A REVIEW ON THE IMPACT OF BUILDING DESIGN AND OPERATION ON BUILDINGS COOLING LOADS

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ABSTRACT

Energy consumption in buildings is considerably high in areas of hot and humid climates due to its association with high cooling loads. Electricity grids are highly affected by the consumption of cooling systems like air-conditioning and large refrigeration facilities, which significantly impact the economic and environmental sectors. As building design and operating parameters influence the cooling demand in the building, it is believed the root cause of the problem may be detected at an early building design stage. Thus, this review identifies the building design parameters that impact the cooling loads in buildings that are geographically restricted to countries with hot and humid climates. The building's design characteristics are classified into four main categories: glass characteristics, wall characteristics, building orientation and dimensions (BO & D), and building cooling system. The review was conducted over high-rise and low-rise buildings. Annual energy requirements (in some cases overlapping with electricity consumption), annual cooling loads, and peak cooling loads are the three forms in which energy demand reductions in buildings are represented. It is found that maximum annual cooling load savings are obtained through cooling systems, followed by wall characteristics, then glass characteristics, with the least for BO & D, with maximum reductions of up to 61%, 59%, 55%, and 21%, respectively. As for the peak cooling load reductions, wall characteristics, cooling systems, and glass characteristics had almost the same average values of 18.7%, 15.2%, and 17.2%, respectively, while BO & D are not reported due to the incomparable number of case studies. The parameters that have the most influence on reductions in peak cooling loads are wall and glass characteristics. In general, savings that are associated with wall characteristics are more significant for low-rise buildings than for high-rise buildings, while the latter is more influenced by glass characteristics. This is a reasonable conclusion since high-rise buildings, in general, acquire higher window-to-wall ratios than the former. In general, most studies considered glass characteristics, while fewer studies considered BO & D. This review has shown various aspects that are vital in studying building cooling load demand and its related energy performance.

Keywords: annual cooling loads, building, building cooling, building energy design, energy, cooling load, hot climates, humid climate, peak cooling loads.

1 INTRODUCTION

In hot countries, cooling demand reaches up to 85% of overall building electricity consumption [1]. The climatological conditions are vital in determining the cooling energy requirements [2]. In general, cooling energy requirements are expected to increase in hot regions, which in turn will increase the worldwide energy demand. Likewise, countries with humid climates experience high rates of cooling energy demand; for instance, Hong Kong, China, has an estimated energy consumption on cooling of 60% [3], while it is almost 48% in Malaysia [4]. One of the main factors in the high electricity consumption in hot areas is urbanization [5], which is correlated to the high ambient temperature [6]. From an environmental point of view, the challenge of cooling buildings in such countries is providing an efficient cooling system to keep CO_2 production as low as possible during a life cycle, especially in countries of interest. Saadatian *et al.* [7] identify mechanical cooling as a leading source of CO_2 emissions as well as hot climates. Qatar is the top country in the world for annual per capita CO_2 emissions [8]. One possible reason is excessive economic growth and fast urban development [9]. While the

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country is currently developing and adopting green building codes to address the environmental concerns [10] related to CO_2 emissions from buildings, more analysis is required to understand the factors that influence the cooling demand of buildings, which is considered to be the primary reason for high energy consumption. Much attention is directed towards the modern urbanization aspect, which may lead to urban heat islands (UHI), one of the severe climatological factors that cause excessive cooling requirements. Energy consumption in buildings accounts for 40% of the total world energy use, with high-rise buildings contributing significantly to this percentage [11]. According to the literature, high-rise buildings require more energy for cooling than low-rise buildings on equivalent foundations. Based on equal occupancy rates, Radhi [12] concluded that the cooling requirements represent 45% and 67% of the total energy consumption for low-rise and high-rise buildings, respectively.

Although there are some review articles that holistically address the factors that impact cooling demands, such as [13] and [14], they lack specific aspects. Chen *et al.* [13] presented a review article about the internal and external influencing factors. They reported ranges of energy savings for various factors, but the reported percentages were in the form of energy savings. However, reporting energy savings in terms of cooling demand and loads may be more significant and provide a more accurate picture of the true contribution of cooling demand to overall energy consumption. Also, Anaya *et al.* [14] concluded that building envelope parameters are one of the most influencing factors on cooling loads, but they did not address the specific envelope parameters within cooling loads since the building envelope involves a considerable number of parameters that vary in their influence, such as glass characteristics, wall insulation, etc. Furthermore, their review is limited to high-rise buildings, in which a building exceeds 23 m only with no consideration of low-rise buildings. Therefore, there is still a need to cover specific aspects related to building design parameters and their association to cooling loads.

