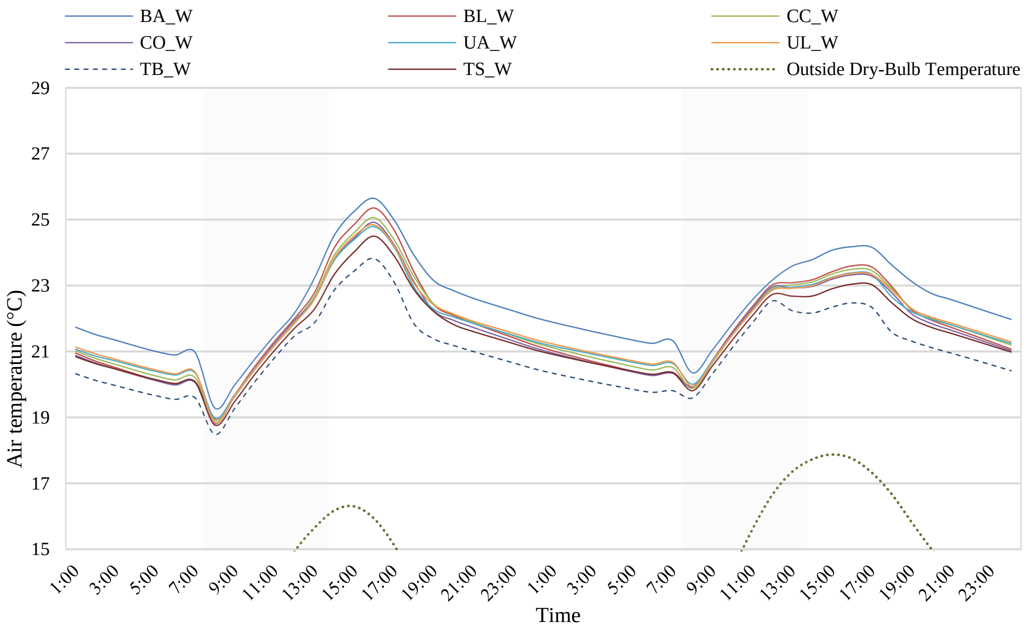

Figure 52. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 12th and 13th of September*

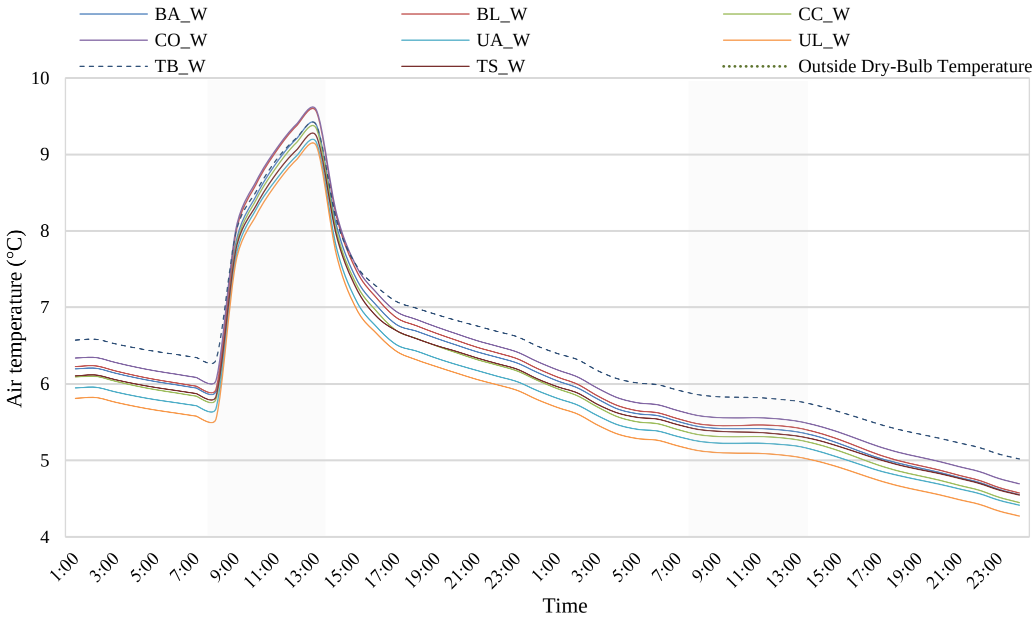

Figure 53. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Zagreb weather file for 6th and 7th of January*

4.3. Climate of Sarajevo

A comparison between annual energy consumption and thermal comfort inside classrooms is illustrated in the figures below to determine the impact of the humid continental climate of Sarajevo in the recommended morphologies.

4.3.1. Energy performance

The figures below illustrate the correlation of annual consumption for heating and cooling loads of the school building model in its eight morphology scenarios. ***Figure 54*** provides a comparison of the monthly heating demand for all typologies with north-oriented classrooms. ***Figure 55*** illustrates the monthly cooling demand for all typologies with north-oriented classrooms. There is a low cooling demand in May and September and no demand in April and October due to influence of the humid continental climate. This shifts the importance of the study for this specific climate context in optimizing heating loads only, as July and August are partially occupied in the case of open-schools and the only month with a considerable need for cooling remains June.

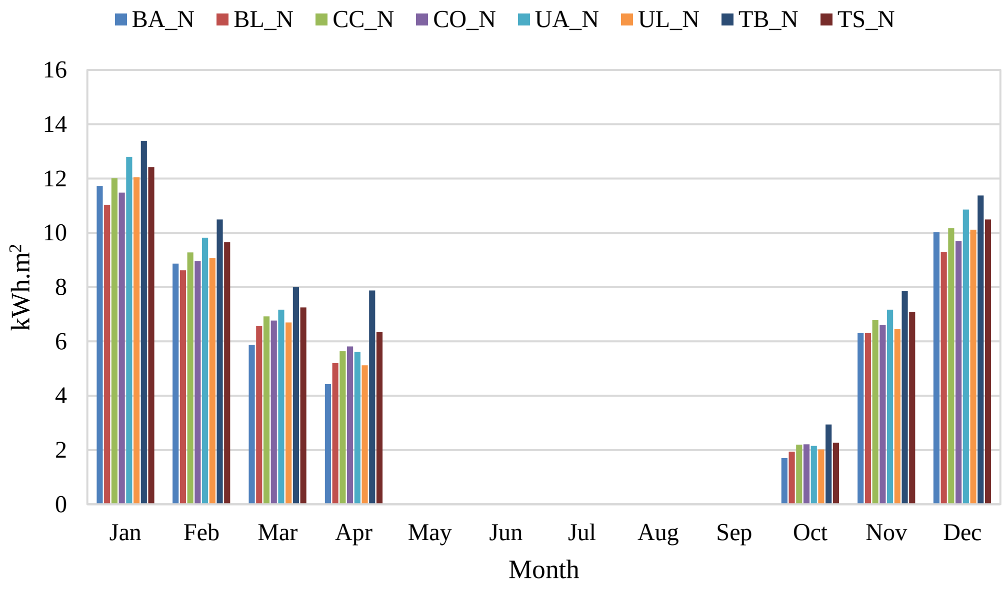

Figure 54. *Comparison of simulated heating demand (kWh.m^{-2}) of north-oriented typologies*

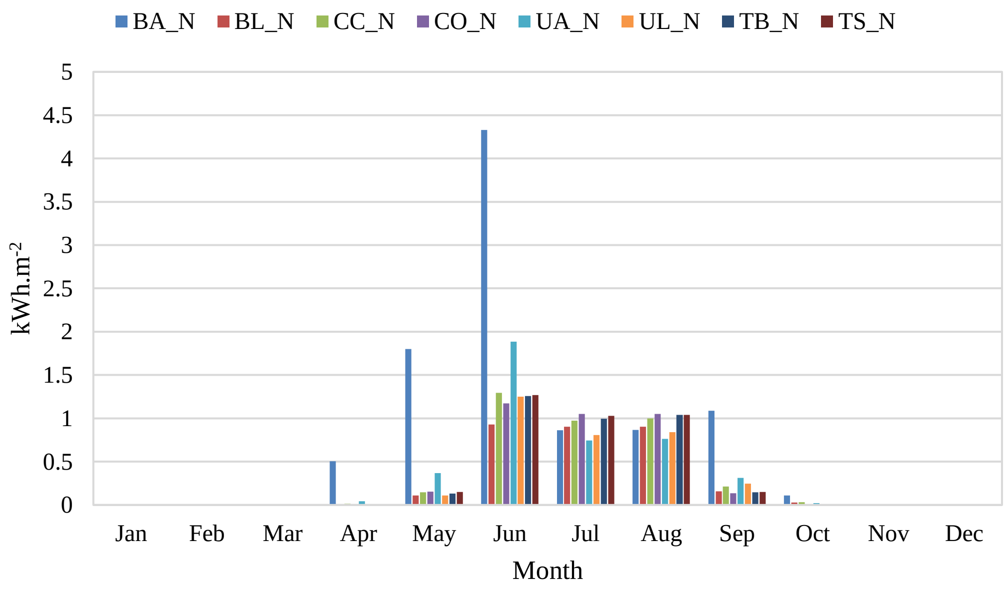

Figure 55. *Comparison of simulated cooling demand (kWh.m^{-2}) of north-oriented typologies*

Figure 56 illustrate***s*** the monthly heating demand for all typologies with east-oriented classrooms. The increase in S_e causes the heating demand to rise. This makes compact typologies which fall under block category perform better for similar climatic contexts with high heating demands. ***Figure 57*** provides a comparison of the monthly cooling demand for all typologies with east-oriented classrooms. The worst performance is that of BA, as the high demand of the atrium itself for air-conditioning increases the cooling demand of the respective typology significantly, thus suggesting a further optimization of the skylight dimension to minimize the impact on cooling loads.

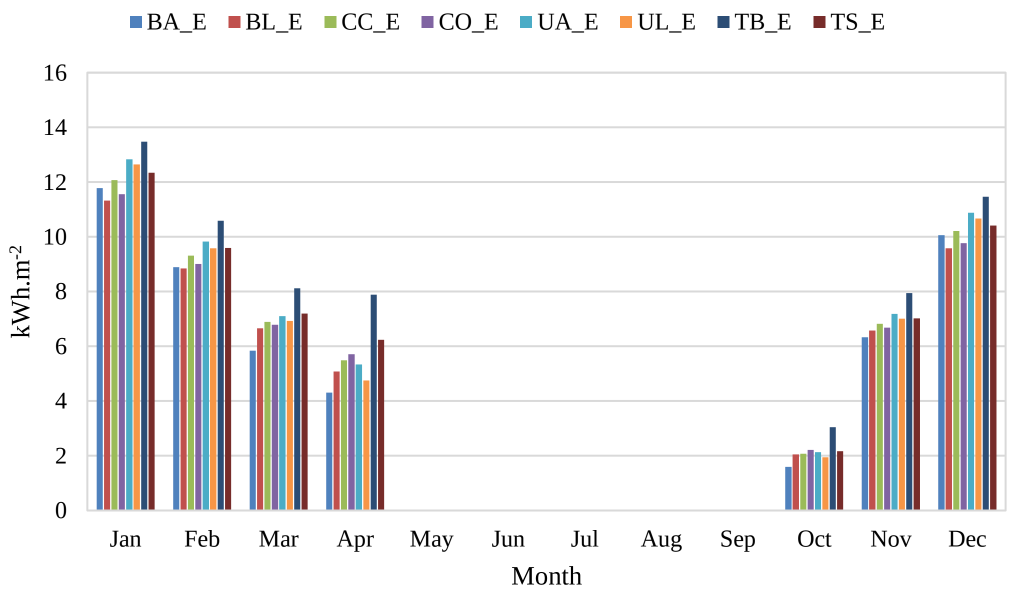

Figure 56. *Comparison of simulated heating demand (kWh.m^{-2}) of east-oriented typologies*

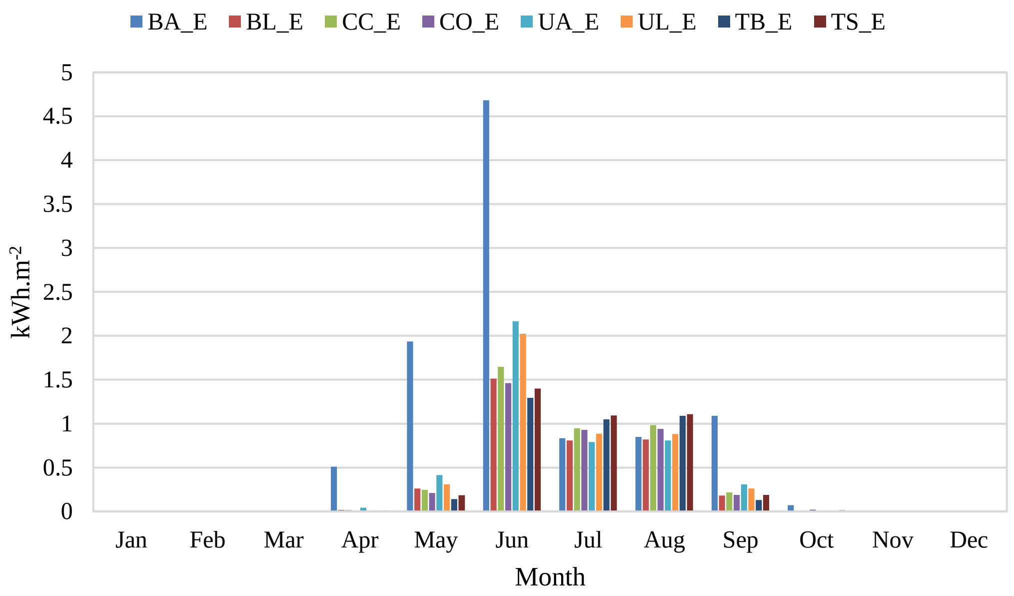

Figure 57. *Comparison of simulated cooling demand (kWh.m^{-2}) of east-oriented typologies*

Figure 58 provides a comparison of the monthly heating demand for all typologies with south-oriented classrooms. ***Figure 59*** illustrates the monthly cooling demand for all typologies with south-oriented classrooms. A ranking similar to the previous orientations is obtained, but with a variance in the amount of energy consumed (kWh.m^{-2}).

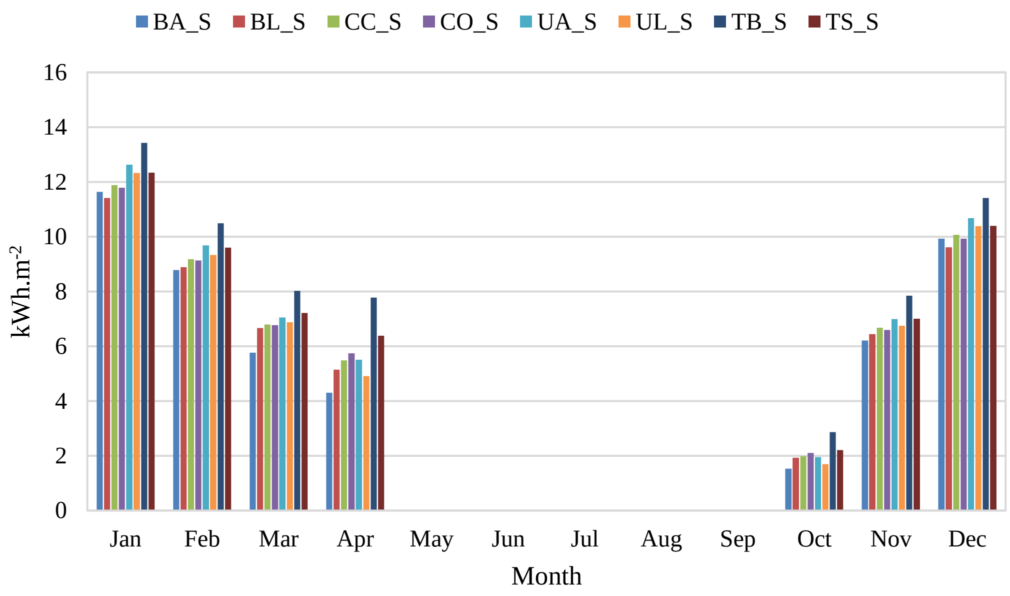

Figure 58. *Comparison of simulated heating demand (kWh.m^{-2}) of south-oriented typologies*

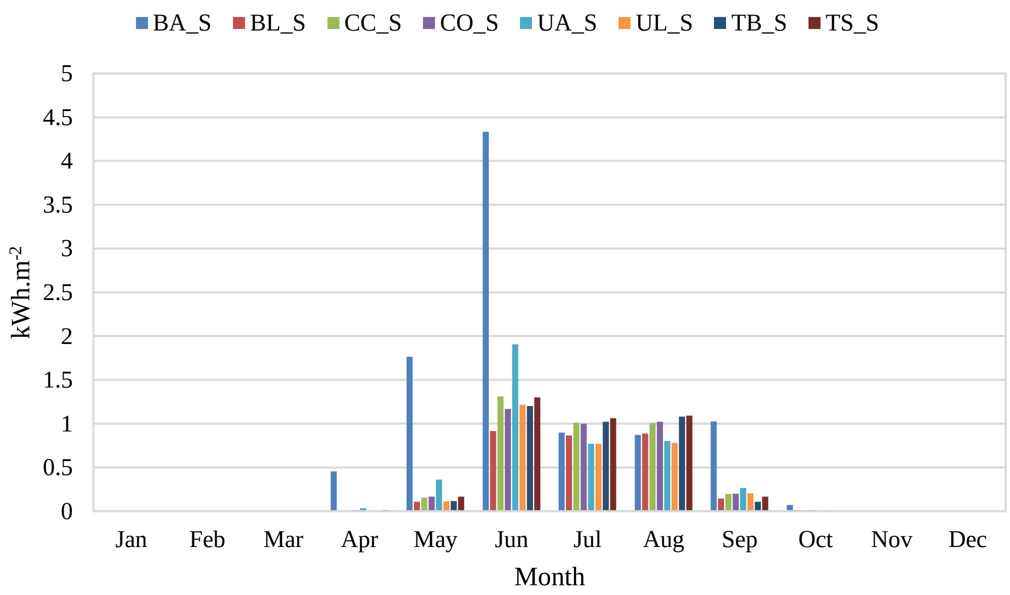

Figure 59. *Comparison of simulated cooling demand (kWh.m^{-2}) of south-oriented typologies*

Figure 60 provides a comparison of the monthly heating demand for all typologies with west-oriented classrooms. TB has a poor performance during the winter months, as its high S_e induces heat loss. ***Figure 61*** illustrates the monthly cooling demand for all typologies with west-oriented classrooms. The relatively high S_e has a positive impact in the reduced cooling loads of TB during summer months, but still the impact is marginal when compared to the one it has on the increased heating loads.

