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RESEARCH ARTICLE

Courtyard design impact on indoor thermal comfort and utility costs for residential households: Comparative analysis and deep-learning predictive model

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Abstract A courtyard is an architectural design element which is often known as microclimate modifiers and is responsible to increase the indoor occupant comfort in traditional architecture. The aim of this study is to conduct a parametric evaluation of courtyard design variants in a residential building of different climates with a focus on indoor thermal comfort and utility costs. A brute-force approach is applied to generate a wide range of design alternatives and the simulation workflow is conducted by Grasshopper together with the environmental plugins Ladybug and Honeybee. The main study objective is the evaluation of the occupant thermal comfort in an air-conditioned residential building, energy load, and cost analysis, derived from different design variables including courtyard geometry, window-to-wall ratio, envelope materials, heating, and cooling set-point dead-bands, and building geographical location. Furthermore, a Deep Learning model is developed using the inputs and outputs of the simulation and analysis to transform the outcomes into the algorithmic and tangible environment feasible for predictive applications. The results suggest that regarding the thermal loads, costs, and indoor thermal comfort index (PMV), there are high correlations between the outdoor weather variation and dead-band ranges, while in extreme climates such as Singapore, courtyard spaces might not be efficient enough as expected. Finally, the highly accurate deep learning model is also developed, delivering superior predictive capabilities for the thermal comfort and utility costs of the courtyard designs.

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1. Introduction

1.1. Research background

Today, more than 30% of total direct and indirect CO_2 emissions are due to the building and construction industries (Brian Edwards et al., 2014), while 70% of building energy demand is associated with air-conditioning systems for indoor cooling and heating. Thus, it is crucial to focus more on energy efficiency in the construction industry by seeking passive strategies from our traditional architecture to achieve energy-efficient buildings while considering indoor thermal comfort. One of the most common examples of climate-responsive architecture is courtyard houses, which based on (Fathy, 1986), might be worthwhile to be reinvestigated and redesigned in our modern architecture, especially in extreme climates (Taleghani et al., 2014).

Courtyard building is one of the oldest types of vernacular design strategies with a historical origin of 5000 years ago and appearing in various forms throughout the world. Traditionally, courtyards are associated with the Middle East, where culture and environment have shaped a specific form and accordingly, the model has been reinterpreted in Latin America, China, and Europe. Unfortunately, despite the courtyard's unique position in the long history of architecture as a modifier of microclimate, it has been unfairly overlooked in recent centuries. The current courtyard houses are being built in several climate locations, where courtyards act as a pleasant outdoor garden. However, few architects look far beyond the beauty aspects of courtyards (Soflaei et al., 2017), to expertly use this element as an open or semi-open space. All in all, the effect of courtyard as a passive design strategy mainly appears in two certain areas: occupants' thermal comfort and energy performance of the building.

In this era, due to the changes in the modern lifestyle and people's expectations of indoor spaces, using active systems, in addition to the traditional passive strategies, are inevitable. To this end, various researchers (Pisello et al., 2016; Belpoliti et al., 2020) examined the combination of active and passive strategies in their studies. For instance, integrating passive cooling and active air conditioning systems (Zhang et al., 2014), evaluating the impact of active and passive strategies on building costs (Hajare and Elwakil, 2020), and combination of envelope and morphology related passive solutions and solar active strategies in the new and existing buildings (Ciardiello et al., 2020) are among those studies.

Thermal comfort is characterized as a state of mind that indicates satisfaction with the thermal situation and is measured subjectively (ASHRAE-55, 2017), so the performance of a building design is determined by the achievement of an appropriate indoor environment. In air-conditioned buildings, the predicted mean vote (PMV) indicator and predicted percentage dissatisfied (PPD) have been proposed as the most significant scale to evaluate thermal comfort (ASHRAE-55, 2017). The application of this scale on the indoor thermal comfort of architectural spaces was studied in (Gilani et al., 2015; Conceição et al., 2018) and reviewed in (Enescu, 2017). However, the accuracy of the PMV-PPD model still is under investigation (Humphreys and Nicol, 2002; T. Cheung, 2019). On the other front, adaptive thermal comfort is the dominant model to evaluate the indoor comfort in naturally-ventilated buildings with respect to indoor operative temperature and prevailing mean outdoor temperature (de Dear and Brager, 1998). This concept allows occupants to passively adapt themselves in discomfort situations.

However, there are numerous studies that addressed the effect of courtyard houses on outdoor thermal comfort. The literature varies from (Taleghain et al., 2015) that analyzed one specific courtyard form to other parametric studies that investigated different courtyard design variables including geometrical properties (Martinelli and Matzarakis, 2017), orientation (Rodríguez-Algeciras et al., 2018), climatic data (Forouzandeh, 2018), shading (Berkovic et al., 2012), materials, vegetation and water use (Sözen and Koçlar Oral, 2019). The impact of courtyard design variants to enhance indoor thermal comfort has been studied less in architectural research. Among the different variables, geometrical properties and materials are two ones that were taken into account in most studies and according to (Soflaei et al., 2020), these are one of the most effective factors to enhance thermal comfort. With respect to the courtyard dimensions (Kubota et al., 2017), investigated courtyard design parameters such as space volume, height, and openness ratio in a hot-humid climate of Malaysia and found significant implications on indoor air temperature and relative humidity. Similarly (Reynolds, 2001), developed a study in a temperate and humid climate of Rabat-Salé medina and highlighted the effect of courtyard length and height on thermal comfort. In addition, the courtyard elevation area is another factor that is evaluated in (Soflaei et al., 2016) and aimed to figure out the concept of the traditional central courtyard as a passive cooling strategy improving indoor thermal comfort. This study examined the effect of the Window-to-Wall Ratio (WWR) and proposed ratios for different facades based on the analysis of fourteen traditional houses located in dry and semi-arid climates of Iran. On the other front, the impact of courtyard materials on improving indoor thermal comfort was the main focus in some studies (Soflaei et al., 2020). According to (Reynolds, 2001), apart from the aspect ratio, orientation, and solar exposure, construction materials of inner floors and external walls depicted another major design consideration. In addition, one study revealed that using vegetation in courtyard roof and ground could minimize the number of discomfort hours by 14% (Taleghani et al., 2014). Utilizing parametric design simulation tools was the focus of a few studies in the literature to investigate different courtyard building design options.

To this end (Soflaei et al., 2020), studied a wide number of variables consisting of orientation, geometry, materials, window sizes, and courtyard eccentricity where results showed an improvement of indoor adaptive thermal comfort by 42.3% in subtropical desert climates.

Furthermore, several studies have considered the role of courtyard design variants on energy consumption. As to the indoor thermal comfort, geometrical properties were found to be important factors in changing the courtyard building energy performance. In a temperate climate (Muhaisen and Gadi, 2006), conducted a comparative analysis within various courtyard proportions in which deeper courtyard forms resulted in the highest cooling and heating loads reduction. In addition, analyzing different courtyard Width/Length (W/L) ratios and their effect on the received solar gains and the energy loads of the building were evaluated in (Manioğlu and Oral, 2015). This study showed that the W/L ratio has a considerable effect on energy loads and solar absorption, therefore, with W/L = 2, the courtyard building shape with 100 m^2 built-up area experiences the lowest heating consumption and the courtyard with W/L = 0.2 has the lowest cooling and total energy loads. Also (Yaşa and Ok, 2014), evaluated the effect of courtyard geometry in different climatic conditions and findings confirmed a direct relation between courtyard length and annual thermal loads. Taking material parameters into account, one research concluded that optimizing design parameters such as windows type, wall thickness, and insulation type and thickness, could save the energy consumption up to 12.31% in the hot and humid climate of Dubai, UAE (Al-Masri and Abu-Hijleh, 2012). Another study by (Aldawoud, 2008) examined a variety of design variables such as location, height, window type, and WWR to assess the courtyard building energy consumption. In this study, the climatic condition was found to be more effective in building energy performance especially in hot-humid and hot-dry climates, compared to that of temperate and cold climates. By comparing the courtyard typology with other urban block layouts in terms of thermal performance and solar gains, both (Quan et al., 2020) and (Zhang et al., 2019) confirmed that the courtyard outperformed other options.

Lastly, some studies extended the knowledge by integrating both thermal comfort and energy performance as the main focus of their studies instead of considering a single objective (Zamani et al., 2019). In particular, the heating loads and summer thermal comfort of low-rise buildings at the current time and four climate scenarios for 2050 of the Netherland were studied in (Taleghani et al., 2014). They concluded that heating loads and summer thermal comfort were also affected by climate change while overheating could be reduced by using open transitional spaces. Considering material effect, a simulation-based study (Mousa et al., 2017) evaluated the impact of window screens on both indoor thermal comfort and cooling load in traditional courtyard houses where removing of window screens resulted in higher indoor temperature by 2.4 °C on average while reducing the cooling loads by 50%.

1.2. Research aim and contribution

On the whole, previous findings revealed that courtyard design variables have significant impacts on both indoor thermal comfort and building energy performance. Geometrical properties including height, length, and width could influence the physical interaction of courtyard building with environmental conditions such as solar gains, air temperature, and wind velocity. Alternatively, envelope material types contributed to the heat gains and losses in addition to the transparent part of the façade in the form of WWR. Furthermore, investigating the building energy performance is mainly coupled with the utilization of air conditioning systems, where thermostat variations can modify the energy demands for heating and cooling of courtyard spaces and utility costs. The reason for this fact is that the fuel and electricity consumptions are highly correlated with energy source prices (Ding and Banihashemi, 2017). However, these interactions could change with different climatic conditions and result in altering the courtyard buildings performance that was the focus of a few studies as outlined in Table 1. Likewise, most of the findings were applicable in certain environmental and building conditions that could not be generalized to other similar or different locations.

