



SUSTAINABILITY OF CROSS-LAMINATED TIMBER (CLT) NUSANTARA HOUSE BASED ON THERMAL COMFORT INDICATORS USING SIMULATION METHOD

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Abstract

Cross-laminated timber (CLT) Nusantara is a building model constructed to achieve the vision of a sustainable house for Indonesia. The integrated evaluation strategy of sustainable habitat systems suggests that the sustainability value can be increased through increased welfare in comfort aspect. Thermal comfort has not been measured in this building, but can be potentially improved. Therefore, this research aims to evaluate the sustainability value of CLT Nusantara building from the perspective of thermal comfort and the potential for enhancing the sustainability value of building design aspects. The adopted method used field measurements and simulation through an adaptive thermal comfort model. The results showed that the percentage of hours experiencing 'hot' conditions was more prevalent during operational hours. The design method exerted a significant influence on the augmentation of 'comfortable' hours. The addition of windows provided opportunities for air entry to increase 'comfortable' hours among the several designs applied in simulation. The shape and orientation of building had the potential to enhance 'comfortable' hours. CLT served as a building material based on the comparison applied in simulation.

Keywords: Sustainability; Thermal Comfort; CLT

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INTRODUCTION

Efforts to mitigate global warming through net-zero carbon have been considered by several countries (Morris et al., 2023), such as Indonesia (Indonesia LTS-LCCR 2050, 2021). The utilization of renewable resources assumes significant importance, considering the capacity to sequester carbon over extended periods (Köhl & Martes, 2023) and lower emissions (Craig et al., 2021). Cross-laminated timber (CLT) is a rigid, slab-shaped product comprising boards/lamellas placed adjacent (Jeleč et al., 2018). This technology poses several advantages regarding mechanical properties, earthquake resistance, and potential as an alternative to concrete or stone (Jeleč et al., 2018; Sandoli et al., 2021). The expense is minimal and the environmental effect is negligible (Bahrami et al., 2021). CLT technology represents a recent innovation for Indonesia, but wood is widely found in Indonesia (Huzairin & Andini, 2022). However, research on CLT potential utilization shows that a significant opportunity has been presented as a sustainable building material (Corpataux et al., 2020).

The development potential of CLT and the efforts to achieve the vision of sustainable housing led to the construction of a building made from CLT Nusantara House. The material used for this purpose is primarily composed of acacia wood. The selection of wood species is determined by several factors, including mechanical and physical capabilities (Mohd Yusof et al., 2019) as well as the availability of local wood species (Corpataux et al., 2020). Building has been designed with various technologies to support the achievement of sustainability goals.

Sustainability in a habitat system can be assessed based on the level of reduction in environmental damage and the quality of life or welfare (Hayashi et al., 2005; Kusumawanto & Astuti, 2014; Matsufuji et al., 2004). The utilization of CLT materials necessitates an evaluation from the perspective of 'welfare,' which includes various factors. An important aspect is comfort level, which serves as a crucial element in sustainable habitat systems. The characteristics of a tropical climate with high temperature and humidity levels are different from the regions where CLT technology was first developed (Brandner et al., 2016). Thermal comfort of CLT Nusantara House building must be assessed. Thermal comfort is also recognized as a factor in determining welfare of building occupants (Li et al., 2021) and as an indicator of the sustainability of a habitat system. Therefore, this research evaluates the sustainability performance of CLT Nusantara building at Gadjah Mada University's Faculty of Engineering from thermal comfort perspective since the assessments remain unexplored. The evaluation focuses on the aspects of the current building conditions and the optimization of the design factors to enhance thermal comfort generated. The results can serve as a valuable reference point in the development of sustainable housing in Indonesia to improve sustainability value.

