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ENVIRONMENTAL PERFORMANCE OF NEXT-GENERATION TIMBER SCHOOLS FOR CLIMATE ACTION: A SIMULATION APPROACH

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ABSTRACT: As the global response to climate change intensifies, timber buildings will play an essential role in reducing carbon emissions from the built environment. This study provides a simulation-driven approach to estimating the environmental performance of timber buildings. In doing so, we present a case study of the UK's next generation of timber school buildings, the New Model School (NMS-timber). We perform a sensitivity analysis of the timber school building to concrete construction (NMS-concrete). The methodology involves an environmental performance estimation of the two building cases' operational energy and thermal comfort characteristics. The results show that NMS-timber has an annual energy usage intensity (EUI) of ~132kW/m^2 and ~146kW/m^2 for NMS-concrete, demonstrating a ~9.6% more energy efficiency per square metre for the timber building. We also find that the timber school building will save ~34.30% heating energy compared to the concrete construction while almost eliminating the cooling energy needs. We conclude that the NMS-timber can offer significantly better environmental performance to concrete buildings. When applied in early stages of the design development, the digital workflow presented promotes informed decisions during the project development stages and enhances the construction of energy-efficient structures.

KEYWORDS: Computational modelling, digital twin, simulation, CFD; energy performance; prefabrication

1 INTRODUCTION

With the building and construction sector contributing around 38% of global carbon dioxide emissions [1], natural materials like timber and advancements in their structural applications have been at the forefront of decarbonising the embodied emissions of the built environment [2]–[4]. However, there are several policy and operational challenges to integrating engineered timber structures in the current built environment which hinder the seamless collaboration and material flow across the supply chain [5].

This study contributes to current discussions on the suitability of engineered timber in decarbonisation of the built environment with a focus on school buildings. The significant shortage of school places in the UK and the government's commitment to deliver a platform for low-carbon schools highlight the importance of reducing their embodied and operational emissions [6, 7]. This study explores the potential of engineered timber to address this challenge by evaluating a timber school case-study using environmental performance analysis metrics. In doing so, the novel aspect of this study is the data-driven and computational simulation-based approach that compares the energy-use demand, environmental characteristics, and occupancy-based optimisation of spaces in a proposed timber building in the UK.

This paper generates a comparative basis for engineered timber buildings like schools with their concrete counterparts. The main objectives of this research are, first, to establish a simulation-driven comparative basis for evaluating the environmental performance of engineered timber buildings and enable its reproducibility for architects, designers, policymakers, and researchers, thus contributing a critical step towards developing a digital twin model of timber buildings. Second, to evaluate characteristic environmental factors that differentiate timber schools from existing concrete schools. When carried out in early stages of the design development, such studies promote informed design decisions and the construction of energy-efficient structures.

2 CONTEXT

The case-study analysed in this paper is the New Model School (NMS), a modular engineered timber school building designed as an extension to the Fawcett Primary state school in Cambridge, UK. The existing school is a concrete structure including teaching spaces, a dining hall, sport facilities, offices, and services. The New Model

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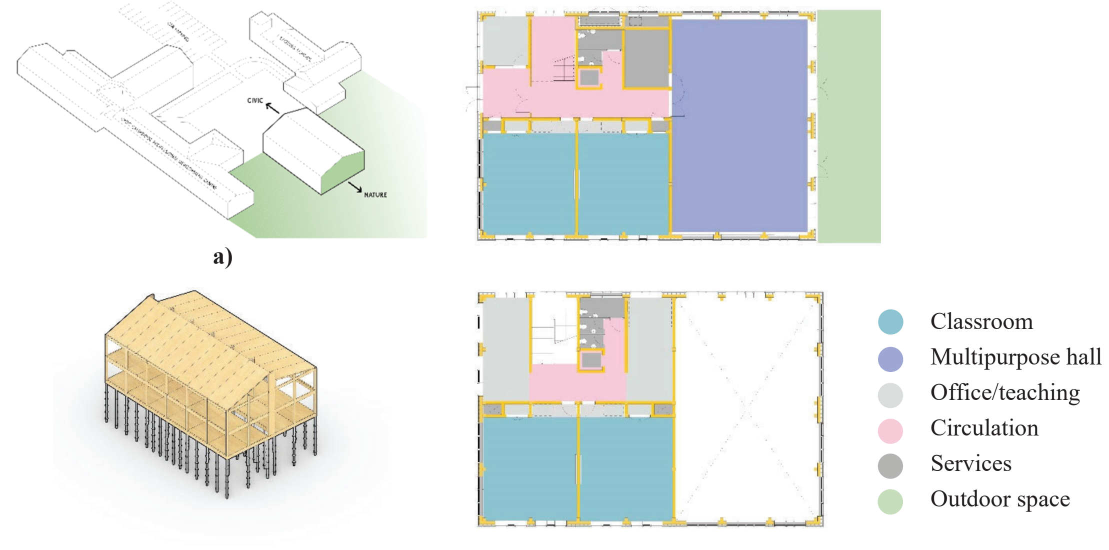
School (NMS) extension was developed in collaboration between academia and industry, aiming to demonstrate the potential of a modular kit-of-parts of engineered timber [8]. The goal of the project was to develop a set of building components that can be combined to create healthy indoor environments and that can then be fully demounted and reconfigured to address a diverse set of programmes and scales. The NMS building is an extension to the existing primary school and has received approval from planning.



