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Learning from Vernacular and Integrating Retrofitting Techniques to Enhance Thermal Comfort in Residential Buildings: Insights from Tiruchirapalli, India

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Abstract

This research investigates the impact of integrated passive design techniques on thermal comfort in a ground-floor residence in Tiruchirapalli, India. The study addresses thermal comfort challenges in order to bridge the gap between theory and practice, providing insights for decision-makers, architects, and urban planners.

It employs quantitative methods. The research integrates pre- and post-retrofit thermal comfort hour analyses to quantify increases after implementing passive design measures. It notes the benefits, such as reduced energy consumption and greenhouse gas emissions.

Results reveal a nuanced understanding of passive design effectiveness, contributing to academic discussions and offering actionable insights for industry practitioners. The analysis of 20 simulations provides valuable insights into the thermal performance of distinct spaces within the residence under various ventilation conditions. While the study focuses on a specific residence, it contributes to the broader discourse on sustainable design practices, offering guidance for creating energy-efficient and comfortable living environments, albeit with limitations. The research underscores the critical role of natural ventilation in achieving thermal comfort and emphasizes the need for thoughtful ventilation strategies in different spaces. The findings provide a foundation for further exploration of passive design strategies and their applicability in diverse residential settings.

Keywords: Passive design techniques, Building Retrofitting, Warn humid climate, Thermal Comfort, Residence

Introduction

The growing interest in sustainable construction has spurred a focus on passive design techniques as a means to enhance thermal comfort and mitigate the environmental impact of active cooling systems, as noted by (Zune et al., 2020). This study explores the possibilities of integrating passive design strategies into conventional buildings.

Wang and Adeli (2014) show that traditional buildings rely on energy-intensive active cooling systems, leading to less energy consumption and greenhouse gas emissions. Interestingly, Tiruchirapalli's vernacular architecture has been acknowledged for providing comfortable living environments without artificial cooling. Indeed, this provides a foundation for investigating the efficacy of retrofitting conventional structures with passive design techniques to enhance occupant comfort and promote environmentally sustainable practices. This research raises the question, whether retrofitting with passive design techniques, inspired by Tiruchirapalli's architectural traditions, could positively influence the thermal comfort hours experienced by occupants. Thus, this study aims to contribute to enhancing the thermal performance of residences in Tiruchirapalli through passive techniques.

The research objectives are as follows.

1. To ascertain the performance of a residence in its existing state.
2. To identify the prevalent passive design techniques specific to the Tiruchirapalli region.
3. To apply these techniques to retrofit the selected residence, identifying the design that optimizes thermal comfort hours.

Theoretical Framework

According to Ličina et al. (2018), thermal comfort is "the state of mind that communicates satisfaction within the thermal environment," often assessed subjectively. Thermal acceptability refers to the mental state expressing approval of the environmental thermal conditions, aligning with Berglund's concept. Thermal sensation is defined as an individual's mental state that evaluates the thermal environment. Specifically, it involves the conscious interpretation of sensory data arising from exposure to a particular thermal condition (Chan et al., 2017).

de Dear et al. (2013) argue that human thermal perception is influenced by the psychophysical dynamics of thermal pleasure. Höppe (2002) and Luo et al. (2018) also suggest that people with perceived control tend to report more positive comfort perceptions. They also indicate the role of psychological aspects in the perception of the thermal environments (Wang et al., 2018).

According to Ca ̂ndido et al. (2010), if we accept that thermal environments slightly warmer than preferred or neutral can still be acceptable, the introduction of airflow with higher velocities into such environments may be desirable. Acceptability related to higher velocities remove sensible and latent heat from the body, re-establishing body temperatures to a comfortable level.

Review of Literature

literature has examined many aspects of thermal comfort including passive design techniques in warm and humid climates. Notably, there has been a recent interest in context-driven strategies for achieving thermal comfort in traditional buildings (Karthikeyan & Kumaraguruparan, 2023). Effective passive design strategies, such as maximizing airflow for natural ventilation in warm and humid tropical climates, have also been emphasized (Dewi and Antaryama, 2017). However, as Ahmed et al. (2014) point out the selection of passive thermal design strategies is heavily influenced by local climatic conditions. Studies suggest that orienting buildings at specific angles to the prevailing wind direction significantly improves thermal comfort and ventilation in warm humid climates. Indeed, the occupancy rate for a building can indicate sprawl in the community (Sarwate, Soni and Acharya, 2023)

Considering the impact of relative humidity on thermal comfort is vital in warm and humid climates. Research indicates that higher relative humidity levels can affect occupants' responses to humid conditions in warm environments. The applicability of thermal neutrality equations to residents' thermal responses in tropical warm-humid urban environments underscores the need to understand specific thermal comfort needs in such climates.