Identifying the impact of specific building design parameters and operating systems represents the starting point towards finding strategies to specifically reduce the annual and peak cooling consumption, and therefore the overall energy demand. Therefore, this review focuses on the energy consumption of buildings. While in the literature, many studies are assessed for cooling and energy requirements, not all are necessarily relevant due to the variation in the climatological conditions of where the building is located. Thus, in this review, the method followed is to consider the cooling requirements of buildings that are geographically restricted to hot and humid climates. To determine the areas of hot and humid climates around the world, the Köppen-Geiger climate classification is used [15]. A world map screening is conducted over the different climates according to universal standards, identifying seven climates and their Köppen-Geiger world map classification codes: Arid/Desert Hot climate (BWh), Tropical Rainforest climate (Af), Tropical Monsoon climate (Am), Mediterranean Hot Summer climate (Csa), Humid Subtropical climate (Cfa), Dry-Winter Humid Subtropical climate (Cwa), and Hot-Summer Continental climate (Dwa).

Thus, this review is subjected to identifying and quantifying the impact of specific design parameters. Figure 1 shows the parameters that are considered in this literature review, namely glass characteristics, wall characteristics, building orientation and dimensions (BO & D), and cooling systems, on cooling loads in hot and humid climates.

2 CASE STUDIES

Table 1 summarizes the design parameters that have a quantified value of cooling and energy demand.

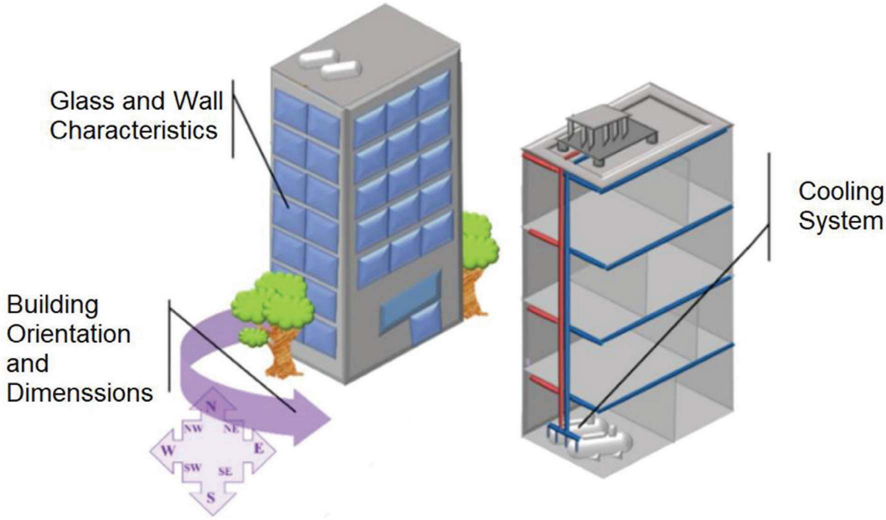

Figure 1: Illustration of some examples of building design parameters used in this review.

2.1 Glass characteristics

The glass characteristics such as Solar Heat Gain Coefficient (SHGC), window-to-wall ratio (WWR), U-value, and the spacing manner have a great impact on the cooling load because of the high and direct solar gains [48, 49]. Assem and Al-Mumin [18] showed that highly glazed buildings can achieve a reduction in energy requirements when SHGC values are below 0.4. Mirrahimi *et al.* [50] showed cooling load reductions of 19% and a peak cooling reduction of 30% can be achieved with double low-E glass, while they are 9.5% and 10% with single tinted glass, respectively. Reducing this value also reduces the savings related to lighting energy. Tibia and Mokhtar [51] showed that the double glazing in glass used in buildings is better than single glazing. Cheung *et al.* [23] identified several glazing types that can save cooling loads of up to 4.6% and 4.9% of annual and peak, respectively. By studying several glazing types under solar absorbance and building orientation effects, up to 10% and 11% can be reduced from their annual and peak cooling loads, respectively. The glass shading coefficient parameter is directly proportional to cooling loads [25]. Chan and Chow [22] studied three glass types: clear, absorptive, and reflective. They found that clear glass shows the best performance in reducing annual cooling load by up to 12%, while reflective glass is up to 8% when the balcony is southwest facing. Solar absorptance is another glass characteristic that has been addressed in several studies. Cheung *et al.* [23] used a wide range of solar absorbance, i.e. from 0.2 to 0.8. They found that as solar absorptance increases, the cooling loads decrease in a linear manner. Reductions start only at a value of 0.5. Katanbafnasab and Aby-Hijleh [39] could save more than 33.5% of their annual energy requirements by employing Electrochromic Glazing. Buratti *et al.* [45] used various U-factors with glass types and could achieve energy savings in the range of 15.2–19.9%. They employed temperable double and single-low-E and super windows.

One of the most influential building envelope parameters is the WWR, which is widely addressed in literature. Sozer *et al.* [30] found that reducing WWR results in reductions in cooling loads of 38% and also showed the effect of facade orientation on the cooling load. For the

Table 1a: Summary of the quantified effects of the building design parameters on cooling energy requirements.