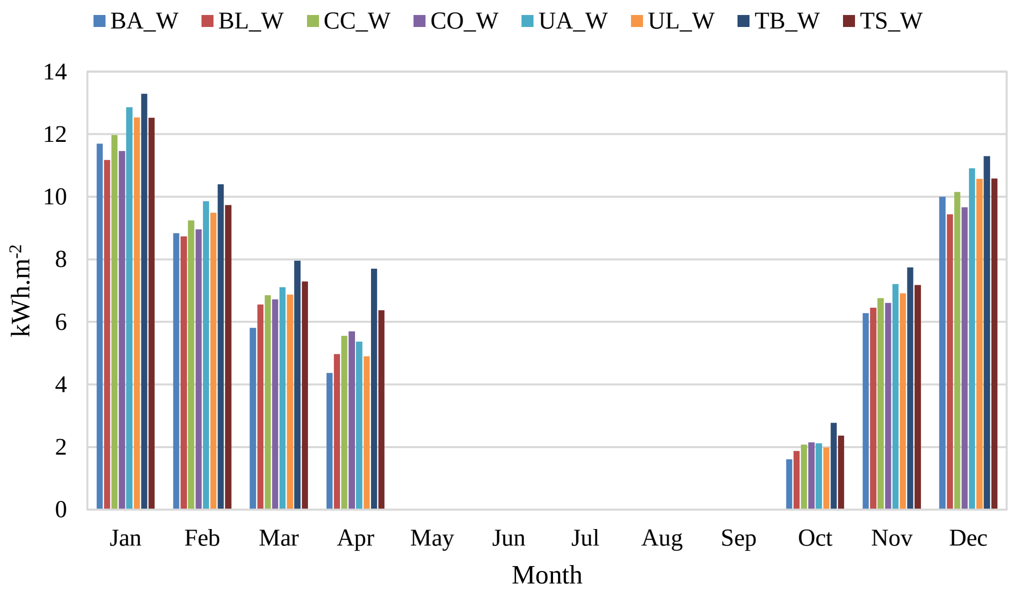

Figure 60. *Comparison of simulated heating demand (kWh.m*$^{-2}$*) of west-oriented typologies*

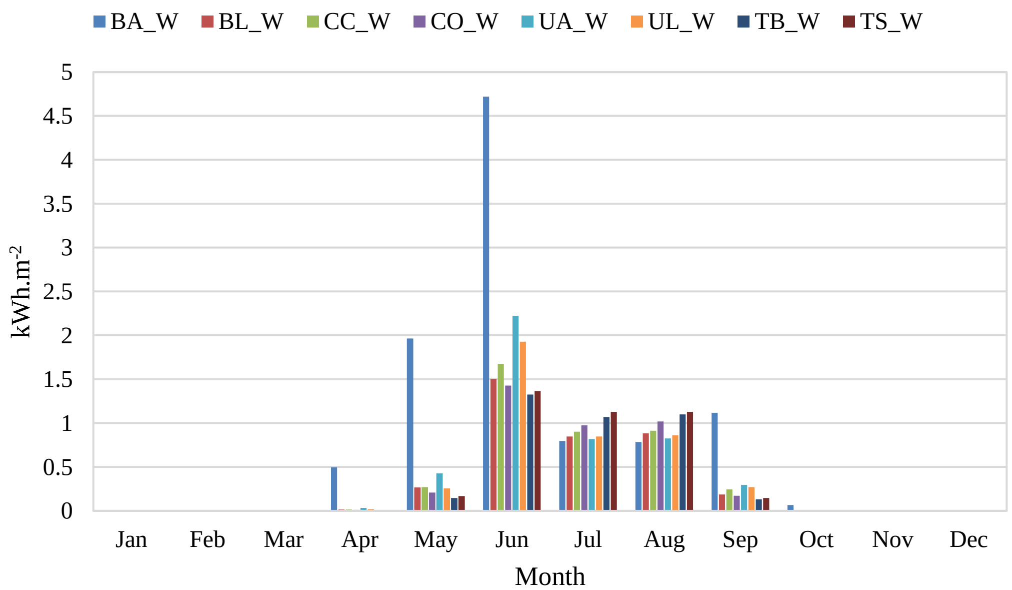

Figure 61. *Comparison of simulated cooling demand (kWh.m*$^{-2}$*) of west-oriented typologies*

4.3.2. Thermal performance

The figures below illustrate the correlation of thermal comfort inside classrooms and eight morphology scenarios. Indoor air temperatures are measured during two winter typical days and two summer typical days when the school is occupied.

Figure 62 displays simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September. The worst performance is obtained from block-type plan, BA, induced by its high relative compactness which deteriorates the thermal performance of classrooms during summer months. ***Figure 63*** provides a comparison between simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January. UL performs worse due to the heat loss caused by its low relative compactness. The higher relative compactness of BL improves the thermal comfort inside classrooms.

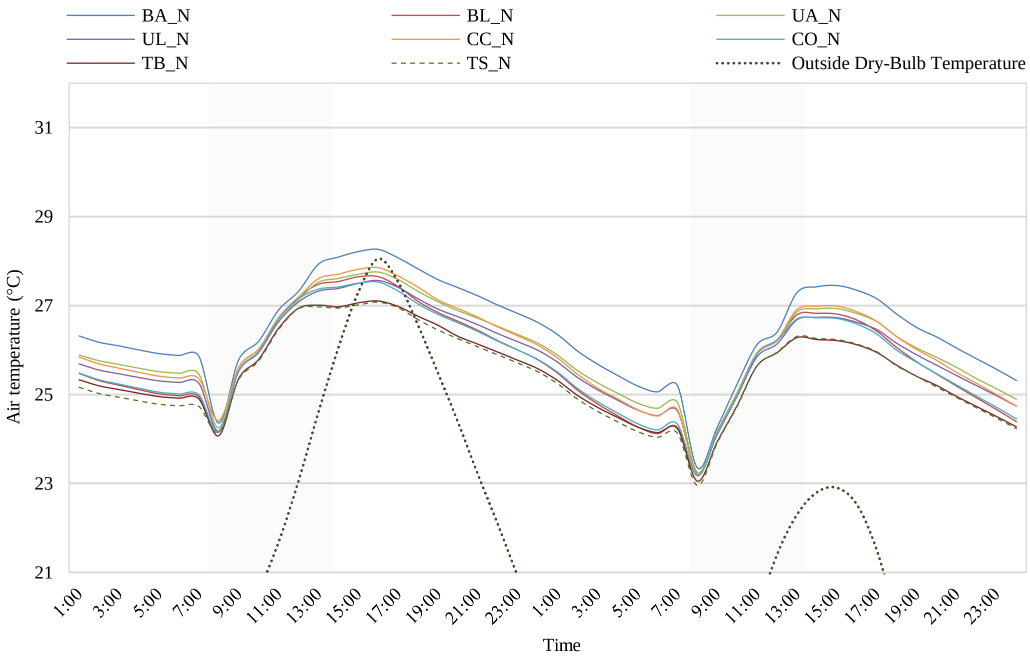

Figure 62. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September*

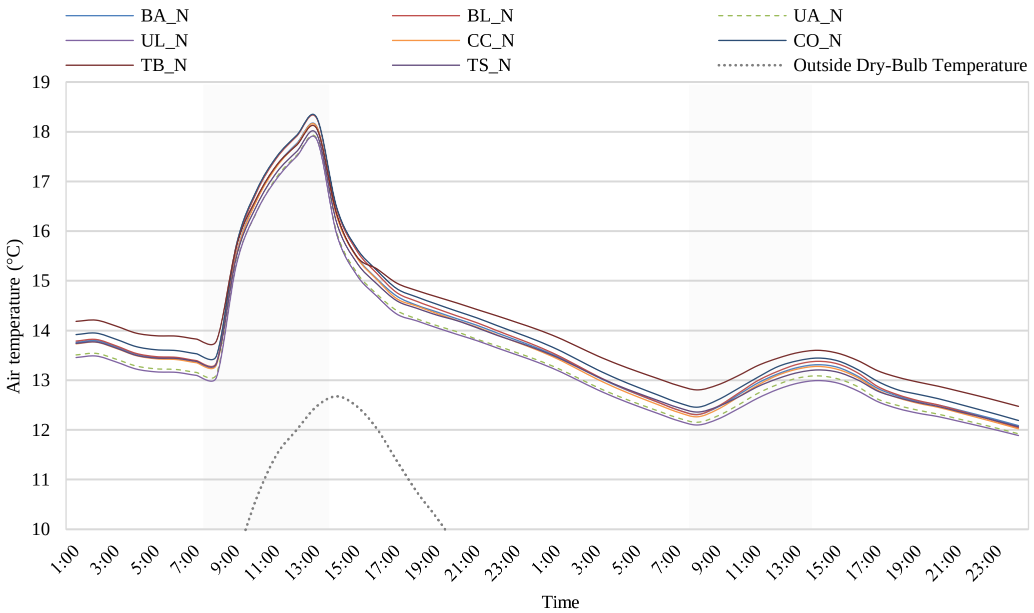

Figure 63. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 6th and 7th of January*

Figure 64 provides a comparison between simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September. The courtyard-facing classrooms of TB and TS typologies manage to maintain air temperatures closer to the comfort temperature. The impact is more noticeable in the second part of the day. ***Figure 65*** illustrates the **s**imulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 6th and 7th of January. The presence of courtyards has adverse effects on thermal comfort during winter, as courtyard-facing classrooms in cluster-plan typologies appear to have lower air temperatures.

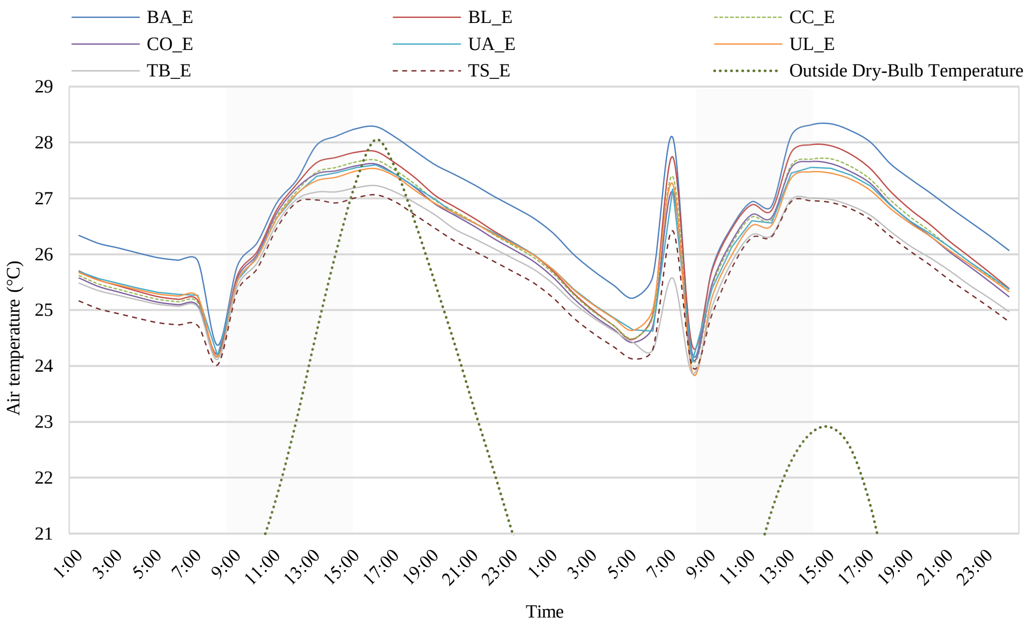

Figure 64. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September*

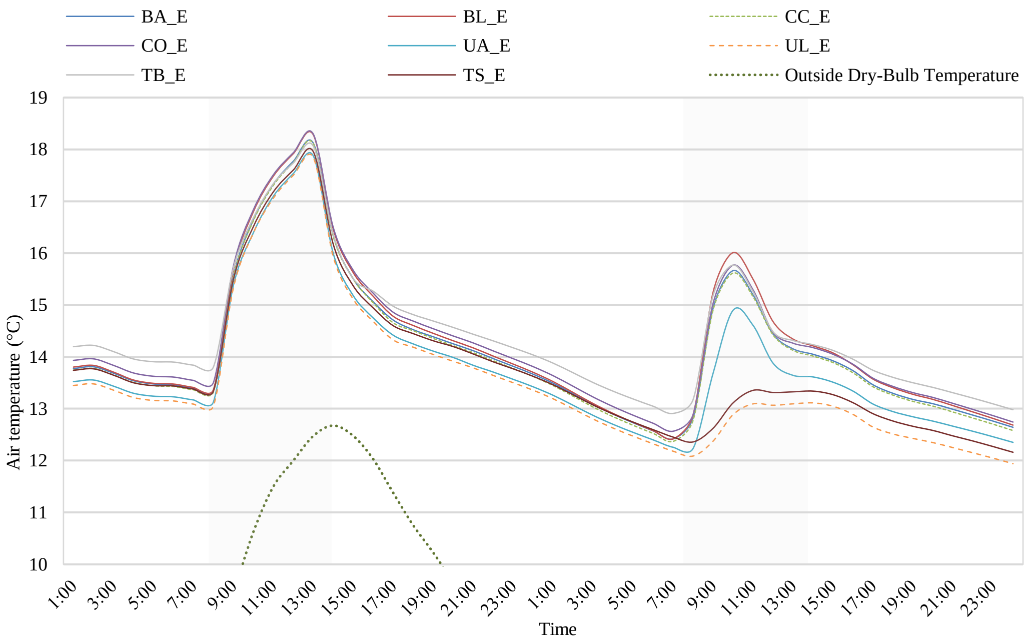

Figure 65. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 6th and 7th of January*

Figure 66 provides a comparison between the simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September. The curves fluctuate and drop slightly during the break due to the natural ventilation schedule regime and the occupants' control actions aiming to improve indoor environmental conditions. ***Figure 67***Figure 51 illustrates the simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January.

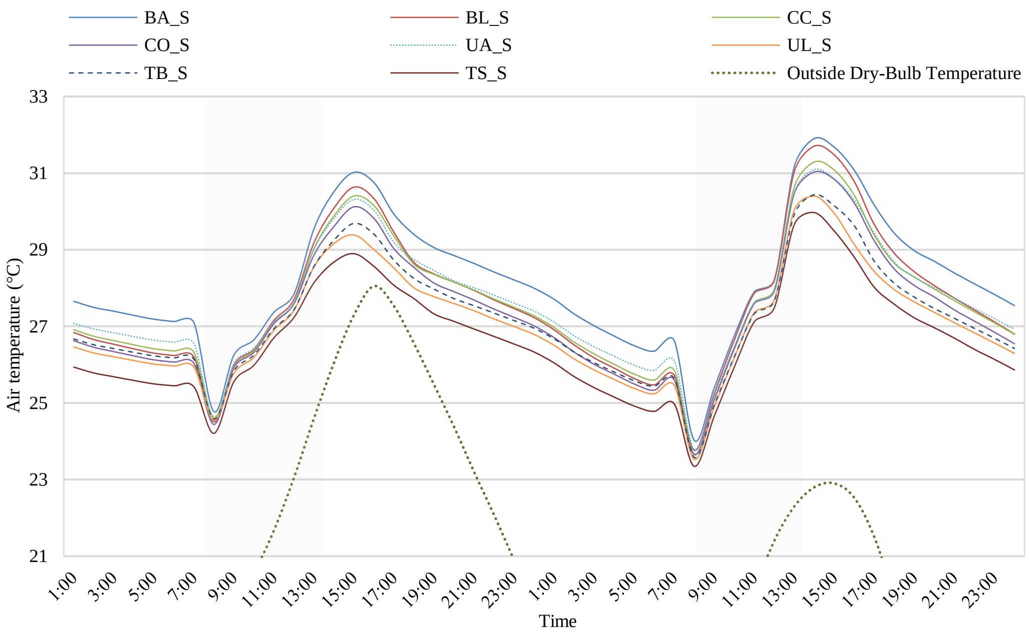

Figure 66. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September*

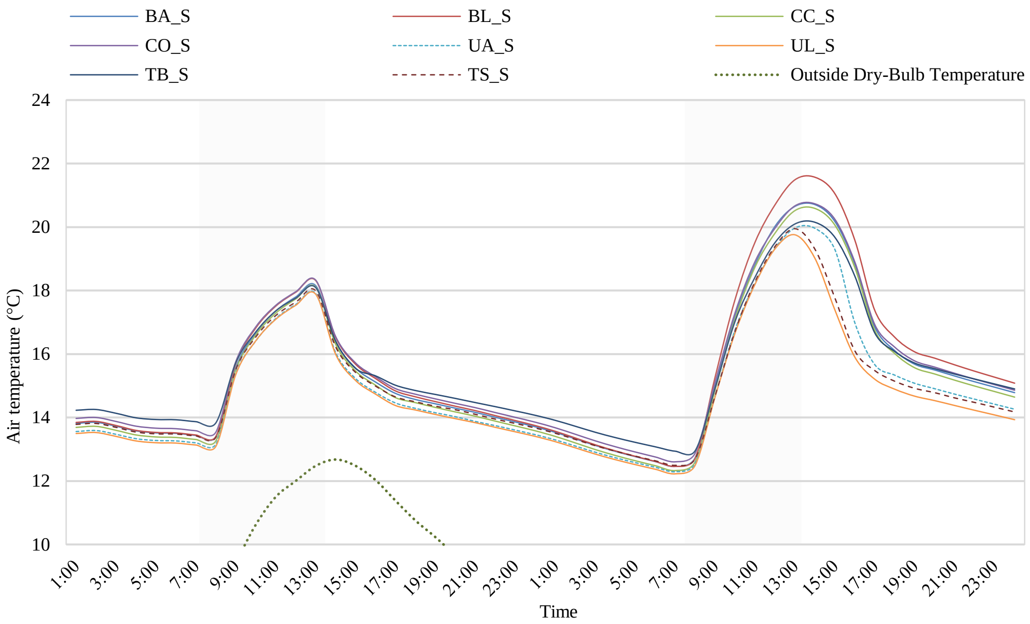

Figure 67. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 6th and 7th of January*

Figure 68 shows the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September. ***Figure 69*** compares the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 6th and 7th of January

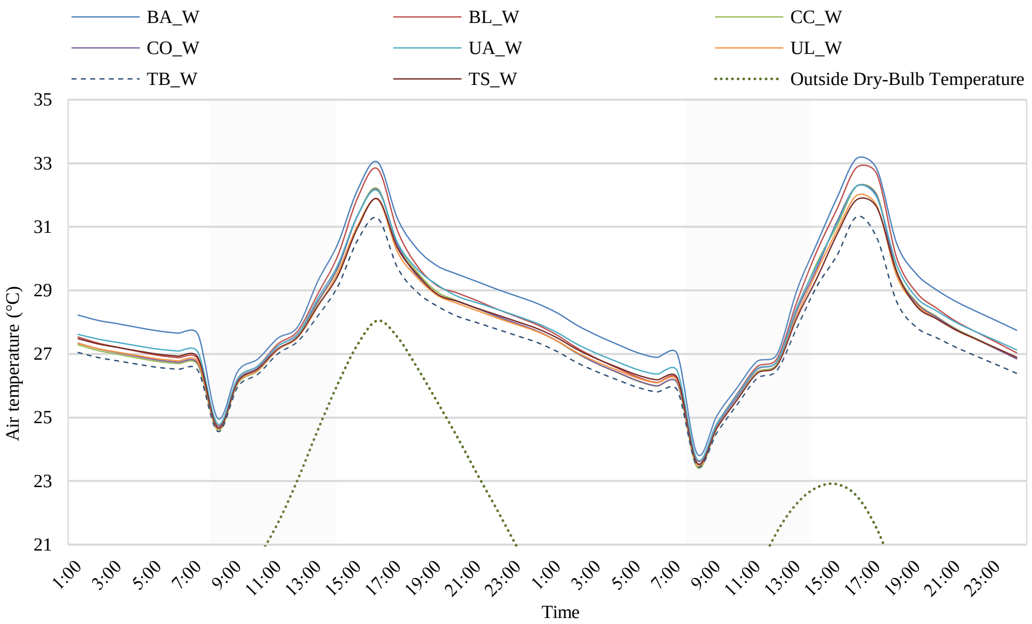

Figure 68. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 12th and 13th of September*

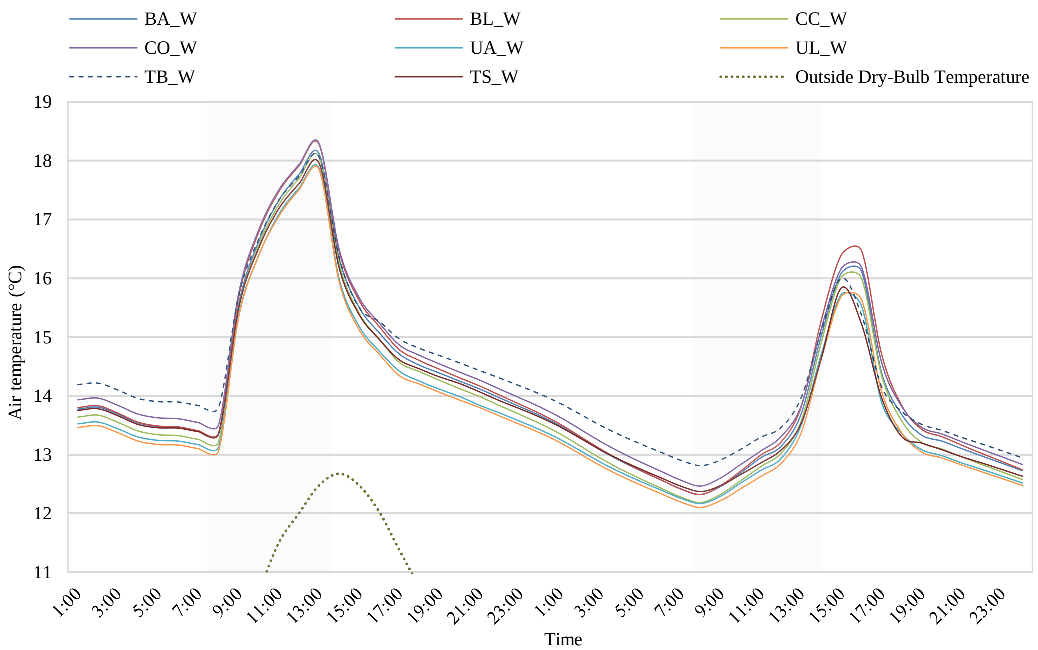

Figure 69. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Sarajevo weather file for 6th and 7th of January*

4.4. Climate of Athens

A comparison between annual energy consumption and thermal comfort inside classrooms is illustrated in the figures below to determine the impact of the Mediterranean climate of Athens in the recommended morphologies.