LITERATURE REVIEW

Sustainable Habitat System

Hayashi et al. (2005) stated that an integrated evaluation strategy for evaluating sustainable habitat systems could be used to reduce environmental damage while maintaining an optimal level of modern quality of life. In the pursuit of enhancing the value of sustainability, concerted efforts are carried out to optimize throughput (T) by augmenting welfare (W) and mitigating environmental damage (D). Furthermore, integrated evaluation uses the 'throughput formula', where T (throughput) is the result of W (welfare) minus D (environmental damage). Welfare includes safety (Sa), relief (R), health (H), comfort (C), and sense (Se). Environmental damage comprises life cycle energy, CO₂, and cost. This formulation can be used and developed to evaluate and manage sustainable habitat system development (Kusumawanto & Astuti, 2014; Matsufuji et al., 2004). Welfare, consisting of several indicators, is achieved when humans and the environment have a supportive and dependent relationship (Abu Bakar et al., 2017). The environment that affects thermal comfort is an important factor influencing the level of welfare (Li et al., 2021).

Adaptive Thermal Comfort

The adaptive model is a method that predicts thermal comfort of occupants (Solano et al., 2021). The model is considered to help design low-energy consumption building. An adaptive thermal comfort model considers local environmental factors and has an adaptive mechanism (Lakhier et al., 2024; Yau & Chew, 2014). American Society of Heating, Refrigerating, and Air-Conditioning Engineers (2017) stated that the operating temperature acceptable to the adaptive comfort model depended on the prevailing mean outdoor air temperature ($t_{pma(out)}$). For the upper and lower 80% acceptance limit, the operating temperature values are obtained from $t_{pma(out)} \times 0.31 + 21.3$ and $t_{pma(out)} \times 0.31 + 14.3$, respectively.

Effect of Building Factors

The design of a building has a significant influence on thermal comfort. The materials used in the construction also have a great impact on comfort level of building. Design factors such as building height, materials, openings, and ventilation can influence thermal comfort of a building (Ariffin, 2015; Pramesti et al., 2021; Zain et al., 2007; Zulkeply et al., 2023). Meanwhile, cladding and opening are design elements considered in the context of CLT building (Husain et al., 2020).

RESEARCH METHODOLOGY

This research used field measurements to evaluate thermal comfort. Further evaluation was carried out by simulation to predict thermal comfort conditions of building for a year. In this context, the design factors were changed from the existing conditions to determine the effect on thermal comfort in building visually represented in Figure 1.

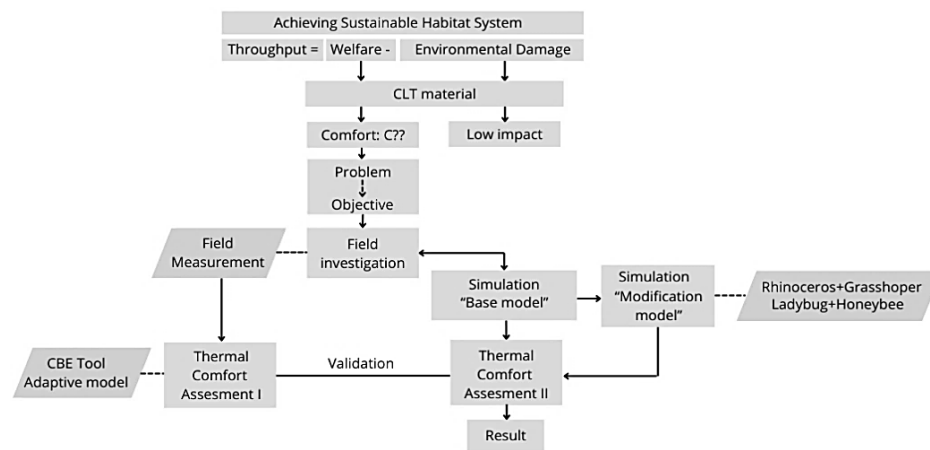


Figure 1: Schematic of Research Methods

Description of Building Model

CLT Nusantara building was located in the Faculty of Engineering campus area of Gadjah Mada University, Yogyakarta, Indonesia, at coordinates -7.765611 LS and 110.371510 BT. The construction of building primarily used CLT materials composed of acacia wood for the walls, ceilings, and floors as shown in Figure 2. In addition, CLT was planned using a 3-layered modular system. Building, with an approximate area of 27 m², was hexagonal and adapted to the modular dimensions of CLT material (1.2m x 2.4m per module). Various components, such as windows and terrace floors, were constructed using Bengkirai wood materials. The roof and foundation were built using a wooden roof truss with a bitumen cover and reused concrete materials from the local area, respectively. Building was designed to use natural ventilation located on the southeast and southwest sides.

