*European Journal of Sustainable Development* (2025), **14**, 4, 192-194 ISSN: 2239-5938
*Doi: 10.14207/ejsd.2025.v14n4p192*

# A Historical and Contemporary Perspective: Thermal Comfort in Prefabricated Timber Houses

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**ABSTRACT:**
Timber construction is gaining popularity worldwide due to its advantages over traditional masonry systems, including energy-efficiency, sustainability, and fast prefabrication. The technology of prefabricated timber buildings has evolved significantly, affecting the indoor environmental quality (IEQ) of such buildings, which are generally perceived as offering high living comfort. While contemporary design practices aim to ensure high performance in new buildings, existing timber structures often fail to meet modern standards. In addition to common issues such as ageing, poor energy-efficiency, and functional inadequacies, problems like seismic vulnerability, fire risk, and the so-called "sick building syndrome" are increasingly relevant. As part of the project Indoor Environmental Quality in Prefabricated Timber Houses: A Historical and Contemporary Perspective, funded through the Public Call Problem-Based Learning for Students in a Work Environment 2024–2027, we investigated IEQ in two houses built by the Slovenian manufacturer Marles hiše Maribor d.o.o. The project was carried out in close collaboration with the company. Using long-term measurements, we assessed and compared thermal comfort and other parameters in an older and a newer prefabricated timber house. The findings offer guidance for both the renovation of existing buildings and the design of new ones, emphasising the importance of aligning energy performance with indoor comfort.

*Keywords: Prefabricated Timber Houses, Indoor Environmental Quality (IEQ), Thermal Comfort, Existing Buildings, Sick Building Syndrome*

## 1. Introduction

In the last few years, we have seen an increase of more than 30% in timber housing construction in Slovenia (Delo in dom, 2010). From 2011 to 2018, the number of manufacturers of timber buildings has also increased from 40 to 90 (Polanc, 2020), with annual sales increasing by almost 60%, indicating a strong interest in timber construction in Slovenia. The popularity of timber in residential construction is also evident in other European countries, with as much as 30% of one- and two-family housing in Austria and up to 90% in Scandinavia (Mrevlje, 2015). The rise in the number of timber buildings has also been driven by significant technological advances in timber construction (Premrov & Žegarac Leskovar, 2023). According to Manja Kitek Kuzman and Dick Sandberg (Kitek Kuzman & Sandberg, 2017), in Slovenia, timber construction primarily uses panel-frame, timber-frame, and CLT systems. Over the past 30 years, the sector has evolved significantly. Moreover, prefabricated houses, introduced in the 1970s, already featured

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excellent thermal performance, surpassing even the 2010 regulation limit of 0.28 W/m²K as early as 1992 (Kitek Kuzman & Sandberg, 2017). Today, contemporary timber buildings are not only considered energy-efficient but also very sustainable, as they consume 28% - 47% less embodied energy over their life cycle compared to concrete and steel buildings (Schenk & Amiri, 2022). The growing popularity is also a reflection of the many advantages of timber construction, such as faster construction (prefabrication), recyclability of materials, $CO_2$ sequestration (sustainability), and savings on energy costs (energy-efficiency), as living in a timber building is comfortable for indoor air temperatures from 18 to 20°C, whereas in a solid building it is only from 22 to 24°C, etc. (Ministry of the Economy Tourism and Sport - Wood Industry Directorate, 2020).

A literature search on the indoor environmental quality (IEQ) of timber buildings in the Web of Science (WOS) and Scopus databases found only 26 references (conference and journal articles), of which 8 were excluded due to duplication and 18 were included in the first screening; finally, 8 studies were subsequently included in the final literature review.