Baruti et al. (2019) reviewing studies on outdoor thermal comfort in warm humid climates emphasizes the challenges posed by informal urban fabric, highlighting the necessity for tailored passive design solutions. Uzakbayev et al. (2023) points out that field surveys help to analyse the role of environmental features. Moreover, Basuki, Antaryama and Samodra, (2022) demonstrate the recognized applicability of direct evaporative cooling as a passive design strategy for improving building thermal conditions in hot-dry climates. They argue that they add to the array of potential solutions.

Muller and O'Gorman (2011), look at the issue of the pursuit of maximizing thermal comfort hours through passive design. They argue that considering the impact of climate change on surface and column water vapor is crucial. They offer significant insights into the design of passive strategies that mitigate the effects of climate change on thermal comfort can be gained by understanding the factors governing the calculated rates of change of water vapor in simulations of global warming scenarios.

Studies on the thermal comfort of people in hot and humid areas confirm the applicability of certain passive design models from warm climates with specific thermal histories. Brager, Zhang and Arens (2015) however acknowledge the limitations of these in certain contexts. Crawley et al. (2008) show that the development of bioclimatic charts for passive building design in warm climates is necessary to utilize passive strategies tailored to the specific climatic conditions of the region. They demonstrate the significance of building performance simulations and support the arguments of Sarwate, Soni & Acharya (2023) who point out that the occupancy rate for a building indicate the sprawl in the community. These research however, are inadequate and insufficient to fully understand the issues of thermal comfort,

Research Methodology

This research examines Tiruchirapalli as a case study due to its notable indigenous architecture. The research technique involves a practical implementation of passive design techniques in retrofitting a residential structure in Tiruchirapalli: the case study. It thus selects an existing residence there, documents its details, and utilizes simulation software to assess thermal comfort hours before and after retrofitting with passive design techniques. It focuses on comparing data to evaluate the potential for creating more sustainable living spaces.

Methodologically, this research draws on building performance simulation, as highlighted by Crawley et al. (2008). It recognizes the importance of accurate modeling and analysis in evaluating the impact of design interventions. The use of the Climate Studio plugin in Rhino aligned with these principles, provide a robust simulation platform to assess thermal comfort hours before and after retrofitting. The research process adopted is depicted in the Figure 1.

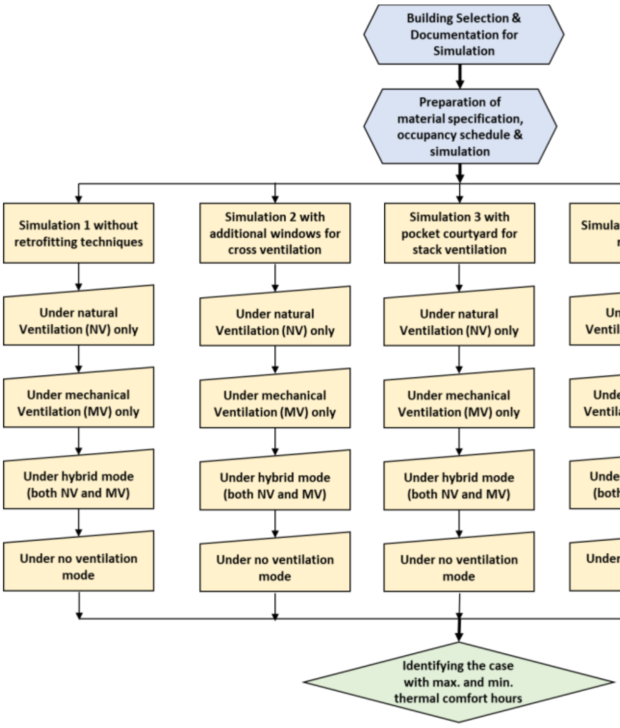

Fig. 1: Research Methodology Flowchart
Source: Author

The Case Study

The selected dwelling exists in Tiruchirapalli. It encompasses 1200 sq. ft., comprised of two bedrooms. It is oriented towards the East. The main entrance of the residence opens onto a front road of 12m, while the adjacent structures are positioned 2 meters away from the side exterior walls. The building image and visual representations of the building are presented in Figure 2 respectively.