Measurement Method

This research used two data collection stages, namely direct field measurement and simulation. Simulation was used as a tool to provide an overview of thermal comfort over a full year and examine the design factors affecting the performance

in CLT Nusantara. Field measurement results functioned as a validation tool for simulation used.

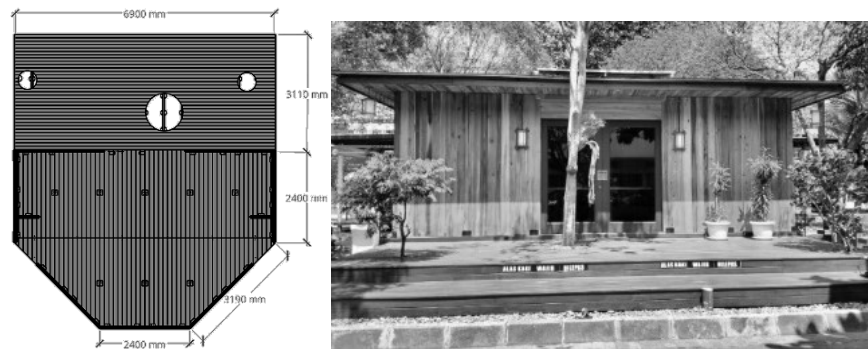


Figure 2: Plan and View of the North Facade of CLT Nusantara Building
Source: Photograph taken by the Authors, 2024

The climatic conditions of field measurements of the outdoor room were conducted from 19 October 2024 to 25 October 2024 for 24 hours over 7 days. The measurement of thermal environmental conditions was carried out during the operational hours, from 08:00 am to 4:00 pm, for 2 days. Subsequently, indoor measurements were taken to obtain air temperature, mean radiant temperature, and air speed in the room. Outdoor microclimate measurements were also conducted to obtain the prevailing mean outdoor temperature. The measurement equipment used for this purpose can be observed in Figure 3 and Table 1. The facility of the laboratory was calibrated regularly to ensure the accuracy of the measurements.

Simulation Method

Simulation used Grasshopper and Rhinoceros modeling software with Ladybug and Honeybee plugins. EPW weather data, which contained air temperature and wind speed in 5 years (2017-2021), from Adi Sutjipto monitoring station, Yogyakarta, was used in simulation. Thermal conductivity data of Acacia wood material were obtained using the results of existing research (Prasojo & Sulisty, 2010).

Data Analysis

Thermal comfort analysis was conducted using an adaptive thermal comfort index model since CLT Nusantara Building was designed to maximise natural ventilation and empower residents to engage in adaptive mechanisms. Field measurements were analyzed using tools developed by the Centre for the Built

Environment (CBE). Based on field measurement, simulation results are validated based on field measurement. Design factors affecting thermal comfort were also modified through simulation, and the results were compared with the base model to ascertain the effect.



Figure 3: Measurement of Microclimate of Outdoor and Thermal Environment of Indoor
Source: Photograph taken by the Author, 2024

Table 1: Specifications of Measurement Equipment.

Specifications	Type	Range of Measurements	Accuracy
Thermometer and Hygrometer (Indoor)	Hobo MX Analog/Temp/RH/Light Logger 1104	-20° to 70°C (-4° to 158°F)	±0.20°C from 0° to 50°C (±0.36°F from 32° to 122°F)
Anemometer (Indoor)	Pitot Tube Anemometer and Differential Manometer Exttech advantage HD350	Air Velocity: 1 to 80.00 m/s	Air Velocity: ±1% full scale
WBGT (Indoor)	Lutron WBGT-208- Heat Index and WBGT Meter	Solar radiation: 0 to 1999 W/m ²	Air temperature: ±0.8°C (±1.5°F) air humidity: ±3% RH
Weather station (outdoor)	Hobo RX3000	-40° to 60°C	±8 seconds per month in 0° to 40°C range; ±30 seconds per month in -40° to 60°C range