An analysis of different timber houses in Slovakia, focusing on LCA analysis and IEQ assessment based on field measurements, concluded that the IEQ in the timber houses poses no significant risk to human health and well-being. (Harcarova et al., 2022; Vilceková et al., 2020). Furthermore, the results of a recent assessment of six CLT-built solid timber houses reveal a very high quality of the indoor environment, with some overheating issues of varied severity (Baborska-Narożny et al., 2023). Among other influences on IEQ, a significant impact of user behaviour has been identified. It is also the activities of building occupants that can be a source of potentially harmful volatile organic compounds (VOCs), as identified in the analysis of two buildings constructed in the timber-frame and logwood construction systems (Vilčeková et al., 2020). Despite the other recognised benefits of wood materials in building interiors, they can also be a potential source of harmful volatile organic compounds (VOCs), which can have a negative impact on IEQ. (Alapieti et al., 2020). IEQ monitoring in a newly constructed Nearly Zero Energy Building (nZEB) (Carletti et al., 2024) highlighted low relative humidity values as a weak point and also identified the important influence of building design (orientation, window-to-wall ratio, and the use of different solar shading devices) on IEQ. The importance of monitoring and ensuring sufficient IEQ is also important in the case of the renovation of existing timber buildings. Current protocols often fail to capture the complex interactions between the technical performance of the envelope, the performance of the building systems, and the behaviour of the occupants, leading to discrepancies between expected and actual performance after renovation (Mirzabeigi et al., 2024). The impact of solid timber buildings on workplace IEQ was investigated using long-term observations in an Australian study (Whyte et al., 2024). Using a mixed-methods behavioural approach, questionnaires, and other IEQ field measurements, the researchers found that working in a timber building can reduce cortisol (stress) levels and have a positive impact on workers' productivity.

From the set of identified references, there seems to be a shortage of research literature on indoor environmental quality (IEQ) specific to prefabricated timber buildings. All included studies were published in 2020 or later, indicating the topical relevance. The studies identified high IEQ in timber buildings but also highlighted potential weaknesses

(VOCs, low relative humidity, overheating occurrence), which can affect the development of sick building syndrome, and indicated other parameters (occupant behaviour, technical systems, building design) that affect IEQ. The studies include buildings that have been in use for some time, buildings to be renovated, and new builds, but none of the studies listed above have made comparisons between newer and older buildings, which is the main objective of this study. The lack of longitudinal comparisons can be attributed to several contributing factors, including the limited availability of long-term measurement data, evolving construction practices and building standards over time, and the methodological complexity involved in aligning performance data across different historical periods. Moreover, earlier research has frequently concentrated on aspects such as energy-efficiency and material sustainability, while giving less attention to user-oriented indicators such as indoor environmental quality (IEQ). As a result, the current knowledge base on long-term IEQ trends in prefabricated timber buildings remains relatively underdeveloped.

The presented research is a part of the project Indoor Environmental Quality in Prefabricated Timber Houses: A Historical and Contemporary Perspective, funded through the Public Call Problem-Based Learning for Students in a Work Environment 2024–2027 (Ministry of Higher Education Science and Innovation, 2024). The project was carried out in close collaboration with the well-known Slovenian manufacturer Marles hiše Maribor d.o.o. The objective of the research is to compare the indoor environmental quality (IEQ), with a focus on the thermal environment, of older and newer prefabricated timber houses, which incorporate state-of-the-art materials and advanced technologies of the time, in order to highlight the advantages and potential for improvements in the event of renovation or new builds. Using long-term measurements, we aim to assess and compare thermal comfort and other parameters in an older and a newer prefabricated panel-framed timber house. This study addresses the identified research gap by comparing historical and contemporary prefabricated timber buildings. It contributes to academic discourse on IEQ and provides a foundation for evidence-based recommendations to improve renovation practices and guide the design of new timber buildings in line with IEQ standards and occupant comfort.

## 2. Methodology

### 2.1 Case Study Buildings

The study examined two case-study (sample) houses located in the same location near the Slovenian city of Maribor, which was one of the arguments for choosing case study buildings in order to limit the influence of micro and mesoclimate on IEQ. Both houses were built in a timber panel-frame construction system (with concrete foundations or foundation slabs) and incorporated the latest technologies and building principles of the time. They were built in 2002 (the older house: Bellevue House) and 2022 (the newer house: Dom24 House). The older one complied with the low-energy standard of the time (according to the German EnEV 2002/2004 standard in force at the time, it did not exceed the limit for annual heating demand of 50 kWh/m²), and used surface heating without a mechanical ventilation system. The newer one complies with the current standard for nearly zero-energy houses (nZEB; it does not exceed the limit for annual heating demand of 15 kWh/m² (Ministry of the Environment and Spatial Planning, 2022)) and is also designed as a so-called smart building with integrated systems for self-regulation of air conditioning, heat recovery ventilation, shading, electricity generation from photovoltaic, etc. Both houses, therefore, represent state-of-the-art in terms of sustainable and energy-efficient development at the time of their construction. The selection of two case-study houses was intentional and aligned with the project's core objective: to assess advancements in construction, design, and indoor environmental quality within a consistent manufacturing framework. Both buildings were constructed by the same company, enabling a focused analysis of its development over two decades.