	Location	Koppen Climate Classification	Influential Factor	Factor Main Category	Result
Afshari *et al.* [16]	Abu Dhabi, UAE	BWh	Chiller COP (from 2.8 to 4)	Cooling system	The cooling peak load reduction is 27%; the annual cooling load reduction is 23%.
			Air changes per hour (ACH) (from 0.3 to 0.1)	Cooling system	The cooling peak load reduction is 9%; the annual cooling load reduction is 5.6%.
			Glazing type (from U-value 2.4 and Solar Heat Gain Coefficient (SHGC) 3.6 to (a) U-value 1.47, SHGC 0.3 (b) U-value 1.7, SHGC 0.3)	Glass characteristics	The cooling peak load reduction is 3.6%; the annual cooling energy reduction is 3.5%.
			Wall insulation (from no insulation to U-value 0.705, 0.444, 0.324)	Wall characteristics	The cooling peak load reduction is 2.8%; the annual cooling energy reduction is 2.6%.
			Roof albedo (from 0.4 to 0.7)	BO & D	Only a minor impact.
Al-Tamimi and Fadzil [17]	Penang, Malaysia	Af	The thickness of extruded polystyrene (EPS) of a thermal insulated wall (25, 50, 75, 100 mm, baseline: 0 mm)	Wall characteristics	The reduction in the annual cooling load is 8.43%, 9.56%, 9.96%, and 10.20%; The reduction in peak cooling is 20.17%, 24.38%, 25.90%, and 26.31%.
			Window to floor area ratio (WFR) (from 10% to 80%, baseline is 30%)	BO & D	1.3% and 27.4% increase in annual cooling load and peak cooling with every 10% increase in WFR.

			External shading	Wall characteristics	The impact is limited, especially for the annual cooling load.
			Employment of double low-E glass instead of the base case type.	Glass characteristics	5.8% and 36% reductions in the annual cooling load and the peak cooling loads, respectively.
Assem and Al-Mumin [18]	Kuwait, Kuwait	BWh	Glazing type (from clear double-pane glazing to clear low-E, tint low-E, and reflective low-E)	Glass characteristics	The reduction in the cooling peak load is 6.8%, 15.5%, and 27.5%.
			Heat recovery	Cooling system	The reduction in peak cooling power demand is 19%.
			COP	Cooling system	The reduction in peak cooling power demand is 15%.
			Overhangs	Wall characteristics	The reduction in peak cooling power demand is 9%.
			Lighting control	Cooling system	The reduction in peak cooling power demand is 8%.
Bojic *et al.* [19–21]	Hong Kong, China	Dwa	Thermal insulation position (inside, middle, and outside)	Wall characteristics	For annual cooling load, performance is case by case: sometimes can reduce cooling load while sometimes can increase it.
			Glazing type (shading coefficient, SC)	Glass characteristics	The reduction of annual cooling load and peak load steadily increases with the decrease of the shading coefficient. Max reduction is around 10% and 11% when SC is 0.25, and the orientation is west.
			Orientation	BO & D	The worst orientation is southwest. The max annual cooling load reduction is 6.7% when orientation changes from southwest to south.

(*Continued*)

Table 1a: Summary of the quantified effects of the building design parameters on cooling energy requirements. (*Cont.*)

	Location	Koppen Climate Classification	Influential Factor	Factor Main Category	Result
Chan & Chow [22]	Hong Kong, China	Dwa	With/without balcony	BO & D	By adding a balcony, the maximum reduction of annual cooling consumption is 12.3% (southwest facing) and the minimum is 3.4% (north-facing).
			Glazing type (clear, absorptive, and reflective glass)	Glass characteristics	For the southwest-facing balcony, clear glass performs best with a 12.3% reduction of annual cooling energy, while the reflective glass is 8%. For the north-facing balcony, the reduction of three glasses is between 2%~4%.
Cheung *et al.* [23]	Hong Kong, China	Dwa	The thickness of extruded EPS of the thermal insulated wall (25, 50, 75, 100 mm, baseline: 0 mm)	Wall characteristics	The maximum reduction is 19.4% in annual cooling energy and 29.2% in peak cooling load, respectively.
			Solar absorptance (from 0.2 to 0.8)	Glass characteristics	The maximum reduction is 12.3% in annual cooling energy and 16.7% in peak cooling load, respectively.
			Window to floor ratio (from 10% to 40%)	BO & D	The maximum reduction is 12.8% in annual cooling energy and 10.4% in peak cooling load, respectively when WFR is 40%.
			Glazing system	Glass characteristics	The maximum reduction is 4.6% in annual cooling energy and 5.4% in peak cooling load, respectively.