Source: (Flir, 2024; HOBO, 2024, 2024)

ANALYSIS AND DISCUSSION

Sustainable Assessment

The evaluation of the sustainability of CLT Nusantara House uses a tool developed for evaluating and managing sustainable habitat system development (Kusumawanto & Astuti, 2014; Matsufuji et al., 2004). In CLT Nusantara building, the environmental impact was found to be minimal. Building applies

net zero energy, uses smart light control to regulate the lighting level of LED lights, and adopts an Internet of Things (IoT) smart garden to control the watering of facade plants. CLT Nusantara building is also operated by maximizing natural ventilation, hence, the energy life cycle is considered low.

Building material used for most of the components is CLT made from Acacia wood. This wood has a very low carbon footprint compared to other construction materials that produce higher carbon emissions (Craig et al., 2021). The foundation materials utilize recycled materials, hence, the life cycle carbon of building is low. In this context, construction costs can be minimized since Acacia is a local timber. The connection system with locally produced steel plates also lowers construction costs.

Increasing welfare of CLT Nusantara House (Safety: Sa, Relief: R, Health: H, Comfort: C, Sense: Se) can maximize the sustainability value. The value of comfort must be improved to realize the vision of sustainable housing development.

Results of Field Investigations

Measurements made for 7 days of microclimate conditions in CLT Nusantara building area show temperature fluctuations in the range of 22.87°C to 34.05°C as shown in Figure 4. The peak temperature value occurs at 13.30 to 14.30 WIB, which decreases in the following hours. The average daily temperature based on the measurement results is 27.39°C . The measured wind speed in the area is in the range of 0.5 m/s from the South.

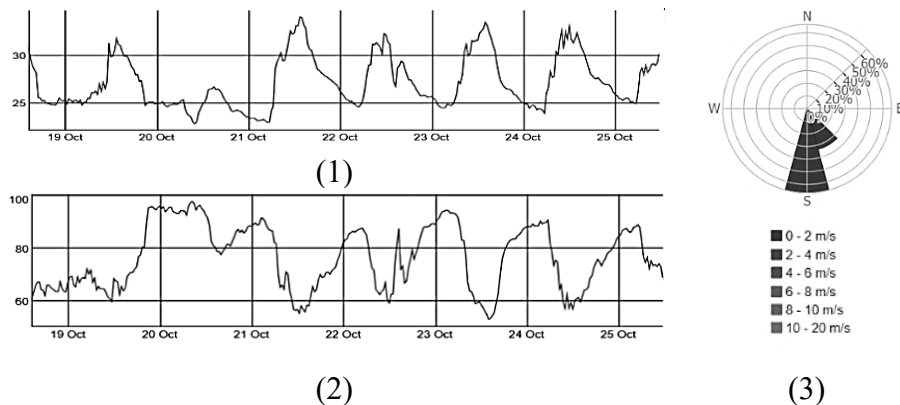


Figure 4: Microclimate Measurement Results: Temperature (1), Relative humidity (2), and Windrose (3)

Source: Author's field data

The results of measuring thermal environment during the operational hours (08.00 a.m. to 4.00 p.m.) of CLT Nusantara House show that the peak temperature is around 2:20 p.m. The measured air and globe temperatures are in the range of 27.03°C to 34.06°C and 27.8°C to 34.1°C, respectively. Meanwhile, the air velocity in the measured room is in the range of 0.25-2 m/s.

CBE thermal comfort tool analysis shows that comfort during operational hours occurs before 10.00 WIB. The times until the end of the operational hours show that the room is 'too hot.' The percentage of hours experiencing 'comfortable' conditions compared to 'too hot' in operational hours is 27.27% and 72.73%. Based on further analysis, the percentage value of 'too hot' can be increased to 'comfortable' conditions by 6.06% through an increase in air speed from 0.3 to 1.2 m/s.