4.4.1. Energy performance

The figures below illustrate the correlation of annual consumption for heating and cooling loads of the school building model in its eight morphology scenarios.

Figure 70 provides a comparison of the monthly heating demand for all typologies with north-oriented classrooms. There is no demand for heating in October. ***Figure 71*** illustrates the monthly cooling demand for all typologies with north-oriented classrooms. There is a low cooling demand in May and October and no demand in April due to influence of the Mediterranean climate. The highest demand for heating is in June, as in July and August open-school premises are partially occupied.

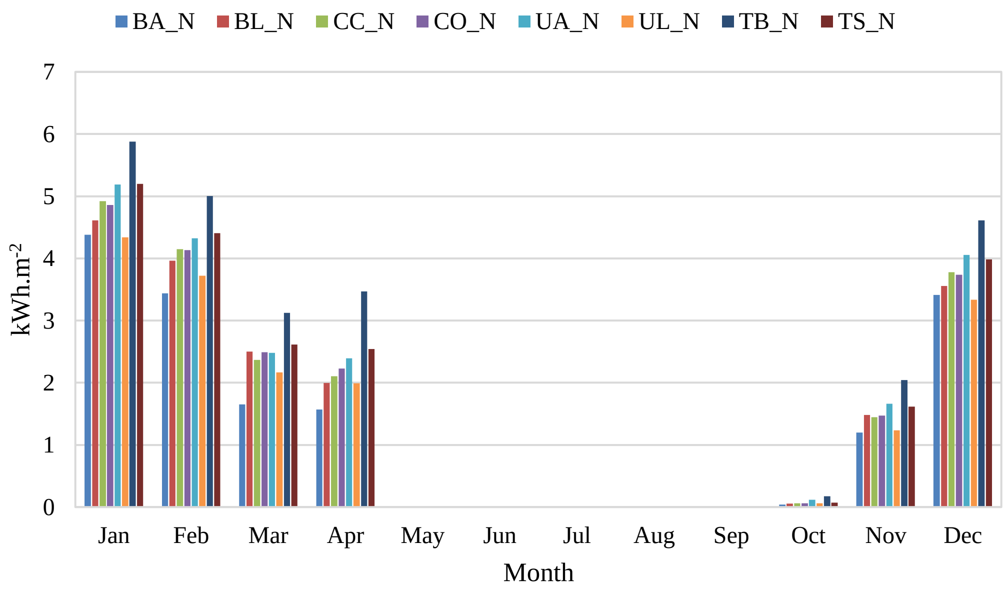

Figure 70. *Comparison of simulated heating demand (kWh.m^{-2}) of north-oriented typologies*

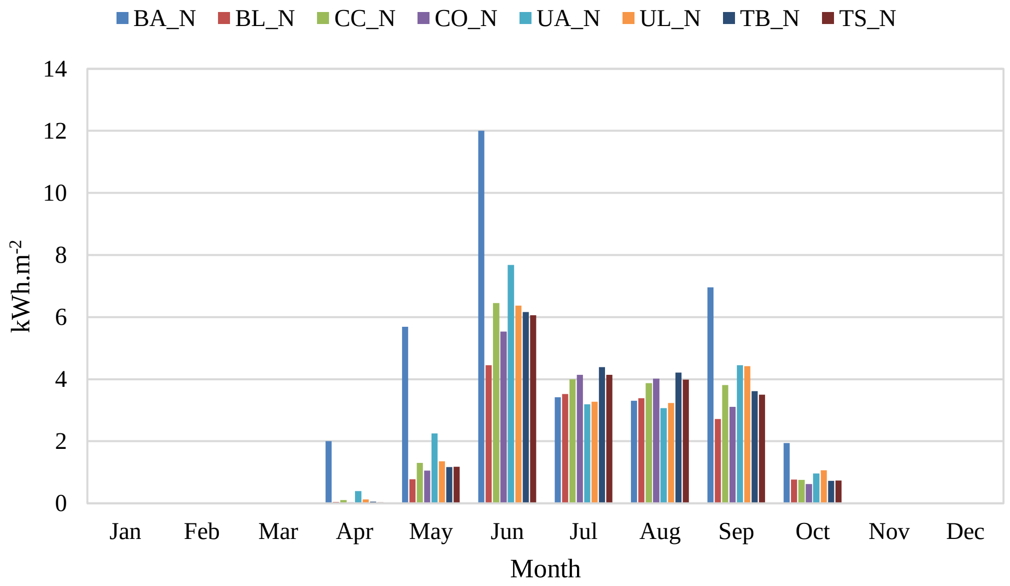

Figure 71. *Comparison of simulated cooling demand (kWh.m^{-2}) of north-oriented typologies*

Figure 72 illustrates the monthly heating demand for all typologies with north-oriented classrooms. Induced by its relatively high S_e (surface of the envelope including ground floor slab), TB displays a poor performance in a Mediterranean climate. The best performance is obtained by BA due to the significant contribution of the atrium on heating energy savings. ***Figure 73*** illustrates the monthly cooling demand for all typologies with north-oriented classrooms. The high demand of the atrium itself for air-conditioning increases the cooling demand of BA significantly, thus casting doubts on the efficiency of its integration in building plans for this specific context.

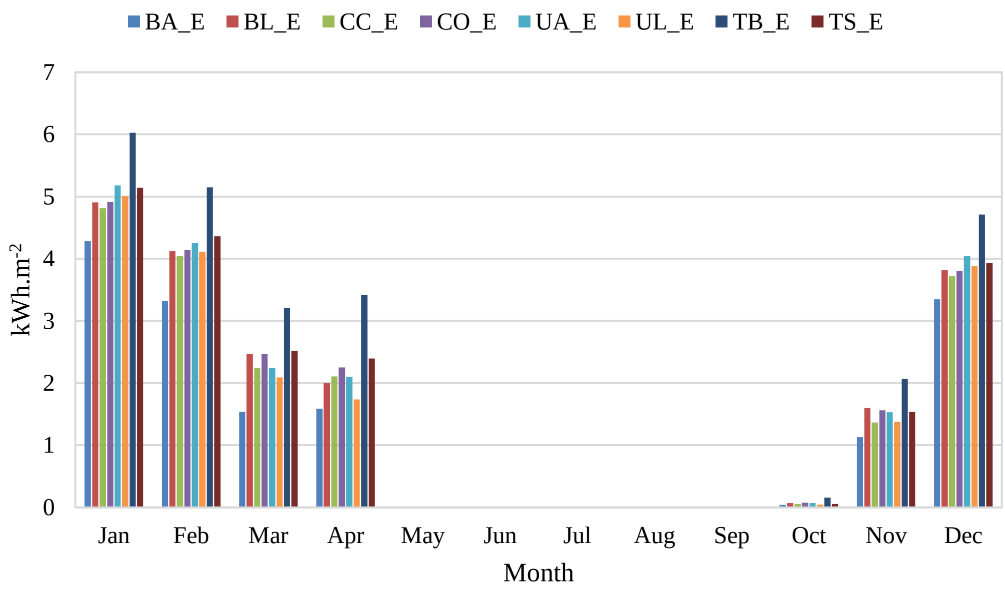

Figure 72. *Comparison of simulated heating demand (kWh.m^{-2}) of east-oriented typologies*

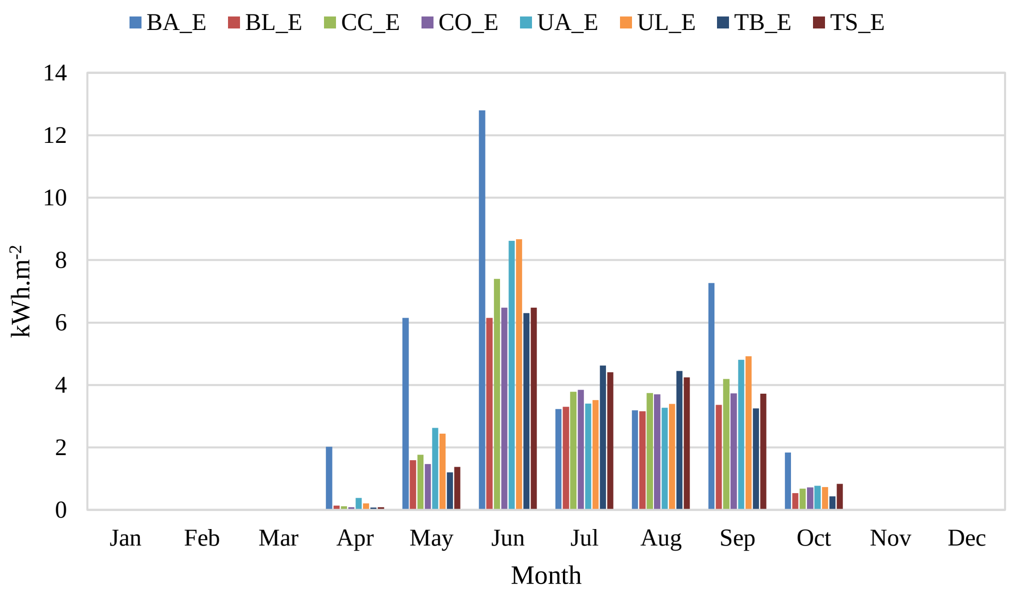

Figure 73. *Comparison of simulated cooling demand (kWh.m-2) of east-oriented typologies*

Figure 74 provides a comparison of the monthly heating demand for all typologies with south-oriented classrooms. ***Figure 75*** illustrates the monthly cooling demand for all typologies with south-oriented classrooms. A ranking similar to the previous orientations is obtained, but with a variance in the amount of energy consumed (kWh.m^{-2}).

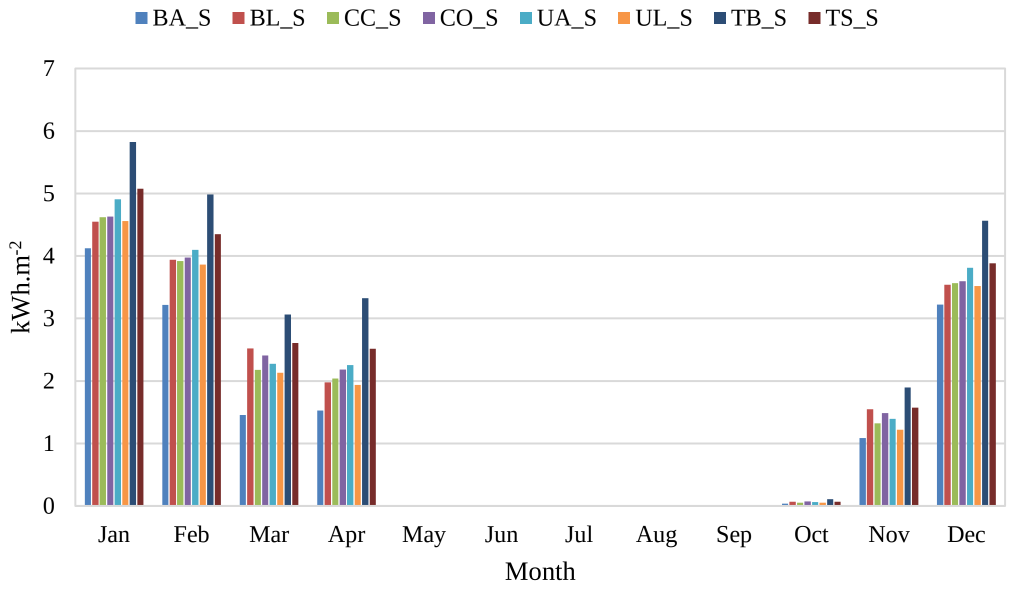

Figure 74. *Comparison of simulated heating demand (kWh.m^{-2}) of south-oriented typologies*

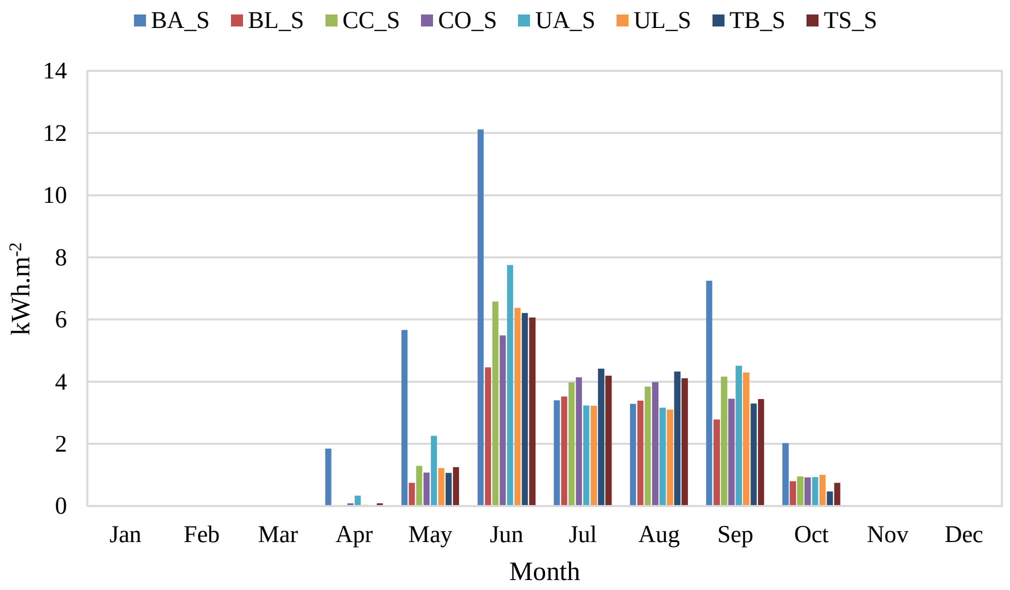

Figure 75. *Comparison of simulated cooling demand (kWh.m^{-2}) of south-oriented typologies*

Figure 76 provides a comparison of the monthly heating demand for all typologies with west-oriented classrooms. ***Figure 77*** illustrates the monthly cooling demand for all typologies with west-oriented classrooms. The impact of the presence of courtyards is higher in the reduction of heating loads than on that of the cooling loads. This is visible in the rankings of CC and UL.

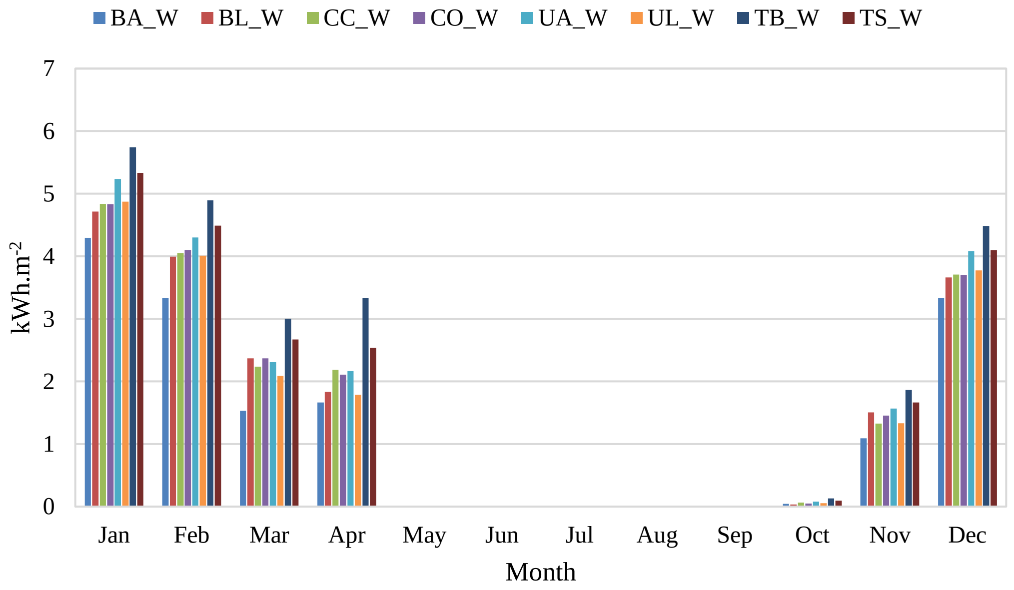

Figure 76. *Comparison of simulated heating demand (kWh.m^{-2}) of west-oriented typologies*

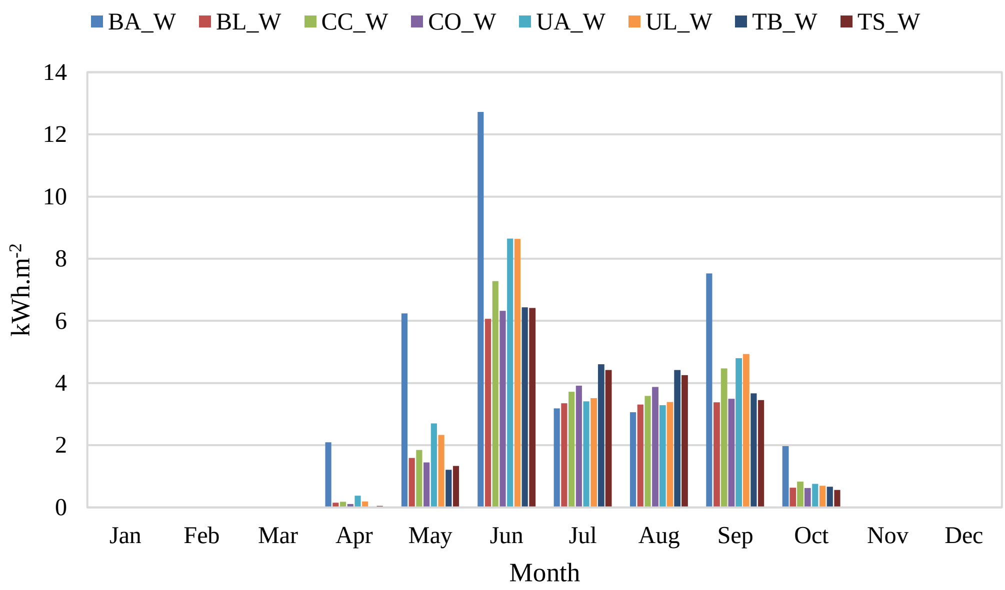

Figure 77. *Comparison of simulated cooling demand (kWh.m^{-2}) of west-oriented typologies*

4.4.2. Thermal performance

The figures below illustrate the correlation of thermal comfort inside classrooms and eight morphology scenarios. Indoor air temperatures are measured during two winter typical days and two summer typical days when the school is occupied.