			Shading (wing wall)	BO & D	The maximum reduction is 4.6% in annual cooling energy and 4.9% in peak cooling load, respectively when the length is 1500 mm.
			Shading (overhang)	BO & D	The maximum reduction is 2.9% in annual cooling energy and 3.2% in peak cooling load, respectively, when the length is 1500 mm.
Du and Pan [24]	Hong Kong, China	Dwa	Orientation	BO & D	The difference in the cooling load caused by the orientation was around 10%.
			Building height	BO & D	The difference in cooling load caused by the building height was around 21%; the cooling load decreased with the increasing floor number with natural ventilation.
Hassan and Al-Ashwal [25]	Kuala Lumpur, Malaysia	Af	The thickness of extruded EPS of a thermal insulated wall (25, 50, 75, 100 mm, baseline: 0 mm)	Wall characteristics	The higher the insulation thickness, the greater the reduction in annual cooling energy consumption; when thermal insulation thicker than 50 mm is used slight reduction in cooling energy is achieved. A reduction in peak cooling is 22% at 25 mm and 29% at 100 mm.
			Glazing type (from single clear glass to single tinted glass, double glass, double clear low-E)	Glass characteristics	The lower the shading coefficient value, the lower the cooling energy consumption and peak load: reduction of cooling energy (7%~9.5%: single tinted glass, 10%~13.5% double glass, 19%: double low-E); reduction of peak load (10%: single tinted glass, 23%: double glass, 30%: double low-E)

(*Continued*)

Table 1a: Summary of the quantified effects of the building design parameters on cooling energy requirements. (*Cont.*)

	Location	**Koppen Climate Classification**	**Influential Factor**	**Factor Main Category**	**Result**
Lau *et al.* [26]	Kuala Lumpur, Malaysia	Af	Shading and façade orientation	BO & D	Egg-crate as the best shading type for optimum cooling energy saving (2.6% ~ 3.4%) and is followed by vertical shading and horizontal shading. Shading devices are recommended on the east and west facades. The estimated annual cooling energy saving increases between 5.0% ~ 9.9% when the shading devices are applied to all orientations.
			Glazing type	Glass characteristics	When low-E double glazed facades are replaced by singe single clear glazing, annual cooling energy savings increase from 5.0% ~ 9.9% to 5.6% ~ 10.4%.
Lima *et al.* [27]	Brazil	Aw	UHI-High-rise buildings	BO & D	The reduction of annual cooling load is 16% ~ 18%.
Raji *et al.* [28]	Singapore	Af	Floor plan	BO & D	The increase in annual total energy is varied from 0.4% to 11.0%.
			Plan aspect ratio (from 1:1 to 10:1)	BO & D	Total energy use can be varied from 117.2 to 127.5 kWh/m^2 yr.
			Orientation	BO & D	The increase in annual total energy is 8%.
Shaikh and Chaudhry [29]	UAE	BWh	Variable speed drive fan	Cooling system	Overall energy consumption is reduced by 8% reduction in the cooling loads by 20%

Sozer *et al.* [30]	Qatar	BWh	Reduced glass area with caving and backyards and the application of cables for shading	BO & D	The reduction in the total cooling load is 55%, and the cooling energy is 57%.
			Spacing (from 10D to 1D)	Glass characteristics	The cooling energy reductions are of 50 ~ 60%.
			Reduced glass area with caving and backyards	BO & D	The reduction in the total cooling load is 38%, and the cooling energy is 39%.
			Reduced glass area with caving	BO & D	The reduction in the total cooling load is 35% and on the cooling energy is 36%
			--		The closer the spacing of the cables, the more significant the reduction in cooling load
			--		The reduction in cooling energy is similar to the decrease in the cooling load.
Sun *et al.* [31]	Hong Kong, China	Dwa	Chiller control strategy	Cooling system	A max reduction of weekly chiller energy consumption is 6.6%; A max increase of daily peak load is 21%.
Tibi and Mokhtar [32]	UAE		Glass SHGC	Glass characteristics	The annual cooling load reduction is 9.7%.
			Glass U-value	Glass characteristics	The annual cooling load reduction is 5.6%.
Weerasuriya *et al.* [33]	Hong Kong, China	Dwa	Natural ventilation	BO & D	The building can save up to 25% and 45% of the electricity consumption if it employs wind-driven and buoyancy-driven natural ventilation instead of mechanical ventilation.

(*Continued*)

Table 1a: Summary of the quantified effects of the building design parameters on cooling energy requirements. (*Cont.*)

	Location	**Koppen Climate Classification**	**Influential Factor**	**Factor Main Category**	**Result**
Mohamed [34]	Cairo, Alexandria, Aswan, and Assut, Egypt	BWh	Thermal insulation thickness in the outer walls and ceilings, and double-layer glazing windows	Glass/wall characteristics	Annual cooling loads reduction 33.5% Peak cooling loads reduction 35.5%
Mushtaha *et al.* [35]	Gaza, Palestine	BSh	Employing shading devices, natural ventilation, and thermal insulation	Wall characteristics	59% reduction of total energy consumption
Taleb [36]	Dubai, UAE	BWh	Passive designed building	BO & D	23.6% reductions in annual energy consumptions
Muhaisen [37]	Gaza, Palestine	BSh	U-value of walls	Wall characteristics	22% reductions in energy consumption (heating and cooling)
Al-Tamimi [38]	Kingdom of Saudi Arabia	BWh	Extruded EPS material insulation thicknesses: 8, 4, and 6 cm on the roof only, the walls only and the roof and wall	Wall characteristics	19.14%, 7.51%, and 29.77% on annual energy consumption, respectively.
Katanbafnasab and Abu-Hijleh [39]	Abu Dhabi, UAE	BWh	Employing Building Integrated Photovoltaic (BIPV) and Electrochromic Glazing	Glass characteristics	Total annual energy saving potential for most orientations, up to 33.5%
Radhi [12]	Bahrain	BWh	Building altitude (high-rise versus low-rise buildings)	Natural ventilation	45% and 66.9% for cooling loads of the total electricity consumption, respectively