Thermal Comfort Simulation and Validation

Simulation results for the base model of CLT Nusantara building (Table 2), report that the average annual indoor and operative temperatures are 27.28°C and 27.42°C, respectively. Based on an evaluation over a year, 56.92% of the room conditions are in a 'comfortable' state. The onset of the 'hot' condition is observed to occur at 09.00 am or 10.00 am, with the cessation occurring at 05.00 pm visually represented in Figure 5. During operational hours (08.00 am to 4.00 pm), 33.64% and 66.36% are in 'comfortable' and 'hot' conditions. Therefore, the prevalence of 'hot' conditions was predominantly during operational hours compared to the entire day.

Table 2: Thermal Conditions of the Base Model of CLT Nusantara Building.

Variabel	Value
Mean operative temperature (°C)	27.42
Mean air temperature (°C)	27.28
Mean radiant temperature (°C)	27.57
Time in Comfort (%) during 24 hours	56.92
Time in Hot (%) during 24 hours	39.28
Time in Cold (%) during 24 hours	3.80
Time in Comfort (%) during operational hours	33.64
Time in Hot (%) during operational hours	64.93
Time in Cold (%) during operational hours	1.43

Source: Author's simulation data

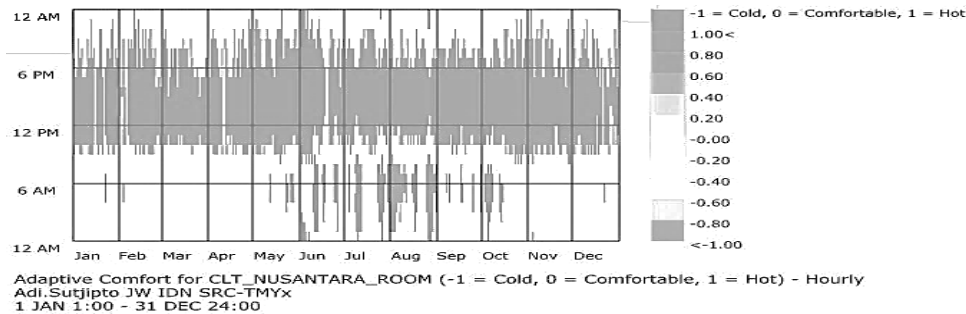


Figure 5: Adaptive Model Thermal Comfort Conditions for 1 Year
Source: Author's simulation data

This simulation shows conditions identical to field measurements and the results of the analysis. The onset of 'hot' conditions occurs at 10.00 am, with 'comfortable' hours reaching a value of 27.27%. These results show conformity with the analysis of thermal comfort conducted based on the results of field measurements.

Results of Simulation for Modified Design Factors

The design factors refer to previous literature, which include shading devices, building height and windows, materials, and building forms.

Shading Device Addition

The installation of shading devices on CLT Nusantara building includes the construction of a roof on the terrace and the roof extension. As the data in Table 3 clearly indicate, the addition of a roof on the north side in an area of 21,459 m² enhances thermal comfort by 57.60% and 34.40% in the 24-hour state and during operational hours, respectively. The modifications, affecting changes in percentages of less than 1% by the addition of the terrace or extension of the roof, can be considered insignificant to the increase in thermal comfort.

Table 3: Thermal Comfort Condition with Shading Modification

Model	Time 24 hours			Operating hours		
	Time Comfort (%)	in Hot (%)	Cold (%)	Time Comfort (%)	in Hot (%)	Cold (%)
Base Model	56.92	39.28	3.80	33.64	64.93	1.43
Modifications						
Terrace roof addition	57.60	38.52	3.88	34.40	63.93	1.67
	Increase/Decrease in Comfort Hours (%)					
	0.68	-0.76	0.08	0.76	-1.00	0.24
	Increase	Decrease	Increase	Increase	Decrease	Increase
Extension of the roof (+50 cm)	57.87	38.36	3.78	34.64	63.87	1.40
	Increase/Decrease in Comfort Hours (%)					
	0.95	-0.92	-0.02	1.00	-1.07	0.06
	Increase	Decrease	Decrease	Increase	Decrease	Increase

Source: Author's calculation

Window and Building Height Addition

The alterations include the addition of windows installed in one-third of the wall area on the south, east, and west sides. The selected additional window can be opened and closed. Simulation results show that the modifications increase thermal comfort by 6.03% and 7.12% in the 24-hour state and during operational hours, respectively. Furthermore, as the data in Table 4 clearly indicate, increasing building height from 2.4 to 3.6 m favors the time in comfort percentage for 24 hours and during operational hours by 1.85% and 1.92%, respectively.