To overcome this knowledge gap, designers need to consider a wide range of design alternatives to find proper courtyard building design solutions to improve indoor thermal comfort and reduce energy and utility costs. Such designs are feasible using a Brute-force approach and through a parametric design. A brute-force or exhaustive approach entails the entire design alternatives based on the parameters variations and their respective output that allows designers to compare and analyze the implications on the design targets (Tabadkani et al., 2021). Moreover, Table 1 outlines the existing diversities among studies considering the main targets and courtyard design variables found in the literature. Courtyard geometrical dimensions and envelope materials were widely used, while different climatic conditions and window size proportions were evaluated less. Interestingly, none of these studies evaluated the impact of HVAC thermostat variations on the energy performance of the air-conditioned courtyard buildings. Regarding the targets, either indoor thermal comfort or energy performance or a combination of both were mainly assessed while none of them verified energy performance implications on utility costs. Therefore, the main research contribution to the state-of-the-art is proposing a parametric simulation-based workflow that allows evaluating a large number of design alternatives including climate zone, courtyard geometrical properties and the envelope characteristics, HVAC systems, and their implications on courtyard design targets, simultaneously.

Furthermore, there is not a high-performance predictive model transforming the analytical and simulation results into tangible applications on the courtyard design. As a result, the aim of this research is twofold. The first focus is to evaluate the different alternatives of an air-conditioned residential courtyard building in various climatic conditions considering utility costs, indoor thermal comfort, and energy consumption. Second, it is intended to develop a Deep Learning-based model to apply the inputs including

Table 1 A summary of findings in the literature.

Articles	Targets			Courtyard design variables				
	Indoor thermal comfort	Energy use	Utility costs	Geometrical properties	Materials	Climatic data	WWR	HVAC
Taleghani et al. (2014)	●			●	●			
Kubota et al. (2017)	●			●	●			
Soflaei et al. (2016)	●			●	●	●	●	
Soflaei et al. (2020)	●			●	●		●	
Zamani et al. (2019)	●	●						
Diouri et al. (2018)	●			●	●			
Al-Masri and Abu-Hijleh (2012)		●		●	●			
Muhaisen and Gadi (2006)		●		●				
Taleghani et al. (2014)	●	●				●		
Aldawoud (2008)		●		●	●	●	●	
Yaşa and Ok (2014)		●		●		●		
Manioğlu and Oral (2015)		●		●				
Mousa et al. (2017)	●	●			●			
Current research	●	●	●	●	●	●	●	●

courtyard physical dimensions, external wall type, window type, dead-band (the difference between heating and cooling set-points), WWR, and climate and deliver predictive outputs including annual energy load and annual utility cost, summer average PMV, and winter average PMV. To this end, this study utilizes a simulation-based parametric design to compare over 19,000 design iterations, develop a Deep Learning model and answer the following research questions:

Q1) How and to what extent do different courtyard design variables affect utility costs and total energy demands of an air-conditioned building?
Q2) What is the relationship between the indoor summer/winter thermal comfort and courtyard design parameters?

2. Methodology

The proposed methodology of this research consists of a comparative analysis using a brute-force method to analyze the implications of courtyard design variables on indoor thermal comfort, energy load, and utility costs. A brute-force method provides an ultimate perspective of the entire design alternatives that can be generated. However, conducting a brute-force approach might be a challenging task without using parametric design tools such as Grasshopper algorithmic interface and its environmental plugins, namely, Ladybug-tools. These plugins are basically using a validated simulation engine namely EnergyPlus (Shrestha, 2006) for building thermal behavior. Moreover, parametric interfaces facilitate autonomous design alterations through a set of algorithmic components that allow a designer to modify the original concept to map its impact on building parameters. For the purpose of this research study, the methodology is divided into four steps as shown in Fig. 1: (1) setting the design variables including building location, courtyard dimensions, and building parameters, (2) assigning the simulation settings through Ladybug-tools, (3) recording the implication of design variables on thermal comfort, energy performance and utility costs, and (4) using MATLAB to post-process the data through Deep Learning Neural Network model.

2.1. Modelling information

The current model is based on a previous research case study done by (Soflaei et al., 2020). Fig. 2 illustrates the geometrical variations of minimum values (left) to maximum values (right) for a residential building. Building orientation is set on the North-South axis since results in the previous study (Soflaei et al., 2020) showed 0-degree orientation as an optimum design alternative. Windows are located at the interior side of the courtyard and none of the exterior facades have any windows. Moreover, an ideal air load air-conditioning system is assigned in which it is an imaginary system that can provide heating/cooling set-points with 100% performance efficiency (EnergyPlus, 2013). As summarized in Table 2, daily operational profiles, thermal properties of roof and floor and ground temperature are assumed fixed values while natural ventilation and shading system are not assigned. These consistencies help to observe a robust study on the research outputs.

On the other front, simulation variables are shown in Table 3 with their respective domains and increments. In this research, a total number of 19,440 generations are simulated through a brute-force approach to analyze their impact on the outputs. According to Table 3, variables are divided into four categories based on their interactions: (1) building locations to represent the climatic variations (Table 4), (2) courtyard geometrical dimensions including width, length, height, and WWR, (3) envelope including windows (Table 5) and external wall thermal properties (Table 6), and (4) mechanical ventilation strategy representing heating/cooling set-point range as dead-band. To

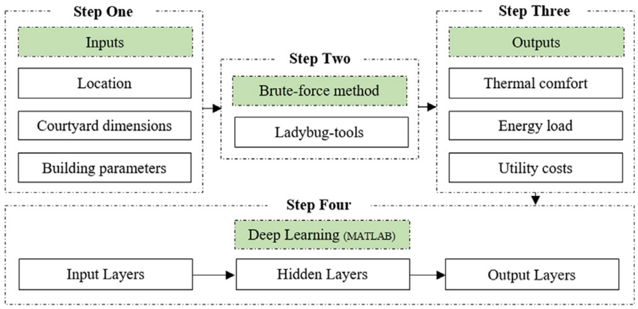

Fig. 1 Research methodology workflow.

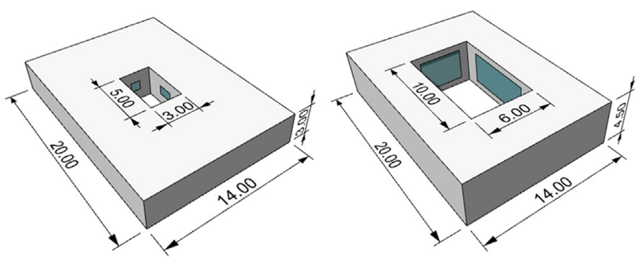

Fig. 2 Case study model.

this end, the dead-band value as a difference between heating and cooling set-points changes are defined in a way that 3 °C stands for 21–24 °C, 5 °C for 20–25 °C, and 7 °C for 19–26 °C as heating and cooling set-points, respectively. The 3 °C is the baseline dead-band according to (ASHRAE, 2019).

With respect to the building location, five climates based on ASHRAE climate zone specification are selected for further analysis including Melbourne (3A), Copenhagen (5A), Singapore (0A), Tehran (3B), and Algiers (3B). The latter two locations have similar climate zones while their weather data variations are different to underline the potential differences in the results. To this end, Fig. 3 depicts mean annual environmental fluctuations regarding three main parameters that are highly effective on indoor thermal comfort and loads: (1) Dry bulb temperature (DBT in °C), (2) Global horizontal solar radiation (GHI in Wh/m^2), and (3) Sky coverage (SC out of ten). Among them, climatic conditions vary the least in Singapore city, while in Tehran, DB and GHI changes are significant with an average clear sky throughout a year. It should be noted that Melbourne city is in the southern hemisphere and thus, results show an inverse variation within seasons, compared to the other locations. Overall, mean annual DB, GHI and SC vary from 0 to 30 °C, 20 to 360 Wh/m^2, and 4/10 to 8.5/10, respectively, to ensure a wide range of climatic considerations on the courtyard design.

Table 2 Fixed assumptions for simulations.

Parameters	Assigned Value(s)
Physical program	Midrise apartment
Building orientation	0 degrees (North-South axis)
Roof	U-Value: 0.96 W/m^{2}K
Ground floor	U-Value: 0.26 W/m^{2}K
Internal loads	Equipment: 5 w/m^2
	Infiltration ratio: 0.0003 m^3/s.m^2
	Lighting density: 7 w/m^2
	Number of people: 2.86 ppl
Natural ventilation	Deactivated
HVAC system	Ideal air load
Shading system	Not assigned
Solar distribution	Full interior and exterior (with reflections)
Ground temperature	Extracted from weather files at 0.5 m depth

2.2. Simulation outputs

Each design alternative can impact building energy performance and thermal comfort differently. In this research, due to the large number of generations, simulation outputs are evaluated based on three main clusters:

1- Indoor thermal comfort – A static thermal comfort model is recommended in air-conditioned buildings by (ASHRAE-55, 2017) for evaluation through Predicted Mean Vote (PMV) (Standardization, 1994). Moreover, the acceptable PMV is considered as a range between −0.5 and + 0.5 as recommended in (ASHRAE-55, 2017).
2- Energy performance – The required energy for space heating and cooling is assessed based on their respective set-point temperatures, and their accumulation is represented as Energy Load in kWh.
3- Utility costs – In order to define the energy sources for air-conditioning system, fuel (natural gas) and electricity are, respectively, selected for heating and cooling of the spaces, and their consumptions are calculated according to the available prices reported on official websites as shown in Fig. 4.

