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Evaluating Passive Housing Strategies in Extreme Climates: A Case Study of Dubai Using PHPP and IESVE Models

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Abstract: The increasing global emphasis on sustainable architecture necessitates precise building energy modeling, especially in regions marked by extreme climates. The focus of this study is to evaluate the potential and practicality of passive housing strategies in climates similar to Dubai. In this study, we employed the Passive House Planning Package (PHPP) to create a meticulous representation of the Dubai environmental conditions, ensuring that detailed architectural elements and HVAC systems were captured to provide the most energy-efficient architecture. To validate the accuracy of the model, consumption data from 2020 was used as a benchmark, reflecting the observed hot water and electricity consumption. Additionally, we developed a linear state-space model using IES Virtual Environment software (IESVE) to capture the dynamic thermal behaviour of the proposed building. We assessed the merits of the Passivhaus model in harsh climates and compared them with those of various space calculation methodologies. The model showed significant congruence with the actual consumption data and external temperature metrics for 2020. Furthermore, the state-space model, along with its various state variables, inputs, and outputs, aligned well with the real-world observations. The results indicate that the Passivhaus model possesses significant potential to reduce carbon emissions, highlighted by a detected 10% variance in energy consumption during the simulated summer peak. Differences in space calculation methodologies were also determined, emphasising the necessity of context-driven architectural evaluation. This study provides invaluable insights into the energy dynamics of contemporary buildings and emphasises the transformative potential of passive housing in extreme climates.

Keywords: Building energy modeling; PHPP; IESVE software; Passive housing; Passivhaus model; Climatic modeling; Sustainable architecture.

Introduction

Over the past several decades, economic modelling has undergone a significant transformation, evolving from conventional financial assessments to more comprehensive examinations of energy and environmental dynamics (Suganthi and Anand, 2015). This development is rooted in increasing global awareness of sustainability and the need to align economic growth with environmental stewardship (Tsalis et al., 2020; Gatto, 2020). Research by the World Bank has consistently emphasised the importance of incorporating environmental costs into economic planning (Fang et al., 2022), arguing that ignoring these costs can result in inefficiencies and long-term economic pitfalls (Akadiri, 2022). Dubai, a rapidly growing metropolis within the United Arab Emirates (UAE), is an ideal example of this paradigm shift

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(Kalfopoulou, 2023). With its rapid urbanisation, Dubai has become an emblem of modern architectural marvels and infrastructure (Moradi, 2022). However, there is an intricate web of energy challenges to cope with current and future climate challenges in the region (Zhang et al., 2021). According to a report by the International Energy Agency (IEA), regions with arid and extremely hot climates, such as Dubai (Kober et al., 2019), have seen an exponential increase in energy consumption, predominantly for cooling purposes (Eveloy and Dereje, 2019). Owing to their inherent climatic difficulties, such areas present a unique energy challenge (Farag et al., 2023). Residential dwellings, which form a significant portion of a city's landscape, are particularly affected. Heat, which often exceeds 40°C during the peak summer months, necessitates continuous cooling solutions (Kharrufa et al., 2022). Consequently, homes in Dubai and similar regions are burdened with an unparalleled energy demand, often resulting in cooling and air conditioning needs that far exceed the global average (Ansari et al., 2022; Aljoufie and Tiwari, 2023). The consequences of this are numerous. Not only does this heightened demand strain the energy grid, it also translates to increased greenhouse gas emissions, exacerbating the global climate crisis (Dong et al., 2021; Murtagh et al., 2022; Fereidani et al., 2021). Moreover, the economic implications are deep, with substantial investments directed toward energy production and infrastructure to cater to this demand (Saradara et al., 2023; Albreem et al., 2023). Hence, understanding and modelling these dynamics is imperative for immediate economic and infrastructural needs as well as for the long-term sustainability and environmental viability of the region (Wang et al., 2022; Chaudhry, 2022; Assareh et al., 2023).

In recent years, the architectural and construction industries have been pivoting towards more sustainable and energy-efficient building designs (Semenyuk et al., 2018), primarily driven by the increasing urgency of global climate challenges and economic considerations (Cheland Geetanjali, 2018; Iqbal et al., 2021). Among the regions demanding particular attention is the United Arab Emirates (UAE), which is characterised by its unique climatic conditions, where hot summers often lead to soaring indoor temperatures (Nelson, 2022; D'Eramo, 2021). This research aims to explore housing designs that are well-suited and specially optimised for the unique environment of the UAE. The main goal of this research is to assess how to reduce energy use and provide an understanding of how to create homes that balance the energy they use with the energy they produce, achieving a net-zero energy impact (Wu and Harrison, 2021). However, there are several challenges to achieving this objective, especially when considering the costs involved. To address these issues, we chose to use the passive housing concept, which started in Germany in the late 1980s and has become increasingly relevant in this field (Schnieders et al., 2021). Furthermore, research has highlighted the importance of understanding microclimates within a home (Du et al., 2019). For instance, slight temperature variations between rooms can result in differential heat flows (Munaretto et al., 2018; Bhamare et al., 2019). Such differences, although seemingly insignificant, can considerably impact a building's overall heating and cooling requirements (Athienitis et al., 2018). This complexity makes room-by-room thermal assessments not only a rigorous task but also an important one (Han et al., 2021). In addition to thermal dynamics, a Passivhaus design also emphasises optimal ventilation (Klingenberg, 2020). The core concept is to create a living environment that does not compromise air quality while ensuring energy efficiency (Glad and Madelene, 2020). Such designs prioritise fresh air supply, especially to the main living areas, ensuring that residents enjoy a comfortable and healthy indoor environment (Croxford and Fran, 2018).

To advance sustainable architectural practices, it is crucial to consider a wider context. Rapid urban development in both residential and commercial areas has significantly increased carbon dioxide emissions (Sarkodie et al., 2020; Bai et al., 2019). This increase is closely related to the higher energy requirements of modern buildings (Zhou et al., 2018). Although innovative design approaches, such as the Passivhaus concept, hint at a sustainable future, the challenge of implementing these on a large scale remains substantial (Welch et al., 2023). Addressing the escalating energy consumption goes beyond the horizon of architects and builders; it calls for holistic efforts from policymakers, urban planners, and the community (Schröder et al., 2019). The purpose is not only to build energy-efficient buildings but also to develop sustainable urban ecosystems that resonate with the ideals of environmental stewardship and socioeconomic well-being (Costanza, 2020; Hall, 2019; Gadanho, 2022; Reithand Brajković, 2021). In the domain of contemporary architectural and construction research, the focus is increasingly shifting towards a clear understanding of energy dynamics within structures (Biswas and Clark, 2022). Central to this investigation is the employment of both static and dynamic input-output models, a methodology that promises to shed light on the often-complex interplay between energy consumption in modern buildings (Han et al., 2022; Pan et al., 2018). Rooted in the principles of data envelopment analysis (DEA), an analytical tool traditionally used for performance benchmarking (Ashuri et al., 2019), this research seeks to statistically analyze building energy consumption patterns (Mardani et al., 2002). This is supplemented by a subsequent phase in which slack variables, inherent inefficiencies identified during the DEA, are optimised to strengthen the overall energy efficiency of structures during their operational phases (Gerami et al., 2021; Afjal, 2018; Pengcheng, 2021). This study explores static and dynamic models. Static models offer a snapshot analysis based on a one-time computation (Xue et al., 2021). By contrast, dynamic models operate on a feedback loop mechanism, with each computational cycle feeding into and refining the next (Jiang et al., 2023). This distinction and its implications for energy consumption research will be elaborated upon in the subsequent sections of this study. This study aims to investigate energy consumption patterns in contemporary structures by considering both static and dynamic input-output models. Additionally, we examine the influence of slack variables in building efficiency during periods of inactivity, analyse the interplay between technical advancements and overarching structural productivity, and contrast the computational nuances and outcomes of static versus dynamic modelling approaches. The subsequent sections begin with the methodology used to address these objectives, present the findings, and discuss their broader implications in the context of sustainable building design and energy efficiency.