Jose Sanchez de la Flor *et al.* [40]	Seville, Spain	Csa	A new methodology allowing the use of different experimental data for facades and courtyards	BO & D	More than 10% reductions in cooling energy requirements
Zhu and Jiang [41]	Beijing, China	Dwa	A single-loop chilled water system with variable-speed chilled water pumps	Cooling system	50% reductions in energy requirements of chilled-water pumps.
Vakiloroaya *et al.* [42]	A hot and dry region	A hot and dry region	A new hybrid evaporative cooling system for improving HVAC efficiency	Cooling system	Above 52% savings in power.
Khandelwal *et al.* [43]	Delhi, India	Cfa	Coupling of water chiller system with direct and regenerative evaporative cooling technologies	Cooling system	12.09% and 15.69% savings in annual energy consumption, respectively
Rahman *et al.* [44]	Queensland, Australia	Cfa	Thermal energy storage (TES) systems in a building	Cooling system	61.19% and 50.26% savings for full and partial chilled storage systems, respectively
Buratti *et al.* [45]	South Korea and in Jeju Island	Cfa	U-factors of 1.98 $W/m^2.K$ for temperable double low-E, 1.44 $W/m^2.K$ for super-window, 1.30 $W/m^2.K$ for double-skin window, 1.19 $W/m^2.K$ for temperable double low-E, and 0.86 $W/m^2.K$ for temperable single low-E	Glass characteristics	Energy savings of 19.9%, 17.1%, and 15.2%, respectively
Vakiloroaya *et al.* [46]	Hot and dry climate	Hot and dry climate	Air-cooled direct expansion (DX) refrigeration systems	Cooling system	9% saving of the average power consumption
Daouas, N. [47]	Tunisia	Csa	Insulation thickness of 10.1 cm	Wall characteristics	71.33% of energy savings (heating and cooling requirements)

latter, they found that window cable spacing increased the cooling loads by up to 3.5 times when changed between the south and the north orientations, while there was a negligible difference between the east and the west orientations. The reductions that are associated with WWR value are reasonable, but no firm conclusion can be drawn without addressing the glazing type. One useful study which addressed this aspect was carried out by Afshari *et al.* [16], who varied the glazing type with two double-pane at the same SHGC values, which showed a small difference of 4.2% and 3.6% for peak and annual cooling loads, respectively. A comparison of these results with the conclusion of Tibia and Mokhtar [51] show that SHGC and U-values are inversely proportional to cooling load reductions. In line with this, a similar conclusion is confirmed by Samuelson *et al.* [52]. Tibia and Mokhtar [51] showed that SHGC has a greater influence on annual load reductions when compared to U-value. They found that WWR has the most influencing factor and that it is directly proportional to the cooling load of all glass types. On the other hand, Yu *et al.* [53] found that the heat-transfer coefficient is the most sensitive parameter at WWR of 25% and 50%, while wall, roof solar absorptance, and roof heat transfer coefficient have a negligible effect and do not depend on WWR. Sozer *et al.* [30] showed that decreasing the value of WWR results in a 38% cooling load saving. Also, they showed that the savings can be further enhanced to 57% if reducing the WWR is applied in tandem with shading by cables.

2.2 Wall characteristics

One building envelope parameter is wall insulation, which is reported in several studies. The building envelope can be defined as the layer that physically separates the indoor and outdoor environments [54], such as exterior walls, roof/floor, transparent elements, interior partitions, internal mass, etc. [55]. Most building envelope parameters have a direct impact on cooling loads. This is because of their direct exposure to solar radiation [56]. It has a direct effect on building temperature as the insulation layer can be used to control the building heat transfer via the building envelope [57], such as façade coloring, which leads to a reduction of solar absorption and hence lower consumption of cooling energy systems [58]. The influence of EPS on cooling loads is addressed by Hassan and Al-Ashwal [25]. They found that as the thickness of the wall insulation increases, the annual cooling reduction drops to 18%. A reduction in the peak cooling load of 22% is achieved at 25 mm, which can be further enhanced to 29% when the thickness increases to 100 mm. Cheung *et al.* [23] tested EPS with various thicknesses (0–100 mm) and found reductions in cooling loads of 19.4% and 29.2% for annual and peak, respectively, when 100 mm of insulation is applied. Bojic *et al.* [19–21] presented annual and peak cooling load reductions of 38% and 16%, respectively. Mohamed [34] employed thermal insulation to the outer layer of the building's walls and ceilings while considering double-layer glazing windows, which saved 33.5% and 35.5% of the annual and peak cooling loads, respectively. Mushtaha *et al.* [35] combined thermal insulation of walls with shading devices along with natural ventilation to find that 59% of energy requirements can be saved. Muhaisen [37] could save 22% of the cooling requirements by applying a U-value of 1.8 W/m^2K to the walls. Daouas [47] showed that 71% of energy requirements can be saved by applying a 10 cm thickness of insulation. However, this percentage includes savings for heating as well as cooling.