Figure 78 displays simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September. The worst performance is obtained from block-type plan, BA, influenced by the presence of a covered courtyard/atrium which contributes significantly in increasing the air temperature of the surrounding environments. ***Figure 79*** provides a comparison between simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January. Organic typologies (TB and TS) perform worse due to the heat loss caused by their low relative compactness.

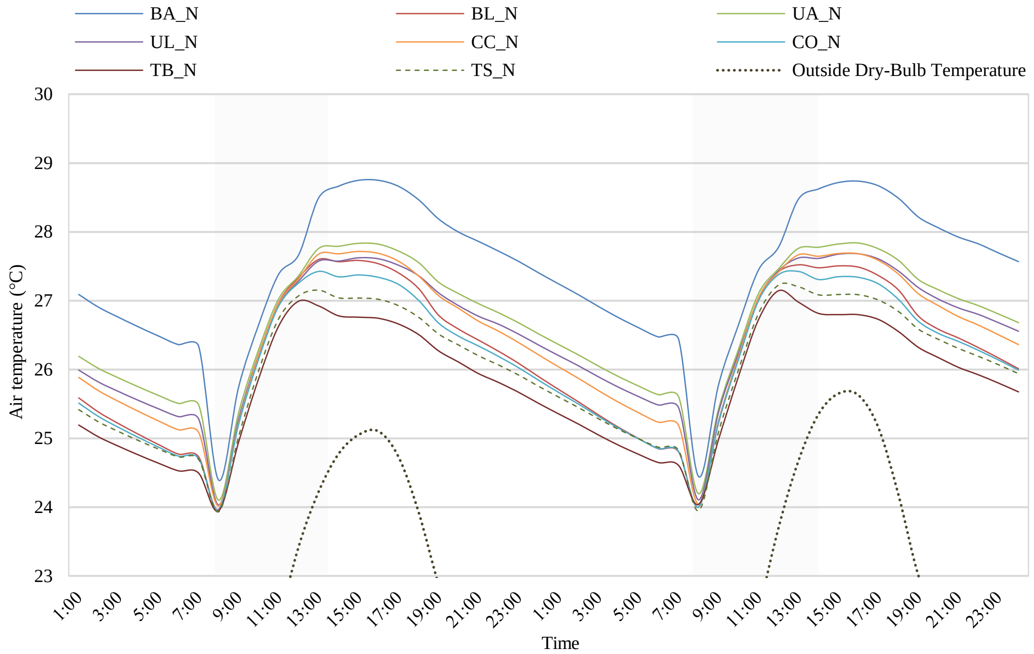

Figure 78. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September*

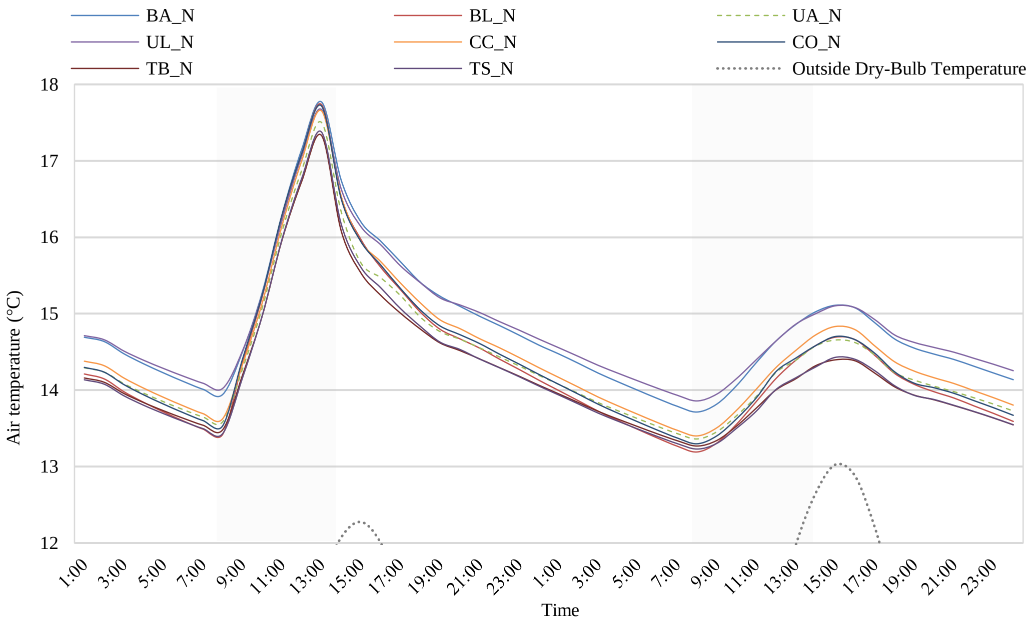

Figure 79. *Simulated indoor air temperatures for north-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 6th and 7th of January*

Figure 80 provides a comparison between the simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September. The curves drop significantly during breaks as scheduled in the natural ventilation regime. The occupants' control actions are aimed at and succeed in improving indoor environmental conditions. ***Figure 81*** illustrates the simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January.

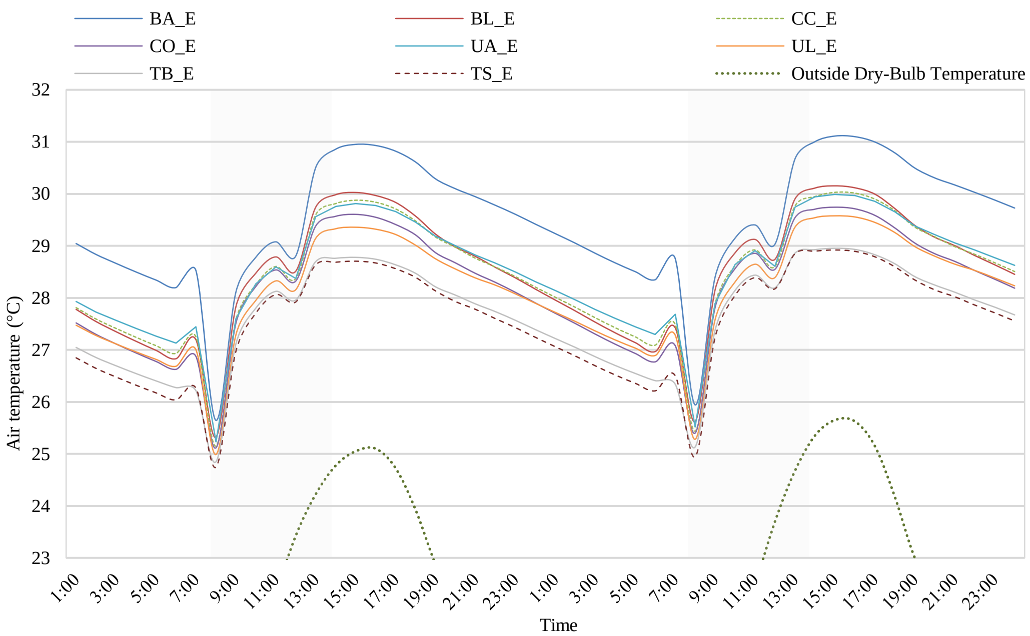

Figure 80. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September*

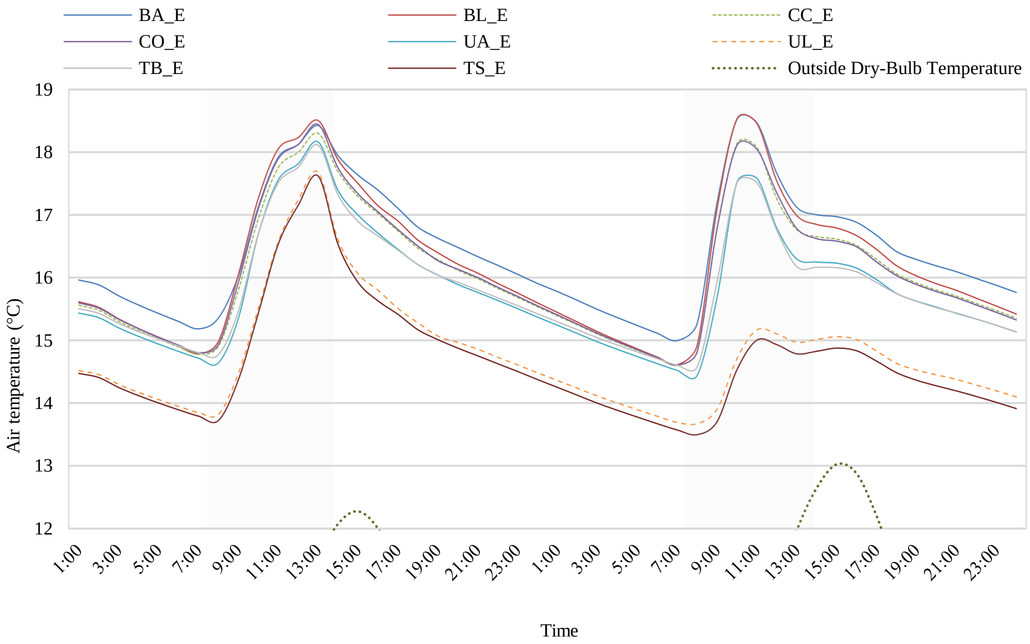

Figure 81. *Simulated indoor air temperatures for east-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 6th and 7th of January*

Figure 82 displays simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September. Courtyard-facing classrooms of TB and TS typologies maintain an air temperature closer to the comfort temperature. ***Figure 83*** provides a comparison between simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature for 6th and 7th of January. The high relative compactness of BL increases the thermal comfort inside classrooms during winter months.

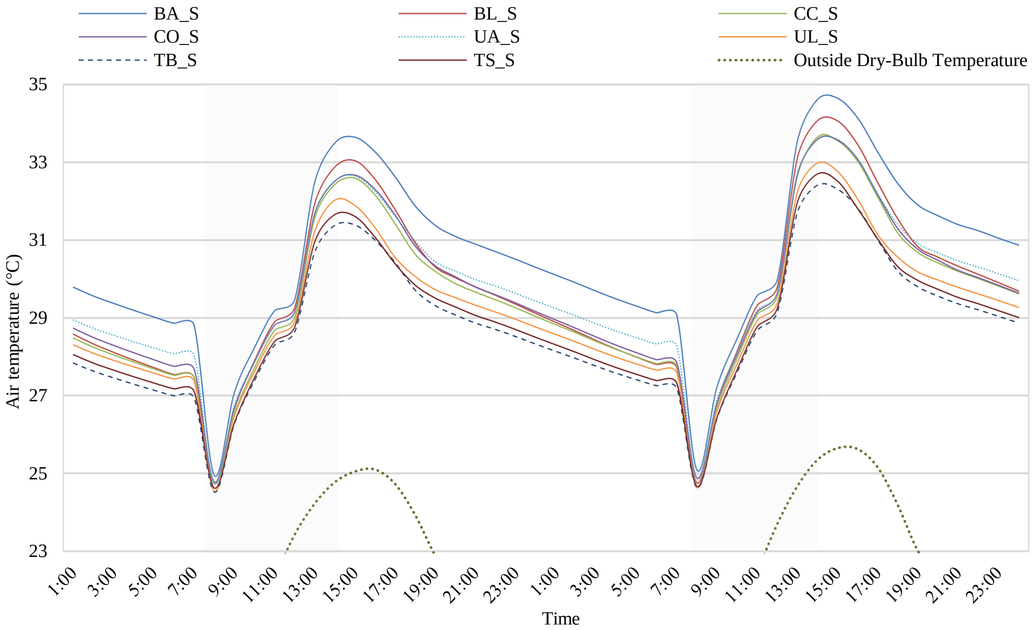

Figure 82. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September*

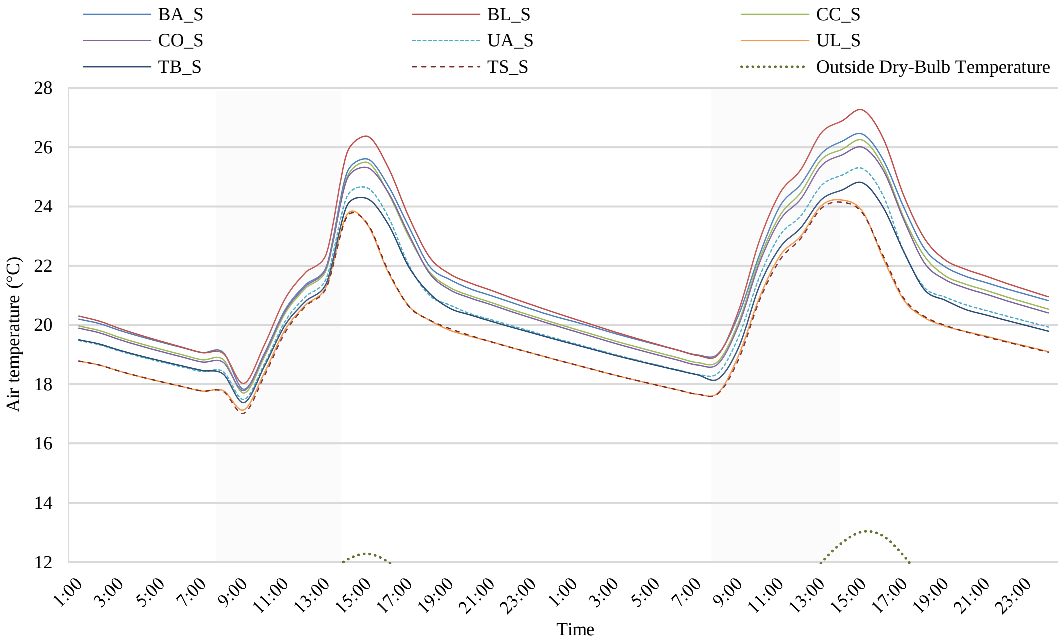

Figure 83. *Simulated indoor air temperatures for south-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 6th and 7th of January*

Figure 84 shows the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September. ***Figure 85*** compares the simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 6th and 7th of January

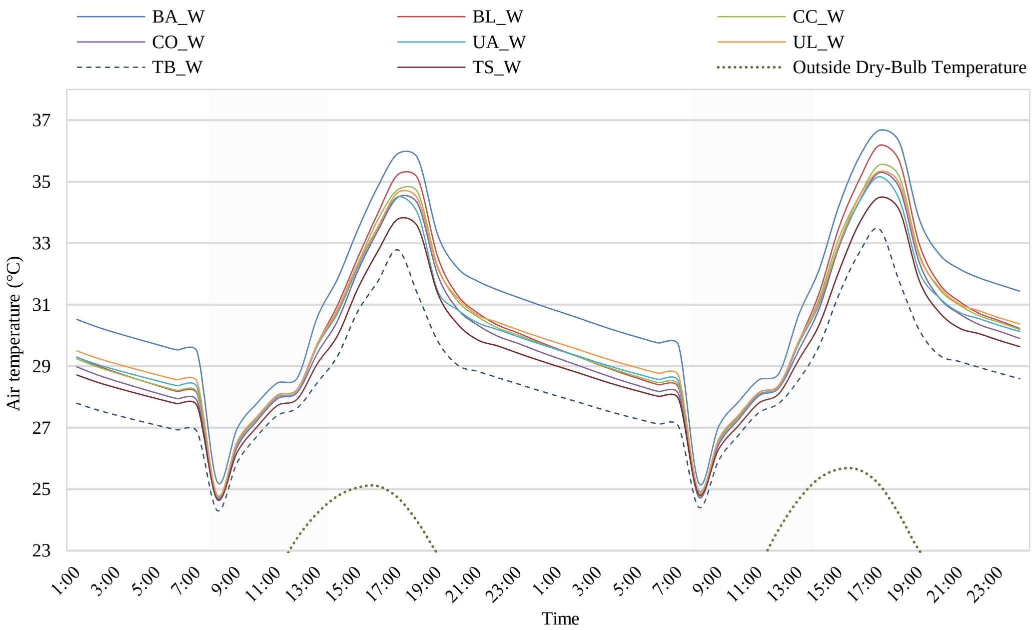

Figure 84. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 12th and 13th of September*

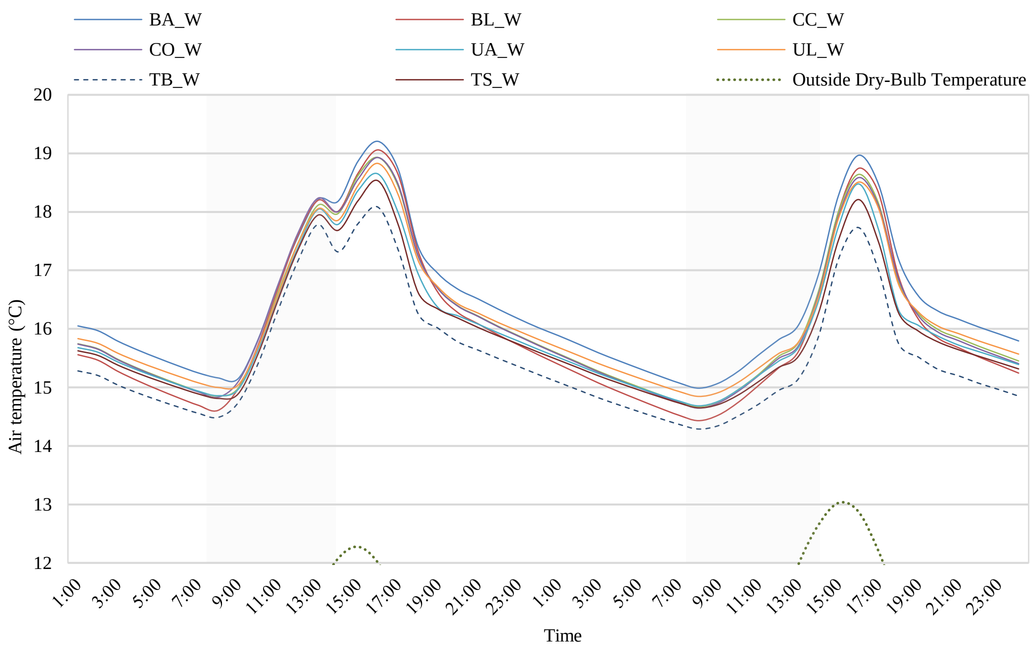

Figure 85. *Simulated indoor air temperatures for west-oriented scenarios, together with the dry-bulb temperature from the Athens weather file for 6th and 7th of January*

CHAPTER 5

DISCUSSIONS

5.1. Climate of Tirana

5.1.1. Energy performance

As illustrated in ***Figure 86***, the comparison of annual simulated energy demand in terms of rotation angle shows an increasing trend when the building is rotated 90° and 270°, which corresponds to classrooms being east and west oriented. The biggest impact of orientation is visible in typologies with longitudinal layouts BL and UL. In UL typology energy consumption is subject to an increase of 5.4 kWh.m^{-2}Y^{-1} when rotated 90° and 4.8 kWh.m^{-2}Y^{-1} when rotated 270°. Slight changes are observed when the typologies are rotated 180° with a difference of ±0.9 kWh.m^{-2}Y^{-1} in energy consumption.