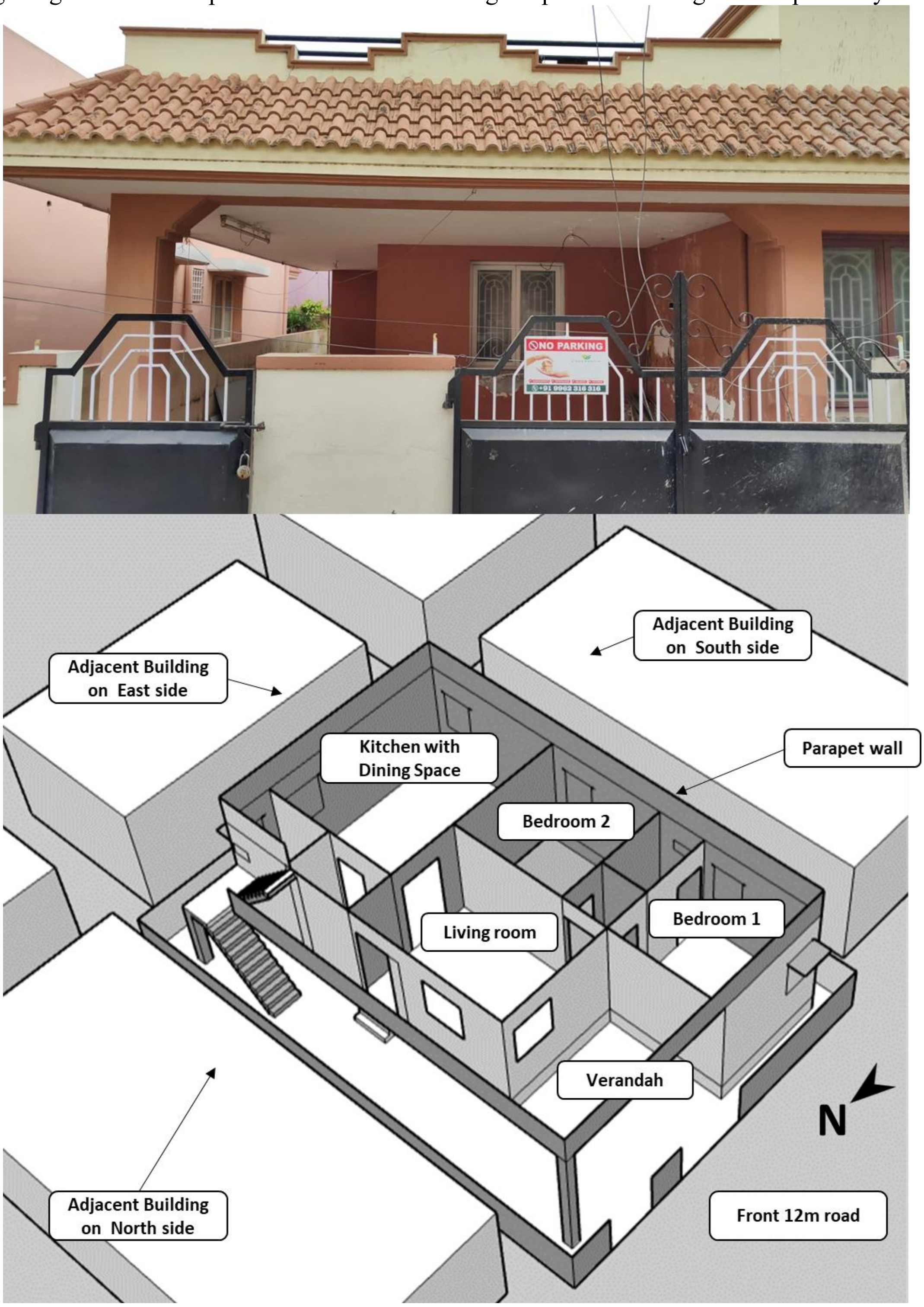

Fig. 2: Building Model created in Climate Studio software
Source: Author

The occupants of the residence are a family of 3 people which includes a mother, father and a daughter. Table 1 outlines the indoor air temperature thresholds deemed acceptable according to the IMAC model for warm humid climate.

Table 1: Acceptable Indoor Temperature according to IMAC model for warm humid climate
Source: Author

Acceptable Indoor Temperature according by IMAC for warm humid climate		
Month	**Min. Temperature in degree Celcius**	**Max. Temperature in degree Celsius**
Jan	24.27	29.03
Feb	24.81	29.57
Mar	26.04	30.8
Apr	27.42	32.18
May	27.67	32.43
Jun	27.36	32.12
Jul	27.34	32.1
Aug	27.37	32.13
Sep	27.03	31.79
Oct	26.17	30.93
Nov	25.41	30.17
Dec	24.75	29.51

A detailed type of breakdown as mentioned by (Yeretzian, A and Karam, 2023) of occupancy schedule specified for each space within the study residence is outlined in Table 2. The initial simulation involves assessing the building's thermal performance under the influence of the IMAC comfort bandwidth, utilizing the Climate Studio software plugin.