Their appearance and a schematic representation of the ground floor layout are given in Figures 1 and 2. Both houses are used as working spaces, and the observed living areas are regularly used for meetings and group work.

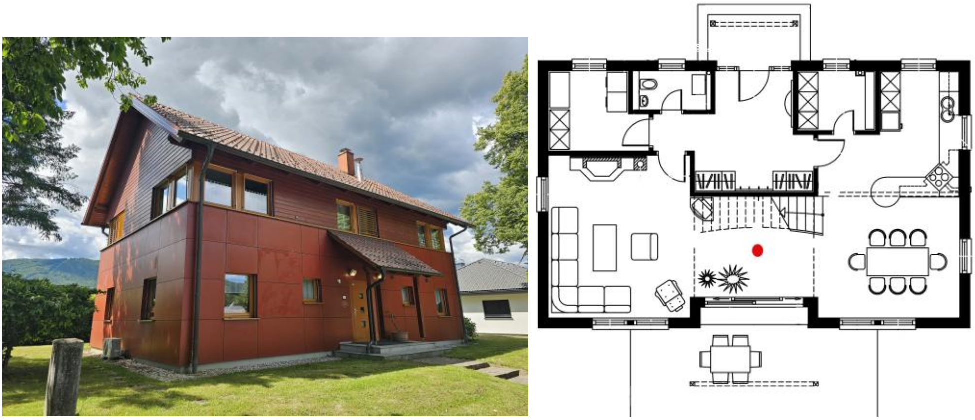

***Figure 1:*** *Older house Bellevue (left) and its ground floor plan (right, a measuring position marked with a red mark)*

***Figure 2:*** *Newer house Dom24 (left) and its ground floor plan (right, a measuring position marked with a red mark)*

### 2.2 Data Collection

Comfort conditions were measured during a longer period of time, for 3 months (from 27.2.2025 to 29.5.2025, using 10-minute intervals), alternately one week in the older and one week in the newer house. The measurement period was limited to the duration of the project, within which we were nevertheless able to take measurements corresponding to the different seasons (winter, spring, and late spring/early summer) and thus to the different air-conditioning regimes.

The Almemo microclimate measuring equipment set was used, comprising a globe thermometer, digital sensors for humidity, temperature, atmospheric pressure, and an omnidirectional thermo-anemometer. The measuring equipment was placed in the centre of the living space of both houses at a height of 1.1 m and an additional temperature sensor at a height of 0.1 m, as marked with red dots in Figures 1 and 2.

Meteorological data for outdoor air temperature ($t_{a,o}$) from the public archive of measurements of the nearest self-operating meteorological station (Maribor - Vrbanski plato) were used to compare the response of indoor air temperatures ($t_{a,i}$) to outdoor climatic conditions (ARSO, n.d.).

### 2.3 Thermal Comfort Evaluation

The standard SIST EN ISO 7730:2006 *Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria* (Slovenian Institute for Standardization, 2006) was used to assess thermal comfort. Based on this standard, we can assess the thermal state of the body as a whole (including predicted mean vote (PMV) and predicted percentage dissatisfied (PPD)) and local thermal comfort (including draught rate (DR) and vertical air temperature difference (percentage dissatisfied (PD)). Accordingly, thermal environment can be classified into three categories (A, B, and C) as presented in Table 1. For the purpose of this study, only the draught rate (DR) and percentage dissatisfied (PD) for the vertical air temperature difference between head and ankles were assessed from the local discomfort domain.