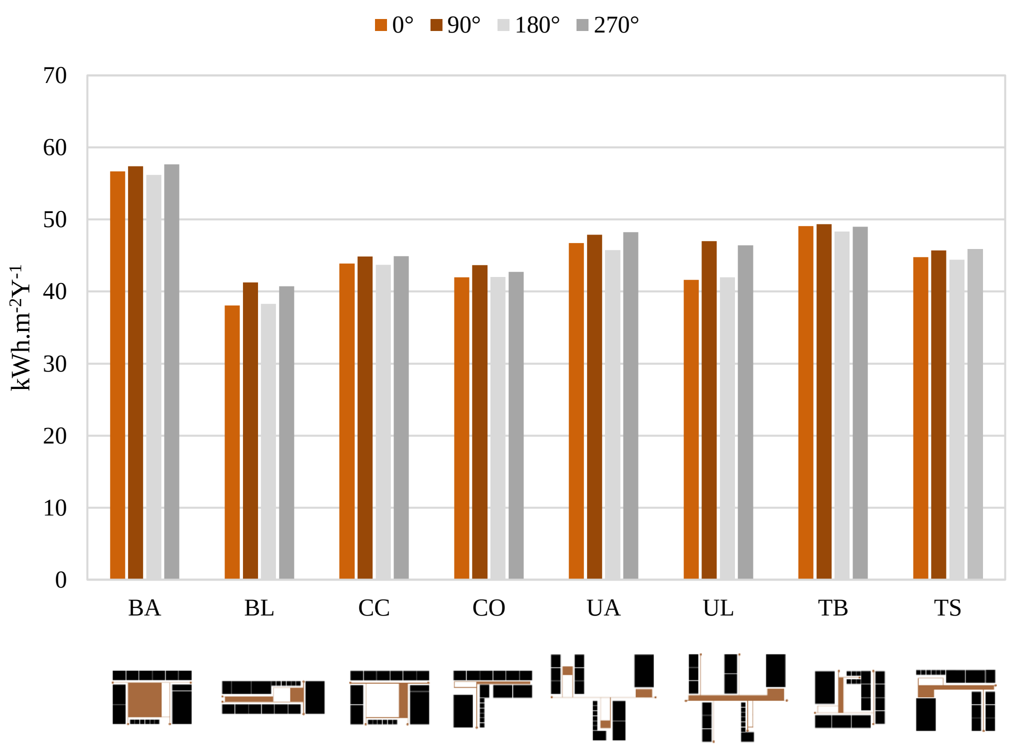

Figure 86. *Comparison of annual simulated energy demand (kWh.m^{-2}y^{-1})*

Table 10 summarizes the simulation results obtained for all the scenarios in the climate of Tirana. A maximum of 32.8% of total energy consumed can be reduced through the selection of the proper morphology for the studied climatic context. The typology with the worst performance in terms of energy loads is BA, thus casting doubts on the appropriateness of block plans organized around a central atrium for the humid subtropical climate of Tirana. The atrium does manage to save approximately 10.5 kWh/m^2 in heating loads with a morphology effectiveness of 53.9% when compared to more organic typologies with a lower relative compactness, but its high demand for air-conditioning increases the cooling demand of BA and reduces the morphology effectiveness by 58.7%. The presence of courtyard, whether open (CO) or closed (CC) makes the morphology gain an approximate effectiveness of 24 ± 2%. Multiple open courtyards are also part of cluster-plan typologies (UA and UL), but the longitudinal plan makes both these typologies perform better only in certain orientations; when rotated 0 and 180 degrees. The sky lighted atrium in the core of each unit of UA, decreases its performance further. It becomes similar to that of TB, the organic typology with a S_e relatively higher than the other typologies simulated.

Table 10. *Simulation results obtained for all the scenarios in the climate of Tirana*

	Annual heating demand			**Annual cooling demand**			**Annual energy demand**		
Scenarios	Total heating [kWh]	Heating/ conditioned area [kWh/m^2]	**Morphology effectiveness [%]**	Total cooling [kWh]	Cooling/ conditioned area [kWh/m^2]	**Morphology effectiveness [%]**	Total energy [kWh]	Total energy/ conditioned area [kWh/m^2]	**Total Morphology effectiveness [%]**
BA_N	49427.7	20.6	_	86340.8	36.0	_	135768.5	56.7	_
BL_N	48080.1	23.2	**-12.5**	30826.7	14.9	**58.7**	78906.8	38.1	**32.8**
CC_N	49043.7	24.7	**-19.7**	38114.1	19.2	**46.7**	87157.7	43.9	**22.5**
CO_N	45351.2	24.5	**-18.6**	32434.9	17.5	**51.4**	77786.0	42.0	**25.9**
UA_N	56901.7	26.2	**-26.8**	44763.8	20.6	**42.9**	101665.5	46.7	**17.5**
UL_N	51100.9	22.8	**-10.7**	42027.9	18.8	**47.9**	93128.8	41.6	**26.6**
TB_N	58143.2	30.4	**-47.6**	35585.5	18.6	**48.3**	93728.7	49.1	**13.4**
TS_N	46955.6	26.3	**-27.4**	33089.0	18.5	**48.6**	80044.6	44.8	**20.9**
BA_S	46920.1	19.6	_	87693.1	36.6	_	134613.2	56.2	_
BL_S	48028.0	23.2	**-18.4**	31341.2	15.1	**58.7**	79369.2	38.3	**31.8**
CC_S	47017.1	23.7	**-20.9**	39809.6	20.0	**45.2**	86826.6	43.7	**22.2**
CO_S	44119.7	23.8	**-21.5**	33767.3	18.2	**50.2**	77887.0	42.0	**25.2**
UA_S	54504.3	25.1	**-28.0**	45054.3	20.7	**43.4**	99558.6	45.8	**18.5**
UL_S	52378.2	23.4	**-19.5**	41586.8	18.6	**49.2**	93964.9	42.0	**25.3**
TB_S	57538.9	30.1	**-53.9**	34714.3	18.2	**50.3**	92253.3	48.3	**14.0**
TS_S	46217.9	25.9	**-32.1**	33184.0	18.6	**49.3**	79401.9	44.4	**20.9**
BA_E	48585.6	20.3	_	88932.2	37.1	_	137517.8	57.4	_
BL_E	49981.2	24.1	**-18.9**	35541.4	17.2	**53.8**	85522.6	41.3	**28.1**
CC_E	48329.8	24.3	**-20.0**	40769.8	20.5	**44.7**	89099.6	44.9	**21.8**
CO_E	45733.2	24.7	**-21.7**	35237.3	19.0	**48.8**	80970.4	43.7	**23.9**
UA_E	56004.4	25.7	**-27.0**	48183.0	22.1	**40.3**	104187.4	47.9	**16.5**
UL_E	55051.7	24.6	**-21.3**	50095.4	22.4	**39.7**	105147.1	47.0	**18.1**
TB_E	59038.4	30.9	**-52.5**	35177.6	18.4	**50.4**	94216.0	49.3	**14.0**

TS_E	46307.8	25.9	**-27.8**	35369.3	19.8	**46.7**	81677.0	45.7	**20.4**
BA_W	48455.6	20.2	_	89739.3	37.5	_	138195.0	57.7	_
BL_W	48380.8	23.3	**-15.4**	36032.9	17.4	**53.6**	84413.7	40.7	**29.4**
CC_W	48293.7	24.3	**-20.3**	40895.7	20.6	**45.0**	89189.4	44.9	**22.1**
CO_W	44707.1	24.1	**-19.3**	34469.5	18.6	**50.4**	79176.5	42.7	**25.9**
UA_W	56551.0	26.0	**-28.5**	48392.0	22.2	**40.6**	104943.0	48.2	**16.4**
UL_W	54258.0	24.2	**-19.9**	49670.5	22.2	**40.7**	103928.5	46.4	**19.5**
TB_W	56762.9	29.7	**-47.0**	36772.8	19.3	**48.6**	93535.6	49.0	**15.1**
TS_W	47749.9	26.7	**-32.1**	34203.5	19.1	**48.9**	81953.4	45.9	**20.5**

5.1.2. Thermal performance

To test the impact of orientation on thermal performance of a classroom, simulated indoor air temperatures of classrooms of the best-performing typology are compared.

Figure 87 compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical summer day. When north and west oriented, classrooms show a similar performance. The temperatures remain within the temperature of comfort until 9:00. The east and west-oriented classroom reach their peak hour when unoccupied. The curves belonging to east and south-oriented classrooms show a similar significant drop during the break as set in the natural ventilation schedule regime, thus associating the thermal performance of buildings to their operational, space utilization characteristics and occupant behavior. East and south-oriented classrooms remain overheated in the occupied hours. ***Figure 88*** compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical winter day. In all 4 orientations the classroom has a temperature below the temperature of comfort. South-oriented classrooms perform better and this becomes significant when the full occupancy of school premises during winter is considered.

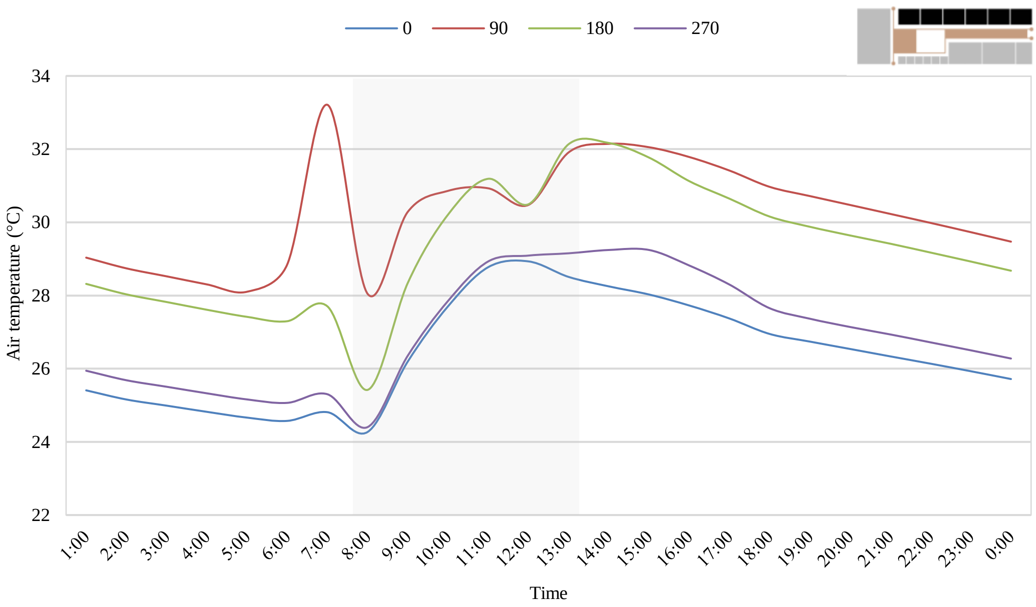

Figure 87. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 12th of September*

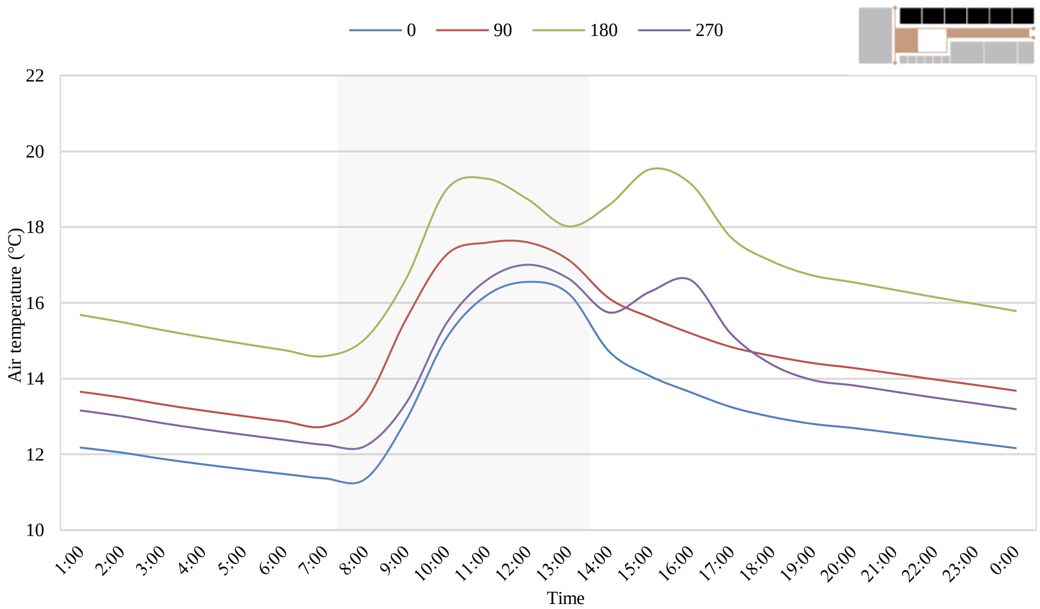

Figure 88. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 6th of January*

Table 11 summarizes the simulation results for the air temperature calculated in the climate of Tirana on the 12th of September. The peak hour varies in accordance with the orientation of the classroom. The worst performance is obtained by BA, with classrooms adjacent to the atrium obtaining a temperature 3.5°C higher than the best-performing courtyard-facing classrooms of TB typology. ***Table 12*** summarizes the simulation results for the air temperature calculated in the climate of Tirana on the 6th of January. Classrooms of BA adjacent to the atrium perform better with a maximum difference of 1.84 °C.

Table 11. *Summary of the simulation results for the air temperature calculated in the climate of Tirana on the 12th of September*

	North, Peak hour; 12:00			**South, Peak hour; 13:00**			**East, Peak hour; 07:00**			**West, Peak hour; 13:00**		
T[°C]	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT
BA	26	29.08	-3.08	26.08	32.63	-6.56	15.8	33.45	-17.65	26.08	29.73	-3.66
BL	26	28.93	-2.93	26.08	32.14	-6.06	15.8	33.21	-17.41	26.08	29.15	-3.08
CC	26	28.92	-2.92	26.08	31.80	-5.73	15.8	33.02	-17.22	26.08	29.26	-3.18
CO	26	28.84	-2.84	26.08	31.79	-5.71	15.8	32.48	-16.68	26.08	29.09	-3.01
UA	26	28.96	-2.96	26.08	31.60	-5.52	15.8	32.58	-16.78	26.08	29.22	-3.15
UL	26	28.89	-2.89	26.08	31.47	-5.40	15.8	32.18	-16.38	26.08	29.29	-3.22
TB	26	28.61	-2.61	26.08	31.04	-4.96	15.8	29.95	-14.15	26.08	28.34	-2.27
TS	26	28.63	-2.63	26.08	31.48	-5.41	15.8	30.84	-15.04	26.08	28.61	-2.54

Table 12. *Summary of the simulation results for the air temperature calculated in the climate of Tirana on the 6th of January*

	North, 8:00			**South, 8:00**			**East, 8:00**			**West, 8:00**		
T[°C]	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT
BA	3.48	11.58	8.10	3.48	14.97	11.49	3.48	13.39	9.92	3.48	12.43	8.95
BL	3.48	11.35	7.87	3.48	15.05	11.58	3.48	13.39	9.91	3.48	12.22	8.75
CC	3.48	11.40	7.93	3.48	14.90	11.43	3.48	13.22	9.75	3.48	12.26	8.78
CO	3.48	11.45	7.97	3.48	14.88	11.40	3.48	13.27	9.80	3.48	12.46	8.98
UA	3.48	11.39	7.91	3.48	14.44	10.96	3.48	12.67	9.19	3.48	12.22	8.75
UL	3.48	11.61	8.14	3.48	14.03	10.56	3.48	11.55	8.08	3.48	12.45	8.97
TB	3.48	11.62	8.14	3.48	14.47	11.00	3.48	13.36	9.89	3.48	12.20	8.73
TS	3.48	11.43	7.96	3.48	13.99	10.52	3.48	11.65	8.17	3.48	12.27	8.80

5.2. Climate of Zagreb

5.2.1. Energy performance

As illustrated in ***Figure 89*** the comparison of annual simulated energy demand in terms of rotation angle shows an increasing trend when the building is rotated 90° and 270°, which corresponds to classrooms being east and west oriented. The biggest impact of orientation is visible in typologies with longitudinal layouts BL, UA and UL. In UL typology energy consumption is subject to an increase of 3.1 kWh.m^{-2}Y^{-1} when rotated 90° and 2.8 kWh.m^{-2}Y^{-1} when rotated 270°. Energy consumption decreases slightly when typologies are rotated 180° with a maximum value of 0.8 kWh.m^{-2}Y^{-1}.

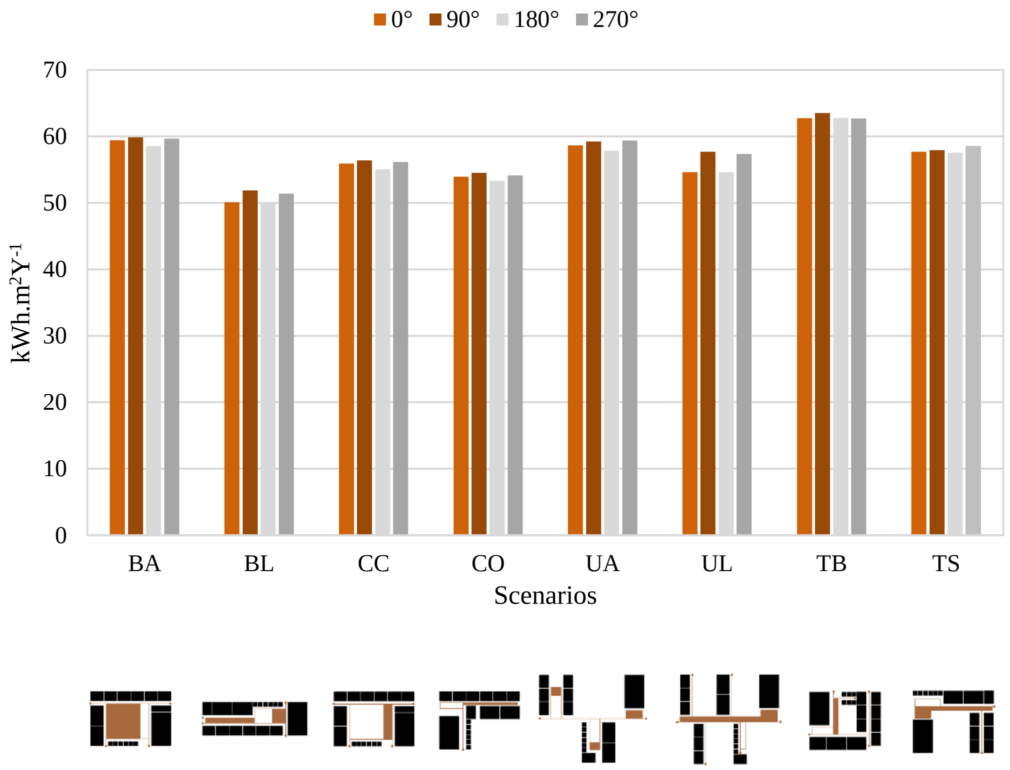

Figure 89. *Comparison of annual simulated energy demand (kWh.m^{-2}Y^{-1})*

Table 13 summarizes the simulation results obtained for all the scenarios in the oceanic climate of Zagreb. A maximum of 20.5% of total energy consumed can be reduced through the selection of the proper morphology for the studied climatic context. The typology with the worst performance in terms of energy loads is TB, thus casting doubts on the appropriateness of organic typologies with a high S_e and low relative compactness for the oceanic climate of Zagreb. The low compactness does help to save approximately 8.2 kWh/m^2 in cooling loads with a maximum morphology effectiveness of 95.5% when compared to more compact typologies. Still in a climate as cold as that of Zagreb with a limited need for cooling only in June and partially in May, July and August, the focus shifts on the impact on heating loads. A minimum of 10.6 kWh/m^2 is wasted by adopting TB typology in regions with a similar climate. The presence of courtyard, whether open (CO) or closed (CC) makes the morphology gain an approximate effectiveness of a range 10-15%. Multiple open courtyards are also part of cluster-plan typologies (UA and UL), but the longitudinal plan makes both these typologies perform better only in certain orientations; when rotated 0 and 180 degrees. The sky lighted atrium in the core of each unit of UA, decreases its performance further.