Table 2: Occupancy Schedule
Source: Author

Rooms	Occupancy time of the day	Number of Occupants	Activity	Equipment (W)	Lighting (W/m^2)
Living Room	6am-7am	2	Mild Activity	Tv & Fan	-
	7am – 8am	3	Mild Activity	Tv & Fan	-
	8am – 11am	1	Serene	Tv & Fan	-
	1pm – 2pm	1	Serene	Tv & Fan	-
	5pm – 7pm	2	Serene	Tv & Fan	1 Fluorescent Light
	7pm – 10pm	3	Serene	Tv & Fan	1 Fluorescent Light
Bedroom	2pm – 4pm	1	Sleep	Fan	-
	6pm – 10pm	1	Frequent Visits	Fan	1 Fluorescent Light
	10pm – 5am	2	Sleep	Fan	1 zero Watts Bulb
Bedroom 2	6pm – 10pm	1	Frequent Visits	Fan	1 Fluorescent Light
	10pm – 5am	1	Sleep	Fan	1 zero Watts Bulb
Kitchen & Dinning	4:30am – 7:30am	1	Cooking	Fridge & Kettle	1 Fluorescent Light
	11am – 12:30pm	1	Cooking	Fridge & Kettle	“
	5pm – 6pm	1	Cooking	Fridge & Kettle	“
	7pm – 8:30pm	1	Cooking	Fridge & Kettle	“

Based on the occupant's activities, equipment and lighting, the data considered for the simulation is given in Table 3.

Table 3: Building Simulation Attributes for the residence
Source: Author

Space	Area (m2)	Air Changes per hour		EPD (W/m2)	LPD (W/m2)	No of Occ. (P)	Ppl Den (P / m2)
		As per NBC	Taken				
Living Room	14.49	3 to 6	5	8.63	2.76	3	0.21
Bedroom Centre	9.29	2 to 4	3	8.07	5.92	1	0.11
Bedroom Corner	9.29			8.07	5.92	2	0.22
Toilet	2.23	6 to 10	8	-	13.45	3	1.35
Kitchen	17.84	6 Min	6	112.11	2.24	1	0.06
Store Room	2.23	6 Min	6	-	6.73	1	0.45
Exterior Toilet	2.23	6 to 10	8	-	13.45	3	1.35

Following this initial simulation, three passive design retrofitting strategies are implemented. These strategies include enabling possible cross ventilation, introducing stack ventilation through a modest ceiling opening, and incorporating cool roof paints for the terrace. Subsequently, the building model undergoes simulations to evaluate its thermal performance in light of these design interventions. In total, 20 simulations have been performed under different scenarios as given in Table 4.

Table 4: Details of the various building simulations
Source: Author

Different Retrofitting Methods	Different conditions of Natural Ventilation (NV) and Mechanical Ventilation (MV)			
Simulation 1 (before retrofitting)	With only Natural Ventilation (NV)	With only Mechanical Ventilation (MV) and doors, windows closed	With both Natural and Mechanical ventilation with doors, windows open	With No mechanical ventilation and doors, windows closed
Simulation 2 (after retrofitting with additional windows for cross ventilation)	With only Natural Ventilation (NV)	With only Mechanical Ventilation (MV) and doors, windows closed	With both Natural and Mechanical ventilation with doors, windows open	With No mechanical ventilation and doors, windows closed
Simulation 3 (after retrofitting with additional pocket courtyard for stack ventilation)	With only Natural Ventilation (NV)	With only Mechanical Ventilation (MV) and doors, windows closed	With both Natural and Mechanical ventilation with doors, windows open	With No mechanical ventilation and doors, windows closed
Simulation 4 (after adding cool roof paint)	With only Natural Ventilation (NV)	With only Mechanical Ventilation (MV) and doors, windows closed	With both Natural and Mechanical ventilation with doors, windows open	With No mechanical ventilation and doors, windows closed
Simulation 5 (An addition of windows, pocket courtyard and cool roof paint to the present condition)	With only Natural Ventilation (NV)	With only Mechanical Ventilation (MV) and doors, windows closed	With both Natural and Mechanical ventilation with doors, windows open	With No mechanical ventilation and doors, windows closed

The crux of the research lies in the comparative analysis of thermal comfort hours between the building's initial state and its retrofitted condition. This comparative study identifies the scenario that provides maximum thermal comfort for the occupants. By scrutinizing the impact of passive design modifications on thermal performance, this research contributes valuable insights into the enhancement of building sustainability and occupant comfort.

Results and the Discussion

The simulations were carried out for different ventilation situations as mentioned from Table 5 to 24. The thermal comfort hours are mentioned in these tables annually. The maximum thermal comfort hours are formatted in blue and the minimum thermal comfort hours are formatted in red.

Table 5: Before retrofitting simulation with hybrid ventilation
Source: Author

Simulation 1 - Windows and Doors open / Mechanical ventilation On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	391	329	204	301	**306**
Feb	312	286	140	253	**248**
Mar	237	239	114	204	**199**
Apr	215	214	102	183	**179**
May	215	232	120	185	**188**
Jun	275	271	139	234	**230**
Jul	365	303	181	295	**286**
Aug	314	274	187	239	**254**
Sep	354	292	208	262	**279**
Oct	238	219	150	189	**199**
Nov	256	222	184	196	**215**
Dec	315	244	215	227	**250**
Total	**3487**	**3125**	**1944**	**2768**	**2831**

From the simulations 1 to 20, one can understand that, Kitchen has the least thermal comfort hours during the months of February to June.