2.3. Post-processing: Deep Learning predictive model development

Deep Learning algorithms are mathematical and computational models in science and engineering fields which are usually utilized to predict the outcome of non-linear statistical problems and model complex relationships between inputs and outputs or to find patterns in datasets (Banihashemi et al., 2017; Pouyanfar et al., 2018). The thermal equations used to analyze and calculate thermal comfort and utility costs are complex, making Deep Learning Neural Networks a good platform to be used for this purpose (Shakouri and Banihashemi, 2019; Nguyen et al., 2014). In this form, the network is presented with datasets obtained from simulations and the values of inputs including length, width, height, external wall type, window type, dead-band, WWR, and the city are fed into each neuron or nod. The weights are then adjusted through

Table 3 Simulation variables and ranges.

Variable	Interaction type	Domain (min-max)	Increment (s)	Iterations	Reference	Total
Building location	Climate	—	—	5	—	19,440 simulations
Width	Courtyard geometry	3—6 m	1 m	4	Soflaei et al. (2020)	
Length	Courtyard geometry	5—10 m	1 m	6	Soflaei et al. (2020)	
Height	Courtyard geometry	3—4.5 m	1.5 m	2	Soflaei et al. (2020)	
WWR	Courtyard geometry	30%—70%	20%	3	(Soflaei et al., 2020; Pilechiha et al., 2021)	
External wall type	Envelope	3 types	—	3	Soflaei et al. (2020)	
Window type	Envelope	3 types	—	3	Curcija (2018)	
Dead band	Mechanical ventilation	3—7 °C	2 °C	3	ASHRAE (2019)	

learning algorithms iteratively until a suitable output is produced (Machairas et al., 2014). Suitable outputs, in this case, predicted annual energy load and annual utility cost and average summer/winter PMV are the ones which are as close as to the simulation results.

One of the most popular and efficient network structures for Deep Learning Neural Network models is the deep learning multilayer perceptron (DL-MLP). DL-MLP consists of the identical interconnected neurons that are organised in layers (Demuth et al., 2014). These layers are also connected in which outputs of a layer act as the inputs for the subsequent layers. Data flow starts from the input layer and ends in the output layer (Kruse et al., 2013). Through this journey, data pass through multiple hidden layers which recode or provide a representation for the inputs. In this study, due to the large number of variables and existing non-linearity among them, DL-MLP network was used to model a significant relationship between the inputs and the outputs and develop a high-performance predictive model.

This study constructed a deep learning MLP model of the feed-forward back-propagation type with 4 output neurons. Back propagation is a method which feeds back the size of the error into the calculation for the weight changes (Zhang et al., 2007). There are 10 neurons in the input layer for the 10 input variables in the model and 4 neurons in the output layer. In the DL-MLP modelling, the data are divided into three groups of training, testing, and validating. The best configuration of DL-MLP model usually depends on some elements such as the number of hidden layers, the type of learning algorithm, and the training-testing proportion of data. The identification of the best configuration is a trial and error process which requires different experiments to find the best architecture and optimal performance (Banihashemi et al., 2015; Shrestha and Mahmood, 2019).

Therefore, this process was commenced with the best architecture identification for the model. When using deep learning neural networks for solving a problem, number of hidden layers is one of the most important issues. It is known that insufficient number of hidden layers leads to the inability of neural networks to effectively solve the problem (Demuth et al., 2014). On the other hand, too many hidden layers lead to overfitting and decreasing of network generalisation capabilities due to increasing of freedom of network more than it is required (Shrestha and Mahmood, 2019).

Therefore, automatic modelling range of 10—100 hidden layers, considering the Levenberg-Marquardt for learning algorithm, transfer functions of hyperbolic tangent and sigmoid and 1000 number of iterations were tested. Consequently, number of 20 hidden layers was found to be the most optimum number for the deep learning hidden layers.

The best performance of the model was measured based on the error produced by the DL-MLP model, which in this

Table 4 Climate zones of the selected cities.

Location	Climate zone
Melbourne	Zone 3A: Warm humid
Tehran	Zone 3B: Warm dry
Algiers	
Copenhagen	Zone 5A: Cool humid
Singapore	Zone 0A: Extremely hot humid

Table 5 Window thermal properties generated by WINDOW LBNL (Curcija, 2018).

Window Type	Description	Thermal and visual properties
Type 1 — Single Pane	Planibel Clear 8 mm	U-value: 5.74 W/m^2K SHGC: 0.82 VT:0.87
Type 2 — Double Pane	Planibel Clear 8 mm Air (10%) — Argon (90%) Dark grey 6 mm	U-value: 2.67 W/m^2K SHGC: 0.53 VT:0.07
Type 3 — Double Pane	Planibel grey 8 mm Air (10%) — Argon (90%) Dark grey 6 mm	U-value: 2.67 W/m^2K SHGC: 0.35 VT:0.03

Table 6 Wall construction thermal properties (adopted from (Soflaei et al., 2020)).

Construction type	Description	Thickness (mm)	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)	U-value (W/m^{2}K)
Type 1	Porphyry	100	2400	2.57	917	0.82
	Air gap	30	1.204	0.25	1008	
	Hemp insulation	100	406	0.12	1030	
	Bouskoura rock	200	1549	1.00	942	
	Cement mortar	20	1800	1.15	840	
Type 2	Gypsum plasterboard	20	1800	1.15	840	0.18
	ECA block	100	1300	0.096	1000	
	EPS Expanded	100	36	0.03	1500	
	ECA block	100	1300	0.096	1000	
	Cement Sand	20	1800	1.15	840	
	Brickwork, outer leaf	30	1700	1.00	840	
Type 3	Paint	2	–	0.25	837	0.52
	Cement render	20	2100	1.40	950	
	Clay brick	120	2000	0.60	1350	
	Cement render	20	2100	1.40	950	
	Maize fibre Insulation	61	964	0.04	1100	
	Cement render	20	2100	1.40	950	
	Paint	2	–	0.25	837	

case, Mean Square Error (MSE) was used as a performance indicator. MSE can give a quantitative indication of the model error in terms of a dimensional quantity (Ramedani et al., 2012). MSE equal to zero indicates a perfect match between the observed and predicted values and is calculated by the following equation:

$$MSE = \frac{\sum_{i=1}^{N} (E_p - E_a)^2}{N} \quad (1)$$

where E_a is the actual value, E_p is the predicted value and N is total number of datasets (Flores, 2011). The model including 20 hidden layers resulted in the mean square error of 3 out of 0–4.72e+7. The conceptual structure of the model is visualised in Fig. 5.

In the DL-MLP conceptual architecture, the information flow starts at the input layer, ending in the output layer and this happens through the hidden layer (Tahmasebi et al., 2011; Goodfellow et al., 2016). Subsequent to the model architecture identification, Levenberg-Marquardt Back propagation algorithm was used as a method to fit the weights during the learning process starting at the output layer and through the input layer.

To find the optimum percentage of dataset to be trained, tested, and validated, test 1 with 60% training-20% testing-20% validating, test 2 with 70% training-15% testing-15% validating and test 3 with 80% training-10% testing-10% validating were performed, as recommended by Shahidehpour et al. (2002). The observations were randomly used for training, testing, and validating since the random observations in DL-MLP design and development are imperative to avoid biases and evaluate the performance more robust (Demuth et al., 2014). Based on the interim results, test 2 when 70%, 15%, and 15% of the dataset were used for training, testing, and validating, was found to be suitable. Furthermore, it can be stated that this batch of percentage is deemed appropriate in terms of providing sufficient number of cases for a proper procedure of training, testing, and validating. Table 7 delivers the summary of the model configuration, analysis, and key details of its development.

3. Results

To investigate an overview of the results, utility costs ($), energy loads (kWh), and indoor thermal comfort are the main derived outputs as a basis for further analysis in the five selected cities (Algiers, Copenhagen, Melbourne, Singapore, and Tehran) that correspond to the different design variables, as shown in Table 3. In the following sections, the implications of each design variable on outputs are described individually and their interactions are explained.