Table 13. *Simulation results obtained for all the scenarios in the climate of Zagreb*

	Annual heating demand			Annual cooling demand			Annual energy demand		
Scenarios	Total heating [kWh]	Heating/ conditioned area [kWh/m2]	**Morphology effective-ness [%]**	Total cooling [kWh]	Cooling/ conditioned area [kWh/m2]	**Morphology effective-ness [%]**	Total energy [kWh]	Total energy/ conditioned area [kWh/m2]	**Total Morphology effectiveness [%]**
BA_N	106286.3	44.4	**19.1**	36134.4	15.1	**-90.2**	142420.6	59.4	**5.3**
BL_N	90584.4	43.7	**20.3**	13178.8	6.4	**19.8**	103763.2	50.1	**20.2**
CC_N	95109.8	47.9	**12.6**	15975.5	8.0	**-1.5**	111085.3	55.9	**10.9**
CO_N	86083.5	46.4	**15.3**	13908.6	7.5	**5.4**	99992.1	53.9	**14.1**
UA_N	108904.0	50.1	**8.7**	18667.4	8.6	**-8.2**	127571.4	58.6	**6.6**
UL_N	105281.8	47.0	**14.2**	16936.7	7.6	**4.6**	122218.5	54.6	**13.0**
TB_N	104701.9	54.8	_	15139.9	7.9	_	119841.8	62.8	_
TS_N	88949.7	49.8	**9.2**	14169.6	7.9	**0.0**	103119.3	57.7	**8.1**
BA_S	104228.9	43.5	**20.8**	36107.8	15.1	**-91.5**	140336.7	58.6	**6.7**
BL_S	90216.7	43.5	**20.7**	13181.5	6.4	**19.2**	103398.2	49.9	**20.5**
CC_S	93069.4	46.9	**14.6**	16260.3	8.2	**-4.0**	109329.7	55.1	**12.3**
CO_S	84650.9	45.7	**16.8**	14181.0	7.6	**2.8**	98831.9	53.3	**15.1**
UA_S	107097.7	49.2	**10.3**	18756.4	8.6	**-9.5**	125854.0	57.9	**7.8**
UL_S	105724.7	47.2	**14.0**	16509.1	7.4	**6.3**	122233.7	54.6	**13.0**
TB_S	104852.4	54.9	-	15029.7	7.9	-	119882.1	62.8	_
TS_S	88468.6	49.5	**9.8**	14362.1	8.0	**-2.1**	102830.7	57.5	**8.3**
BA_E	105783.1	44.1	**20.4**	37632.9	15.7	**-95.5**	143416.0	59.9	**5.8**
BL_E	92113.6	44.5	**19.9**	15419.7	7.4	**7.4**	107533.3	51.9	**18.3**
CC_E	94645.1	47.7	**14.1**	17355.5	8.7	**-8.8**	112000.5	56.4	**11.2**
CO_E	86129.9	46.5	**16.3**	14976.1	8.1	**-0.5**	101106.0	54.5	**14.1**
UA_E	108574.3	49.9	**10.0**	20269.1	9.3	**-16.0**	128843.3	59.2	**6.7**
UL_E	108277.3	48.4	**12.8**	20835.8	9.3	**-15.9**	129113.1	57.7	**9.2**
TB_E	105932.7	55.5	-	15342.3	8.0	-	121275.0	63.5	-
TS_E	88419.8	49.5	**10.8**	15146.9	8.5	**-5.5**	103566.7	58.0	**8.7**
BA_W	105557.0	44.1	**19.1**	37469.5	15.6	**-89.3**	143026.5	59.7	**4.8**
BL_W	90829.8	43.8	**19.5**	15627.0	7.5	**8.7**	106456.8	51.4	**18.1**
CC_W	94451.3	47.6	**12.6**	17112.2	8.6	**-4.3**	111563.5	56.2	**10.4**
CO_W	85574.2	46.2	**15.2**	14826.1	8.0	**3.2**	100400.4	54.2	**13.6**
UA_W	108778.6	50.0	**8.2**	20386.4	9.4	**-13.5**	129165.1	59.4	**5.3**
UL_W	107834.9	48.2	**11.5**	20524.8	9.2	**-11.0**	128359.7	57.4	**8.5**
TB_W	103969.7	54.4	-	15770.4	8.3	-	119740.1	62.7	-
TS_W	89763.6	50.2	**7.7**	14828.8	8.3	**-0.5**	104592.4	58.5	**6.7**

5.2.2. Thermal performance

To test the impact of orientation on thermal performance of a classroom, simulated indoor air temperatures of classrooms of the best-performing typology are compared. ***Figure 90*** compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical summer day. When south oriented, classrooms shows the best performance. The temperatures remain within the temperatures of comfort. The south and west-oriented classroom reach their peak hour when unoccupied. North oriented classrooms remain below the comfort temperatures in the occupied hours. ***Figure 91*** compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical winter day. Orientation has no significant impact in thermal performance during winter as all 4 orientations show a similar curve, below the temperature of comfort.

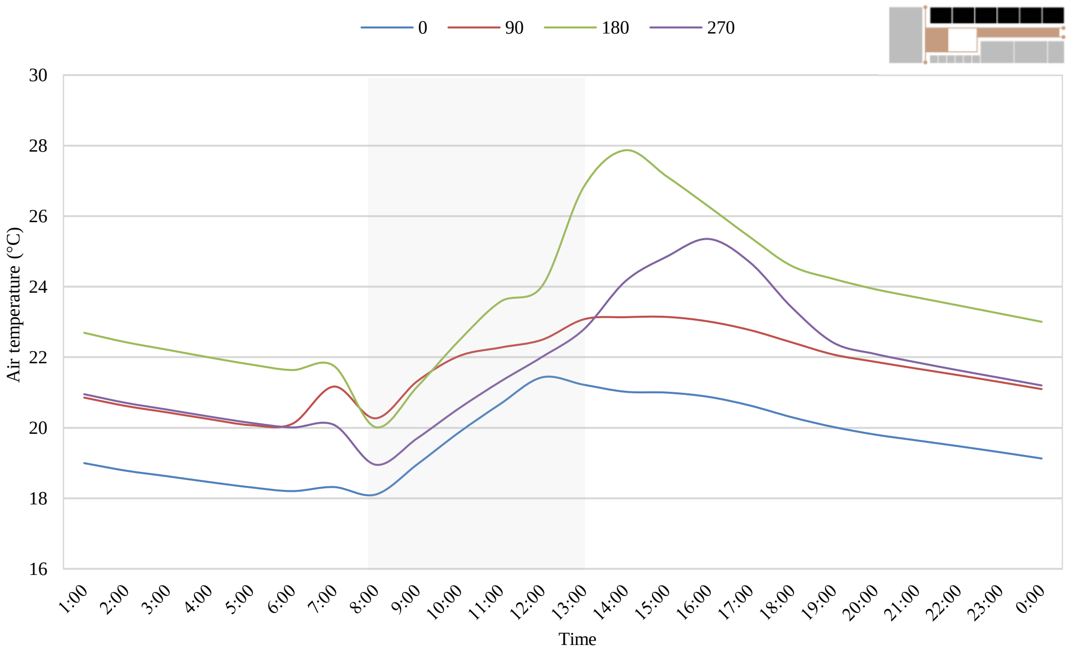

Figure 90. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 12th of September*

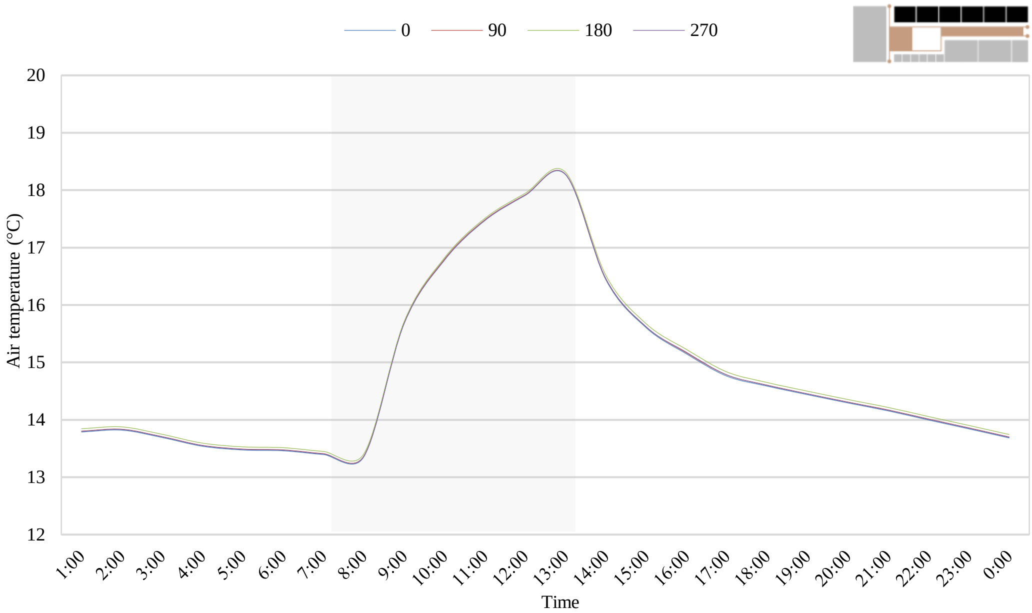

Figure 91. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 6th of January*

Table 14 summarizes the simulation results for the air temperature calculated in the climate of Zagreb on the 12th of September. The peak hour shows no variance accordant with the orientation of the classroom. The worst performance is obtained by BA, with classrooms adjacent to the atrium obtaining a temperature approximately 1.3°C higher than the best-performing courtyard-facing classrooms of town-like typologies. ***Table 15*** summarizes the simulation results for the air temperature calculated in the climate of Zagreb on the 6th of January. Courtyard-facing classrooms of town-like typologies perform better, still differences are marginal and temperatures lower than the comfort temperature.

Table 14. *Summary of the simulation results for the air temperature calculated in the climate of Zagreb on the 12th of September*

	North, Peak hour; 12:00			South, Peak hour; 13:00			East, Peak hour; 13:00			West, Peak hour; 13:00		
T[°C]	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT
BA	14.93	21.59	-6.67	15.65	26.79	-11.14	15.65	23.41	-7.76	15.65	23.23	-7.58
BL	14.93	21.43	-6.51	15.65	26.83	-11.18	15.65	23.07	-7.42	15.65	22.79	-7.14
CC	14.93	21.30	-6.37	15.65	26.34	-10.69	15.65	22.84	-7.19	15.65	22.68	-7.03
CO	14.93	21.40	-6.48	15.65	26.25	-10.60	15.65	22.76	-7.11	15.65	22.60	-6.95
UA	14.93	21.31	-6.39	15.65	26.19	-10.54	15.65	22.74	-7.09	15.65	22.61	-6.96
UL	14.93	21.33	-6.40	15.65	25.78	-10.13	15.65	22.36	-6.71	15.65	22.58	-6.93
TB	14.93	21.03	-6.10	15.65	25.53	-9.88	15.65	22.13	-6.48	15.65	21.88	-6.23
TS	14.93	21.14	-6.21	15.65	25.60	-9.95	15.65	21.99	-6.34	15.65	22.29	-6.64

Table 15.*Summary of the simulation results for the air temperature calculated in the climate of Zagreb on the 6th of January*

	North, 8:00			South, 8:00			East, 8:00			West, 8:00		
T[°C]	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**
BA	1.70	5.91	4.21	1.70	5.91	4.21	1.70	5.91	4.21	1.70	5.91	4.21
BL	1.70	5.93	4.23	1.70	5.93	4.23	1.70	5.94	4.24	1.70	5.93	4.23
CC	1.70	5.81	4.11	1.70	5.81	4.11	1.70	5.81	4.11	1.70	5.80	4.10
CO	1.70	6.05	4.35	1.70	6.05	4.35	1.70	6.05	4.35	1.70	6.05	4.35
UA	1.70	5.68	3.98	1.70	5.68	3.98	1.70	5.68	3.98	1.70	5.68	3.98
UL	1.70	5.55	3.85	1.70	5.55	3.85	1.70	5.55	3.85	1.70	5.54	3.84
TB	1.70	6.32	4.62	1.70	6.32	4.62	1.70	6.32	4.62	1.70	6.32	4.62
TS	1.70	5.84	4.14	1.70	5.84	4.14	1.70	5.84	4.14	1.70	5.84	4.14

5.3. Climate of Sarajevo

5.3.1. Energy performance

As illustrated in ***Figure 92*** the comparison of annual simulated energy demand in terms of rotation angle shows a slight increase when the building is rotated 90° and 270°, which corresponds to classrooms being east and west oriented. The biggest impact of orientation is visible in UL typology with energy consumption being subject to an increase of 4.2 $kWh.m^{-2}Y^{-1}$ when rotated 90° and 4.9 $kWh.m^{-2}Y^{-1}$ when rotated 270°. Energy consumption decreases slightly when typologies are rotated 180° with a maximum value of 1.1 $kWh.m^{-2}Y^{-1}$.

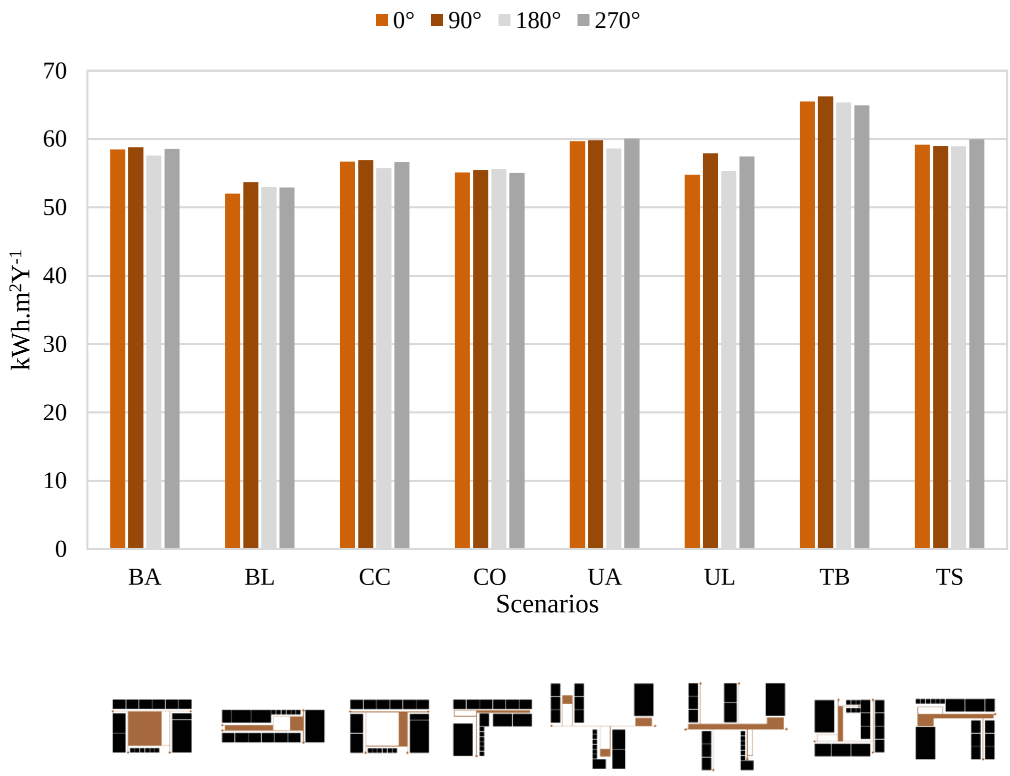

Figure 92. *Comparison of annual simulated energy demand (kWh.m^{-2}Y^{-1})*

Table 16 summarizes the simulation results obtained for all the scenarios in the humid continental climate of Sarajevo. A maximum of 20.6 % of total energy consumed can be reduced through the selection of the proper morphology for the studied climatic context. The typology with the worst performance in terms of energy loads is TB, thus casting doubts on the appropriateness of organic typologies with a high S_e and low relative compactness for the humid continental climate of Sarajevo. The low compactness does help to save approximately 6 kWh/m^2 in cooling loads with a maximum morphology effectiveness of 167.2% when compared to more compact typologies. Still in a climate as cold as that of Sarajevo with a limited need for cooling only in June and partially in May, July and August, the focus shifts on the impact on heating loads. A minimum of 7 kWh/m^2 is wasted by adopting TB typology in regions with a similar climate. The presence of courtyard, whether open (CO) or closed (CC) makes the morphology gain an approximate effectiveness of a range 12.8-16.2 %. Multiple open courtyards are also part of cluster-plan typologies (UA and UL), but the longitudinal plan makes both these typologies perform better only in certain orientations; when rotated 0 and 180 degrees. The sky lighted atrium in the core of each unit of UA, decreases its performance further.