Table 6: Before retrofitting simulation with mechanical ventilation only
Source: Author

Simulation 1 - Windows and Doors Closed / Mech Vent On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	385	330	203	303	**212**
Feb	273	288	140	238	**166**
Mar	176	198	116	189	**123**
Apr	168	187	102	183	**117**
May	211	230	120	186	**135**
Jun	269	276	133	232	**162**
Jul	371	310	178	296	**202**
Aug	323	281	188	248	**183**
Sep	358	295	207	269	**198**
Oct	209	204	148	190	**135**

Nov	255	231	186	195	**154**
Dec	334	260	227	242	**186**
Total	**3332**	**3090**	**1948**	**2771**	**2785**

Table 7: Before retrofitting simulation with no ventilation mode
Source: Author

Simulation 1 - Windows and Doors Closed / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	385	330	198	310	**213**
Feb	262	285	135	238	**162**
Mar	168	192	115	191	**120**
Apr	154	180	98	181	**112**
May	205	223	115	188	**132**
Jun	265	274	131	232	**160**
Jul	373	312	177	296	**203**
Aug	323	280	185	246	**182**
Sep	359	298	207	270	**199**
Oct	199	204	149	190	**133**
Nov	250	232	188	198	**154**
Dec	336	261	229	249	**188**
Total	**3279**	**3071**	**1927**	**2789**	**2767**

Table 8: Before retrofitting simulation with only natural ventilation.
Source: Author

Simulation 1 - Windows and Doors Open / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	390	330	244	305	**220**
Feb	313	291	169	257	**181**
Mar	241	239	145	197	**146**
Apr	221	217	134	188	**137**
May	215	230	146	185	**139**
Jun	265	271	158	228	**164**
Jul	366	302	199	294	**203**
Aug	315	270	196	238	**180**
Sep	353	291	212	264	**196**
Oct	239	222	169	194	**147**
Nov	256	221	201	189	**154**
Dec	335	259	255	242	**191**
Total	**3509**	**3143**	**2228**	**2781**	**2815**

Table 9: Retrofitting with additional windows for cross ventilation with only natural ventilation.
Source: Author

Simulation 2 - Windows and Doors Open / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	390	330	244	306	**221**
Feb	313	288	168	248	**179**
Mar	235	233	142	193	**143**
Apr	217	213	131	181	**134**
May	207	212	141	180	**133**
Jun	261	253	155	223	**159**
Jul	367	306	195	290	**203**
Aug	310	274	193	234	**178**
Sep	354	293	208	260	**196**
Oct	238	216	166	189	**144**
Nov	254	219	202	190	**153**
Dec	335	260	254	245	**191**
Total	**3481**	**3097**	**2199**	**2739**	**2879**

Table 10: Retrofitting with additional windows for cross ventilation with hybrid ventilation.
Source: Author

Simulation 2 - Windows and Doors open / Mechanical ventilation On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	391	329	246	302	**220**
Feb	313	290	169	250	**179**
Mar	239	236	143	194	**145**
Apr	219	215	131	183	**135**
May	215	229	141	181	**138**
Jun	267	270	156	224	**163**
Jul	365	302	195	293	**202**
Aug	315	270	195	236	**179**
Sep	353	291	209	259	**195**
Oct	239	220	166	191	**146**
Nov	255	218	200	191	**153**
Dec	333	258	255	241	**190**
Total	**3504**	**3128**	**2206**	**2745**	**2896**

Table 11: Retrofitting with additional windows for cross ventilation with mechanical ventilation only
Source: Author

Simulation 2 - Windows and Doors Closed / Mech Vent On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	385	330	204	303	**213**
Feb	272	283	134	230	**162**
Mar	176	197	114	186	**122**
Apr	168	185	102	179	**116**
May	211	223	120	184	**133**
Jun	268	275	132	228	**160**

Jul	372	311	174	294	**202**
Aug	322	279	185	243	**181**
Sep	358	296	204	266	**197**
Oct	208	203	149	189	**134**
Nov	255	230	186	192	**153**
Dec	334	262	228	244	**187**
Total	**3329**	**3074**	**1932**	**2738**	**2768**

Table 12: Retrofitting with additional windows for cross ventilation with no ventilation
Source: Author

Simulation 2 - Windows and Doors Closed / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	386	330	200	308	**213**
Feb	261	278	131	228	**159**
Mar	157	180	113	186	**115**
Apr	130	160	96	174	**103**
May	188	198	111	180	**123**
Jun	247	254	130	224	**152**
Jul	372	315	174	290	**202**
Aug	316	284	184	240	**181**
Sep	358	301	199	267	**197**
Oct	194	195	149	188	**131**
Nov	248	230	187	195	**153**
Dec	336	263	228	252	**189**
Total	**3193**	**2988**	**1902**	**2732**	**2704**

Table 13: Retrofitting simulation with introducing pocket courtyard for stack ventilation with only natural ventilation
Source: Author