3.1. Effect of dead-band of HVAC systems on utility costs

The temperature ranges within the set-points of the heating and cooling systems, namely, dead-bands, show different implications on utility costs depending on building locations. As shown in Fig. 6, the relation between the dead-band variation and utility costs is highlighted by the following results:

- There is a high variation of annual electricity cost when dead-band changes comparing to fuel costs. This means, in climates with higher DBT, cooling loads should fluctuate more with dead-bands, although this is not the case in Tehran with the high DBT and GHI. This finding

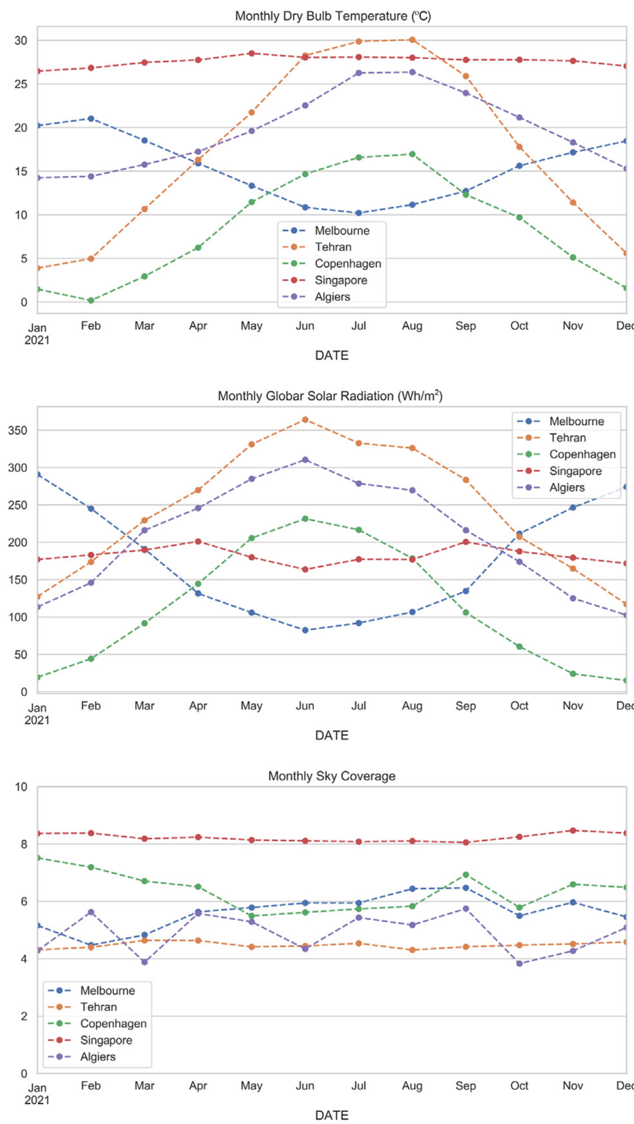

Fig. 3 Selected environmental variations of each climate.

outlines the significance of an average cloudy sky over the year that could impact the cooling loads magnitude.

- When the outdoor environmental condition is consistent throughout the year and intense like Singapore city, cooling loads are remarkably higher and vary with dead-band changes more than the locations with seasonal environmental changes. In Singapore, the annual electricity cost of courtyard building alternatives is considerably high (about \$9000) compared to other locations; although, by changing dead-band values, this city does not meet significant fluctuation (29%) in the annual median electricity cost.
- Considering the annual median electricity cost, Copenhagen and Tehran have the highest (210%) and lowest (20%) fluctuations, respectively.
- The annual median fuel cost in Copenhagen, Melbourne, and Tehran is not influenced by the dead-band changes. According to the Fig. 3, since the average monthly DBT in these cities is nearly under the lowest value of heating system set-point (19 °C), it is highly expected that the annual fuel cost is not affected by heating set-point change from 21 to 19 °C.
- Except for Singapore city which is not heating dominant, Algiers has the least annual median fuel cost (around \$8) compared to the other cities. This is mainly due to both low heating demand and low Natural Gas price in Algiers (0.003 \$/kWh). It is worth mentioning that the change of dead-band in Algiers results in a 2% fluctuation of annual median fuel cost.

3.2. Effect of the exterior wall type of courtyard house on utility costs

The thermal properties of the exterior wall construction are one of the main factors determining the amount of heat transfer through the walls. Three types of wall materials are considered to evaluate their impacts on utility costs while changing other design variables as shown in Fig. 7 along with the following results:

- Wall Type 2 with the lowest U-value (0.18 W/m^{2}k) has the best effect on the reduction of electricity cost in Algiers, Singapore, and Tehran. This finding shows that the impact of the wall with higher insulation in climates with higher DBT is more than the climates with lower DBT during a year.
- Using Wall Type 1 with the highest U-value (0.82 W/m^{2}k) results in the lowest annual median electricity cost in Copenhagen and Melbourne. As opposed to the other cities, applying the wall for a courtyard house with a low U-value does not necessarily lead to an optimum result in colder climates.
- Changes of wall material types in Copenhagen has the highest percentage of influence (56%) on the annual median electricity cost, unlike Singapore which records the lowest percentage by only 3% fluctuation.
- In contrary to dead-band changes, higher thermal performance of the courtyard envelope resulted in a remarkable fluctuation of the annual median fuel cost. With this respect, Algiers with 30% and Melbourne with 16% have the highest and lowest fluctuations, respectively.

3.3. Effect of windows type of courtyard house on utility costs

Following the envelope properties of the courtyard housing, three types of windows including one single-pane and two double-panes are selected to determine their impact on the utility costs. According to Table 4, the one single-pane window has the largest U-value factor (5.74 W/m^{2}K) and SHGC equal to 0.82 in comparison with the other two windows. Double-pane windows have the same U-value factor (2.67 W/m^{2}K) with two different SHGC (0.53 and 0.35). Based on Fig. 8, the following findings are outlined:

- Double-pane Window Type 3 with the lowest SHGC value (0.35) and U-value factor (2.67 W/m^{2}K) shows the best

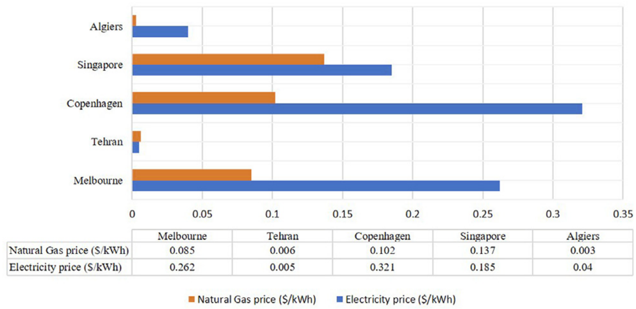

Fig. 4 Utility costs (adopted from (Valev)).

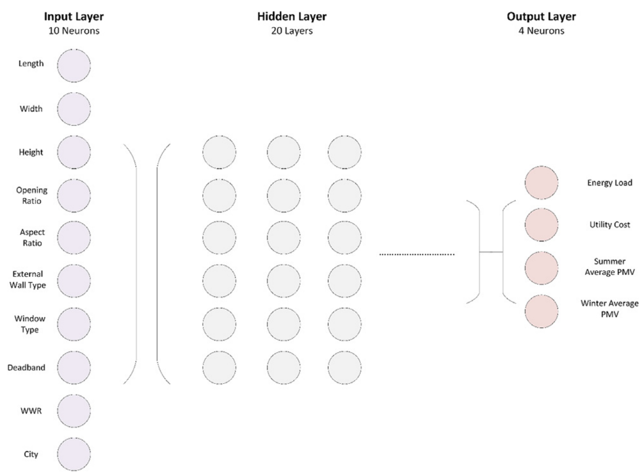

Fig. 5 The conceptual structure of the developed DL-MLP.

impact on the reduction of annual electricity cost in all climates This is due to minimizing the solar heat gain through windows on cooling demand reduction.

- With respect to the fuel cost, single-pane Window Type 1 has the best effect on Algiers with the annual median fuel cost of $7.74 and double-pane Window Type 2 performs better in Copenhagen, Tehran, and Melbourne with the median values of $4070.50, $77.34, and $742.29, respectively. Since the average DBT in Copenhagen, Tehran, and Melbourne cities in the winter season are lower than Algiers, using a window type with a lower U-value and higher SHGC (Window Type 2) leads to a higher reduction in heating demand and thus reduces the fuel cost. In addition, higher SHGC (Window Type 1) in Algiers has more impact on decreasing heating loads of courtyard houses compared to the window U-value.
- In comparison with other locations, the analysis of different courtyard alternatives in Copenhagen and Singapore regarding their window material types results in the highest and lowest fluctuation of the annual median electricity cost by 66% and 8%, respectively.
- Changes in window types do not show a considerable effect on annual fuel costs, though, Algiers and both Copenhagen and Tehran cities show only 6% and 3% of fluctuation, respectively. However, decreasing both U-value and SHGC results in lowering cooling loads and thus the electricity costs. On the other hand, the reduction of SHGC has a negative impact on absorbing solar heat in terms of heating loads. Thereby, altering the windows of courtyard houses does not impact the heating load as significant as the cooling load.

3.4. Effect of WWR of the courtyard house on utility costs

A transparent façade can affect the amount of heat transfer and solar heat gain entering the interior space, therefore the WWR factor could influence the utility costs. Fig. 9 shows the relation between WWR (30%, 50%, and 70%) and annual electricity and fuel costs through the following highlights:

- Since increasing WWR leads to the higher exposure to solar gains and heat loss, both annual electricity and fuel costs are reduced with a 30% WWR in all locations. However, a negligible improvement (17$) in annual fuel cost is observed in Algiers when a WWR of 70% is applied.
- Copenhagen and Singapore with 94% and 11% have the highest and lowest changes of the annual median electricity cost, respectively. This can be explained by the extremely cold and tropical weather conditions of Copenhagen and Singapore, respectively, and how WWR can be an essential factor in cold climates, especially, when they are internally exposed to the courtyard space.
- Changing WWR from 30% to 70% in both Algiers and Melbourne and Copenhagen provides the lowest (2%) and highest (7%) fluctuation on the annual median fuel cost, respectively.