Table 16. *Simulation results obtained for all the scenarios in the climate of Sarajevo*

	Annual heating demand			Annual cooling demand			Annual energy demand		
Scenarios	Total heating [kWh]	Heating/ conditioned area [kWh/m2]	**Morphology effective-ness [%]**	Total cooling [kWh]	Cooling/ conditioned area [kWh/m2]	**Morphology effective-ness [%]**	Total energy [kWh]	Total energy/ conditioned area [kWh/m2]	**Total Morphology effectiveness [%]**
BA_N	117228.5	48.9	**21.0**	22922.5	9.6	**-167.2**	140151.0	58.5	**10.7**
BL_N	101492.1	49.0	**20.9**	6302.9	3.0	**15.0**	107795.1	52.0	**20.6**
CC_N	105259.7	53.0	**14.4**	7288.1	3.7	**-2.5**	112547.7	56.7	**13.5**
CO_N	95515.6	51.5	**16.8**	6613.3	3.6	**0.4**	102128.9	55.1	**15.9**
UA_N	120887.2	55.6	**10.2**	9007.4	4.1	**-15.7**	129894.6	59.7	**8.8**
UL_N	115284.6	51.5	**16.8**	7287.8	3.3	**9.0**	122572.4	54.8	**16.4**
TB_N	118217.8	61.9	_	6836.0	3.6	_	125053.8	65.5	_
TS_N	99202.3	55.5	**10.3**	6512.7	3.6	**-1.8**	105715.0	59.2	**9.7**
BA_S	115372.0	48.1	**22.1**	22567.0	9.4	**-166.8**	137939.0	57.6	**11.9**
BL_S	103788.9	50.1	**19.0**	6076.6	2.9	**16.9**	109865.5	53.0	**18.9**
CC_S	103384.9	52.1	**15.8**	7335.4	3.7	**-4.7**	110720.3	55.8	**14.7**
CO_S	96481.3	52.0	**15.8**	6635.9	3.6	**-1.4**	103117.2	55.6	**14.9**
UA_S	118525.1	54.5	**11.9**	9006.0	4.1	**-17.3**	127531.1	58.6	**10.3**
UL_S	116958.5	52.3	**15.5**	6927.5	3.1	**12.3**	123886.1	55.4	**15.3**
TB_S	118054.4	61.8	_	6739.5	3.5	_	124794.0	65.4	_
TS_S	98528.1	55.1	**10.8**	6782.8	3.8	**-7.5**	105310.9	58.9	**9.8**
BA_E	116948.4	48.8	**21.9**	23894.4	10.0	**-168.4**	140842.8	58.8	**11.2**
BL_E	103860.2	50.1	**19.8**	7464.7	3.6	**3.1**	111324.9	53.7	**18.9**
CC_E	104983.6	52.9	**15.4**	8076.8	4.1	**-9.5**	113060.4	56.9	**14.0**
CO_E	95881.9	51.7	**17.3**	6966.8	3.8	**-1.1**	102848.6	55.5	**16.2**
UA_E	120288.9	55.3	**11.5**	9866.6	4.5	**-22.1**	130155.5	59.8	**9.6**
UL_E	119787.6	53.5	**14.4**	9777.4	4.4	**-17.6**	129565.0	57.9	**12.6**
TB_E	119353.2	62.5	_	7095.8	3.7	_	126449.0	66.2	_
TS_E	98246.9	55.0	**12.0**	7137.1	4.0	**-7.5**	105384.0	59.0	**10.9**
BA_W	116440.2	48.6	**20.6**	23841.3	10.0	**-163.3**	140281.5	58.5	**9.9**
BL_W	101959.2	49.2	**19.6**	7693.3	3.7	**1.7**	109652.5	52.9	**18.5**
CC_W	104491.8	52.6	**14.0**	7999.2	4.0	**-6.6**	112491.0	56.6	**12.8**
CO_W	95018.5	51.3	**16.2**	7080.2	3.8	**-1.1**	102098.7	55.1	**15.2**
UA_W	120585.4	55.4	**9.4**	10070.6	4.6	**-22.5**	130656.0	60.1	**7.5**
UL_W	119215.6	53.3	**12.9**	9372.6	4.2	**-10.8**	128588.2	57.5	**11.5**
TB_W	116800.8	61.2	_	7214.7	3.8	_	124015.6	64.9	_
TS_W	100153.9	56.0	**8.4**	7046.6	3.9	**-4.4**	107200.6	60.0	**7.6**

5.3.2. Thermal performance

To test the impact of orientation on thermal performance of a classroom, simulated indoor air temperatures of classrooms of the best-performing typology are compared.

Figure 93 compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical summer day. When east and north oriented, classrooms display a similar performance. The temperatures remain within the temperatures of comfort until 11:00. The south and west-oriented classroom reach their peak hour when unoccupied. ***Figure 94*** compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical winter day. Orientation has no significant impact in thermal performance during winter in a humid continental climate as all 4 orientations show a similar curve, below the temperature of comfort.

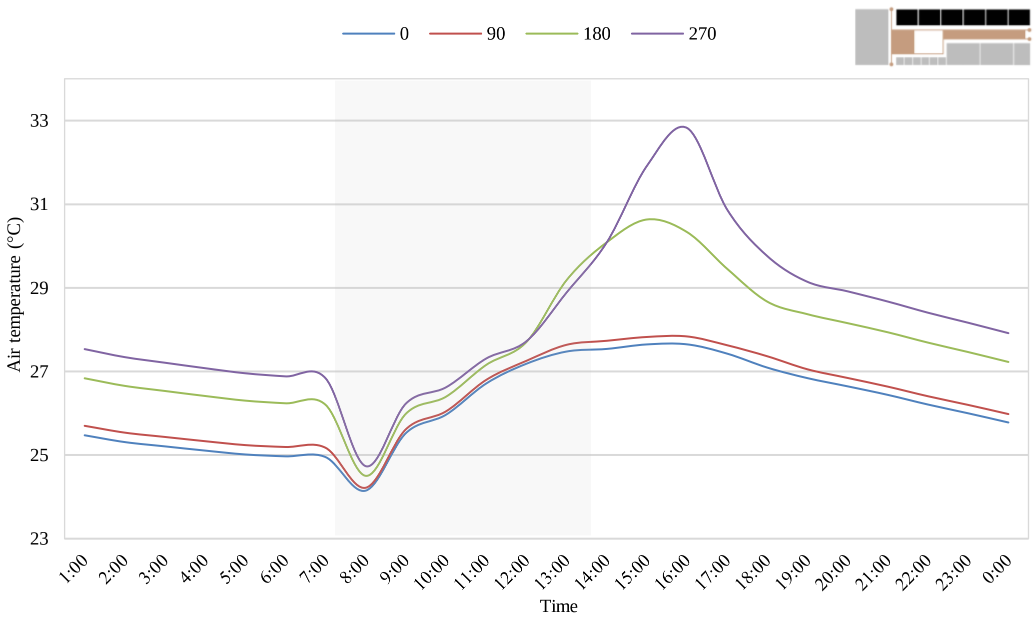

Figure 93. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 12th of September*

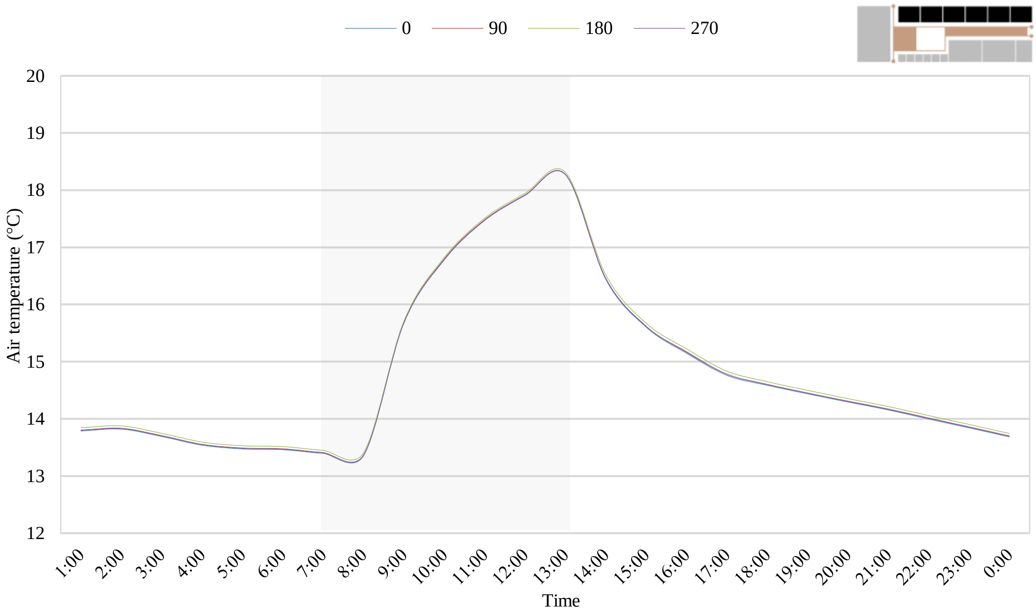

Figure 94. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 6th and 7th of January*

Table 17 summarizes the simulation results for the air temperature calculated in the climate of Sarajevo on the 12th of September. The peak hour shows no variance accordant with the orientation of the classroom. The differncess between typologies are marginal, still the worst performance is obtained by BA, with classrooms adjacent to the atrium obtaining a temperature approximately 1°C higher than the best-performing courtyard-facing classrooms of town-like typologies. ***Table 18*** summarizes the simulation results for the air temperature calculated in the climate of Sarajevo on the 6th of January. Courtyard-facing classrooms of town-like typologies perform better, still differences are marginal and temperatures lower than the comfort temperature.

Table 17. *Summary of the simulation results for the air temperature calculated in the climate of Sarajevo on the 12th of September*

	North, Peak hour; 13:00			South, Peak hour; 13:00			East, Peak hour; 13:00			West, Peak hour; 13:00		
T[°C]	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT	Outdoor	Indoor	ΔT
BA	24.6	27.93	-3.33	24.60	29.55	-4.95	24.6	27.95	-3.35	24.60	29.28	-4.68
BL	24.6	27.48	-2.88	24.60	29.18	-4.58	24.6	27.64	-3.04	24.60	28.89	-4.29
CC	24.6	27.60	-3.00	24.60	29.03	-4.43	24.6	27.47	-2.87	24.60	28.61	-4.01
CO	24.6	27.37	-2.77	24.60	28.86	-4.26	24.6	27.44	-2.84	24.60	28.66	-4.06
UA	24.6	27.52	-2.92	24.60	29.01	-4.41	24.6	27.39	-2.79	24.60	28.75	-4.15
UL	24.6	27.32	-2.72	24.60	28.55	-3.95	24.6	27.31	-2.71	24.60	28.49	-3.89
TB	24.6	27.01	-2.41	24.60	28.56	-3.96	24.6	27.11	-2.51	24.60	28.19	-3.59
TS	24.6	26.97	-2.37	24.60	28.14	-3.54	24.6	26.97	-2.37	24.60	28.51	-3.91

Table 18. *Summary of the simulation results for the air temperature calculated in the climate of Sarajevo on the 6th of January*

	North, 8:00			**South, 8:00**			**East, 8:00**			**West, 8:00**		
T[°C]	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**
BA	8.40	13.34	4.94	8.40	13.39	4.99	8.40	13.36	4.96	8.40	13.35	4.95
BL	8.40	13.35	4.95	8.40	13.41	5.01	8.40	13.37	4.97	8.40	13.36	4.96
CC	8.40	13.31	4.91	8.40	13.26	4.86	8.40	13.32	4.92	8.40	13.22	4.82
CO	8.40	13.49	5.09	8.40	13.54	5.14	8.40	13.50	5.10	8.40	13.50	5.10
UA	8.40	13.12	4.72	8.40	13.16	4.76	8.40	13.13	4.73	8.40	13.13	4.73
UL	8.40	13.06	4.66	8.40	13.09	4.69	8.40	13.05	4.65	8.40	13.06	4.66
TB	8.40	13.79	5.39	8.40	13.83	5.43	8.40	13.80	5.40	8.40	13.80	5.40
TS	8.40	13.34	4.94	8.40	13.38	4.98	8.40	13.34	4.94	8.40	13.35	4.95

5.4. Climate of Athens

5.4.1. Energy performance

As illustrated in ***Figure 95*** the comparison of annual simulated energy demand in terms of rotation angle shows an increase when the building is rotated 90° and 270°, which corresponds to classrooms being east and west oriented. The biggest impact of orientation is visible in longitudinal typologies, BL and UL, with energy consumption being subject to a maximum increase of 9.5 $kWh.m^{-2}Y^{-1}$ when rotated 90° and 8 $kWh.m^{-2}Y^{-1}$ when rotated 270°.

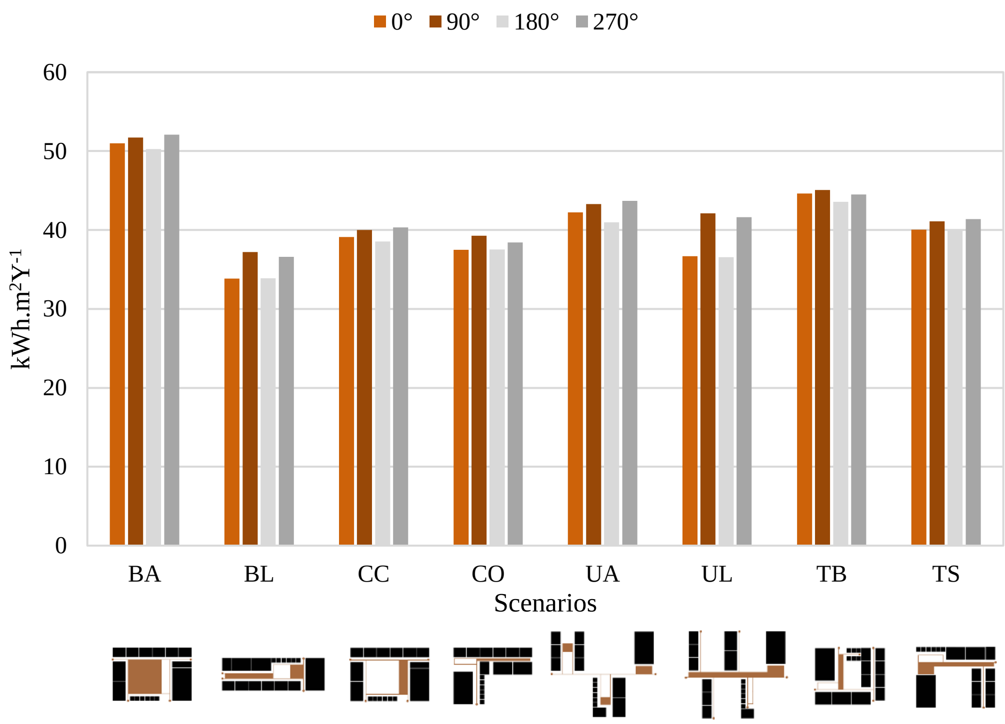

Figure 95. *Comparison of annual simulated energy demand (kWh.m^{-2}Y^{-1})*

Table 19 summarizes the simulation results obtained for all the scenarios in the Mediterranean climate of Athens. A maximum of 33.7 % of total energy consumed can be reduced through the selection of the proper morphology for the studied climatic context. The typology with the worst performance in terms of energy loads is BA, thus casting doubts on the appropriateness of block plans organized around a central atrium for the Mediterranean climate of Tirana. The atrium does manage to save approximately 8.6 kWh/m2 in heating loads with a maximum morphology effectiveness of 62.3 % when compared to more organic typologies with a lower relative compactness, but its high demand for air-conditioning increases the cooling demand of BA and reduces the morphology effectiveness by 55.7 %. The presence of courtyard, whether open (CO) or closed (CC) makes the morphology gain an approximate effectiveness of 25 ± 2%. Multiple open courtyards are also part of cluster-plan typologies (UA and UL), but the longitudinal plan makes both these typologies perform better only in certain orientations; when rotated 0 and 180 degrees. The sky lighted atrium in the core of each unit of UA, decreases its performance further.

Table 19. *Simulation results obtained for all the scenarios in the climate of Athens*

	Annual heating demand			Annual cooling demand			Annual energy demand		
Scenarios	Total heating [kWh]	Heating/ conditioned area [kWh/m^2]	**Morphology effective-ness [%]**	Total cooling [kWh]	Cooling/ conditioned area [kWh/m^2]	**Morphology effective-ness [%]**	Total energy [kWh]	Total energy/ conditioned area [kWh/m^2]	**Total Morphology effectiveness [%]**
BA_N	37598.8	15.7	_	84608.1	35.3	_	122207.0	51.0	_
BL_N	37647.0	18.2	**-15.8**	32456.9	15.7	**55.6**	70103.9	33.8	**33.7**
CC_N	37385.4	18.8	**-20.0**	40304.6	20.3	**42.5**	77690.0	39.1	**23.3**
CO_N	35170.4	19.0	**-20.9**	34336.9	18.5	**47.5**	69507.3	37.5	**26.5**
UA_N	43974.0	20.2	**-28.8**	47886.9	22.0	**37.7**	91860.9	42.2	**17.2**
UL_N	37711.2	16.8	**-7.4**	44409.1	19.8	**43.8**	82120.2	36.7	**28.1**
TB_N	46395.0	24.3	**-54.8**	38802.1	20.3	**42.5**	85197.1	44.6	**12.5**
TS_N	36511.7	20.4	**-30.2**	35068.7	19.6	**44.4**	71580.4	40.1	**21.5**
BA_S	35149.3	14.7	_	85253.4	35.6	_	120402.7	50.2	_
BL_S	37592.1	18.1	**-23.7**	32635.1	15.7	**55.7**	70227.2	33.9	**32.6**
CC_S	35140.7	17.7	**-20.6**	41381.7	20.8	**41.4**	76522.4	38.5	**23.3**
CO_S	34018.9	18.4	**-25.1**	35529.1	19.2	**46.1**	69548.0	37.5	**25.3**
UA_S	40906.1	18.8	**-28.2**	48275.7	22.2	**37.6**	89181.8	41.0	**18.4**
UL_S	38662.2	17.3	**-17.8**	43120.2	19.3	**45.8**	81782.4	36.5	**27.3**
TB_S	45372.7	23.8	**-62.0**	37829.2	19.8	**44.3**	83201.9	43.6	**13.3**
TS_S	35866.5	20.1	**-36.8**	35554.9	19.9	**44.1**	71421.5	40.0	**20.5**
BA_E	36525.8	15.2	_	87443.3	36.5	_	123969.1	51.7	_
BL_E	39322.8	19.0	**-24.5**	37793.5	18.2	**50.0**	77116.3	37.2	**28.1**
CC_E	36427.6	18.3	**-20.3**	43041.6	21.7	**40.6**	79469.2	40.0	**22.6**
CO_E	35640.0	19.2	**-26.1**	37142.8	20.0	**45.1**	72782.8	39.3	**24.1**
UA_E	42244.3	19.4	**-27.4**	51943.6	23.9	**34.6**	94187.8	43.3	**16.3**
UL_E	40849.9	18.3	**-19.7**	53438.6	23.9	**34.6**	94288.5	42.1	**18.6**
TB_E	47229.9	24.7	**-62.3**	38846.2	20.3	**44.3**	86076.1	45.1	**12.9**
TS_E	35636.5	19.9	**-30.8**	37787.7	21.1	**42.1**	73424.3	41.1	**20.6**
BA_W	36622.1	15.3	_	88187.0	36.8	_	124809.2	52.1	_
BL_W	37535.7	18.1	**-18.5**	38327.4	18.5	**49.7**	75863.1	36.6	**29.7**
CC_W	36539.2	18.4	**-20.4**	43526.2	21.9	**40.4**	80065.3	40.3	**22.6**
CO_W	34512.7	18.6	**-21.8**	36681.0	19.8	**46.2**	71193.7	38.4	**26.3**
UA_W	42935.8	19.7	**-29.1**	52146.4	24.0	**34.9**	95082.2	43.7	**16.1**
UL_W	40093.3	17.9	**-17.2**	53062.8	23.7	**35.6**	93156.0	41.6	**20.1**
TB_W	44764.3	23.4	**-53.4**	40186.5	21.0	**42.8**	84950.8	44.5	**14.6**
TS_W	37323.1	20.9	**-36.7**	36606.2	20.5	**44.3**	73929.3	41.4	**20.6**

5.4.2. Thermal performance

To test the impact of orientation on thermal performance of a classroom, simulated indoor air temperatures of classrooms of the best-performing typology are compared.