Several studies examined the impact of extruded polystyrene (EPS) in thermally insulated walls on cooling loads. Al-Tamimi [59] and Al-Tamimi and Fadzil [17] showed that more than 10% and 26% of annual and peak cooling loads can be saved, respectively. Their results

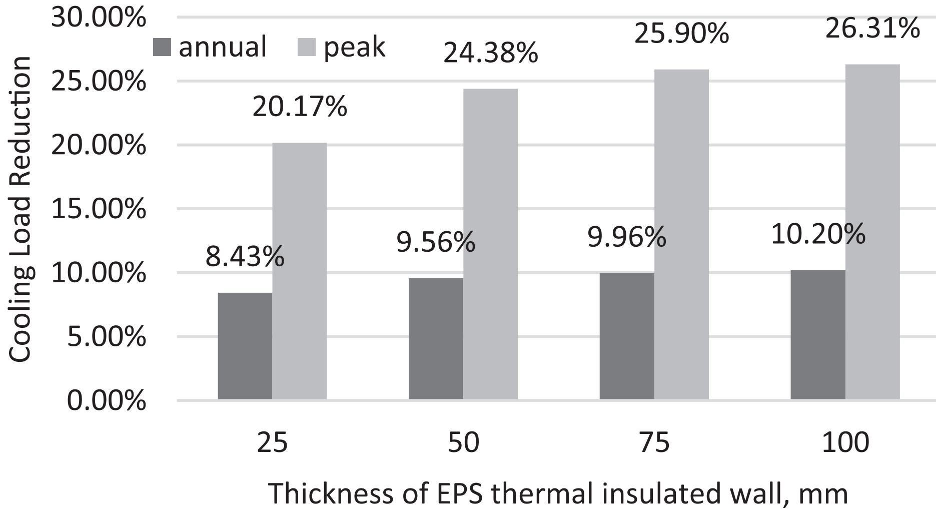

Figure 2: The effect of increasing the thickness of EPS of thermal insulated wall on cooling loads [17, 59].

are summarized in Fig. 2. Also, Al-Tamimi [38] found that more than 19%, 7%, and 29% of annual energy consumption can be saved by applying EPS insulation with thicknesses of 8, 4, and 6 cm on the roof only, the walls only, and the roof and wall, respectively.

2.3 Building orientation and dimensions

Building orientation and dimensions involve many design parameters that have a considerable influence on cooling loads, such as building shading at a given orientation, building altitude, window to floor area, passive building design, presence of courtyards and balconies in the building, etc.

Savings in cooling loads may be earned by re-orienting the building only. Du and Pan [24] found a difference of 10% in cooling loads when changing the orientation of the apartment. Bojic *et al.* [19–21] showed that 6.7% can be saved by reorienting an apartment. Various design parameters can be considered when considering building orientation. Cooling loads can be reduced. For instance, Tibi and Mokhtar [32] indicated that orientation is a significant parameter for determining the building glass type. Furthermore, shading and orientation are two dependent parameters that affect the cooling loads of buildings, as they help in controlling the amount of solar irradiation received by the buildings. There are several ways to apply shading. Faisal and Aldy [60] have demonstrated that several techniques and orientations of shadings can be applied. Examples of these techniques are the wing wall and the overhang of windows. Cheung *et al.* [23] showed that by applying the wing wall shading, reductions of 4.6% and 4.9% are attained for the annual and peak cooling loads, respectively, while the overhang reduces them by 2.9% and 3.2%. Friess *et al.* [61] showed that a peak reduction of up to 9% can be attained with overhangs of 1-m depth. Lau *et al.* [26] found that the egg-crate shading type saves 3.4% of cooling loads. Also, they found that 10% savings are achieved when shading is applied at all orientations, with special attention to the west and east façades of a building. The west and east orientations were highlighted by Naamandadin *et al.* [62], who found they receive the highest sun intensity, which results in high cooling energy consumption. However, Daouas [47] does not recommend the west- and east-facing walls in the cooling season for a case study in Tunisia. One reason for this contradiction is the difference in climate, as the former two articles' case studies were conducted in Kuala Lumpur, Malaysia, which has an Af climate, while the latter was in Tunisia, which has a Csa climate. In particular, Aflaki *et al.* [63] found that indoor temperature and relative humidity were impacted by orientation and height. Overall, although building orientation is widely addressed, it shows a small impact on cooling loads [17, 59]. None of the reviewed articles that consider building orientation showed savings above 10% for all climates.