**Table 1:** Categories of thermal environment according to SIST EN ISO 7730:2006

| | Thermal state of the body as a whole | | Local discomfort | |
|---|---|---|---|---|
| Category | PPD (%) | PMV | DR (%) | PD (%) Vertical air temperature difference |
| A | <6 | - 0.2 < PMV < + 0.2 | <10 | <3 |
| B | <10 | - 0.5 < PMV < + 0.5 | <20 | <5 |
| C | <15 | - 0.7 < PMV < + 0.7 | <30 | <10 |

The identification of the recommended indoor air temperatures ($t_{a,i}$) according to the indicative operational temperatures and PMVs given in the standard for each comfort category depends on a number of factors such as metabolic rate ($M$), clothing insulation ($clo$), air velocity ($v_{ar}$), relative humidity ($RH$), etc. The assessment of the latter for the selected input data, taking into account the metabolic rate ($M$ = 1.2 W/m²), can be seen in Table 2. The average measured values for air velocity ($v_{ar}$) and relative humidity ($RH$) for actual selected days of each season and both buildings are considered.

**Table 2:** Calculated recommended indoor air temperatures according to SIST EN ISO 7730:2006, taking into account the actual average measured values of relative humidity and air velocity

| Season | Clothing (CLO) | Relative humidity (new–old) | Air velocity (m/s) (New–old) | Comfort category | PMV range | Recommended air temperature (°C) |
|---|---|---|---|---|---|---|
| Winter | 1.0 | 28.4 – 29.4 | 0.08 – 0.01 | A | −0.2 to +0.2 | 21.0 – 22.0 |
| | | | | B | −0.5 to +0.5 | 20.0 – 23.0 |
| | | | | C | −0.7 to +0.7 | 19.0 – 24.0 |
| Spring | 0.7 | 33.5 – 35.0 | 0.07 – 0.01 | A | −0.2 to +0.2 | 22.0 – 23.0 |
| | | | | B | −0.5 to +0.5 | 21.0 – 24.0 |
| | | | | C | −0.7 to +0.7 | 20.0 – 25.0 |
| Summer | 0.5 | 43.2 – 45.7 | 0.06 – 0.01 | A | −0.2 to +0.2 | 24.0 – 25.0 |
| | | | | B | −0.5 to +0.5 | 23.0 – 26.0 |
| | | | | C | −0.7 to +0.7 | 22.0 – 27.0 |

As the official cooling season according to cooling degree days (CDD) methodology (mean temperature ($T_m$) ≤ 24°C; CDD = 0 (Eurostat, 2024)) had not officially started at the time of the measurements, despite some hot days, we used criteria for the winter and spring seasons to classify the results of the measurements.

Although observed relative humidity (*RH*) values remained within acceptable limits, the older building showed slightly lower humidity, which may warrant further investigation, particularly with regard to occupant comfort and potential VOC emissions, which are known to depend on, among other things, indoor air temperature and relative humidity and can therefore affect the symptoms of Sick Building Syndrome.

### 2.4 Assumptions and Limitations of the Study

This study acknowledges several limitations that may have affected the comparability and generalizability of the results. One of the main constraints was the inability to conduct simultaneous in-situ measurements in both buildings, primarily due to limitations in available monitoring equipment. As a result, measurements were carried out sequentially in each building, which may have introduced a degree of temporal bias. Although measurement periods were selected to be as close as possible and the same instrumentation and protocols were applied consistently across both cases, seasonal variations and differences in occupancy patterns could have influenced the indoor environmental conditions and thus affected the comparability of the results. Moreover, the monitoring campaign did not cover the official cooling season, which limits the scope of conclusions related to summer thermal comfort.

## 3. Results and Discussion

### 3.1 Ambient Air Temperature

The following graphs (Figures 3–5) show the indoor and outdoor air temperature ($t_{a,i}$ and $t_{a,o}$) trends for a typical winter, spring, and late spring/early summer week in the newer and the older house in relation to the recommended air temperatures corresponding to comfort categories A, B, and C (listed in Table 2).