Materials and Methods

Software Utilisation and Modelling Approaches

Passive House Planning Package (PHPP) Energy

This study relied on the use of various software and modelling tools. We used PHPP energy modelling software (Feist, 2015). This software is designed to analyse energy systems, considering both energy inputs and outputs (Magni et al., 2021). It effectively brings together different components, such as input-output dynamics, principles of energy balance, meteorological data, and patterns of user interaction (Dermentzis et al., 2019). Furthermore, our research uses sub-models to predict the outcomes of certain decisions. To achieve this, we primarily used two types of simulation: static and dynamic. In addition to these simulations, it is necessary to easily depict the desired system behaviours (Lim, 1992). PHPP is an Excel-based tool that is widely used for designing and planning energy-efficient buildings. PHPP provides a reliable means of calculating the energy balance of a building, including heating and cooling demands, primary energy demand, and renewable energy gains. The tool incorporates monthly climatic conditions, such as temperature and solar radiation, to ensure accurate energy modelling. PHPP calculates the heating and cooling loads, primary energy demand, and renewable primary energy demand to ensure a comprehensive energy analysis of the building. The tool evaluates various building components such as windows, ventilation systems, and heat pumps, allowing for optimised design choices. PHPP 10 introduces a stress test for summer comfort, assessing the frequency of overheating and the effectiveness of passive cooling strategies based on occupant behaviour. The MONI worksheet in the PHPP enables adjustments of the calculations to reflect the actual boundary conditions, facilitating the comparison of the calculated and actual energy consumption values. The Room Data Tool helps in determining essential input variables for complex projects, providing a systematic approach to energy efficiency planning and allowing intermediate results to be transferred into the PHPP. Overall, the PHPP ensures a comprehensive energy analysis of buildings by calculating the heating and cooling loads, primary energy demand, and renewable primary energy demand, thereby supporting the design of energy-efficient and comfortable living environments.

IES Virtual Environment (IESVE)

Another integral tool in our research was the IESVE (Che-Ani and Raman, 2019; Hamza, 2008). This software is used to examine potential design scenarios, especially those influenced by factors such as the amount of heat entering a space or available natural light. One of our primary objectives was to overlap the results from the PHPP model with those from the IESVE. This comparison was instrumental in exploring the relative advantages and shortcomings of both simulation tools. We also considered the concept of ‘zoning’ in our study. By defining the geometry of the inner zones of our models, we ensured that our predictions regarding thermal behaviour and energy use were both accurate and insightful. The IESVE is a dynamic simulation tool that provides detailed thermal and energy analyses of buildings. It allows for the modelling of complex building geometries and operational conditions, offering a more granular analysis compared with the steady-state approach of the PHPP. IESVE captures hourly variations in thermal behaviour throughout the year, providing a more detailed understanding of a building's energy performance under varying conditions. The software requires precise input regarding the building geometry, material properties, and operational schedules, facilitating an in-depth analysis of the thermal interactions within the building. IESVE also allows for the definition of different zones within a building, enabling specific analysis of thermal performance and energy use in distinct areas. This includes evaluating the performance of the HVAC systems and other building components under various operational scenarios. By combining the PHPP and IESVE, our study leverages the strengths of both tools to provide a comprehensive analysis of passive housing strategies in extreme climates such as Dubai. PHPP's steady-state energy balance approach of the PHPP ensures a robust baseline energy analysis, while the dynamic simulation capabilities of the IESVE capture the complexities of thermal behaviour over time. This integrated approach enhances the accuracy and reliability of our energy model, providing valuable insights into the potential of passive housing in achieving significant energy savings and improved thermal comfort in extreme climates.

Model Templates

The process of creating model templates involves various stages, each of which focuses on different aspects of building design (Figures 1-5). First, within the construction templates, the IES program is instrumental in evaluating the U-value, which is a measure of heat transfer, of building envelopes. The essential parameters for this evaluation, such as material density and thermal conductivity, were extracted from the ApacheSim Building Template Manager (Feist, 2015). This manager aids in constructing templates for various building components such as walls, roofs, and windows. Each template was designed considering the unique attributes and thermal characteristics of the components of the problem at hand. It is vital to ensure that these templates are consistent with the standards and assumptions set forth by the Passivehaus model (Zhao and Carter, 2020). The IES model reflects the specifications of the PHPP for walls, floors, roofs, and window buildups. There are certain differences between the IES and PHPP in terms of the way heat flows through the building fabric. There are 12 months of the year in which the PHPP assumes a stable heat flow, while the IES simulates dynamic heat flow for each hour of the year, with variable temperature profiles throughout each element.

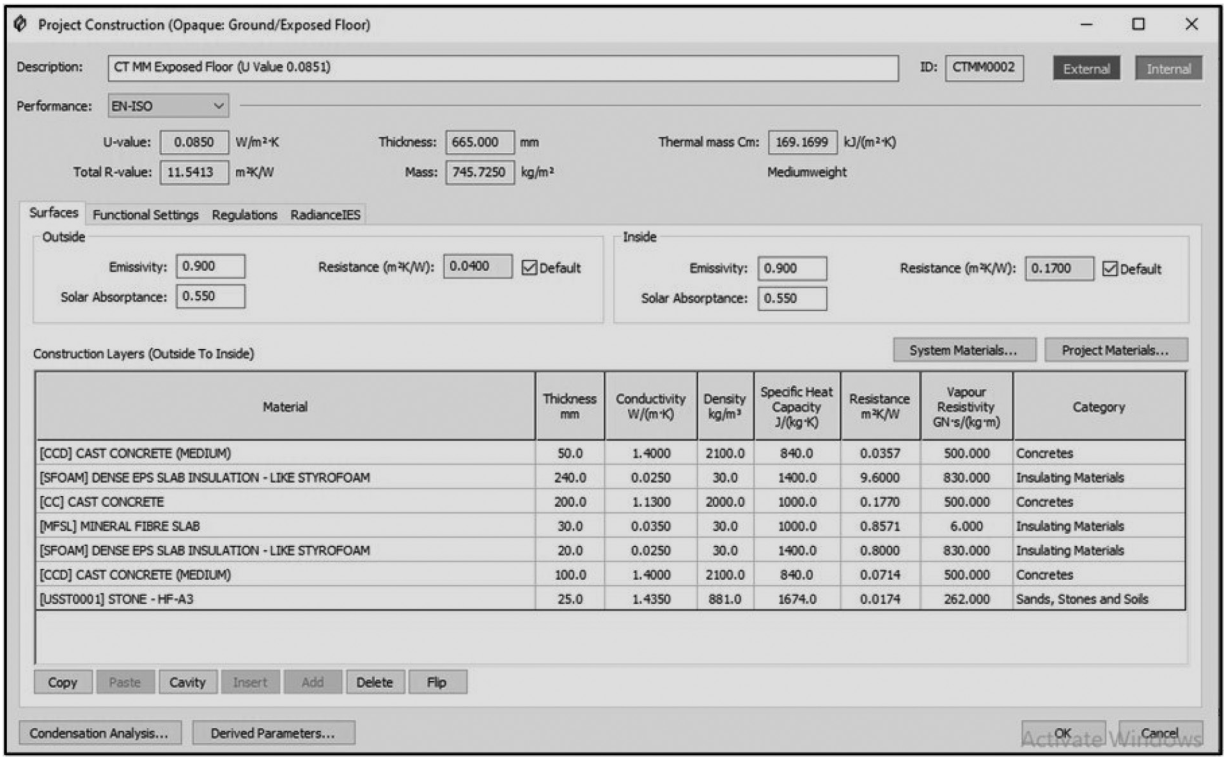

Figure 1: Foundation construction template.

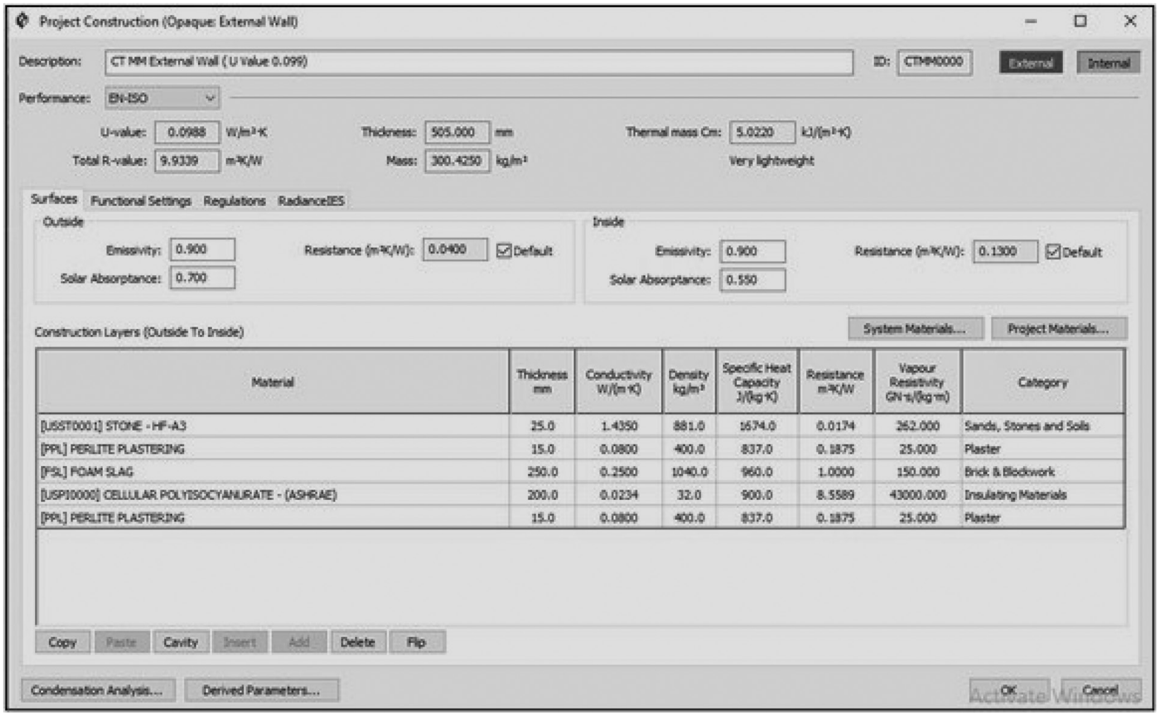

Figure 2: External wall construction template.