Building altitude is addressed in several studies that reported cooling and energy requirements. Also, some have considered the building geometry of high-rise buildings [64]. Radhi [12] conducted a comparison between two buildings (high and low rise) and showed that a high-rise building requires 66.9% of the total electricity consumption for cooling, while a low-rise building with same occupancy rate requires 45%, that is, a difference of 21.9%. In a study of Bruelisauer *et al.* [65], the effect of some parameters by building altitude is addressed. They indicated that the stack effect results in an increase in the temperature by 13°C with increasing building altitude. Furthermore, the cooling loads were affected by building orientation differently for the case of floors located higher than others. Weerasuriya *et al.* [33] found that the apartments that are located near the windward side of higher floors have higher energy saving up to 23% relative to the apartments in the middle and lower floors. This conclusion is also confirmed by Du and Pan [24], who considered a number of flats at floors 3 and 39, finding that at higher floors, cooling loads reduce by up to 12% due to climatic factors, i.e. wind speed. Also, Du and Pan [24] found that electricity bills of apartments on 20th floor and higher are up to 26% lower than those of lower floors due to the different usage of air-conditioning and natural ventilation, i.e. opening windows.

UHI are discussed in literature as a factor that affects the demand for cooling energy. It is a phenomenon that occurs when a combination of high-rise buildings is constructed nearby, affecting the local environmental conditions that are known as the microclimate and leading to an increase in temperature. Accordingly, it is addressed as a building altitude parameter as it is initially caused by high-rise buildings. Palme *et al.* [66] addressed the UHI to study the humidity and sensitivity to solar gains. They found that humidity levels get lower and solar radiation gains are found to be sensitive to building orientation; hence, higher temperatures are captured by the building. A key observation is that high-rise buildings acquire more than twice the amount of cooling demand, showing that the effect of the building height is dominant over the urban area, i.e. rural areas, different urban layouts, etc. Also, this shows that high-rise buildings are significant energy consumers for cooling requirements. They found that up to 18% in cooling energy reduction is obtained due to the shading that is induced by the surrounding buildings. On the other hand, Radhi and Sharples [67] found an increase in the consumption of air-conditioning electricity of up to 10% due to the UHI effect. They found an increase of up to 17% in Cooling Degree Days in comparison to rural areas. Furthermore, Radhi *et al.* [68] reported up to a 5°C increase in ambient temperature due to the UHI effect. Yang *et al.* [69] showed that UHI has a different impact as the tree cover factor affects the night and daytime cooling for a high-rise building through evaporative cooling at night. Giridharan *et al.* [3] showed that a reduction in UHI intensity during the daytime can be achieved by increasing tree cover.

Building dimension parameters include plan shape and depth, WFR, relative compactness (RC), etc. WFR is a building design parameter that specifies the WWR relative to floor area.

Cheung *et al.* [23] found that when WFR increases from 10% to 40%, 12.8%, and 10.4% reductions in annual and peak cooling loads are attained, respectively. Plan shape and plan depth are other shape-related parameters. Raji *et al.* [28] showed that when switching from the ellipse plan shape to the Y plan shape, the total energy consumption increases by 15.7% and 12.8% in humid subtropical and humid tropic climates, respectively. The effect of building morphology on cooling loads is addressed by Krem *et al.* [70]. They found that the position of the vertical structural core/wall, the aspect ratio, and the floor plan have significant impacts. AlAnzi *et al.* [71] found that the building's RC is inversely proportional to the cooling load at various building shapes when WWR is assumed to be zero (no windows) and at 50%. When RC decreases from 0.99 to 0.17, cooling energy increases by 115%. This can be justified by the building's exterior wall area and solar exposure since it is described by the reciprocal RC. The effect of the different building shapes on the cooling load depends on RC, WWR, and solar heat gain coefficient (SHGC). Ourghi *et al.* [72] found that increasing RC, WWR, and SHGC decreases the cooling loads. Furthermore, Friess *et al.* [61] concluded that square compact buildings perform better in terms of cooling energy performance than elongated ones.

Passive cooling, balconies, and courtyards are considered parameters of building design and layout in this review. According to Chan and Chow [22], incorporating a balcony with a southwest orientation can reduce annual cooling loads by 12%, but only 3.4% when it is located in the north. The use of balcony and opening windows in a high-rise residential building as presented by Weerasuriya *et al.* [33] reveals that up to 27% energy savings can be achieved when wind-driven natural ventilation is used. The authors also reported higher savings that can reach 45% if the wind and buoyancy-driven natural ventilation are facilitated. The buoyancy-driven ventilation that is also known as the stack-effect is addressed by Moffitt Natural Ventilation Solutions to promote air flow and enhance the cooling profile by natural ventilation [73]. Jose Sanchez de la Flor *et al.* [40] experimented with various values for facades and courtyards and found that up to 10% of energy requirements can be saved. Lopez-Cabeza *et al.* [74] have found that courtyards can be key elements in the passive conditioning of buildings in hot climates. Taleb [36] showed savings of 23.6% by employing passive design in the building. The courtyard energy savings per unit of wall area are constant regardless of adjacent space floor area [40].