3.5. Energy load evaluation based on all variables

With respect to the implications of the courtyard house design parameters on energy loads, the following results can be observed from Fig. 10:

- Regardless of the type of variables, Melbourne and Singapore consume the lowest and highest energy, respectively, where the mean energy load varies from 10,890 to 12,910 kWh in Melbourne and from 43,150 to 55,460 kWh in Singapore.
- It is highly expected that increasing the dead-band value can have a positive impact on thermal loads where in all locations employing an HVAC system with 7 and 3 dead-band results in the lowest and highest mean thermal load values, respectively.
- In terms of thermal loads, Singapore is more sensitive to the dead-band extreme ends by 22.21% which is mainly because the DBT in Singapore varies within a range of 24—26 °C. In contrast, in Copenhagen, the DBT is approximately below the heating set-point (19 °C), as a result, energy loads are expected to have the least variation (less than 1%).

Table 7 Key details of the model configuration and results.

Model Structure	Deep Learning	Deep Multilayer Perceptron Neural Network
	Model design	Feed-Forward Back-Propagation type
	Inputs	10
	Outputs	4
	Hidden layer	20
Algorithms	Data division	Divide Random function
	Training	Levenberg- Marquardt
	Performance	Mean Square Error (MSE)
Progress	Epoch	1000 iterations
	Time	4:37
	Performance	37 (0−4.72e+7)
	Gradient	1.01e+03 (9.12e+7 −1.00e-7)
	Mu	1.00 (0.001−1.00e+10)
	Validation checks	6
Data division	Training	70%
	Test	15%
	Validation	15%

- Wall Type 2 and Type 1 with the lowest and highest U-values have the best and the worst impact on reducing thermal loads in all cities where the two ends of the spectrum are 9900 and 1580 kWh variation in Copenhagen and Singapore, respectively.
- Utilizing Window Type 3 in Algiers, Singapore, and Tehran results in the lowest annual median energy loads due to the higher DBT and GHI. This finding shows that even if the windows are internally exposed in courtyard houses, but they should have a low U-value and SHGC. On the other side, in Melbourne and Copenhagen cities with lower DBT and GHI, it is recommended to employ windows with higher SHGC (Window Type 2) to increase the solar heat gains during cold months and reduce the thermal loads.
- Increasing the WWR could significantly increase the thermal loads due to the higher exposure to solar gains or heat loss. This is even more evident by comparing Algiers and Tehran with similar climate zones, where the energy loads in Tehran are higher than Algiers due to higher GHI throughout the year.
- A consistent and extreme environmental condition like in Singapore dedicated additional attention to choose appropriate window type and WWR where energy loads vary significantly within alternatives. In particular, changing the window type and WWR could result in 3720 and 5100 kWh difference of energy loads.

Table 8 indicates the mean energy load fluctuation in kWh. Dead-band could impact the most in Algiers, Melbourne, and Singapore, while in Copenhagen and Tehran, wall construction types are more effective. Despite the fact that the indoor temperature in this study is controlled by HVAC systems, the other three design parameters could remarkably influence the energy loads in all locations, although, from Table 8, the following prioritization based on their impact factors can be listed: 1) Dead-band, 2) Wall type, 3) WWR, and 4) Window type.

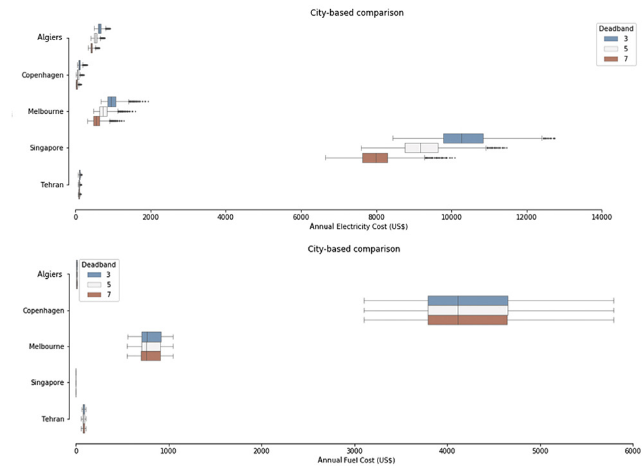

Fig. 6 Dead-band variation and its implication on utility costs.

Alternatively, Fig. 11 shows how all variables on courtyard design can lead to a wide range of heating and cooling loads (kWh) in the selected five cities and underlines the following findings:

- Due to the cool humid climate of Copenhagen and the extremely hot humid climate of Singapore, these two cities experience a high amount of heating and cooling loads respectively. The median thermal load to heat the courtyard building in Copenhagen is 40,331 kWh, and the median cooling load for courtyard houses in Singapore is 49,642 kWh. In addition, a courtyard designed in Singapore does not need any heating demand and in Copenhagen, it requires the least energy for cooling (189 kWh).
- Due to the higher DBT in Singapore, Tehran, and Algiers, cooling load is the main demand in courtyard buildings while in Copenhagen and Melbourne with the lower DBT, courtyard houses experience dominant heating loads.
- Courtyard houses in Copenhagen and Algiers meet the highest (32,885 kWh) and lowest (966 kWh) fluctuation of heating loads, while Singapore and Copenhagen meet the highest (26,355 kWh) and lowest (2408 kWh) fluctuation of cooling loads, respectively.

3.6. Thermal comfort evaluation

Following the evaluation of the effectiveness of each design variable on indoor thermal comfort, the average summer and winter PMV values are calculated for each city considering an acceptable range between −0.5 and 0.5 based on the ASHRAE 55 standard. The following results are obtained from Fig. 12 and Fig. 13:

- Similar to energy loads, dead-band causes the highest variation in both summer and winter average PMV. For

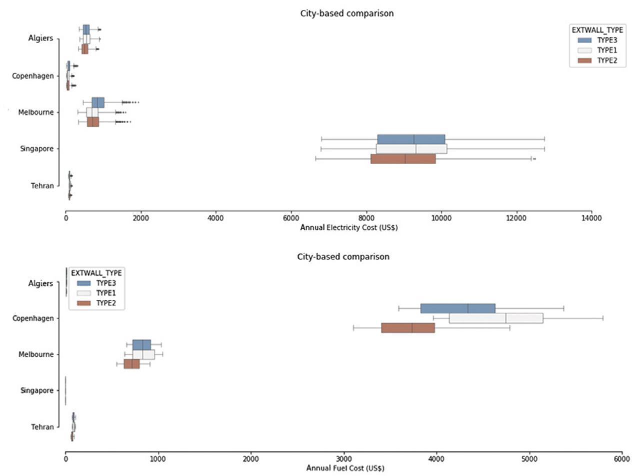

Fig. 7 External wall typologies and their implications on utility costs.

instance, Melbourne experiences the highest variation in average summer PMV (0.35), and Singapore meets the highest variation in average winter PMV (0.23).

- To change the average summer thermal comfort, exterior wall type, window type, and WWR are the most effective factors in Tehran compared to the other locations. This city experiences the highest variation of average summer PMV with 0.14, 0.09, and 0.11 by changing exterior wall types, window types, and WWR, respectively.
- Considering average winter thermal comfort, exterior wall type and WWR play the most important role in Copenhagen and change the average PMV in winter by 0.18 and 0.8, respectively. Also, window type could influence the average PMV in winter in Algiers the most by 0.09.

3.7. Relation between indoor thermal comfort and courtyard house aspect ratio and openness ratio

In order to consider the geometrical configuration of the courtyard and its impact on both summer and winter average PMV values, two factors are driven from the width, length, and height of the courtyard: (1) Aspect Ratio (AR) to indicate the proportions of courtyard space by dividing the building height to the width (Rodríguez-Algeciras et al., 2018), and (2) Openness Ratio (OR) as the portion of the roof area in relation to the total plan area (Kubota et al., 2017).

The calculated range of both AR and OR vary from 0.5 to 1.5 and 0.06 to 0.27, respectively, depending on the dimension. The vertical axis in Fig. 14 shows the average PMV variation from −3 to 3 as the extremes while the acceptable range is assumed to be between −0.5 and 0.5 for further analysis of the findings as follows:

- With respect to the acceptable range of summer thermal comfort, all ranges of AR are optimum in Singapore so that a courtyard geometry with 0.93 for AR and 0.12 for OR is an accepted one in Singapore, Tehran, and Algiers, commonly. This result shows square-shaped courtyards (e.g., 6 m length and 5 m width) with 4.5 m height tends to meet summer thermal comfort in such climatic conditions. While in the case of the winter season, designing a courtyard with 0.52AR - 0.22OR in both Tehran and Algiers and 0.93AR - 0.12OR in Singapore leads to an optimum result, but not an acceptable range since in all cases average winter PMV is below 0.5. As a result, the optimum courtyard shape for the summer and winter seasons in Singapore is similar but in Tehran and Algiers, the rectangular and low height courtyard shape (for instance: 10 m length, 5 m width, and 3 m height) performs better in the winter season.
- Similarly, in Melbourne the average winter PMV values are below −0.5 in all cases; however, to improve indoor thermal comfort, Table 9 outlined possible alternatives for this location. Alternatively, in a few cases of courtyard designs, they meet the acceptable average summer PMV. As shown in Fig. 14 and Table 9, the appropriate AR for the courtyard in Melbourne is 0.61 while OR is better to be 0.22 which results in the rectangular and low height courtyard shape (for instance: 10 m length, 5 m width, and 3 m height).
- Copenhagen is the only city that does not experience any acceptable summer and winter thermal comfort by different courtyard geometries. The range of average summer and winter PMV values in the entire design cases vary from −1.56 to −2.21 and −2.06 to −2.49, respectively.
- Studying the thermal comfort from a wider perspective, Fig. 15 shows the suitable range of each parameter that results in the best summer thermal comfort whereas Copenhagen is the only city that does not experience the acceptable average thermal comfort in summer.