a)

b)

c)

Figure 1: *a) The proposed two-storey engineered timber school extension and its relationship with the existing school building on site. b) The structure of the New Model School, made from engineered timber components. c) Programme distribution on the two storeys.*

The NMS forms a stand-alone two-storey structure of 660m^2 and its design is based on a repeatable grid of size *ca* 56m^2 that meets the spatial and programmatic requirements for primary schools according to the Department for Education, as shown in Fig. 1 [9]. It is a lightweight glulam frame-based structure with composite CLT and ribbed glulam beam components for the roof and first floor slabs. The substructure uses a suspended softwood timber cassette sat atop glulam ground beams supported on recycled steel screw piles. The façade is made of modular insulated timber panels, while a vertical service wall traverses the building and incorporates natural ventilation shafts and service risers.

3 METHODOLOGY

The aim of this study is to assess the impact of the building envelope on the environmental performance of school buildings. The New Model School is used as a case-study and by maintaining the building orientation, programme, and openings identical, we generate two digital models of the school: one using the proposed engineered timber structure and envelope of the New Model School (*NMS-timber*) and one using the conventional construction of the existing school building with a concrete structural frame and brick infill walls (*NMS-concrete*). Since the focus of this study is placed on the impact of the building envelope, the two structural systems are applied interchangeably, without accounting for potential changes in the sizing and configuration of structural elements.

We adopt a simulation-driven methodology to evaluate and compare the environmental performance of the two school models. The simulation has three main components. First, setting up the site parameters and calibrating with climatic parameters; second, setting up the building parameters; third, setting up the energy simulation parameters to evaluate annual thermal comfort variations in the NMS using two variables: operating temperature and mean radiant temperature. These act as guides to assess the thermal comfort of users within the space. Finally, we estimate and compare the annual energy use intensity (EUI, kW/m^2) for heating and cooling demands in the NMS-timber and NMS-concrete, which provide an insight to the operational energy required.

3.1 SITE AND CLIMATE

The historical climate data is accessed from University of Cambridge's Digital Technology Group [10] and diurnal weather data from Cambridge Airport's weather monitoring station [11]. The actual NMS-site is within a 5km radius from these data locations.

3.2 BUILDING DESIGN PARAMETER SETUP

The NMS-timber envelope is an insulated timber frame with air-tight and well-insulated façade panels. Designed for high energy efficiency, it has low U-values (walls: 0.05 W/m2K; windows: 1.36 W/m2K; roof: 0.26 W/m2K; ground: 0.08 W/m2K). The concrete building envelope, on the other hand, is made of brick infill walls with layers of insulation and air gap, concrete floor slabs and an insulated lightweight concrete roof. When applied to the digital model, the respective U-values increase (walls: 0.42 W/m2K; windows: 1.36 W/m2K; roof: 0.39 W/m2K; ground: 0.52 W/m2K). Each classroom is 7.2x7.8m and has four south-facing windows (30% of total surface area), which are partially operable for free cooling in the summer and cross-ventilation through natural ventilation shafts on the service wall. The occupancy ratio of the building is defined according to government guidelines for schools [12]. It is assumed that the local community will use the building for extra-curricular activities; hence the analysis period spans the whole calendar year.

3.3 SIMULATION SETUP

The computational models of NMS were set up as a multizonal energy simulation (MES) using EnergyPlus v22.2.0 [13] and OpenStudio v3.5.1 [14] to estimate energy usage intensity (kW/m^2), season sensitive energy demand, heat balance and thermal comfort estimations (operational and radiant temperatures, and relative humidity (%)), heating and cooling energy demand.

Occupancy scheduling was done on a whole-year basis instead of following a typical UK school term, as the timber school is also designed for community events and activities, apart from the regular classroom services.