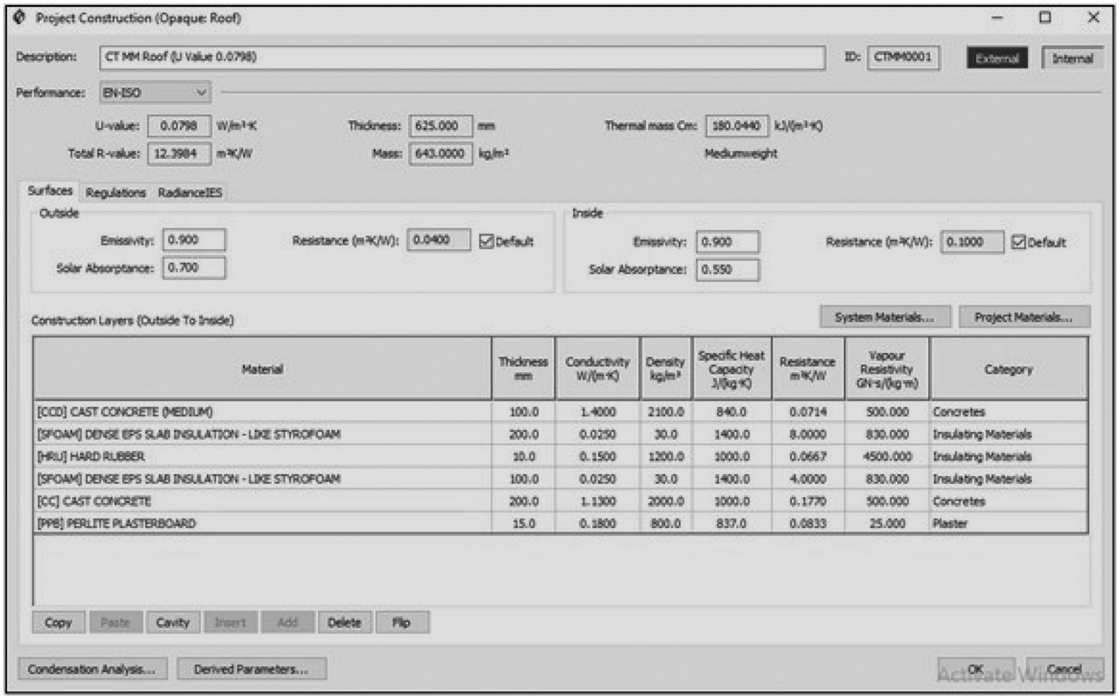

Figure 3: Roof construction template.

Following the establishment of the construction templates, we worked on thermal templates. These templates are important for determining the specific ventilation and heat recovery mechanisms within a building (Yang et al., 2018). Our research opted for the ApSYS HVAC system from the IES, which is renowned for its efficacy. To enhance the accuracy of our model, we referred to the PHPP design and specifications provided by the Zehnder Comfo Air Q450 datasheet when setting up the HVAC system (Corney et al., 2012). Finally, we accounted for internal gains within the building. Internal gains refer to the heat added to spaces

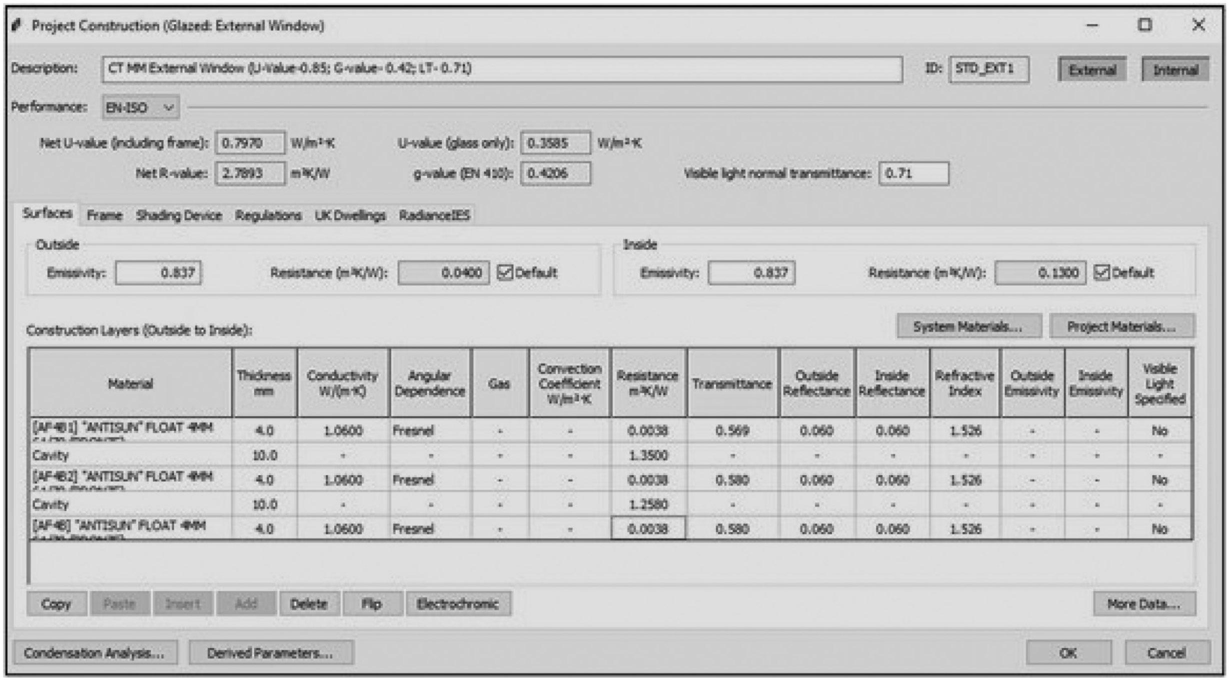

Figure 4: Windows construction template.

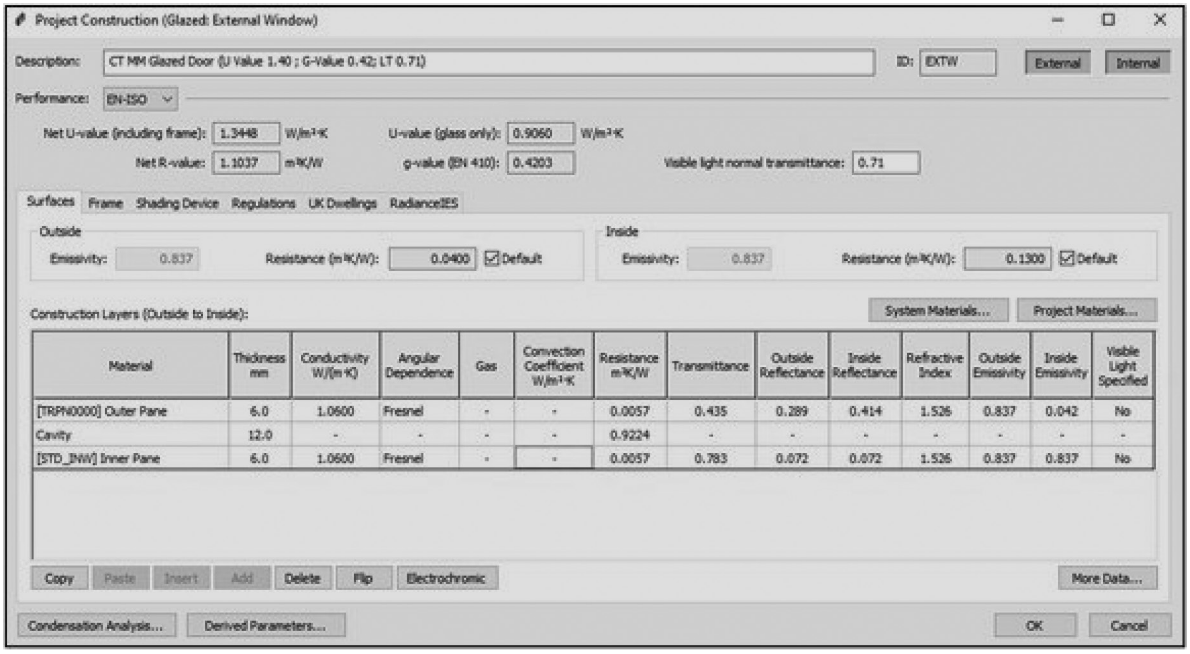

Figure 5: Door construction template.

from various sources such as occupants, electrical equipment, and lighting fixtures (Bradshaw, 2010).