3.8. Best courtyard design alternatives based on utility costs and thermal comfort

Tables 10 and 11 show the best and worst courtyard design alternatives with respect to the lowest and highest utility costs in each location in addition to the following findings:

- The lowest utility cost in all cities is driven by the courtyard geometry of 6 m width and 10 m length. Although, designing a courtyard with 6 m width for Algiers, Singapore, and Melbourne and 10 m length for all cities except for Tehran can even lead to the highest utility costs. Therefore, the width and length cannot be adequate values to independently define the best utility costs and it is necessary to consider the impact of other values such as wall type, window type, WWR, and the dead-band.
- In all locations except for Tehran, 3 m courtyard height was found to be an optimum solution to decrease the utility costs while in Tehran, 4.5 m courtyard height performs better. This observation outlines the courtyard height as an effective design parameter in climates with large average monthly temperature changes (25 °C), a high amount of annual global horizontal radiation (2928 Wh/m^2), and average cloud cover (around 4.5) during the year.

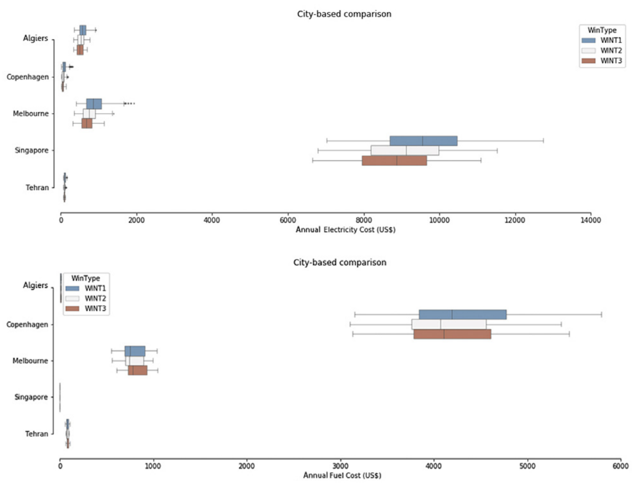

Fig. 8 Window typologies and their implications on utility costs.

- It is evident that a wall type with a low U-value (Wall Type 2) decreases the utility costs in all cities to the minimum level. In a cold climate city like Copenhagen, utilizing Wall Type 1 with the highest U-value results in the worse utility costs. In addition, choosing Wall Type 3 as the thinnest wall (24.5 cm) could also lead to high utility costs in all locations.
- Regarding window types, except for Copenhagen that Window Type 2 with 2.67 W/m^2K and 0.53 SHGC performed efficiently, in other cities, implementing Window Type 3 with the same U-value and lower SHGC (0.35) are associated with the lowest utility costs. In contrast, utilizing Window Type 1 which is a single pane window with a high U-value (5.74 W/m^2K) results in the highest utility costs.
- Due to the significant impact of dead-band changes, the highest and lowest difference between heating and cooling set points in all locations leads to the lowest and highest utility costs.

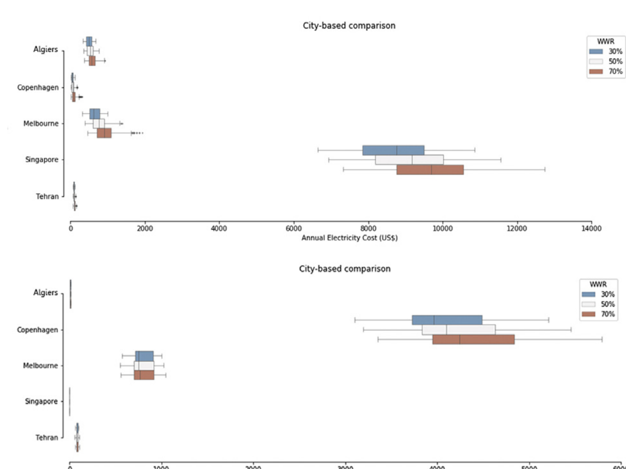

Fig. 9 WWR and their implications on utility costs.

- Decreasing WWR should reduce the costs generally due to the lower thermal loss through windows, thus 30% WWR performs the best. But this is not the case in Tehran where 70% of WWR was found to be an alternative solution for lower utility costs.

With respect to the indoor thermal comfort, none of the courtyard design alternatives could experience the acceptable range for winter thermal PMV. According to Tables 10 and 11, the courtyard buildings designed in Tehran, Singapore, and Algiers in both cases with the highest and lowest utility costs experience summer thermal comfort. However, in scenarios with the highest utility costs, the courtyard spaces meet better summer thermal comfort in Tehran and Singapore. Additionally, courtyard buildings in Melbourne and Copenhagen cannot meet the acceptable summer thermal comfort in both conditions with the highest and lowest utility costs, which means more design alternatives need to be considered in these two climates in future studies.

3.9. Final DL-MLP model

Given the identification of the best architecture and configurations for DL-MLP model in the methodology section, the final run of DL-MLP with 10, 20, and 4 neurons in input,

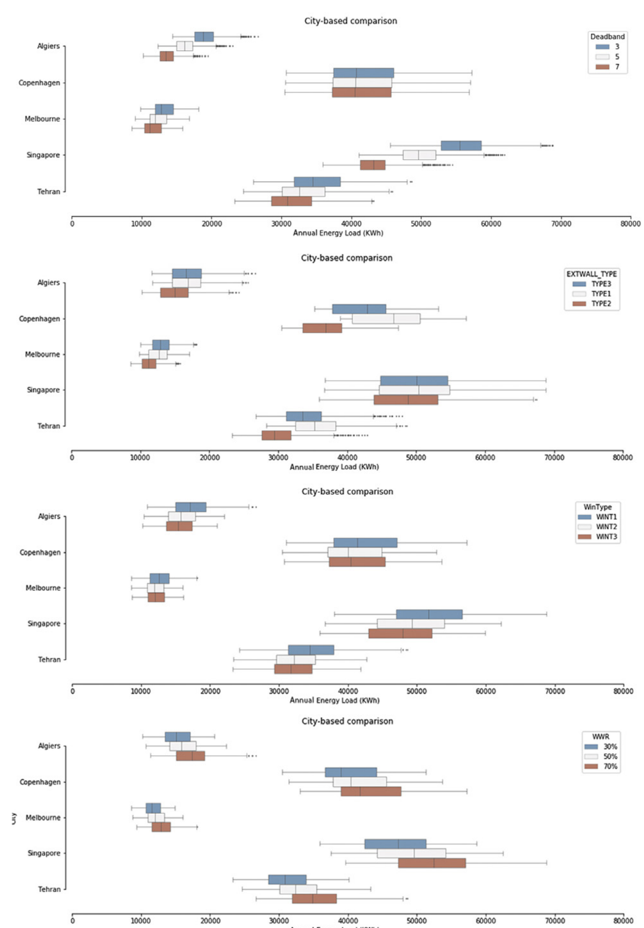

Fig. 10 Design variables' implications on energy loads.

Table 8 Mean energy load fluctuation based on the variable changes (kWh).

Locations	Dead-band	Wall type	Window type	WWR
Algiers	5370	1930	1740	2290
Copenhagen	220	9900	1260	2820
Melbourne	1910	1730	630	1260
Singapore	12,320	1580	3720	5100
Tehran	3590	5860	2590	3970

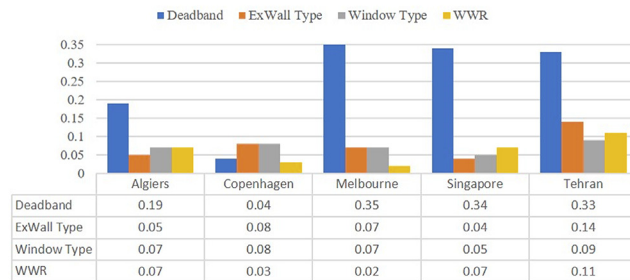

Fig. 12 Average summer PMV variation.

hidden and output layers were started including 70% training, 15% testing, and 15% validating. The hyperbolic tangent function was the activation function chosen for the input layer, the sigmoid transfer function was applied between the hidden layers and the output layer, and the Levenberg-Marquardt Back propagation algorithm was set as the learning algorithm. The program was then instructed to run for 1000 iterations as maintained by Demuth et al. (2014) and Shahidehpour et al. (2002) and the error for each run of iteration was measured. In this model, 1000 iterations were found to be adequate for the optimal training process (Banihashemi et al., 2018).

The iteration should be terminated when no obvious change and/or improvement is observed. Hence, in order to avoid overtraining, it was intended that training to be stopped when the error remains unchanged for 6 consecutive iterations (Rawat et al., 2013). Overtraining has a significant impact on the DL-MLP structure design. If too many hidden layer neurons are used, the model is trained to keep too much detail of the training data, and so, it performs much worse in the testing data (Goodfellow et al., 2016). Fig. 16 illustrates that the minimum gradient of 129 and Mu (momentum constant) of 1 for training data recorded at the 1000th epoch. These values demonstrate perfect convergence of the developed DL-MLP. This error was deemed acceptable in comparison with the literature (Flores, 2011; Cohen and Feigenbaum, 2014).