3.4 BENCHMARKING

The simulation results of NMS-timber and NMS-concrete are benchmarked against recent studies that used the Non-domestic National Energy Efficiency Data (ND-NEED) [15], the Display Energy Certificates (DEC) database [16] and CIBSE TM46 standards [17]. The ND-NEED provides standards for energy use in non-domestic buildings in Great Britain, based on actual readings. Similarly, the CIBSE TM46 and DEC databases include national-scale statistical data and benchmarks of energy consumption for educational buildings.

4 RESULTS

The analysis was run for a one-year period and the results presented focus on the environmental performance of the four classrooms (c1; c2; c3; c4) to evaluate the impact of building fabric, mainly concrete (NMS-concrete) and engineered timber (NMS-timber). Results show that NMS-timber has higher operating temperature values across all months, especially peaking in July (see Fig 2a). The NMS-timber demonstrates ~2°C higher operating temperature in peak summer months (July) compared to the NMS-concrete model. Similarly, for peak winter (Dec-Feb), NMS-timber shows ~1.8 - 2.2°C higher operating temperatures than NMS-concrete (see Fig 2a). In addition, the relative humidity levels were ~0.9% higher (on average) in the NMS-timber than in NMS-concrete, as shown in Fig 2c. While the peak temperatures in the summer months are on the limits of thermal comfort levels, a more detailed digital model of the school's environmental performance is needed to better understand

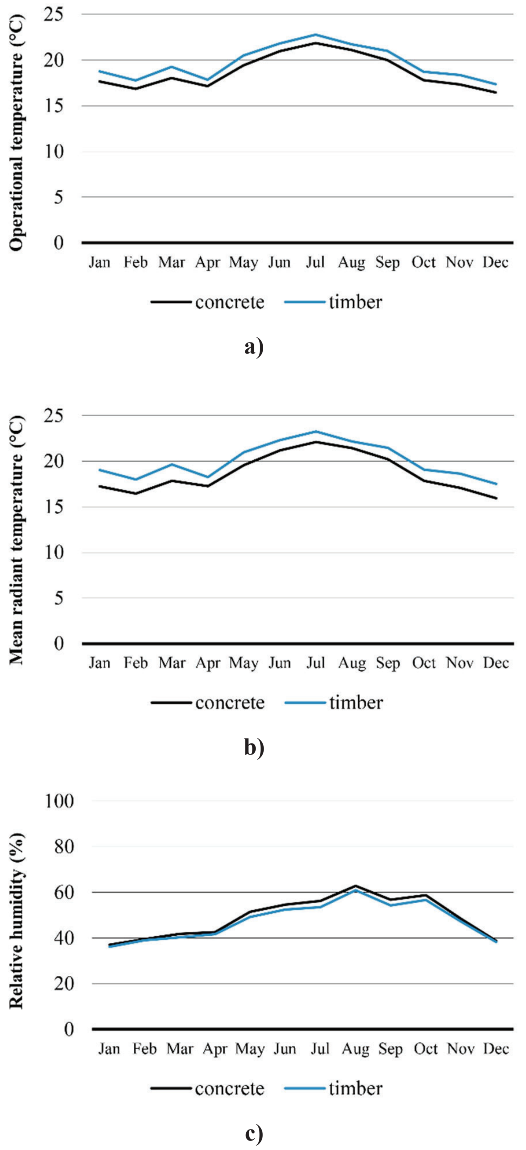


Figure 2: *Simulated annual environmental parameters for NMS-timber and NMS-concrete a) Operational temperature (°C); b) Mean radiant temperature (°C), and c) Relative humidity (%).*

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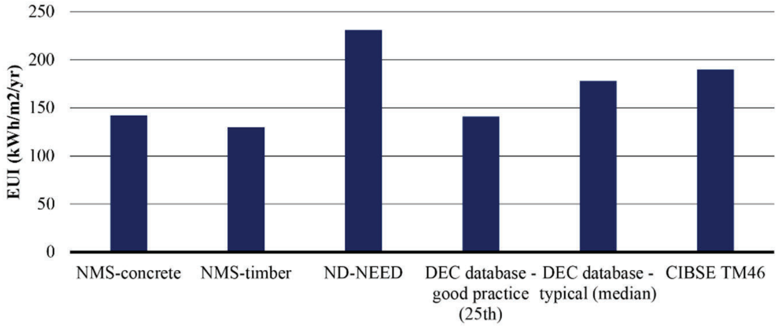

Figure 3: *Energy consumption in kWh/m²/year of the timber and concrete models of the school in comparison to benchmarks from literature.*