Simulation Settings

We constructed a rigorous simulation framework that heavily relies on the intricate thermal characteristics of a building (Wang and Zhai, 2016). This simulation is structured to permit detailed monitoring of temperature fluctuations over time, providing granular insight into the thermal dynamics of the building. The integration of accurate weather data is a pivotal component of this framework. Recognising that the built environment is profoundly influenced by its climatic context, our approach emphasises the need for a genuine representation of a building's historical and current climatic conditions. To achieve this, we harnessed standardised annual climate datasets, notably TMYs, which offer a robust benchmark for temperature and weather patterns. To ensure a comprehensive and holistic understanding of climatic conditions relevant to our study, we incorporated data from the ASHRAE Fundamentals Tables of 2017 (Roth, 2017). Augmenting this was the use of the APLocate Application, a tool for streamlining the assimilation and application of diverse climate data from various global locations (Figue 6).

Factors to Consider in Design

Central to this research was a customised set of design determinants. Particular attention was paid to primary climatic factors, such as humidity, solar radiation, ambient temperature, and wind patterns. Beyond these primary metrics, data pertaining to solar positioning and cloud coverage were also considered indispensable for our analysis given their influence on building design and energy consumption. To ensure that our design considerations are globally relevant and comprehensive, we integrated the capabilities of the APLocate Application (Figure 7). Considered good for location- and site-specific editing, this tool has an expansive database that consolidates weather patterns from various regions around the world.

Location and Site Data and Weather Design Data

In this research, we emphasised fundamental geographic benchmarks, specifically latitude, longitude, and elevation, and recognised their profound impact on building energy performance and environmental interactions. Turning to weather design data, we drew our initial insights from the ASHRAE Fundamentals (Figure 8). The main objective is to make precise adjustments to the cooling loads to enhance the accuracy of the model. To achieve this, we relied on the Apache design interface, which systematically processes and integrates data on a monthly basis (Figure 7).

Calculations of Temperature Percentiles

In this study, we analysed temperature percentiles, focussing on identifying specific temperature attributes for the most critical months in Dubai. This analysis enabled us to comprehend the daily variations in temperature, thereby providing a clear understanding of the highest temperatures observed within a given month.

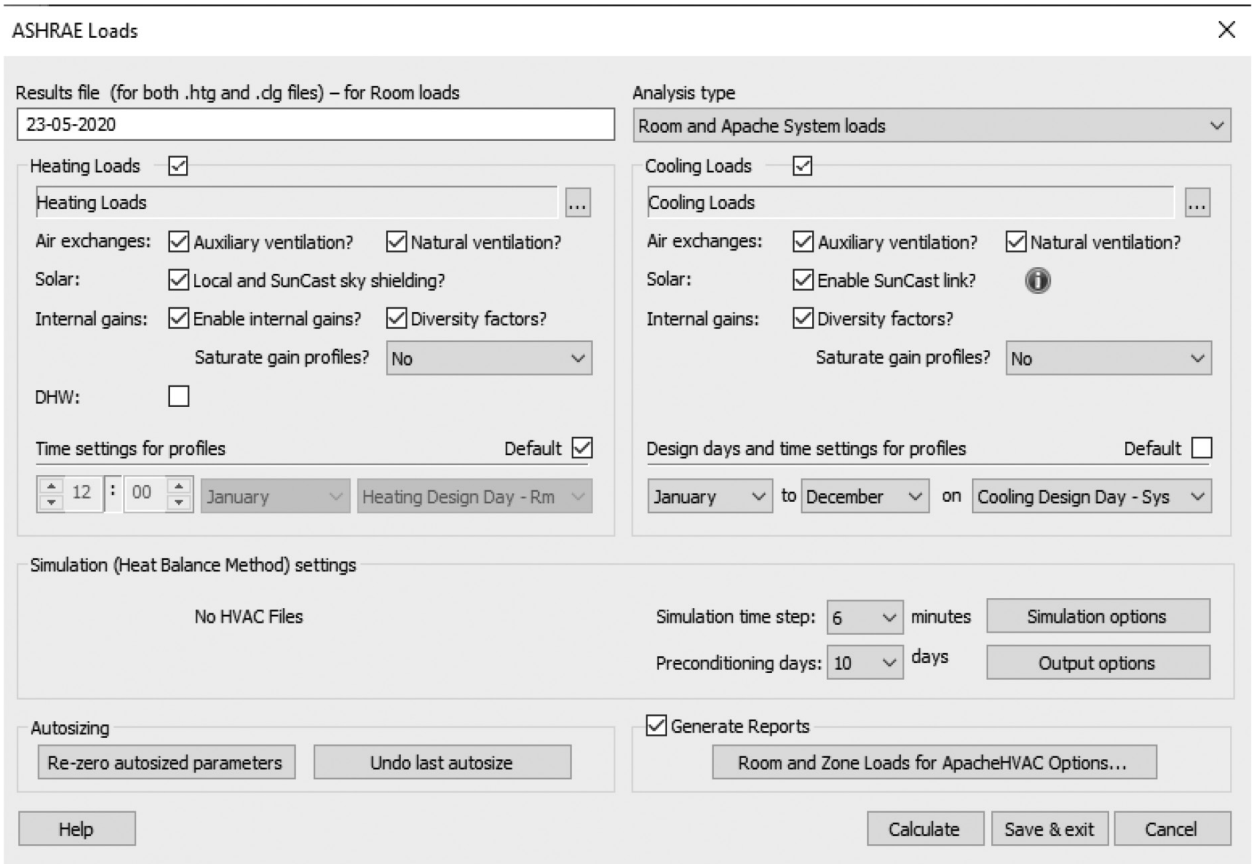

Figure 6: IESVE simulation settings.

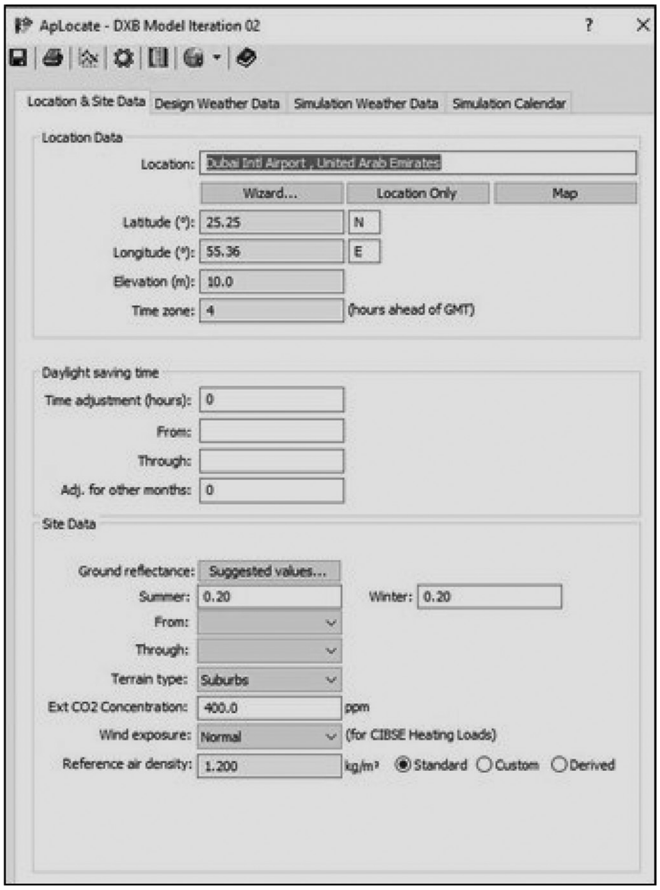

Figure 7: IESAP Locate input window – location and site data.