As the training stops after six consecutive increases in the validation error (stopping criteria), the best performance was found on the 1000th epoch with the lowest validation error of 32.1584 (Fig. 17). The MSE trend is on the constant drop, reaching to the plateau in the end and this fact indicates that the model is well-rescued from an overfitting problem.

Furthermore, graphically demonstrating the model performance, the correlation coefficient graph (R) indicates how much close predicted outputs fit to the actual loads. A closer R value to 1 shows that the predicted values are closer to the actual results (Lebart, 2013). Fig. 18 illustrates that the R values of the developed DL-MLP were calculated at 0.98, 0.96, 0.96, and 96.66 for the training, test, validation, and all average, respectively. These numbers present a strong performance of the prediction model in comparison with the statistical perfection of 1. Therefore, the second main objective of this research in developing a high-performance predictive model for the courtyard design was successfully achieved.

4. Discussion on the findings

Designing courtyard spaces as microclimate modifiers for air-conditioned buildings could have a positive impact on utility costs and energy loads as well as occupants' thermal comfort. To deal with a large number of simulations to assess different design variables, a parametric-based simulation method can be an ultimate choice for architects to find an optimum solution based on the design target. Thereby, this study utilized a brute-force approach by running 19,440 iterations to capture a wide range of

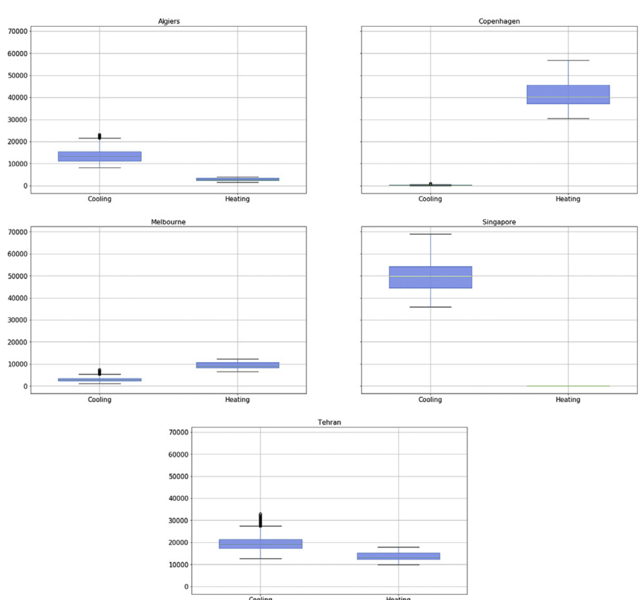

Fig. 11 Annual heating and cooling loads.

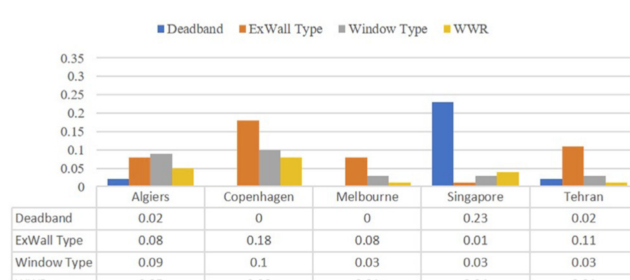

Fig. 13 Average winter PMV variation.

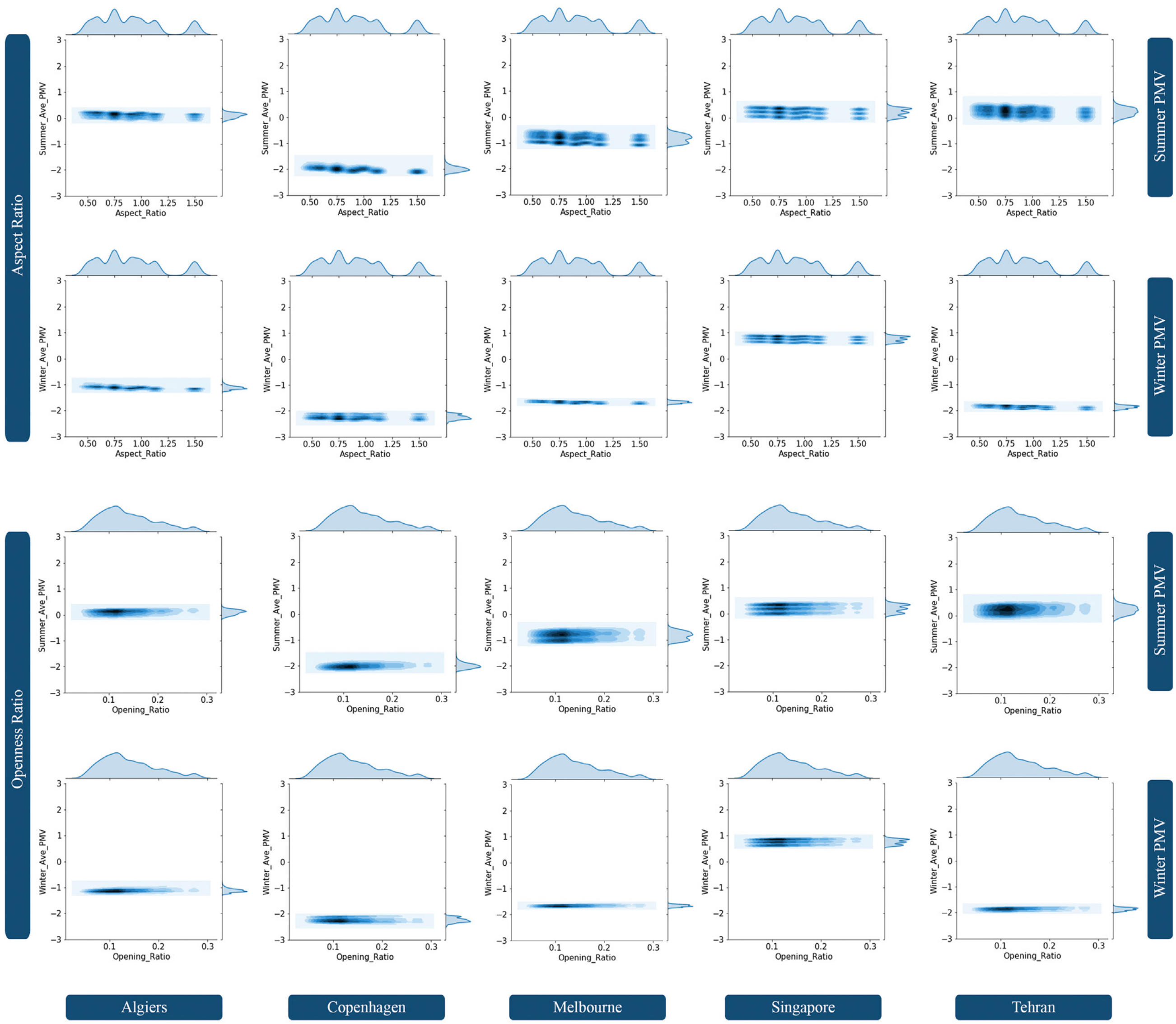

Fig. 14 Interrelation between AR and OR and summer and winter PMV in each city.

residential courtyard building design variations and their implications on utility costs and indoor thermal comfort.

Climatic conditions and dead-band values were found to be the most significant factors influencing the utility costs. In particular, there is a strong relation between HVAC system set-points and electricity cost that is attributed to the outdoor DBT in all climates. Additionally, the lowest U-value of the external walls could significantly reduce the utility costs in all climatic conditions while the results showed that choosing the best window type depends on the climatic conditions. In climates with high DBT and GHI such as climate zone 0 A and 3 B, using Window Type 3 with lower U-value (2.67 W/m^{2}K) and SHGC (0.35) performs the best while in cool-humid and warm-humid climates, there is a negligible difference in utility costs even if Window Type 2 with the same U-value and higher SHGC is applied.

From an indoor thermal comfort point of view, results reveal that none of the proposed courtyard spaces could experience the acceptable winter thermal comfort range in all cities. and Likewise, it could not be met in summer in Copenhagen city with a cold-humid climate. This observation confirms the higher efficiency of courtyard buildings in warm or extremely hot climates in which outdoor DBT

Table 9 Optimum AR and OR values considering average summer and winter PMV.

	Summer season		Winter season	
	Aspect Ratio	Openness Ratio	Aspect Ratio	Openness Ratio
Algiers	0.93	0.12	0.52[a]	0.22[a]
Copenhagen	0.54[a]	0.27[a]	0.91[a]	0.12[a]
Melbourne	0.61	0.22	0.52[a]	0.27[a]
Singapore	all	0.12	0.93[a]	0.12[a]
Tehran	0.93	0.12	0.52[a]	0.22[a]

[a] Values represent the closest to meet the comfort range.