Figure 96 compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical summer day. When north oriented, classrooms shows the best performance. The temperatures remain within the temperature of comfort until 9:00. The south and west-oriented classroom reach their peak hour when unoccupied. The curves belonging to east, west and south-oriented classrooms show a similar significant drop during the break as set in the natural ventilation schedule regime, thus associating the thermal performance of buildings to their operational, space utilization characteristics and occupant behavior. ***Figure 97*** compares the simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for a typical winter day. When north, east and west oriented the classrooms maintain a temperature below the temperature of comfort. South-oriented classrooms perform better and this becomes significant when the full occupancy of school premises during winter is considered.

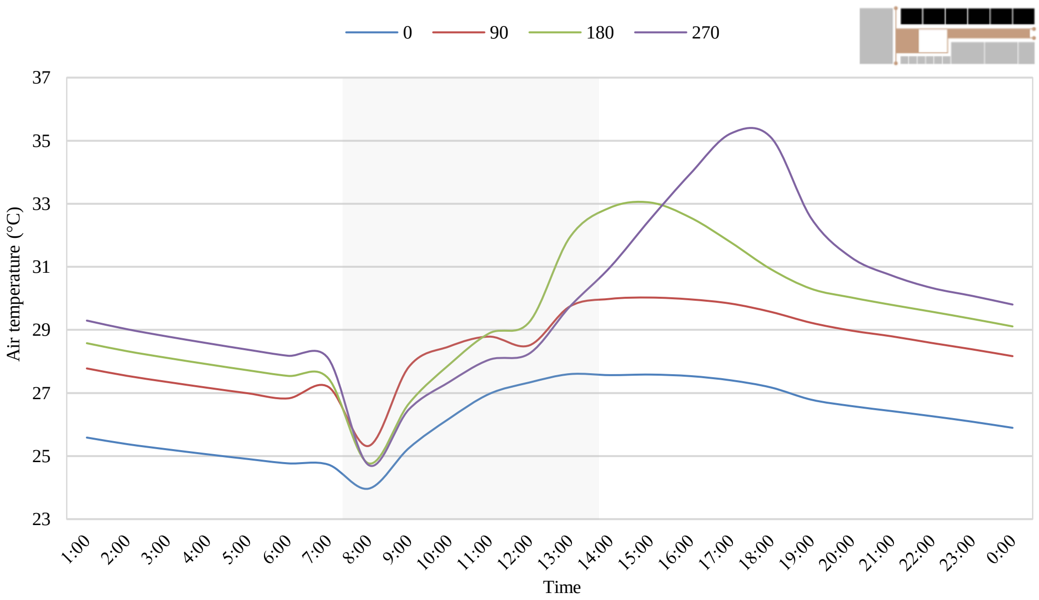

Figure 96. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 12th of September*

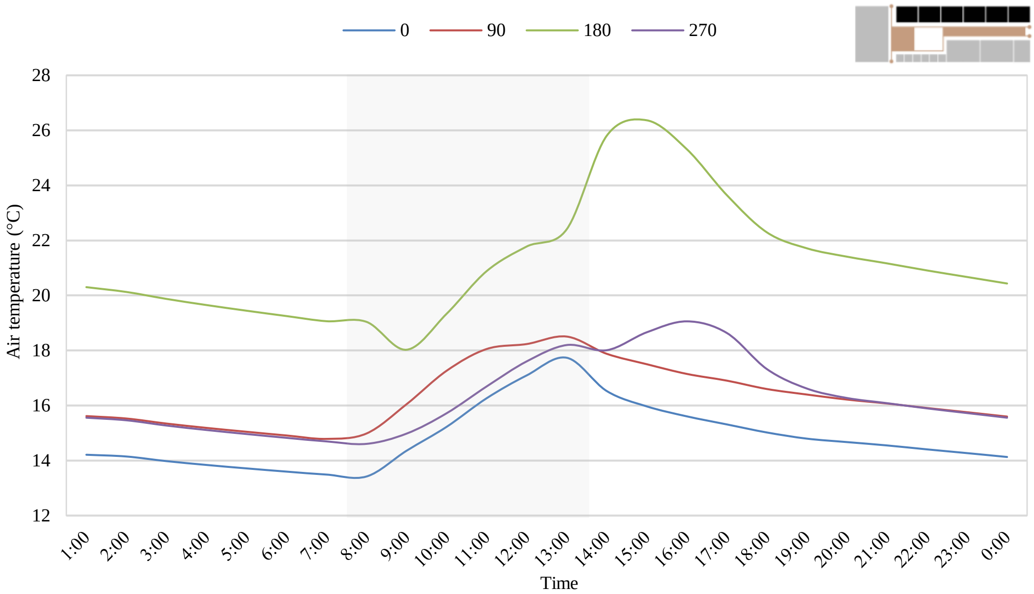

Figure 97. *Simulated indoor air temperatures of classrooms of BL typology in terms of rotation angle for 6th of January*

Table 20 summarizes the simulation results for the air temperature calculated in the climate of Athens on the 12th of September. The peak hour shows no variance accordant with the orientation of the classroom. The worst performance is obtained by BA, with classrooms adjacent to the atrium obtaining a temperature approximately 2.4°C higher than the best-performing courtyard-facing classrooms of town-like typologies. ***Table 21*** summarizes the simulation results for the air temperature calculated in the climate of Athens on the 6th of January. Classrooms of BA adjacent to the atrium perform better with an approximate difference of 1.6 °C.

Table 20. *Summary of the simulation results for the air temperature calculated in the climate of Athens on the 12th of September*

	North, Peak hour; 13:00			South, Peak hour; 13:00			East, Peak hour; 13:00			West, Peak hour; 13:00		
T[°C]	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**	**Outdoor**	**Indoor**	**ΔT**
BA	24.23	28.49	-4.27	24.23	32.49	-8.26	24.23	30.51	-6.28	24.23	30.61	-6.39
BL	24.23	27.60	-3.37	24.23	31.94	-7.71	24.23	29.74	-5.52	24.23	29.74	-5.51
CC	24.23	27.68	-3.45	24.23	31.56	-7.34	24.23	29.60	-5.37	24.23	29.67	-5.45
CO	24.23	27.42	-3.20	24.23	31.68	-7.45	24.23	29.38	-5.16	24.23	29.43	-5.21
UA	24.23	27.76	-3.53	24.23	31.70	-7.48	24.23	29.38	-5.16	24.23	29.68	-5.45
UL	24.23	27.57	-3.35	24.23	31.22	-7.00	24.23	29.15	-4.92	24.23	29.74	-5.51
TB	24.23	26.92	-2.70	24.23	30.69	-6.46	24.23	28.70	-4.47	24.23	28.47	-4.25
TS	24.23	27.15	-2.93	24.23	30.95	-6.73	24.23	28.64	-4.41	24.23	29.09	-4.86

Table 21. Summary of the simulation results for the air temperature calculated in the climate of Athens on the 6th of January

	North, 8:00			South, 8:00			East, 8:00			West, 8:00		
T[°C]	**Exterior**	**Interior**	**ΔT**	**Exterior**	**Interior**	**ΔT**	**Exterior**	**Interior**	**ΔT**	**Exterior**	**Interior**	**ΔT**
BA	6.50	13.94	7.44	6.50	19.07	12.57	6.50	15.36	8.86	6.50	15.16	8.66
BL	6.50	13.42	6.92	6.50	19.04	12.54	6.50	14.98	8.48	6.50	14.61	8.11
CC	6.50	13.63	7.13	6.50	18.83	12.33	6.50	14.91	8.41	6.50	14.85	8.35
CO	6.50	13.53	7.03	6.50	18.74	12.24	6.50	14.93	8.43	6.50	14.83	8.33
UA	6.50	13.59	7.09	6.50	18.42	11.92	6.50	14.64	8.14	6.50	14.86	8.36
UL	6.50	14.02	7.52	6.50	17.78	11.28	6.50	13.82	7.32	6.50	15.00	8.50
TB	6.50	13.48	6.98	6.50	18.34	11.84	6.50	14.77	8.27	6.50	14.49	7.99
TS	6.50	13.43	6.93	6.50	17.75	11.25	6.50	13.72	7.22	6.50	14.81	8.31

5.5. Climate comparison

Figure 98 compares the simulated energy demand (kWh.m^{-2}Y^{-1}) for south-oriented typologies, in 4 climatic contexts. The humid continental climate of Sarajevo displays the highest energy demand. Ranked second, Zagreb's oceanic climate displays a similar performance to that of Sarajevo. When located in the Mediterranean climate of Athens, the hypothetical open-school models display the lowest energy demand. Only BA typology has a similar performance in all 4 climates studies.

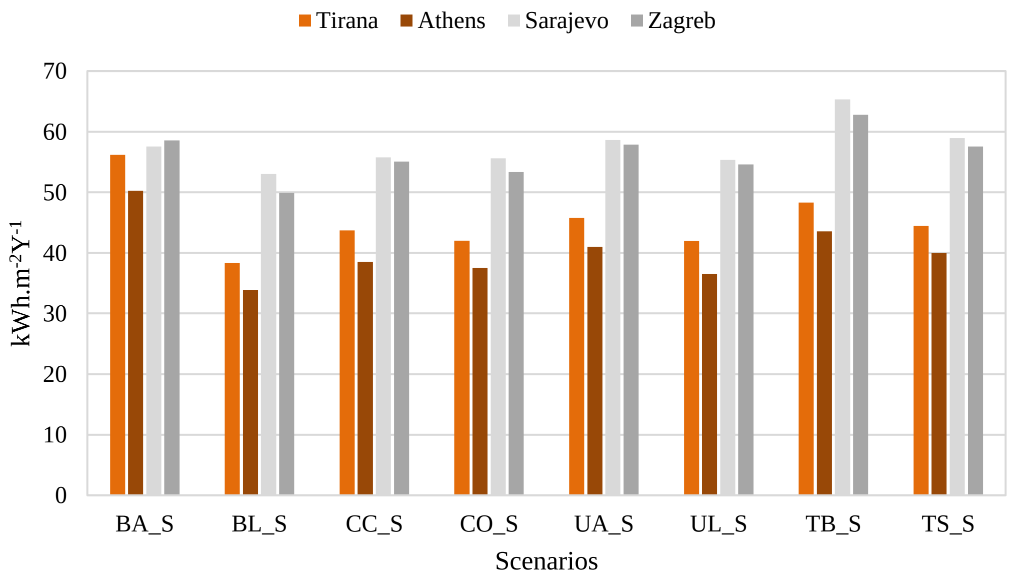

Figure 98. *Comparison of annual simulated energy demand (kWh.m^{-2}Y^{-1}) for south-oriented typologies, in 4 climatic contexts*

According to the suitability gradient of the ***Figure 99*** set based on the results of the simulation scenarios, BA typology is not suitable for location displaying a climate similar to that of Tirana and Athens, but can be adopted in cold climates of Zagreb and Sarajevo. Still, further optimization is needed to obtain a better performance. Typologies with a high S_e possess the lowest ranking in oceanic and humid continental climates. TB and UL are ranked highest in all 4 climates.

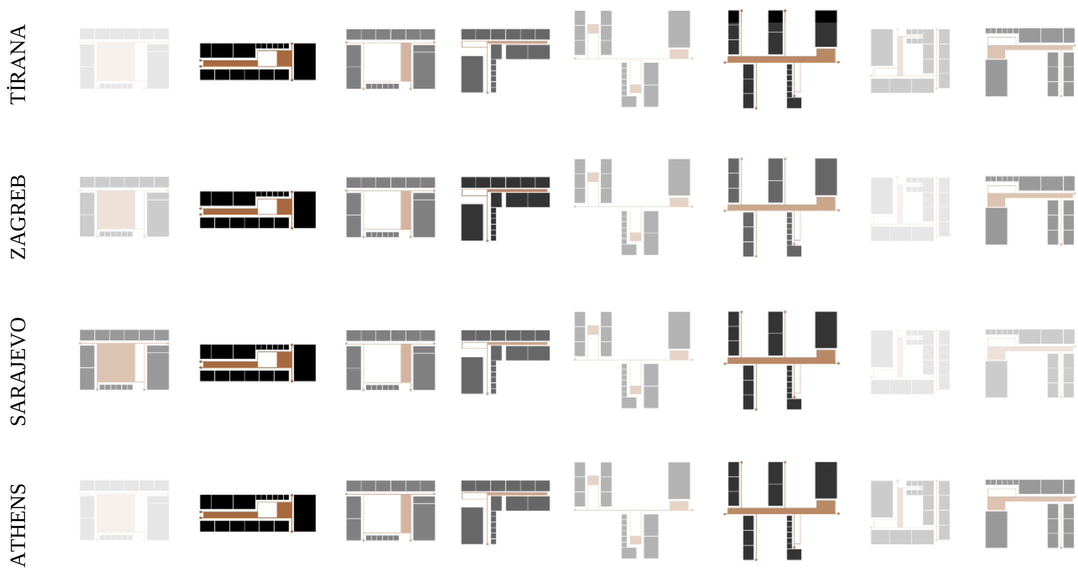

Figure 99. *Suitability gradient of school morphologies in the studied climatic contexts*

A higher optimization of energy consumption in terms of morphology selection can be reached in hot climatic regions, as displayed in ***Table 22.***

Table 22. *Total Morphology effectiveness (%)*

	Tirana	**Zagreb**	**Sarajevo**	**Athens**
BA_N	_	5.3	10.7	_
BL_N	32.8	20.2	20.6	33.7
CC_N	22.5	10.9	13.5	23.3
CO_N	25.9	14.1	15.9	26.5
UA_N	17.5	6.6	8.8	17.2
UL_N	26.6	13.0	16.4	28.1
TB_N	13.4	_	_	12.5
TS_N	20.9	8.1	9.7	21.5
BA_S	_	6.7	11.9	_

BL_S	31.8	20.5	18.9	32.6
CC_S	22.2	12.3	14.7	23.3
CO_S	25.2	15.1	14.9	25.3
UA_S	18.5	7.8	10.3	18.4
UL_S	25.3	13.0	15.3	27.3
TB_S	14.0	_	_	13.3
TS_S	20.9	8.3	9.8	20.5
BA_E	_	5.8	11.2	_
BL_E	28.1	18.3	18.9	28.1
CC_E	21.8	11.2	14.0	22.6
CO_E	23.9	14.1	16.2	24.1
UA_E	16.5	6.7	9.6	16.3
UL_E	18.1	9.2	12.6	18.6
TB_E	14.0	_	_	12.9
TS_E	20.4	8.7	10.9	20.6
BA_W	_	4.8	9.9	_
BL_W	29.4	18.1	18.5	29.7
CC_W	22.1	10.4	12.8	22.6
CO_W	25.9	13.6	15.2	26.3
UA_W	16.4	5.3	7.5	16.1
UL_W	19.5	8.5	11.5	20.1
TB_W	15.1	_	_	14.6
TS_W	20.5	6.7	7.6	20.6

A variance based on climatic patterns is found even on classroom overheating in a typical summer day, as shown in ***Table 23.*** Tirana is ranked first, followed by Athens and Sarajevo. A classroom in Zagreb remains within the comfort temperatures in the studied summer day.

Table 23. *Classroom overheating in the 12th of September*

	Tirana				Zagreb				Sarajevo				Athens			
	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	
BA	1.63	3.89	4.46	1.91	-5.67	-2.98	-3.97	-4.84	0.41	1.07	0.43	1.15	0.72	2.56	2.49	1.95
BL	1.40	3.63	4.42	1.63	-5.96	-2.99	-4.09	-5.11	0.17	0.82	0.26	0.92	0.22	2.24	2.11	1.43
CC	1.41	3.39	4.26	1.67	-6.06	-3.29	-4.35	-5.21	0.26	0.78	0.15	0.74	0.24	2.04	1.92	1.36
CO	1.30	3.43	4.14	1.62	-6.01	-3.27	-4.34	-5.21	0.14	0.70	0.18	0.82	0.15	2.16	1.85	1.30
UA	1.49	3.31	4.14	1.69	-5.98	-3.26	-4.40	-5.20	0.20	0.80	0.13	0.88	0.32	2.17	1.94	1.42
UL	1.43	3.25	3.79	1.72	-6.01	-3.58	-4.72	-5.23	0.11	0.56	0.11	0.73	0.22	1.88	1.64	1.46
TB	1.12	3.01	3.42	1.24	-6.38	-3.65	-4.79	-5.67	-0.06	0.60	0.00	0.58	-0.12	1.63	1.42	0.74
TS	1.11	3.26	3.37	1.38	-6.25	-3.68	-4.99	-5.40	-0.07	0.30	-0.09	0.76	-0.02	1.75	1.34	1.11

CHAPTER 6

CONCLUSIONS

6.1. Conclusions

A new comprehensive framework is proposed aiming to initiate an analytical and quantitative approach towards evaluating the thermal and energy performance of open-school building morphologies in various climatic contexts. The study is based on an energy performance analysis, taking into account different design variables: shape, orientation. The main novelty and significance consists in evaluating and optimizing the energy and thermal performance of diverse morphologies of 21st century open-schools, thus contributing to the increment of the climatic awareness of designers and architects in the decision-making process. The proposed approach is an enhancement of methodologies proposed earlier and provides novel and worthy contributions compared to the mentioned studies as it reveals the following findings:

- The humid continental climate of Sarajevo displays the highest energy demand. Ranked second, Zagreb's oceanic climate displays a similar performance to that of Sarajevo with an average difference of 5 $kWh.m^{-2}$. When located in the Mediterranean climate of Athens, the hypothetical open-school models display the lowest energy demand, approximately 18 $kWh.m^{-2}$ lower than when in Sarajevo.

- BA typology is not suitable for location displaying a climate similar to that of Tirana and Athens, but can be adopted in cold climates of Zagreb and Sarajevo. Still, further optimization of the atrium dimensions is needed to obtain a better performance. Typologies with a high S_e possess the lowest ranking in oceanic and humid continental climates. BL and UL are ranked highest in all 4 climates.

- In hot climatic regions a higher optimization of energy consumption in terms of morphology selection can be reached. A maximum of 32.8% for the humid subtropical climate of Tirana, 20.5% for the oceanic climate of Zagreb, 20.6% for the humid continental climate of Sarajevo and 33.7 % for the Mediterranean climate of Athens of total energy consumed can be reduced through the selection of the proper morphology.

• The comparison of annual simulated energy demand in terms of rotation angle shows an increasing trend when the building is rotated 90° and 270°, which corresponds to classrooms being east and west oriented. The biggest impact of orientation is visible in typologies with longitudinal layouts and in hot climates of Athens and Tirana.

• Orientation has no significant impact in thermal performance during winter in a cold climate (humid continental/oceanic) as all 4 orientations show a similar curve, below the temperature of comfort. In hot climates (humid subtropical/Mediterranean) the best performance on winter days is obtained by south-oriented classrooms.

• The air temperature curves of classrooms show a significant drop during the break as set in the natural ventilation schedule regime, thus associating the thermal performance of buildings to their operational, space utilization characteristics and occupant behavior.

6.2. Recommendations for future research

Overall, the results highlight the promising thermal and energy benefits from the morphological impact. Nevertheless, the model development process and analysis are in accordance with the respective scientific studies and experimentations reviewed considering the influence of climatic conditions, construction properties, HVAC, and internal loads, delivering optimal model performance. To further explore the research, experimental studies on building geometries should be performed. Therefore, several priority areas are suggested for future inquiry.

• involving internal space organization as a variable in the simulation-assisted research process

- including shading strategies in the results

- optimization of aspect ratio of the morphologies

- further optimization of the dimensions of the courtyards introduced in each typology, whether covered or uncovered

Overall though, the developed study represents an effective and well-documented step towards an analytical approach and states once more that building shape, if properly observed and evaluated by architects in the early stages of the design, not only will reduce the energy consumption of open-school buildings but will minimize the environmental impact.

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