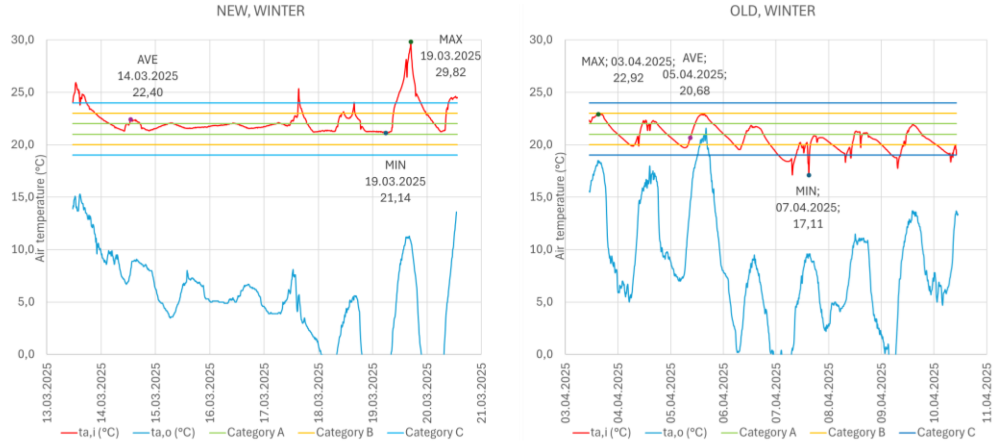


***Figure 3:*** *Indoor and outdoor air temperature ($t_{a,i}$ and $t_{a,o}$) trends for a typical winter week in the newer (left) and the older (right) house*

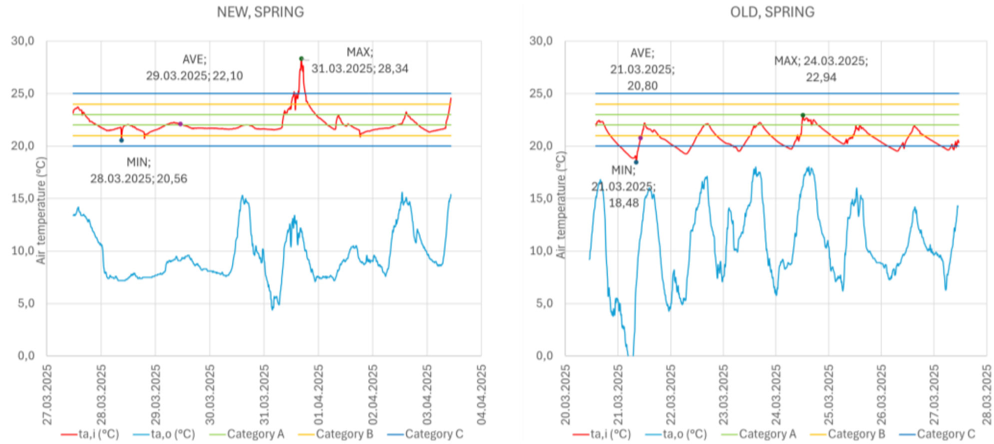


***Figure 4:*** *Indoor and outdoor air temperature ($t_{a,i}$ and $t_{a,o}$) trends for a typical spring week in the newer (left) and the older (right) house*

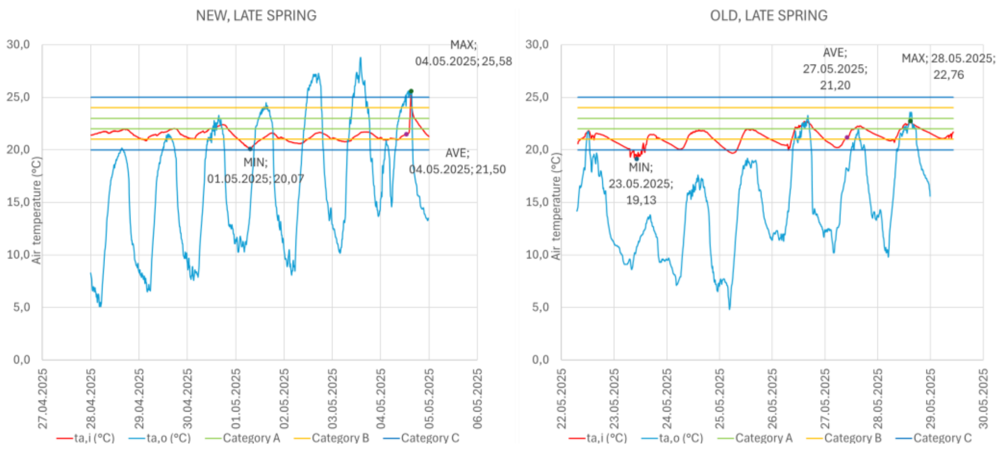


***Figure 5:*** *Indoor and outdoor air temperature ($t_{a,i}$ and $t_{a,o}$) trends for a typical late spring/early summer week in the newer (left) and the older (right) house*