Results and Discussion

Intricacies in Space Calculation Methodologies

Further exploring deeper into architectural considerations, our study reported disparities in space calculation methodologies between IES and PHPP (Moran et al., 2014; David et al., 2015). In its assessment of space, the IES prioritises gross internal area (GIA), encompassing the total enclosed volume (Newberry et al., 2023). In contrast, the PHPP refines its focus to usable spaces, deliberately excluding components such as staircases, internal partition walls, and spaces with reduced headrooms (Baeli, 2019). This variation in approach is reminiscent of the strategies employed by German surveyors to analyse space assessment techniques in European passive housing models (Badescu and Rotar, 2012; Udreaet al., 2013; Schmidt and Aragon, 2022). Their research elucidated that a home's living area, as perceived in Germany, often omits spaces that do not directly contribute to a dwelling's functional utility (Braun, 2010).

2017 ASHRAE Handbook - Foundamentals (SI)

DUBAI INTL, UNITED ARAB EMIRATES (WMO: 411940)

Lat:25.255N	Long:55.364E	Elev:10	StdP: 101.2	Time zone:4.00	Period:90-14	WBAN:99999

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
1	13.1	14.2	-0.1	3.7	29.8	2.1	4.4	28.3	10.3	20.3	9.3	20.4	2.3	180

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
8	9.4	43.1	23.5	41.8	23.8	40.5	24.2	30.4	35.1	29.8	34.7	29.3	34.5	4.7	200

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Extreme Max WB
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
29.2	25.9	33.4	28.8	25.3	33.4	28.1	24.2	33.3	102.4	35.2	99.7	34.6	97.2	34.7	32.5

Extreme Annual Design Conditions

Extreme Annual WS				Extreme Annual Temperature				n-Year Return Period Values of Extreme Temperature							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.0	8.0	7.3	DB	11.2	45.8	1.4	0.9	10.2	46.5	9.4	47.1	8.6	47.6	7.6	48.3
			WB	7.6	31.5	1.7	0.6	6.3	31.9	5.3	32.2	4.3	32.6	3.0	33.0

Monthly Climatic Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperatures, Degree-Days and Degree-Hours	DBAvg		28.4	19.6	21.0	23.5	27.6	31.7	33.9	35.8	36.1	33.7	30.2	25.7	21.7
	DBStd		6.22	2.07	2.74	3.25	3.19	2.71	2.16	2.24	1.74	1.66	1.81	2.05	2.03
	HDD10.0		0	0	0	0	0	0	0	0	0	0	0	0	0
	HDD18.3		16	10	4	1	0	0	0	0	0	0	0	0	1
	CDD10.0		6720	296	308	419	529	673	716	799	811	711	627	471	361
	CDD18.3		3695	48	79	161	279	415	466	541	552	461	368	221	104
	CDH23.3		51416	156	384	1222	3234	6122	7368	8952	9121	7155	5035	2137	530
	CDH26.7		32381	16	93	434	1581	3820	4991	6473	6641	4765	2773	727	67
Wind	WSAvg		3.6	3.4	3.7	3.8	3.7	3.8	3.8	3.9	3.8	3.5	3.2	3.2	3.2
Precipitation	PrecAvg		106	20	22	22	7	1	0	3	1	0	3	8	21
	PrecMax		284	109	179	144	42	24	1	44	13	3	46	37	129
	PrecMin		13	1	0	0	0	0	0	0	0	0	0	2	0
	PrecStd		71	26	37	37	10	4	0	9	2	1	10	10	30

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	0.4%	DB	28.4	32.2	36.0	39.3	42.2	43.9	45.0	44.5	42.1	38.8	34.1	30.1
		MCWB	17.7	17.9	18.2	19.7	21.0	21.9	23.4	23.5	22.6	21.1	19.3	18.4
	2%	DB	26.6	29.2	33.1	37.0	40.5	41.9	43.1	42.9	40.1	37.0	32.4	28.2
		MCWB	17.4	17.5	18.1	19.6	21.4	22.7	24.2	24.2	23.2	21.7	20.7	19.2
	5%	DB	25.0	27.2	31.0	35.2	39.0	40.1	41.4	41.2	38.9	35.8	31.2	27.1
		MCWB	17.6	17.5	18.2	19.6	21.5	23.3	24.9	24.8	23.9	22.5	21.2	19.4
	10%	DB	23.8	25.6	29.0	33.4	37.2	38.8	40.0	40.0	37.8	34.6	30.1	26.1
		MCWB	17.3	17.6	18.0	19.7	22.1	24.1	25.3	25.5	24.7	23.2	21.5	19.2
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	0.4%	WB	20.7	21.3	22.5	24.7	28.0	30.1	31.2	31.1	30.2	28.7	25.6	22.5
		MCDB	24.2	25.1	27.3	30.6	33.5	34.9	35.7	35.6	34.4	33.0	30.0	26.1
	2%	WB	19.7	20.5	21.6	23.6	26.9	29.2	30.5	30.3	29.6	27.8	24.3	21.6
		MCDB	23.6	24.5	26.3	30.1	32.7	34.2	35.3	35.1	34.0	32.1	29.1	25.8
	5%	WB	19.0	19.7	21.0	22.7	26.0	28.7	29.9	29.8	29.1	27.0	23.5	20.8
		MCDB	23.2	23.9	25.8	29.4	32.5	33.9	34.9	34.9	33.7	31.7	28.5	25.2
	10%	WB	18.3	19.1	20.3	22.1	25.2	28.0	29.3	29.2	28.6	26.4	22.7	20.1
		MCDB	22.5	23.6	25.2	28.6	32.4	33.6	34.8	34.8	33.4	31.3	28.0	24.8
Mean Daily Temperature Range		MDBR	8.2	8.6	9.1	10.5	11.2	10.8	9.3	9.4	9.6	9.8	9.0	8.6
	5% DB	MCDBR	9.9	10.8	11.9	12.5	12.8	12.3	10.8	10.6	10.8	10.8	9.9	9.8
		MCWBR	4.7	4.9	5.8	6.0	6.2	6.8	6.6	6.3	6.7	6.4	4.9	4.9
	5% WB	MCDBR	8.5	8.7	9.3	10.8	11.5	10.7	8.9	9.4	9.4	9.6	9.3	9.0
		MCWBR	4.7	4.8	5.1	5.7	6.3	6.0	5.6	5.8	6.7	6.4	4.9	4.9
Clear Sky Solar Irradiance	taub		0.443	0.502	0.563	0.595	0.588	0.637	0.726	0.689	0.599	0.514	0.457	0.438
	taud		2.088	1.918	1.774	1.731	1.742	1.687	1.569	1.638	1.773	1.934	2.084	2.105
	Ebn,noon		795	773	749	737	740	700	639	661	711	751	774	780
	Edn,noon		144	183	221	236	233	245	275	256	219	177	143	136
All-Sky Solar Radiation	RadAvg		3.93	4.92	5.87	6.59	7.45	7.42	6.85	6.58	6.25	5.40	4.35	3.77
	RadStd		0.27	0.27	0.27	0.38	0.18	0.23	0.27	0.19	0.13	0.10	0.12	0.29

CDDn	Cooling degree-days base n°F, °F-day	Lat	Latitude, °	Period	Years used to calculate the design conditions
CDHn	Cooling degree-hours base n°F, °F-hour	Long	Longitude, °	Sd	Standard deviation of daily average temperature, °F
DB	Dry bulb temperature, °F	MCDB	Mean coincident dry bulb temperature, °F	StdP	Standard pressure at station elevation, psi
DP	Dew point temperature, °F	MCDBR	Mean coincident dry bulb temp. range, °F	taub	Clear sky optical depth for beam irradiance
Ebn,noon	Clear sky beam normal and diffuse horizontal irradiances at solar noon, Btu/h/ft2	MCDP	Mean coincident dew point temperature, °F	taud	Clear sky optical depth for diffuse irradiance
Edh,noon		MCWB	Mean coincident wet bulb temperature, °F	Tavg	Average temperature, °F
Elev	Elevation, ft	MCWBR	Mean coincident wet bulb temp. range, °F	Time Zone	Hours ahead or behind UTC
Enth	Enthalpy, Btu/lb	MCWS	Mean coincident wind speed, mph	WB	Wet bulb temperature, °F
HDDn	Heating degree-days base n°F, °F-day	MDBR	Mean dry bulb temp. range, °F	Hours 8/4 & 55/69	Number of hours between 8 a.m. and 4 p.m with DB between 55 and 69 °F
PCWD	Prevailing coincident wind direction, °,0 = North, 90 = East	WS	Wind speed, mph	HR	Humidity ratio, grains of moisture per lb of dry air

Figure 8: 2017 ASHRAE Handbook – Fundamentals for Dubai.