Simulation 3 - Windows and Doors Open / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	390	330	244	304	**220**
Feb	313	288	168	250	**179**
Mar	236	233	143	195	**144**
Apr	217	213	130	181	**133**
May	207	213	139	180	**133**
Jun	260	255	155	222	**159**
Jul	367	306	194	288	**202**
Aug	311	274	192	234	**178**
Sep	353	293	208	261	**196**
Oct	238	217	166	186	**144**
Nov	254	219	201	189	**153**
Dec	335	260	255	244	**191**
Total	**3481**	**3101**	**2195**	**2734**	**2878**

Table 14: Retrofitting simulation with introducing pocket courtyard for stack ventilation with no ventilation.
Source: Author

Simulation 3 - Windows and Doors Closed / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	385	330	198	310	**213**
Feb	262	285	135	238	**162**
Mar	168	192	115	191	**120**
Apr	154	180	98	181	**112**
May	205	223	115	188	**132**
Jun	265	274	131	232	**160**
Jul	373	312	177	296	**203**
Aug	323	280	185	246	**182**
Sep	359	298	207	270	**199**
Oct	199	204	149	190	**133**
Nov	250	232	188	198	**154**
Dec	336	261	229	249	**188**
Total	**3279**	**3071**	**1927**	**2789**	**2767**

Table 15: Retrofitting simulation with introducing pocket courtyard for stack ventilation with only mechanical ventilation
Source: Author

Simulation 3 - Windows and Doors Closed / Mech Vent On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	385	330	201	303	**212**
Feb	266	282	134	232	**161**
Mar	167	187	112	184	**118**
Apr	145	169	102	177	**109**
May	194	206	117	179	**126**
Jun	252	258	132	225	**154**
Jul	371	314	173	290	**201**
Aug	317	284	185	240	**181**
Sep	359	300	202	266	**198**
Oct	198	199	149	187	**132**
Nov	254	231	188	193	**154**
Dec	334	261	229	243	**187**
Total	**3242**	**3021**	**1924**	**2719**	**2727**

Table 16: Retrofitting simulation with introducing pocket courtyard for stack ventilation with hybrid ventilation
Source: Author

Simulation 3 - Windows and Doors open / Mechanical ventilation On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	391	329	246	303	**220**
Feb	313	290	170	250	**180**
Mar	235	233	144	194	**144**
Apr	217	213	130	181	**133**
May	209	215	139	179	**134**
Jun	261	257	156	222	**159**

Jul	365	305	194	290	**202**
Aug	311	274	192	233	**178**
Sep	353	291	209	260	**195**
Oct	237	216	165	186	**144**
Nov	253	219	199	189	**153**
Dec	333	258	255	240	**190**
Total	**3478**	**3100**	**2199**	**2727**	**2876**

Table 17: Simulation with cool roof paint with only hybrid ventilation
Source: Author

Simulation 4 - Windows and Doors open / Mechanical ventilation On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	391	329	246	304	**221**
Feb	313	289	169	256	**180**
Mar	236	234	145	196	**145**
Apr	217	213	134	188	**135**
May	211	219	146	185	**137**
Jun	263	263	161	228	**162**
Jul	366	304	201	294	**204**
Aug	312	272	196	240	**180**
Sep	354	291	212	265	**197**
Oct	238	219	168	194	**146**
Nov	254	221	200	189	**153**
Dec	333	257	255	238	**190**
Total	**3488**	**3111**	**2233**	**2777**	**2902**

Table 18: Simulation with cool roof paint with only mechanical ventilation
Source: Author

Simulation 4 - Windows and Doors Closed / Mech Vent On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	385	330	203	305	**213**
Feb	266	283	140	237	**163**
Mar	168	190	116	190	**120**
Apr	148	169	102	180	**110**
May	196	210	120	186	**129**
Jun	253	263	132	229	**156**
Jul	371	312	178	294	**202**
Aug	318	281	187	245	**182**
Sep	359	300	207	269	**199**
Oct	198	198	148	189	**132**
Nov	254	230	187	195	**154**
Dec	334	260	228	243	**187**
Total	**3250**	**3026**	**1948**	**2762**	**2747**

Table 19: Simulation with cool roof paint with no ventilation
Source: Author

Simulation 4 - Windows and Doors Closed / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	386	330	198	310	**213**
Feb	262	283	135	238	**162**
Mar	158	183	115	193	**118**
Apr	131	164	96	178	**105**
May	189	207	115	185	**126**
Jun	248	261	131	229	**155**
Jul	373	315	177	294	**203**
Aug	316	283	185	245	**181**
Sep	359	301	206	271	**199**
Oct	194	197	149	189	**131**
Nov	249	231	188	198	**154**
Dec	336	261	229	250	**188**
Total	**3201**	**3016**	**1924**	**2780**	**2730**

Table 20: Simulation with cool roof paint with only natural ventilation
Source: Author