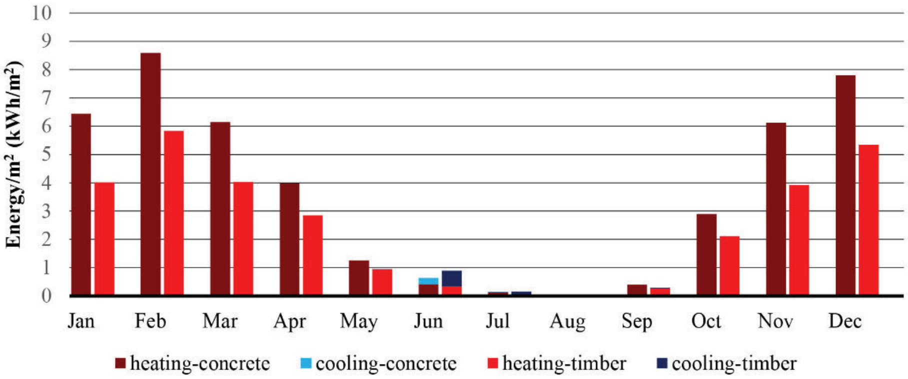

Figure 4: *Monthly energy demand per square metres for cooling and heating of all 4 classrooms for the engineered timber (NMS-timber) and concrete school (NMS-concrete).*

the internal environment, considering airflow characteristics and their impact on temperature and thermal comfort.

However, in terms of mean radiant temperature, the simulated temperature differences were significantly higher in peak winter months ~4°C (see Fig2b) for the timber building compared to the concrete structure. Therefore, NMS-timber can offer greater thermal comfort in winter than NMS-concrete. Similarly, simulated results show that the temperature difference for peak summer months (June - August) is in the range of ~1.9 - 2.1°C, offering NMS-concrete to be cooler. Our ongoing study will use on-site environmental performance measurement to confirm this trend and verify with occupant-led subjective comfort ratings.

The results from the energy performance analysis show that NMS-timber has an annual energy usage intensity (EUI) of ~132kW/m2 and ~146kW/m2 for NMS-concrete (see Fig 3). Therefore, this demonstrates that the timber building is ~9.6% more energy efficient per square metre than the concrete construction of similar configurations. Furthermore, in the benchmarking tests, we find the NMS-timber to be 40%, 9%, 20% and 30.5% less energy intensive per m2 compared to ND-NEED, DEC-good practice, DEC-typical and CIBSE TM46 standards, respectively (see Fig 3).

Fig 4 shows the simulated heating and cooling energy demand for the NMS-timber and NMS-concrete buildings. The timber building in general has less heating and cooling energy demand per square metre by 29.22%. More specifically, the heating energy demand for November - February is 34.30% less in NMS-timber than in NMS-concrete. Similarly, the cooling energy demand for NMS-timber is negligible (~0.08kWh/m²) between June - August, as compared to NMS-concrete (~0.8kWh/m²). Thus, emphasising that timber school building has better winter and summer energy performance characteristics.

5 CONCLUSION

This paper presents an environmental performance basis for engineered timber buildings like schools (NMS-timber) with an existing concrete school structure (NMS-concrete). We used an environmental performance simulation approach to estimate the two building cases' operational energy and thermal comfort characteristics. The results from the energy performance analysis show that NMS-timber has an annual energy usage intensity (EUI) of ~132kW/m² and ~146kW/m² for NMS-concrete, demonstrating a ~9.6% more energy efficiency per square metre for the timber building. Moreover, when benchmarked against recent studies, our results showed the NMS-timber to be 40%, 9%, 20% and 30.5% less energy intensive per m2 compared to ND-NEED, DEC-good practice, DEC-typical and CIBSE TM46 standards, respectively.

We also find that the timber school building will save ~34.30% heating energy annually compared to the concrete construction while almost eliminating the cooling energy needs. Thus, the NMS-timber building developed can offer significantly better environmental performance to concrete buildings.

Our future work will expand the verification and validation of this study's simulation approach using in-site environmental sensors and establish an experimental protocol for streamlining such measurements for upcoming timber building stocks. It also includes a detailed analysis of the school's Building Integrated Photovoltaics (BiPV) systems that need to be integrated into the timber school, per UK government norms. Moreover, further optimization of the building parameters, BiPV and school ancillary services will be performed to improve the accuracy of the energy simulation. This will include estimating airflow characteristics using a computational fluid dynamics (CFD) workflow, which, when overlaid with the MES analysis, gives a comprehensive insight to the school's environmental performance, In this manner, this study intends to set a workflow for a digital twin model of the school where different materials and emission reduction scenarios can be used to measure its sustainability over the long run.

As the global response to climate change intensifies, timber buildings will play an essential role in reducing embodied carbon emissions of the built environment. Our study proposes a digital workflow that enables the comparative assessment of alternative construction materials based on their environmental performance in a robust and resource-efficient manner. When carried out in the early stages of a project, this approach can promote informed design decisions during the project development stages, improve the environmental performance of new buildings and act as a guide to policymaking.

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