It can be seen that for all three periods observed, the average indoor air temperatures in the newer house are higher (22.40°C, 22.10°C, and 21.50°C) than those in the older house (20.68°C, 20.80°C, and 21.20°C), assuming the same setpoint temperature is used in both houses. Based on the measurements shown in the winter, spring, and late spring/early summer seasons, the temperature comfort in the newer house can be classified as category A or B, while the older house can be classified as category C, with occasional temperature drops even below this category.

In the newer house, however, we observe occasional temperature peaks (e.g., on the 19th and 31st of March, when it reached almost 30°C), which may be due to a measurement error (due to the large glazed areas on the west side, there is a possibility of direct sun exposure of the sensors in the afternoon), due to the influence of the user behaviour (occasional meetings with a large number of participants, heating setup, etc.), or due to the settings of automatically controlled air conditioning and shading. Otherwise, the daily fluctuation of indoor air temperatures in relation to the fluctuation of outdoor air temperatures is less pronounced in the newer house. The more constant temperatures in the newer house can be attributed to the thermal envelope with lower thermal transmittance, the choice of thermal insulation (cellulose insulation) that offers some accumulative capacity, and the mechanical ventilation of the building. In an older house, we observe greater fluctuations in indoor air temperature as a result of the greater sensitivity to outdoor temperature changes due to the higher thermal transmittance and accumulative capacity of the thermal envelope.

All this shows the sensitivity of IEQ to user behaviour and the settings of technical systems in contemporary buildings, as well as the strong influence of the design and energy performance of existing (older) buildings.

### 3.2 Categories of Thermal Environment

Figures 6-8 show the analysis of the thermal state of the body as a whole (including predicted percentage dissatisfied (PPD)) and local thermal comfort due to draught rate

(DR) and vertical air temperature difference (percentage dissatisfied (PD)) for average days from each of the selected seasons previously analysed in Figures 3-5.

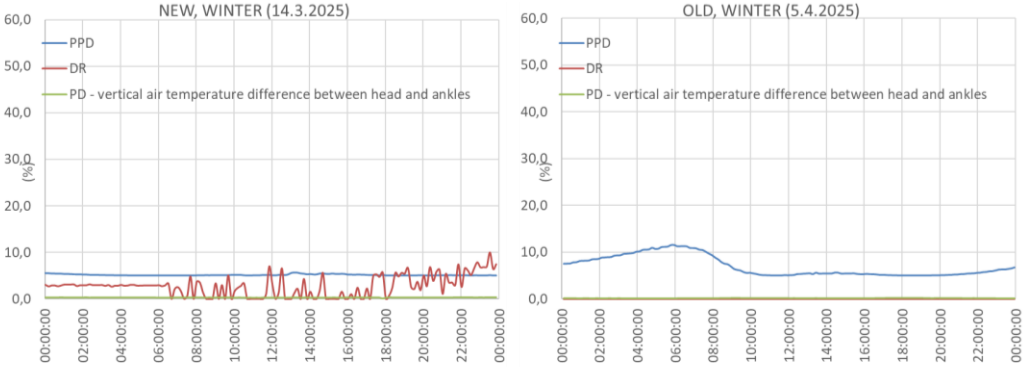


***Figure 6:*** *Predicted percentage dissatisfied (PPD), draught rate (DR), and percentage dissatisfied (PD) for the vertical air temperature difference between head and ankles for an average winter day in the newer (left) and the older (right) house*