2.4 Cooling system

The cooling system of a building is a part of its HVAC system. Examples of various cooling systems are passive cooling (sea breeze) supported by a heat absorption element [75], radiant cooling and underfloor air supply based on absorption chillers and electric chillers, air–soil heat exchanger, and concrete core activation based on a solar absorption chiller [76]. Actually, the HVAC system is the most significant energy consumer in the building [12]. Considerable cooling requirements savings are expected by optimizing/improving HVAC systems since these systems account for 40%–60% of the total buildings' energy use [77]. Indeed, the capacity to reduce costs by modifying HVAC systems has a significant impact on a building's ability to maintain its environmental sustainability [78]. Some examples of the cooling system include chillers either connected over a district and supplied to various buildings through pipeline networks, as in the case of a district cooling system [79], or chillers employed within the building itself. Afshari *et al.* [16] found that chillers, pumps, and fans are responsible for this high consumption, which makes the cooling system a subject for improvements. Deng *et al.* [80] discovered, for example, that systematic optimization of operational and control parameters can save 35% and 29% of energy, respectively. Chen and Yang [81] and Deng *et al.* [80] suggested optimization methods for high-rise building systems to minimize energy consumption.

In literature, strategies and techniques for reducing energy use by upgrading cooling systems are reported. Sun *et al.* [31] found that 6.6% can be saved by altering some operational strategies, which represents a 21% peak cooling load difference. Attia *et al.* [82] found that the coupling of the ceiling fans with the air-conditioning yearly schedule calibration strategy is the most significant. Heat recovery of HVAC systems during hot seasons, according to Assem and Al-Mumin [18], can reduce cooling requirements by 15% and 18% for water- and air-cooled systems, respectively. Zhu and Jiang [41] investigated that a single-loop with a variable-speed pump can save up to 50% of the cooling requirements. Vakiloroaya *et al.* [42] could save more than 52% by employing a hybrid evaporative to enhance the cooling efficiency of their HVAC system. Khandelwal *et al.* [43] coupled direct and regenerative cooling technologies in chillers, which led to savings of up to 15.69% of annual energy requirements. Vakiloroaya *et al.* [46] found that a refrigeration system with air-cooled direct expansion can save 9% of power consumption. Rahman *et al.* [44] employed an energy storage system, which saved up to 61% of the building's electricity cost required for cooling. Shaikh and Chaudhry [29] found that by employing the variable speed drive fan, 20% of cooling loads can be saved. Also, a 30% saving can be achieved by using the variable refrigerant flow principle. Although some studies reported modest savings, there are considerable savings that can reach up to 60% of cooling requirements. This variation in savings creates a wide range of opportunities to improve the cooling systems. Furthermore, as reviewed, cost savings can be achieved not only by improving the system mechanics and equipment efficiency but also by altering and improving the operational methods and strategies. The latter can be achieved by optimizing the dynamics of the cooling equipment and refrigeration cycle and by applying optimized control strategies. In addition to this, the material used to run the cooling systems can be subjected to optimization. For example, Anaya *et al.* [83] provided an assessment of the dynamic behavior of dual chillers by optimizing the refrigerants. Thus, the cooling profile of buildings can be holistically improved when research develops multiple aspects to enhance the savings.

3 CONCLUSION

This review aims to provide a holistic view of the building design parameters that influence cooling loads in high-rise and low-rise buildings in humid and hot climates. Climates were selected based on Koppean climate classification as follows: BWh, Cfa, Cwa, Csa, Dwa, Af, and Am climates. The building design parameters that are considered are glass characteristics, wall characteristics, BO & D, and cooling systems. BO & D includes building altitude, shading with respect to building orientation, plan depth and layout, use of balconies, courtyards, and passive cooling design, among others. The reductions in energy requirements were found in three forms in the reviewed articles: peak cooling load, annual cooling load, and annual energy consumption. The latter is considered electricity consumption in some cases. It is found that the highest annual cooling load savings are attained with decreasing order by cooling systems, wall characteristics, glass characteristics, and BO & D. The highest values are reported at 61%, 59%, 55%, and 21%, respectively. Reported annual energy consumption showed the same average values for glass characteristics, BO & D, and cooling system of almost 21%, while wall characteristics showed a higher value of almost 50%. This is a reasonable value since energy demand considers both cooling and heating requirements, and hence insulating the wall will save cooling as well as heating loads, which makes greater savings. The building envelope's parameters (wall and glass) have the greatest influence on reductions in peak cooling loads. Overall, cooling loads were more affected by wall characteristics at low-rise buildings in comparison to high-rise buildings, while the latter were shown to be influenced more by glass characteristics. One disclaimer that should be addressed is that the number of case studies that provide quantification of energy savings is small, and hence the conclusion of this review would be more significant if there were more articles that provided quantified case studies.

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