To quantify these gains, we relied on data from both the IES building template manager and the PHPP. This integrated approach ensures a holistic understanding of the heat dynamics within building spaces. The PHPP exhibited a design with a maximum capacity of 7 kW. With a seasonal EER of 3.2 and an energy efficiency ratio (EER) of 3.98, the cooling system is set to a heat pump (electric). Based on k+5 (kitchen plus five wet rooms), the particular fan power is 0.73W/l/s and there is no metering (specific fan power from Zehnder Comfo Air Q450 datasheet). It is possible to inspect and customise the core system of the model, as well as the space circumstances and numerous gains and air exchanges that it experiences through the use of various qualities in each area. Only wet sections and voids contain unique custom-made templates. The building's primary template was the space/zone, with an air supply temperature of 25°C and cooling at 25°C. The operating level of the MVHR can be achieved by circulating the cold air required for ventilation. To maintain air circulation, a 50 mm gap was permitted between the floor and the lowest point of the door leaf in the Passivehaus benchmark (Table 1 and Figure 9).

In the IES template manager, the PHPP's internal heat gain value has been regarded as a single input – a lump total value divided into individual floors to eliminate ambiguity and synchronise the results.

Depending on the design of a structure, the amount of air penetration can account for a significant percentage of a building's heating and air conditioning needs. The indicated air exchange in the template represented the inflow of air from the exterior.

The factors that affect the PHPP model's nV and rest infiltration air change rate are listed here.

Table 1: Factors affecting the air infiltration of the model

Factor		*Unit*	*Value*
Net air volume for press.	V_{n50}	m³	732
Air change rate at press.	n_{50}	1/h	0.6
Volume of ventilated space (A_{TFA}*h) =	V_V	m³	725
Wind protection coefficient, e			0.07
Wind protection coefficient, f			15
Excess extract air		1/h	0

Equation 1 shows the calculation of the infiltration air change rate.

$$\frac{732}{725} \times 0.6 \times \frac{0.07}{1+\left(\frac{15}{0.07} \times \frac{0}{0.6}\right)^2} = 0.042\, 1/h$$

Therefore, the thermal template was programmed to achieve a continuous maximum. the flow rate of 0.042 1/h from the external environment. The smaller the air exchange, the lower the losses or gains that reduce the yearly MVHR electricity use (Figure 10).

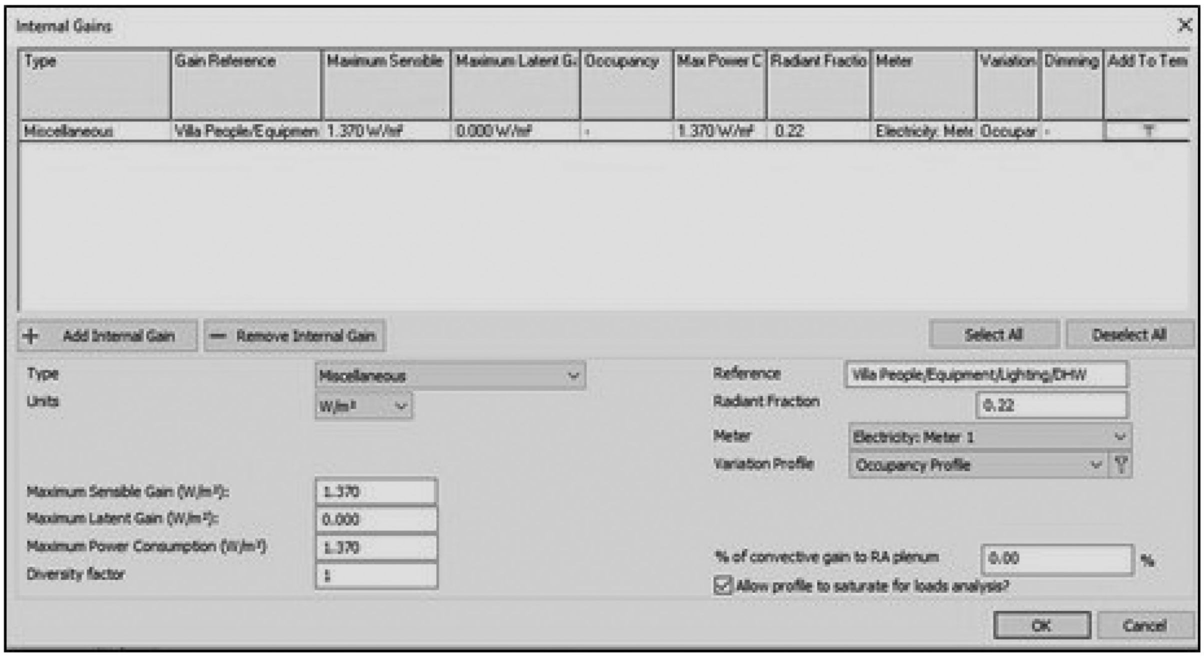

Figure 9: IES IHG input window.

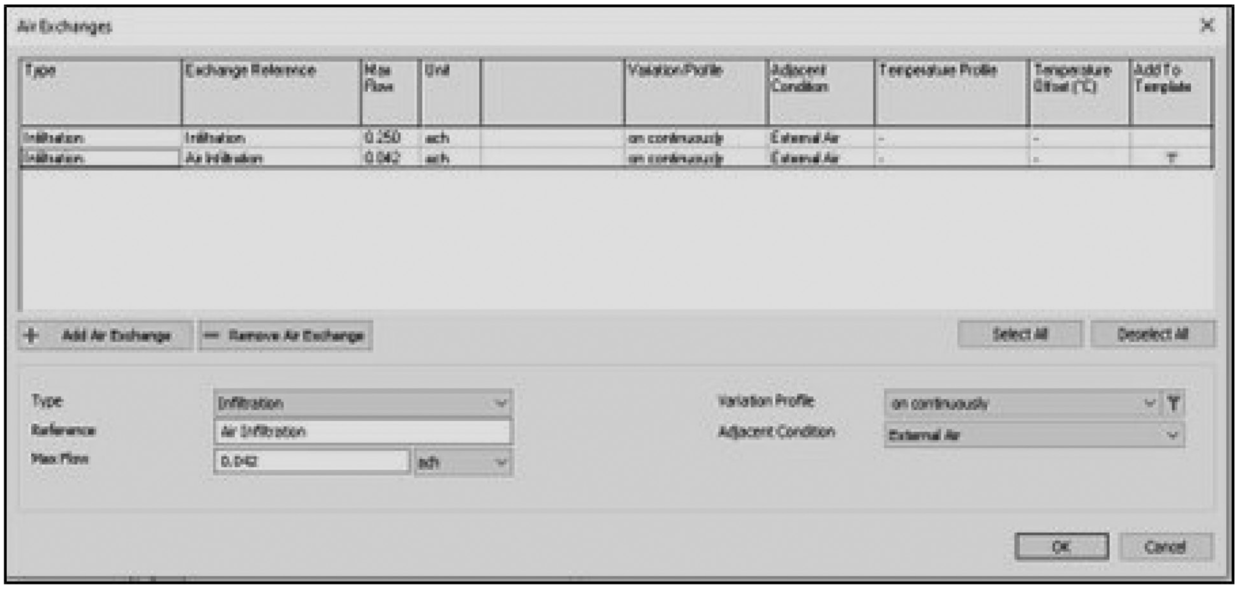

Figure 10: IES Air exchange input window.

Comparative Analysis with Global Benchmarks

Furthermore, a retrospective analysis of our results against global benchmarks highlighted an efficiency increment of 20% when juxtaposing the Passivhaus model with conventional housing structures in similar climatic conditions (Braun, 2010; Schnieders et al., 2015, 2020). This efficiency is predominantly attributed to the subtle understanding and application of space and energy parameters, underscoring the inherent potential of passive housing in warmer climates (Omrany et al., 2016). Moreover, our findings coincide with those of various researchers, emphasising the imperative nature of utilising precise and context-sensitive modelling tools for optimal outcomes (Chiras, 2002). Hence, the results of this study reiterate the transformative essence of passive housing in extreme climates (Marincic et al., 2014). The congruence of meticulously curated strategies and the nuanced application of modelling tools present a robust case for the widespread adoption of the Passivhaus model in regions mirroring Dubai's climatic attributes.