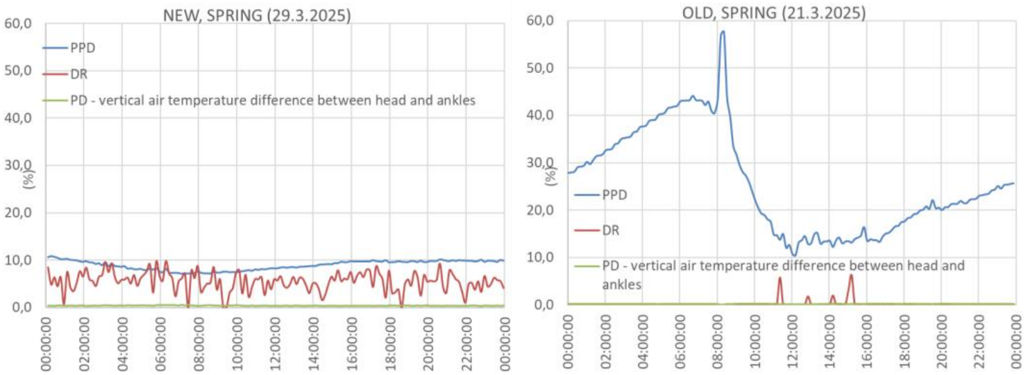


***Figure 7:*** *Predicted percentage dissatisfied (PPD), draught rate (DR), and percentage dissatisfied (PD) for the vertical air temperature difference between head and ankles for an average spring day in the newer (left) and the older (right) house*

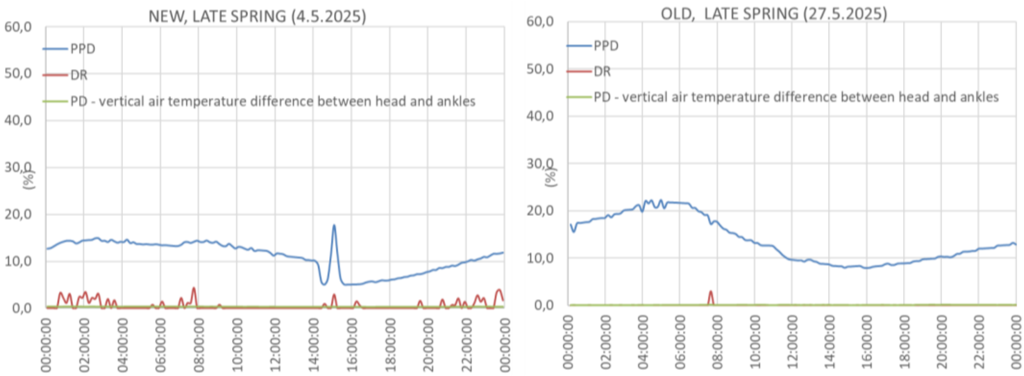

***Figure 8:*** *Predicted percentage dissatisfied (PPD), draught rate (DR), and percentage dissatisfied (PD) for the vertical air temperature difference between head and ankles for an average late spring/ early summer day in the newer (left) and the older (right) house*

The predicted percentage dissatisfied (PPD) results show the percentage of users who are dissatisfied with the thermal environment in the building, which is a key indicator for assessing thermal comfort. From the graphs shown we can see that the average PPD values for the newer house (5% in winter, 9% in spring, and 11% in early summer) are lower than those of the older house (7% in winter, 26% in spring, and 14% in early summer). We can conclude that thermal comfort is higher during the heating season than in the intermediate or early summer seasons. This is particularly pronounced in the older house, where for an average spring day the PPD significantly exceeds category C from Table 1. The PPD is also marginally high in the late spring/early summer season, which may prove problematic, especially in an older house since it does not have a central cooling system. The daily variation of the values throughout the day is less pronounced in the newer house, further indicating a higher level of comfort.

The results shown for local thermal comfort due to draught rate (DR) reflect the percentage of people experiencing local thermal discomfort due to draughts, which is particularly important in the colder parts of the year. The average DR values are higher in a newer house (3% in winter, 5% in spring, and 1% in early summer) due to mechanical ventilation compared to an older house (0% in all seasons), which does not have any ventilation system, as expected. The values are in all cases lower than 10%, which, according to Table 1, is the upper limit for category A. The results shown for the percentage dissatisfied (PD) for the vertical air temperature difference between head and ankles are low for both buildings compared and never exceed 3%, which is the upper limit for category A according to Table 1. It can therefore be concluded that none of the observed local thermal comfort parameters has a negative impact on the thermal environment and therefore on the IEQ in general.