Simulation 4 - Windows and Doors Open / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	390	330	244	306	**221**
Feb	313	289	169	256	**180**
Mar	236	234	145	197	**145**
Apr	217	213	134	188	**135**
May	208	218	146	188	**137**
Jun	261	262	159	228	**162**
Jul	367	305	200	293	**204**
Aug	312	273	197	238	**180**
Sep	353	293	212	265	**197**
Oct	238	220	169	194	**146**
Nov	254	221	202	189	**154**
Dec	335	259	255	242	**191**
Total	**3484**	**3117**	**2232**	**2784**	**2904**

Table 21: Simulation with cross ventilating windows, stack ventilating courtyard and cool roof paint with only natural ventilation
Source: Author

Simulation 5 - Windows and Doors Open / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	390	330	243	303	**220**
Feb	311	289	166	243	**177**
Mar	236	234	140	191	**143**
Apr	216	211	129	177	**132**
May	206	207	138	174	**131**

Jun	257	251	154	220	**157**
Jul	367	308	188	283	**201**
Aug	310	277	191	233	**178**
Sep	355	297	206	257	**196**
Oct	239	213	165	188	**144**
Nov	254	221	200	190	**153**
Dec	335	261	255	244	**192**
Total	**3476**	**3099**	**2175**	**2703**	**2863**

Table 22: Simulation with cross ventilating windows, stack ventilating courtyard and cool roof paint with no ventilation
Source: Author

Simulation 5 - Windows and Doors Closed / Mechanical ventilation turned off					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	386	330	199	307	**213**
Feb	260	275	128	221	**156**
Mar	156	180	111	180	**114**
Apr	129	152	95	171	**101**
May	183	196	113	174	**121**
Jun	241	249	128	219	**149**
Jul	369	316	167	280	**199**
Aug	314	284	183	238	**180**
Sep	357	302	198	262	**196**
Oct	196	193	147	188	**130**
Nov	250	231	187	198	**154**
Dec	336	266	228	253	**190**
Total	**3177**	**2974**	**1884**	**2691**	**2682**

Table 23: Simulation with cross ventilating windows, stack ventilating courtyard and cool roof paint with only mechanical ventilation
Source: Author

Simulation 5 - Windows and Doors Closed / Mech Vent On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	386	330	202	304	**213**
Feb	264	281	130	223	**159**
Mar	168	187	113	179	**117**
Apr	145	165	100	173	**107**
May	190	199	117	175	**124**
Jun	243	252	132	220	**151**
Jul	369	315	168	280	**199**
Aug	316	284	183	240	**180**
Sep	358	300	198	263	**196**
Oct	198	198	147	186	**131**
Nov	254	233	184	194	**153**
Dec	334	262	229	248	**188**
Total	**3225**	**3006**	**1903**	**2685**	**2705**

Table 24: Simulation with cross ventilating windows, stack ventilating courtyard and cool roof paint with hybrid ventilation
Source: Author

Simulation 5 - Windows and Doors open / Mechanical ventilation On					
Months	**Bedroom 1**	**Bedroom 2**	**Kitchen**	**Living Hall**	**Average**
Jan	391	329	245	299	**220**
Feb	310	288	167	243	**177**
Mar	235	233	141	191	**143**
Apr	217	211	129	177	**132**
May	208	210	138	174	**132**
Jun	255	250	154	219	**156**
Jul	366	307	188	282	**200**
Aug	309	277	191	233	**178**
Sep	355	297	206	255	**195**
Oct	238	211	164	187	**143**
Nov	253	221	197	190	**153**
Dec	333	261	256	239	**191**
Total	**3470**	**3095**	**2176**	**2689**	**2858**

Upon analyzing all 20 simulations, it becomes evident that Bedroom 1 achieves the highest thermal comfort hours annually, totalling 3509, relying solely on natural ventilation. Conversely, the kitchen records the lowest thermal comfort hours, registering 1884 hours per year without any form of ventilation. A room-wise breakdown reveals that in the Bedroom 1, situated in the Southwest, the 1st and 2nd types of simulations under natural and hybrid ventilation modes yield the maximum thermal comfort hours. Conversely, the 2nd and 5th types of retrofit simulations under no ventilation conditions result in the minimum comfort hours due to inadequate natural ventilation and increased heat trapping from west-facing sunlight.

Similar trends are observed in the Bedroom 2, located in the South. For the kitchen, the 4th type of retrofit simulation under hybrid and natural ventilation conditions exhibits the maximum thermal comfort hours. The kitchen's discomfort in other scenarios, especially in the 2nd and 5th types of simulations under no ventilation, is attributed to its significant exterior walls on the Southeast, leading to heat trapping exacerbated by cooking activities.