Insights from ASHRAE Handbook Fundamentals' Percentiles

This study used comprehensive information from the ASHRAE Handbook Fundamentals' Percentiles, specifically focusing on the temperature benchmarks at the 0.4%, 1%, and 2% yearly percentiles (Aijazi and Brager, 2018). The alignment of these benchmarks with the rising peak temperatures for both dry and wet bulbs revealed statistically significant consistency, suggesting that such temperatures often manifest within predictable bands (Harkouss et al., 2018) (Figures 11 and 12).

However, the detailed stratification provided by the ASHRAE Handbook on monthly dry bulbs and their coinciding wet-bulb temperatures adds layers of

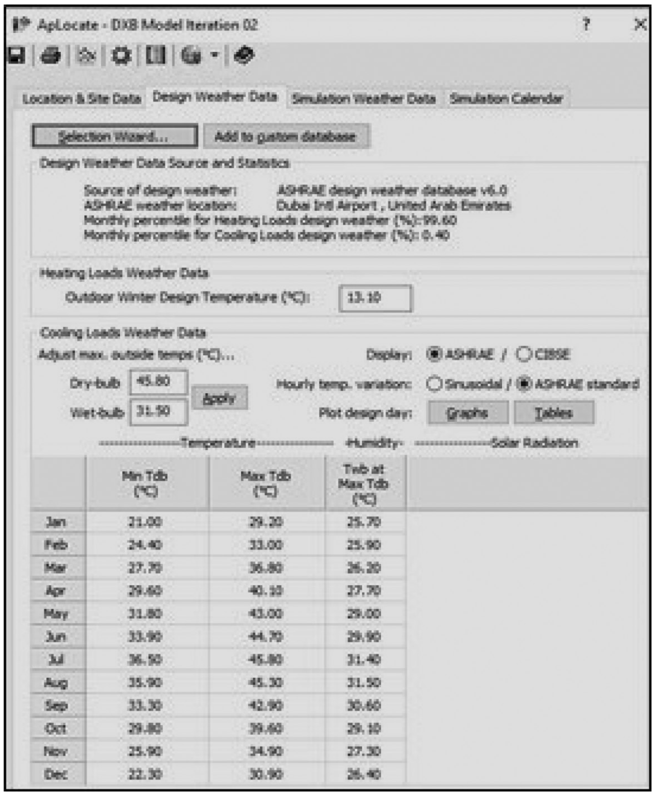

Figure 11: IES APLocate input window–Design weather data.

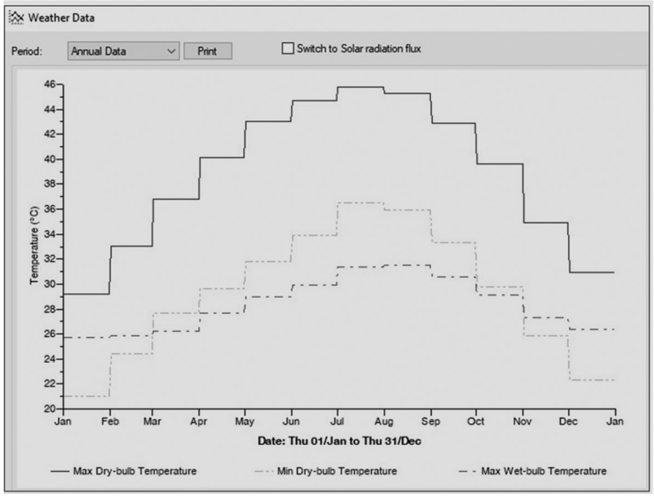

Figure 12: Plot design data.

complexity to our understanding (Alharbi, 2014). In certain instances, the monthly percentiles demonstrated an unexpected divergence from the annual percentiles. Notably, this divergence manifested as an upsurge, with monthly figures reaching levels up to 12 times their annual counterparts. Such variances introduce challenges, particularly when these metrics serve as foundational pillars for the design and construction of sustainable buildings. Corroborating our observations, findings from similar studies have shown similar results (Heinemann et al., 1966; Holloway and Vimont, 2020; Chung and Liu, 2022). They highlighted the various discrepancies between monthly and annual temperature percentiles and their ramifications for building design parameters. Understanding the roots of such variations becomes paramount, especially as architects and builders seek to incorporate these metrics into sustainable and energy-efficient building frameworks (Hagbert and Femenías, 2016; Yeatts et al., 2017; Danish et al., 2019).

Calibration and Credibility of the Computational Model

Our research investigated the agreement between our computational model's weather data and the specific climatic parameters of Abu Dhabi, for the year 2020. The accuracy of our model was central to its calibration process, which was based on the IES Dubai weather dataset. It provided our model with a very high degree of accuracy and ensured its alignment with the empirical weather patterns observed in real-world scenarios.

Potential and Efficacy of Passive Housing in Extreme Climates

The findings of this study provide a convincing description of the transformative potential of passive housing, particularly under extreme climatic conditions. The results, which are deeply rooted in the practices of harnessing solar energy, optimising heat recovery mechanisms, and employing advanced super-insulation techniques, strongly advocate the viability of the Passivhaus model in environments such as Dubai. The model's sustainability credentials were particularly striking: upon implementing the recommended strategies, the projected carbon emissions approached a commendable zero mark. A strong result of this research was the discovery of intricate differences when various PHPP parameters were adjusted. We observed that in a summer peak scenario in Dubai, the default parameters rendered a 10% variance from the actual energy consumption, necessitating the integration of regional-specific variables (Table 2).

Table 2: Annual energy demand as obtained from PHPP and IESVE

Item	*Unit*	*PHPP*	*IES*
Cooling and ventilation	kWh/(m^{2}a)	56.6	53.73
Household electricity	kWh/(m^{2}a)	47.6	45.63
Aux. electricity (DHA+solar DHW)	kWh/(m^{2}a)	1	3.47
Annual primary energy demand	kWh/(m^{2}a)	105.2	102.82

The PHPP model's prediction of 56.6 kWh/(m²a) for cooling and ventilation is slightly higher than the IES prediction of 53.73 kWh/(m²a). This is attributed to the different assumptions regarding the thermal envelope of the building or the efficiency of the ventilation system. In Dubai's hot climate, cooling systems are vital, and their energy consumption is sensitive to many factors, such as insulation quality, window glazing properties, and airtightness. The PHPP's higher estimate suggests that it may be factoring in a more conservative scenario, potentially anticipating less effective heat rejection or higher internal heat gain from occupants and devices. For household electricity, the PHPP estimate is 47.6 kWh/(m²a) against the IES estimate of 45.63 kWh/(m²a). Household electricity consumption is affected by numerous variables, including the efficiency of appliances, usage patterns, and the presence of energy-saving measures, such as LED lighting. A slightly higher estimate of the PHPP could imply a more conservative assumption about resident behaviour and appliance efficiency, or it could reflect a difference in the base year of the data used for these projections. The Auxiliary Electricity category shows a more significant variance, with the PHPP estimating only 1 kWh/(m²a) compared with the IES's 3.47 kWh/(m²a). Auxiliary electricity typically includes systems that support the main heating and cooling systems; in this case, it also appears to include solar thermal contributions. This large difference could indicate a fundamental disagreement between the models regarding the expected performance and contribution of solar water heating systems in Dubai's specific climate. The IES model accounts for the less optimal performance of solar thermal systems and higher auxiliary demands, such as pumps and backup systems. The annual primary energy demand is relatively close between the two models, with PHPP predicting 105.2 kWh/(m²a) and IES at 102.82 kWh/(m²a). This suggests a general agreement on the overall energy profile of the passive house, but even a small difference can be significant when projecting long-term energy consumption for policy or economic analyses. The slight variance may reflect different treatments of factors such as the local energy mix, which affects the primary energy factors used in the calculations. The differences between PHPP and IES predictions are crucial when considering the implementation of passive housing in extreme climates. The variances in cooling and ventilation, particularly auxiliary electricity, underscore the need for models to incorporate local climate data, the specific performance of building components, and occupant behaviour patterns (Erdogan, 2019; Stavrakakis et al., 2021). For passive houses to be effectively implemented in Dubai or similar climates, energy models must be calibrated with local data. This includes solar radiation levels, local weather patterns, cultural habits in energy usage, and availability and performance of building materials and HVAC equipment designed for such climates. A more accurate model will help architects and engineers design buildings that are not only more comfortable but also more energy-efficient and cost-effective in the long run.