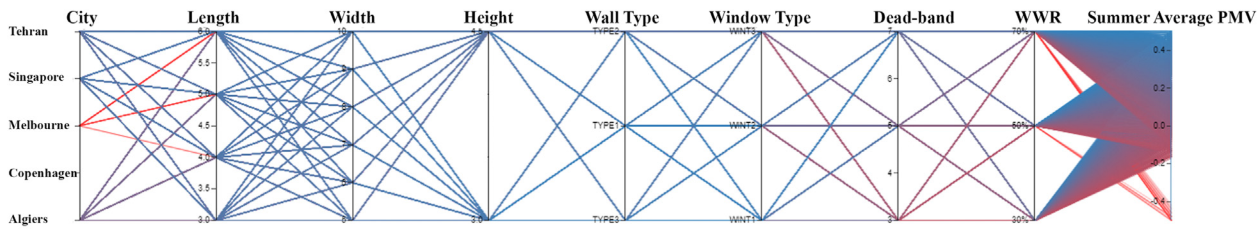

Fig. 15 Existing correlations design variables and average summer PMV.

Table 10 Properties of a courtyard building with the lowest utility costs in each city.

City	Width	Length	Height	Wall type	Window type	Dead band	WWR	Summer average PMV	Winter average PMV
Tehran	6	10	4.5	TYPE2	WINT3	7	0.7	0.31	−1.88
Algiers	6	10	3	TYPE2	WINT3	7	0.3	0.18	−1.1
Copenhagen	6	10	3	TYPE2	WINT2	7	0.3	−1.88	−2.07
Singapore	6	10	3	TYPE2	WINT3	7	0.3	0.35	0.87
Melbourne	6	10	3	TYPE2	WINT3	7	0.3	−0.64	−1.6

Table 11 Properties of a courtyard building with the highest utility costs in each city.

City	Width	Length	Height	Wall type	Window type	Dead band	WWR	Summer average PMV	Winter average PMV
Tehran	3	5	3	TYPE3	WINT1	3	0.3	0.03	−1.85
Algiers	6	10	4.5	TYPE3	WINT1	3	0.7	0.18	−1.03
Copenhagen	3	10	4.5	TYPE1	WINT1	3	0.7	−2.12	−2.47
Singapore	6	10	4.5	TYPE3	WINT1	3	0.7	0.17	0.73
Melbourne	6	10	4.5	TYPE3	WINT1	3	0.7	−1	−1.66

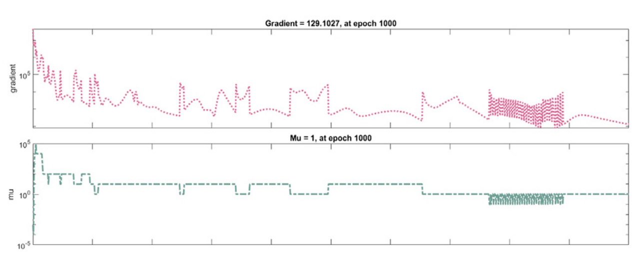

Fig. 16 Convergence state of the model.

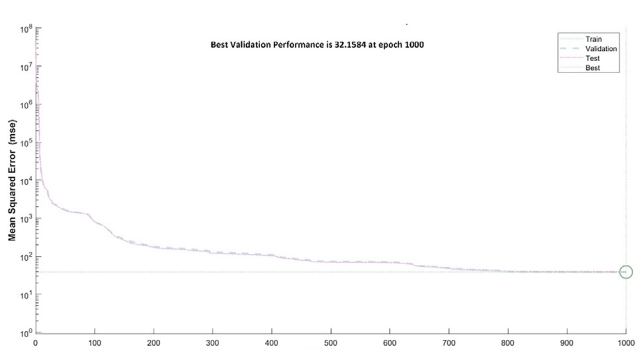

Fig. 17 Best validation performance of the model.

exceeds 25 °C during summer days in which performing the entire cooling/heating system set-points (or dead-bands) ensure summer thermal comfort. This finding enables the designer to choose the wider dead-band in summer to reduce the utility costs while maintaining indoor comfort at an acceptable level. On the other hand, WWR variations could only impact the indoor thermal comfort in climates with similar monthly sky coverage distribution, unlike Tehran and Singapore with extreme conditions.

In terms of the geometrical proportion of courtyard building, designing a square-shaped courtyard could lead to an acceptable summer/winter indoor thermal comfort in extremely hot-humid climates like Singapore and only summer thermal comfort in warm-dry climates like Tehran and Algiers. This finding explains that the compact shape helps to reduce solar absorption through the envelope and contributes to increasing the thermal comfort in climates with high DBT. In contrast, the rectangular-shaped courtyard design performs better in winter thermal comfort of warm-dry locations and in summer thermal comfort of warm-humid climate like Melbourne. Rectangular courtyards with lower heights could meet the winter thermal comfort due to the higher solar gains through the envelope, as opposed to square-shaped courtyards.

Furthermore, the discussed findings provide comprehensive knowledge for designers to, firstly, understand the

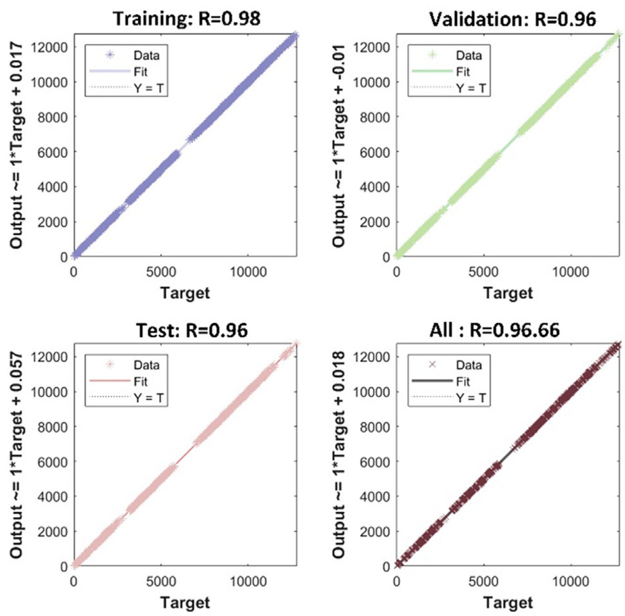

Fig. 18 Regression plots of the training, test, validation, and all average.

role of geometrical, architectural, and mechanical factors on utility costs and thermal comfort of occupants in courtyard households. Secondly, it evaluates the potentials and limitations of the courtyard as microclimate spaces in different climates, Thirdly, the developed DL-MLP model works well on the predictive application of the parametric simulation outcomes and transforms the numerical investigations of the inputs into the highly accurate predictions of energy load, utility cost, and summer and winter average PMVs.

5. Conclusions

This paper conducted a parametric study to investigate the courtyard design variables and their implications on indoor thermal comfort, building energy performance, and utility costs including electricity and fuel consumptions in five locations across the world with four distinguished climate zones. Accordingly, an algorithmic-based physical model was developed in Grasshopper interface together with Ladybug-tools to answer the following research questions out of 3888 design alternatives for each location:

Q1) How and to what extent do different courtyard design variables affect utility costs and total energy demands of an air-conditioned building?

This study evaluated eight different design variables that were found in the literature as potential factors affecting the performance of courtyard buildings. According to the results, climate and dead-band were the two main factors that influence the utility costs and thermal loads of courtyard spaces, where climate indicated an effective role in the relation of WWR, utility costs and total thermal loads. In contrast, there was no correlation between the width and length of the courtyard and utility costs and thermal loads of the building. With respect to material types, using wall and windows with the lowest U-value result the best in all cities. However, choosing appropriate SHGC for windows depends on the outdoor temperature and solar radiation of the courtyard location. Ultimately, the parametric simulations and findings assisted to prioritize the courtyard design variables based on their impact factor on utility costs in the descending order as follows: 1) Dead-band, 2) Wall type, 3) WWR, and 4) Window type.

Q2) What is the relationship between indoor summer/winter thermal comfort and courtyard design parameters?

This research considered a range of -0.5 and 0.5 as the acceptable values for indoor thermal comfort. Based on all design variables, none of the courtyard buildings could deliver the acceptable winter thermal comfort, where in a cool humid climate, none of them could meet both summer and winter thermal comfort. With respect to the thermal performance, dead-band was the main factor that caused the highest variation on indoor temperature and average summer/winter PMV values. Therefore, more investigations are needed in mixed-mode buildings if there is a possibility for occupants to control their indoor environment through shading systems, and window operations. The geometrical proportion was an effective factor in controlling the indoor thermal comfort in a way that square-shaped courtyards resulted in improving both summer and winter seasons of extremely hot-humid locations and only summer season of a warm-dry climate. On other fronts, rectangular-shaped courtyards could perform better in the winter season of warm-dry climates and summer season of warm-humid climates.

Alternatively, this study is applicable only for specific cases due to several existing limitations. First, the findings are based on five selected climatic conditions; thus the results are not generalizable and should be interpreted with caution. Second, the observations due to energy loads and utility costs are limited to an imaginary mechanical system that is considered to be fully-efficient for heating and cooling. Third, the effect of the courtyard design on reducing the lighting energy consumption is not considered in this research. Fourth, the implications of occupancy behavior on controlling the building services (e.g., windows) are not considered.

Following these limitations, the effects of irregular courtyards' geometries on thermal comfort and energy loads of courtyard building are still unknown. In the same vein, other passive courtyard design variables such as vegetation and plants, and shading systems (e.g., blinds) are excluded from this research due to computational limitation and can be explored in future studies to assess their impact on the microclimate of courtyard space. Moreover, the interaction of different occupant-related parameters and behaviour with courtyard houses can be further studied.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foar.2022.02.006.

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