These findings further support the argument that modern construction and building systems in newer prefabricated timber houses contribute to better thermal performance and occupant comfort across seasons. However, the inability to conduct simultaneous measurements in both buildings introduces potential seasonal and behavioural variability, which should be addressed in future studies through parallel or rotational monitoring to ensure more robust comparability.

## 4. Conclusions

This study provides a comparative evaluation of thermal comfort conditions in two prefabricated timber houses built two decades apart, reflecting the evolution of construction systems and energy standards. Although previous existing studies acknowledge the high indoor environmental quality of timber buildings, none of them have actually investigated (measured) the differences in indoor environmental quality between older and newer buildings. Long-term field measurements revealed that the newer nZEB-standard house ensured more stable and comfortable indoor temperatures across the observed seasons, with higher thermal performance and a lower predicted percentage of dissatisfied occupants (PPD), corresponding predominantly to comfort categories A and B under EN ISO 7730:2006. In contrast, the older house showed lower and more fluctuating indoor temperatures, typically falling within comfort category C or below, particularly in the transitional seasons. This confirms that advancements in construction systems and energy standards positively influence user comfort. Additionally, the less pronounced daily fluctuations in temperature and PPD in the newer house further support a more stable and comfortable indoor environment. Regarding local thermal comfort due to draught rate (DR), the slightly higher values observed in the newer house are attributable to the use of mechanical ventilation; however, these values remain within the upper limit of category A, indicating no significant discomfort. Similarly, the low Percentage Dissatisfied (PD) values related to vertical air temperature differences in both buildings suggest adequate thermal balance indoors. The results clearly demonstrate that modern systems in newer prefabricated timber houses improve both overall thermal comfort and specific local conditions, thereby enhancing indoor environmental quality. The findings therefore support some of the potential weaknesses (low relative humidity, overheating occurrence potential) of the previous studies, but also further highlight the possibility of fluctuating indoor temperatures and the important role of occupant behaviour and system control, even in high-performance buildings. These findings are important for guiding renovation strategies in older timber buildings, where targeted material and technical upgrades could help achieve similar levels of comfort and occupant satisfaction to newer buildings.

However, due to limited measuring equipment, simultaneous measurements in both buildings were not feasible in this study. Future studies should aim to address this limitation by employing parallel data collection to improve result comparability. Moreover, since the measurement period did not include the official cooling season, additional monitoring during summer months is desirable. This would help assess the risk of overheating in the older house, which—due to its lower thermal mass and lack of mechanical ventilation—may be more susceptible to overheating under warmer conditions. Given the thermal variability and absence of mechanical ventilation in the older house, some of the conditions observed may contribute to sick building syndrome-related symptoms, especially in the warmer months.

Based on the findings, several recommendations can be made for the renovation of older prefabricated timber houses. Enhancing the thermal transmittance and thermal mass of the envelope could help reduce indoor temperature fluctuations, while the installation of mechanical ventilation systems would likely improve both thermal comfort and indoor air quality, preventing the development of sick building syndrome. In future studies, it would be valuable to investigate whether such interventions could bring the indoor environmental quality of renovated buildings to a level comparable to that of newly constructed timber buildings.

Overall, the results support the continued development of timber construction as a sustainable and high-performance alternative in both new builds and renovation projects, while emphasising the importance of integrated design approaches that align energy performance with human comfort. Future research could also explore the impact of targeted renovation measures, such as thermal insulation upgrades and the integration of mechanical ventilation on indoor environmental quality (IEQ) in older prefabricated timber houses. Moreover, incorporating real-time occupant feedback systems could help bridge the gap between objective performance metrics and subjective comfort perception. Such approaches would not only support more responsive building operation, but also offer valuable data for refining renovation guidelines and optimizing the user's experience in timber housing.

**Acknowledgment**: The authors gratefully acknowledge the financial support of the Ministry of Higher Education, Science and Innovation within the framework of the Public Call Problem-Based Learning for Students in a Work Environment 2024–2027. The research was conducted as part of the project Indoor Environmental Quality in Prefabricated Timber Houses: A Historical and Contemporary Perspective.
Special thanks are extended to the Slovenian timber house manufacturer Marles hiše Maribor d.o.o. for their valuable collaboration, technical support, and access to the case-study buildings, which enabled the successful implementation of the research.

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