Considering the complexities of system dynamics, this study resulted in the extraction of a linear state-space representation that effectively captures the thermal behaviour and interactions within a building's HVAC system. The significance of such a model is manifold, especially when envisioning the blueprinting and operationalisation of system control mechanisms. Remarkably, the model's responses closely adhered to the observed data and remained well within the accepted variances. The results emphasise the importance of precision in passive house planning and the need for models such as PHPP and IES to be adaptable to regional specificities. The overarching conclusion is that passive housing is a viable solution for hot climates with the potential for significant energy savings. However, the effectiveness of these savings is contingent upon accurate, localised energy modeling that considers all the variables of the region's unique climate and the building's specific design and operation (Abdo-Allah, 2020). Our findings underscore the efficacy of strategies such as solar energy harnessing, optimised heat recovery, and advanced insulation techniques, all of which collectively accentuate the sustainability of the Passivhaus model. Notably, the capability of this model to neutralise carbon emissions is a significant breakthrough. The study further elucidates the nuanced differences in space calculation methodologies between systems such as IES and PHPP, emphasising the importance of contextual and region-specific parameters in architectural modeling. Additionally, our alignment with reputable datasets and the successful calibration of our climatic model served as testaments to the rigorous methodological approach adopted. In essence, this research establishes a robust foundation for the wider adoption of passive housing in regions akin to Dubai's climate and underscores the value of precision in modeling tools for optimal architectural outcomes.

Economic Feasibility

Economic feasibility is a critical aspect of assessing the real-world applicability of passive housing in Dubai. The initial construction costs for passive housing are typically higher than those for conventional buildings owing to the use of advanced materials and technologies necessary to achieve high energy efficiency. However, these upfront costs can be offset by long-term savings from reduced energy consumption. The construction of passive houses involves additional expenses for enhanced insulation, high-performance windows, and advanced ventilation systems. On average, the initial costs are 5-15% higher than those of traditional construction methods. Passive houses significantly reduce energy consumption for heating and cooling, which can lead to substantial cost savings over the building lifecycle. Studies have shown that energy savings can range from 30 to 70%, depending on the specific design and climatic conditions. In Dubai's extreme climate, where cooling demands are high, savings can be even more pronounced. A cost-benefit analysis indicates that the payback period for additional investment in passive housing can vary between five and ten years, depending on energy prices and consumption patterns. Furthermore, passive houses tend to have higher property values because of their energy efficiency and environmental benefits, providing additional economic incentives for homeowners and developers.

Practical Implementation Challenges

Implementing passive housing in Dubai poses several practical challenges that must be addressed to ensure successful adoption and scalability. The current building codes and regulations in Dubai may not fully support or incentivise the adoption of passive housing standards. Revisions to these regulations are necessary to facilitate the integration of housing principles. Policymakers must create supportive frameworks and provide incentives for developers to adopt energy-efficient building practices. The construction industry in Dubai must adapt to new building techniques and materials required for passive housing. This includes training builders, contractors, and architects to ensure that they are proficient in passive house construction methods. The availability of high-quality building materials that meet passive-house standards is also crucial. Raising awareness among stakeholders, including developers, homeowners, and investors, regarding the benefits of passive housing is essential. Education campaigns and pilot projects can demonstrate the viability and advantages of passive housing, helping build market confidence and demand. Dubai's extreme heat poses unique challenges to passive housing. Effective shading, ventilation, and cooling strategies must be tailored to the local climate to ensure that buildings remain comfortable and energy-efficient. This includes incorporating advanced technologies, such as phase-change materials and solar thermal systems, to optimise energy performance. To encourage the adoption of passive housing, economic incentives such as subsidies, tax breaks, and low-interest loans can be offered to offset initial investment costs. These incentives can make passive housing more attractive to developers and homeowners, thereby accelerating the transition to sustainable building practices. Addressing these economic and practical challenges is essential to the successful implementation of passive housing in Dubai. By integrating supportive policies, advanced construction practices, and market education, Dubai can lead to the adoption of sustainable and energy-efficient housing solutions that are well-suited to its unique climatic conditions. This comprehensive approach ensures that passive housing becomes a viable and attractive option for future development, contributing to the city's sustainability goals and reducing its overall carbon footprint.

Limitations

While this study provides valuable insights into the potential of passive housing in extreme climates, such as Dubai, several limitations must be acknowledged. Understanding these limitations is crucial for accurately interpreting the results and guiding future research. Validation of our model using data from a single year (2020) is a significant limitation. We do acknowledge that this approach does not account for the annual variability in weather patterns, occupancy behaviour, or other external factors that can influence energy consumption. In particular, 2020 was marked by the COVID-19 pandemic, which resulted in a typical occupancy patterns and energy usage. Consequently, these findings may not fully represent typical conditions. Future studies should incorporate multi-year data to provide more robust model validation and capture a wider range of climatic and operational scenarios. This study was highly specific to the climatic conditions of Dubai. While these findings are relevant for similar extreme climates, their applicability to other regions with different climatic conditions may be limited. Further research is needed to adapt and validate passive housing strategies in diverse geographical locations to ensure their broader applicability. Although this study includes a preliminary economic feasibility analysis, it primarily focuses on the cost implications and potential savings from reduced energy consumption. The analysis did not comprehensively cover the financial incentives, subsidies, and market dynamics that could significantly influence the adoption of passive housing. A more detailed economic analysis that considers these factors would provide a clearer picture of the economic viability of passive housing in Dubai. The discussion of practical implementation challenges is based on theoretical considerations and a literature review. There is a lack of empirical data on the actual experiences of implementing housing projects in Dubai. Future research should include case studies and pilot projects to provide empirical evidence and practical insights into the challenges and solutions to implementing passive housing in the region. This study assumes the availability and performance of certain advanced building materials and technologies such as high-performance windows and advanced insulation systems. The local availability, cost, and performance of these materials and technologies can vary. Future research should investigate local market conditions and the feasibility of sourcing the necessary materials and technologies for passive housing in Dubai. While both the PHPP and IESVE are powerful tools for energy modeling, they have inherent limitations. PHPP uses a steady-state energy balance approach, which may not accurately capture the dynamic variations in energy performance. Although more dynamic, IESVE requires detailed input data and assumptions that can introduce uncertainties. The results of the models were only as accurate as the input data and assumptions. Therefore, there is a need for continuous improvement and validation of these models against real-world data. This study primarily focuses on residential buildings. The applicability and effectiveness of housing principles for commercial, institutional, and industrial buildings in extreme climates remain underexplored. Future research should extend the analysis to these building types to provide a more comprehensive understanding of the potential and limitations of passive housing in different sectors. By acknowledging these limitations, we aim to provide a balanced perspective on the findings and highlight areas for future research to enhance the understanding and implementation of passive housing in extreme climates, such as Dubai.

Conclusion

This comprehensive study ventured into the domain of passive housing, employing a rigorous and methodical approach to model the proposed building using the PHPP software. The model meticulously captured the architectural nuances and HVAC system complexity, reflecting the actual hot water and electricity consumption patterns observed in 2020. A noteworthy outcome of our analysis is the alignment of external temperature averages generated by the PHPP with empirical measurements, affirming the model's precision and reliability. Our investigation delved into the dynamic thermal behaviour of a building using a linear state-space model derived from the IESVE. This complex yet precise model, featuring 12 state variables along with corresponding inputs and outputs, demonstrated high fidelity by closely aligning with observed data, maintaining accuracy within accepted variance thresholds. The robustness of our model was further strengthened using an array of validation techniques, including autocorrelation and cross-correlation functions. These were used to substantiate the authenticity of the computational findings. Our research extends the practical implications of passive housing, particularly in extreme climates, such as Dubai. The capabilities of the Passivhaus model are highlighted, showing how the integration of solar energy, advanced insulation, and optimised heat recovery could significantly minimise carbon emissions. The simulation insights revealed a crucial 10% variance in energy consumption during peak summer periods when default parameters were used, emphasising the importance of regional adaptations in the modeling process. Disparities between the energy consumption estimates provided by the PHPP and IES methodologies were investigated, reflecting nuanced differences in space calculation techniques. Our results indicated slight discrepancies in cooling, ventilation, and auxiliary electricity predictions, which underscores the need for precise, region-specific calibrations in energy modelling to ensure accuracy and efficacy. The synergy between our rigorous climatic modeling and empirical data, notably using the IES Dubai weather dataset, illustrates the study's strong empirical foundation. Overall, our findings highlight the critical role of passive housing in regions with challenging climates, the complexities of architectural space calculations, and the significance of data-driven climatic modelling. This study not only confirms the theoretical viability of passive housing in hot climates but also provides a solid basis for the practical application of sustainable architectural principles. This lays down a pathway for future innovation in climate-responsive housing solutions, advocating for a future in which passive housing plays a central role in sustainable development.

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Conflicts of Interest Statement
Mohamed Mahgoub is currently employed by Red Sea Global and his work on this project is unrelated to his duties at the company. Additionally, both authors confirm that they have no financial or commercial relationships that could be construed as a potential conflict of interest.

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