Table 4: Thermal Comfort Conditions with Modified Openings

Model	Time 24 hours			Operating hours		
	Time Comfort (%)	in Hot (%)	Cold (%)	Time Comfort (%)	in Hot (%)	Cold (%)
Base Model	56.92	39.28	3.80	33.64	64.93	1.43
Modifications						
Window additions	62.95	30.14	6.92	40.76	57.29	1.95
	Increase/Decrease in Comfort Hours (%)					
	6.03	-9.14	3.12	7.12	-7.64	0.52
	Increase	Decrease	Increase	Increase	Decrease	Increase
Building height	58.77	35.70	5.54	35.56	62.59	1.86
	Increase/Decrease in Comfort Hours (%)					
	1.85	-3.58	1.74	1.92	-2.34	0.43
	Increase	Decrease	Increase	Increase	Decrease	Increase

Source: Author's calculation

Material Modifications

The materials are modified by changing the thickness of the walls, which are changed to 25 mm and 125 mm. The wall material is also changed to 100 mm bricks with two-sided plastering of 15 mm each. Simulation results show that decreasing and increasing the wall and CLT thickness reduce and improve the percentage of total ‘comfortable’ hours, respectively. Changes to the wall material by replacing with brick show an increase in ‘comfortable’ hours from the results presented in Table 5.

Table 5: Thermal Comfort with Modified Wall Materials

Model	Time 24 hours			Operating hours		
	Time Comfort (%)	in Hot (%)	Cold (%)	Time Comfort (%)	in Hot (%)	Cold (%)
Base Model	56.92	39.28	3.80	33.64	64.93	1.43
Modifications						
Wood (25 mm)	53.60	37.63	8.78	23.87	75.22	0.91
	Increase/Decrease in Comfort Hours (%)					
	-3.32	-1.66	4.98	-9.77	10.29	-0.52
	Decrease	Decrease	Increase	Decrease	Increase	Decrease
CLT (125 mm)	59.54	38.74	1.71	36.01	63.32	0.67
	Increase/Decrease in Comfort Hours (%)					
	2.63	-0.54	-2.09	2.37	-1.61	-0.76
	Increase	Decrease	Decrease	Increase	Decrease	Decrease
Brick plaster	60.89	36.45	2.66	37.72	61.25	1.04
	Increase/Decrease in Comfort Hours (%)					
	3.97	-2.83	-1.14	4.08	-3.68	-0.40
	Increase	Decrease	Decrease	Increase	Decrease	Decrease

Source: Author's calculation

Building Form Modifications

Modifications to building form can investigate the sustainability potential of wider application of CLT materials. A total of three roof forms, as shown in Figure 6, with the same building mass volume were simulated with different aspect ratios of 1:1, 1:2, 1:3, 3:1, and 2:1 at heights of 2.4 m and 3.6 m.

The use of a gable and hip roof shapes provides a mean percentage of comfortable time of 56.83 % and 56.16 %, with a combination of 54.98 %. The percentage of comfortable time increases when the ratio of length to width is changed to 3:1 and 2:1. Based on building height, ‘comfortable’ hours increase and decrease during operating hours and 24-hour state, respectively.