The living room, a space where occupants spend a substantial time, attains its highest thermal performance in the 1st and 3rd types of simulations without any ventilation. This is attributed to the open space in the living room, reducing heat trapping. Paradoxically, the thermal performance is lowest in the 5th type of simulation with mechanical ventilation and hybrid mode. This is due to the courtyard space and open doors and windows causing temperatures to fall below acceptable indoor levels during winter months, resulting in discomfort.

Figure 3 compares the five types of simulations under different ventilation modes for further analysis.

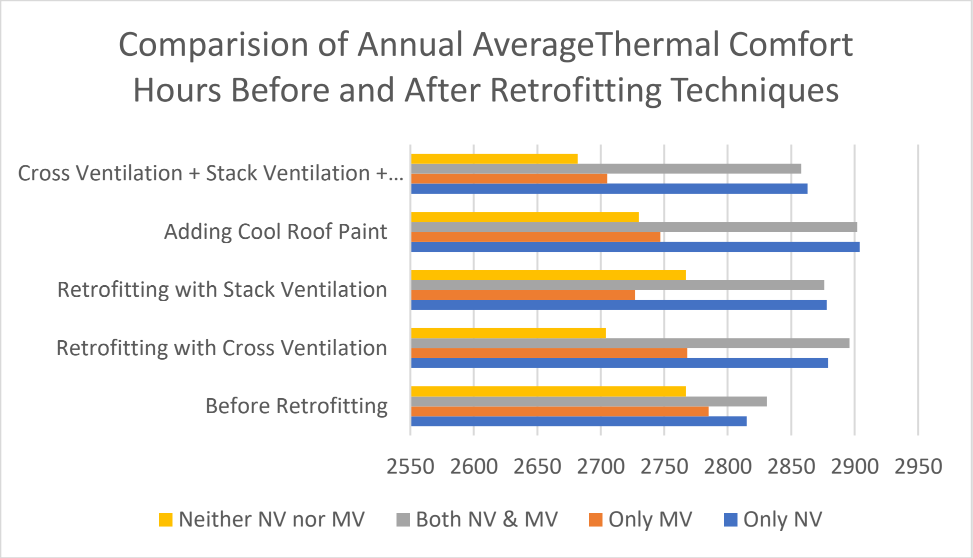

Fig. 3: Comparative analysis for the annual thermal comfort hours in various retrofitting techniques and different mode of ventilation
Source: Author

Conclusion

The analysis of 20 simulations yields valuable insights into the thermal performance of distinct spaces within the residence under various ventilation conditions. Bedroom 1 emerges as the most thermally comfortable space, primarily relying on natural ventilation, while the kitchen faces challenges with the lowest thermal comfort hours due to specific architectural characteristics and heat-trapping issues. This breakdown by room underscores the importance of ventilation strategies, with Bedrooms 1 and 2 benefiting from well-designed natural ventilation, and the kitchen relying on natural ventilation for optimal performance.

The thermal performance of the living room presents an intriguing paradox, with the highest comfort hours observed in simulations without any ventilation, but a counter-intuitive decrease in comfort with mechanical ventilation and hybrid modes. This underscores the nuanced dynamics of open spaces and emphasizes the need for thoughtful consideration in incorporating ventilation strategies.

The study highlights the critical role of natural ventilation in achieving thermal comfort, especially in spaces with specific orientations and heat-trapping challenges. The insights offer valuable guidance for architects, builders, and homeowners in optimizing thermal comfort through strategic ventilation design. While focused on a specific residence, the study contributes to the broader discourse on sustainable design practices, providing actionable insights for creating energy-efficient and comfortable living environments, although case study findings are not generalizable.

Acknowledging limitations, including a focus on a warm humid climate, single residences smaller than 1100 sq.ft, and an exclusive analysis of the ground floor, is essential. Adding to these findings, other research indicates that the choice of roof design can significantly impact thermal performance, with Gable roofs proving more efficient in ventilating hot air (Noithapthim et al., 2023). Design factors such as the optimal area and number of openings, as highlighted by Ibrahim and Hassan (2023), and the ratio of openings, as emphasized by Werdiningsih et al. (2023) play crucial roles in influencing thermal performance. Cultural practices, such as window repetition in Indonesia also contribute to enhanced thermal efficiency (Nugroho et al., 2023). Moreover, as Ahmed and Al Ali, (2023) points out, the integration of climate-responsive design in restored traditional buildings influences occupants' psychological behavior. Residences with a perimeter-area ratio of 0.8:0.65 exhibit superior thermal comfort, as suggested by Srivastava and Das (2023). Building floor height also proves influential, as mentioned by Guntur et al. (2023). Additionally, simulations conducted by Mansour et al. (2023) demonstrate that introducing a 3mm nano coating on building walls can significantly reduce heat flux by up to 52%.

Future research could explore broader parameters for a more comprehensive understanding of thermal dynamics in diverse residential settings, with further exploration and refinement of passive design strategies, considering seasonal variations and occupancy patterns, to enhance the overall effectiveness of residential spaces.

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