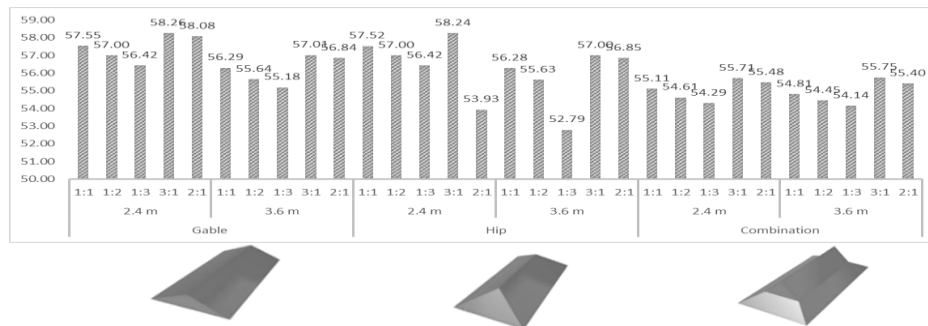


Figure 6: Total Time in Comfort (Over 24 Hours) of Modified Building Forms
Source: Author's simulation data

DISCUSSION

Some modifications to the design factors affect the value of thermal comfort and sustainability of CLT Nusantara building based on an integrated evaluation method of habitat systems (Hayashi et al., 2005; Kusumawanto & Astuti, 2014; Matsufuji et al., 2004). The modifications to building height, shading, materials, openings, and ventilation (Pramesti et al., 2021; Zain et al., 2007; Zulkepely et al., 2023) changed the percentage of 'comfortable' hours with different effects.

The addition of shading changes the percentage of 'comfortable' hours by less than 1%. The modification is influenced by the high-temperature conditions in the area during operational hours. In this research, shading was added on one north side and the entire area for the roof terrace and extension, respectively. Shading in one orientation only shows a lower comfort improvement value. This is because the effectiveness of devices is influenced by building orientation (Lau et al., 2016; Rana et al., 2022).

Modifications to the height of building and the addition of windows have a greater impact on increasing 'comfortable' hours than the addition of shading. The use of windows provides an opportunity for increased air speed to improve thermal comfort with adaptive models. The presence of sufficient air speed enhances comfortable thermal conditions (Zain et al., 2007). The material changes made to CLT Nusantara building provide interesting results. In this context, the thickness of the material influenced the change in the percentage of 'comfortable' hours. Wood possessing a thinner thickness is evaluated with a lower percentage of 'comfortable' hours than thicker types. The result is influenced by the properties of the wood, where thinner types tend to have a lower thermal resistance (R-value). Furthermore, changing CLT wall to a brick increases 'comfortable' hours. The percentage of 'comfortable' hours is close to the value of the brick wall when CLT thickness is increased to 125 mm. Assessment of thermal comfort using adaptive models (Amaripadath et al., 2023) may provide different results from other models with more variables. Therefore,

the optimal thickness to achieve a better comfort value needs to be analyzed using different comfort methods.

Increasing the width-to-depth ratio of building plan from 1:1 to 1:2 and 1:3 decreases the percentage of 'comfortable' hours. This result occurs in roof types and building heights used. Building model places the wall plane width and depth in the north-south and east-west orientations, respectively. The east-west-facing wall plane becomes larger in area when the wall depth ratio is increased. This phenomenon is also observed when the wall depth ratio is decreased to 3:1 and 2:1, showing an increase in the percentage of 'comfortable' hours. The size of the east-west-facing plane influences solar heat gain throughout the day, affecting the percentage of 'comfortable' hours. Therefore, the orientation of building and the area exposed to the sun must be considered since thermal comfort is affected (Ariffin, 2015). This research is subject to certain limitations, namely the restriction of evaluating comfort to a single model. The temporal span of the measurements needs to be addressed by future research, with particular emphasis on the development of field methods.

CONCLUSION

In conclusion, a design method can be taken to improve thermal comfort, impacting the sustainability value of CLT Nusantara building based on an integrated evaluation of sustainable habitat systems. Design aspects supporting the improvement of thermal comfort need to be considered when using CLT materials for building. Furthermore, the ratio of width and thickness of building considers the orientation, planning of windows and openings, and adjustment to the thickness of CLT materials. These materials have the potential to be used as building components in comparison with CLT and brick walls. The addition of windows and selection of the shape and orientation of building increase comfort hours more significantly than other methods. Efforts to enhance the sustainability value of building using CLT need to consider design factors affecting thermal comfort value.

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