World Conference on
Timber Engineering
Oslo 2023

THE NEW CENTRE FOR ADVANCED TIMBER TECHNOLOGY: A LIVING LAB FOR DESIGNERS, INDUSTRY, AND EDUCATION

Gabriele Tamagnone[1], Robert Hairstans[2]

ABSTRACT: To meet the net zero requirements, UK industry will need to change how it operates, relying on more sustainable resources and practices. Within this scheme, the construction industry must move, when possible, from carbon-intensive material to more environmentally-friendly ones (e.g., timber). The general lack of expertise, however, is likely to slow down the transition process. With this in mind, the Centre for Advanced Timber Technology, in Hereford, has been established to form the professionals of the future and to upskill and reskill those willing to learn more about advanced timber practises. Part of this mission is played be the implementation of a living lab approach within the building, through which data will be gathered to inform the curricula and to provide external proof of good or bad practices in timber buildings, which will impact the industry at different levels (e.g., construction practices, design specification or insurance stipulations). This paper analyses the steps taken in this living lab project so far, analysing literature cases, presenting the methodology, and listing the projects involved in the gathering of the data through monitoring of the building.

KEYWORDS: Living lab, Building monitoring, Structural monitoring, Timber education

1 INTRODUCTION

The Centre for Advanced Timber Technology (CATT) at the New Model Institute for Technology and Engineering (NMITE) in Hereford is established to act as Centre of excellence for timber engineering and, more broadly, to deliver high quality teaching in the field of sustainable built environment. In alignment with NMITE's ethos "learning by doing", CATT wants to create learning material underpinned as much as possible by research and first-hand data. This is why the building hosting the Centre is to be a living lab, where features and performances of the building are measured to inform learners, and influence change in the construction industry, raising awareness about timber in constriction and act as test cast to inform how more reliable and durable timber buildings can be built.

1.1 CATT'S MISSION

The declared mission is to establish a centre of timber engineering excellence by:

- Implementing collaborative frameworks;
- Establishing connected ecosystems; and
- Leveraging opportunities.

The first point has been crucial since the beginning, when the Centre was founded in collaboration with Edinburgh Napier University (ENU) as well as external industry stakeholder and representative groups, including Timber Development UK.

The second point has to do with how the research carried out within the Centre can inform and help both inside and outside, and how other experiences of other Centres, Institutions, or research can inform and influence the activities of the CATT. A main asset to this is the implementation of a living lab approach within the building, which will be discussed in later sections.

Figure 1: *Centre for Advanced Timber Technology and Centre for Automated Manufacturing exterior (credits Bond Bryan Architects).*

[1] Gabriele Tamagnone, NMITE New Model Institute for Technology and Engineering, CATT Centre for Advanced Timber Technology, gabriele.tamagnone@nmite.ac.uk
[2] Robert Hairstans, NMITE New Model Institute for Technology and Engineering, CATT Centre for Advanced Timber Technology, robert.hairstans@nmite.ac.uk

https://doi.org/10.52202/069179-0555

The third and final point is all about seizing the day, balancing opportunity with feasibility and financial sustainability, yet always with a proactive approach to external discussions and proposals that align with the strategic intent of the centre.

The intent is for the CATT/CAM (Centre for Automated Manufacturing, co-located) building to act as a Living Lab within a portfolio of Living Lab projects working with industry and external stakeholders. This approach will ensure the educational model is actively engaged with industry and informed by live projects and real-world challenges. The delivery of the CATT/CAM building will derive the methodological approach to this. The emphasis will be to collate and codify information during the building delivery and post occupancy phases (including user occupant behaviours) to enrich a Building Information Model (BIM) and correlate it with predicted performance via a feedback loop in accordance with digital twinning approaches and the “Gemini Principles” [1]. Rolling this concept out to other projects will create an ecosystems of assets capable of demonstrating the virtues of utilising advanced timber technologies for built environment delivery when combined with manufacturing techniques, with an emphasis on regenerative design, circularity, socio-economic impact and health and wellbeing [1]-[3]. The aim is to create the necessary condition for a mass validation exercise of predicted performance relative to actual performance considering a range of metrics including, but not limited to, productivity, time/cost certainty, thermal, structural, acoustic, quality assurance, safety (including fire), and environmental impact. Curriculum content will be curated utilising the case study content captured and learning from each project will be through a particular lens or series of lenses tailored to the correct level of educational attainment and necessary learnings of the derived competency framework. The CATT/CAM building will be the HUB of this ecosystem, acting as the showcase given the opportunity to continually test, learn, iterate, and innovate. Further, the co-location of CAM with CATT will result in a symbiosis of timber engineering and advance timber technologies with automated manufacturing and integrated engineering approaches, generating further learning, including the need to consider, for example, the integration of mechanical, electrical, and renewable technologies, utilisation of robotics and interfacing with alternative materials. The CATT/CAM living lab will therefore instil holistic mindsets and collaborative working approaches through the embedded educational model whilst deriving industry solutions and value return to the sector, challenging traditional construction business model and procurement practices.

2 THE CONTEXT

According to the last data, the built environment, when considered as the union between construction industry and building utilisation, is responsible for the 37% of equivalent CO_2 emissions and 34% of global energy consumption, forming the highest portion of human induced climate change [4]. The way we build in the future and how we improve the built environment will have a huge impact on the net zero policies pursued by governments and communities around the world.

Wood, as a natural material, is seen as one of, if not the, main answers of the construction world to global warming contribution. Trees are excellent carbon storers, with 1.83kg of CO_2 stored in each kilogram of wood, on average. Improving the timber industry can result in a better management of woodlands, as wood would become a more and more valuable resource, raising the level of attention to detect wildfires and diseases. However, this is true as long as structures are built to last and materials are procured sustainably, otherwise the carbon stored in the materials is released after too short a period of time, resulting in a counterproductive effort to implement more natural materials, ending in a situation where the use of less sustainable products, but longer lasting, would have produced a more sustainable outcome.

It is, in fact, at least in the UK, the maintenance and durability of timber one of the main causes of concern when a wider implementation of this material in the built environment is discussed. The majority of warranty provider don’t see wood as reliable, and to insure the same structure, but built with a more traditional material, such as concrete or steel, can cost up to eight times less when compared to the same made of timber [5]. This fact, together with other misconception around the material, such as the behaviour in case of fire or its reaction to water, have undermined utilisation.

Although it is true many things around timber are misunderstood, it is also true many are the things we still don’t know about this material in constructions and its reaction to external actions naturally occurring during erection or in use. Some of the questions that need an answer are, but not limited to:

- How should a building team behave towards timber elements that get wet on-site during construction and how should they assess that those same elements have dried enough to continue with the subsequent construction phases?
- What is the actual difference in sustainability between a timber structure and a more “common” one when everything, from origin of materials to construction and use, is considered?
- Is there a natural decay of mechanical properties of timber elements outdoor or indoor?
- Do systems need to be tweaked, especially air conditioning and heating, when a timber building is considered?
- Do general rules apply adequately to timber constructions with exposed wood?

Numerous are the doubts still surrounding many aspects of these kind of constructions, and many of them need to be addressed to build more sustainably, more reliably, and at lower cost.

Although, things are changing, and CATT acting as a Living Lab has the aim of creating evidence-based information and educational content to this shift towards a more sustainable way to build.

2.1 OBJECTIVES

Goals for CATT acting as a Living Lab can be grouped in four areas:

2.1.1 Durability and Warranty

Timber is regarded as a natural and sustainable material, but being natural can also be a weakness when it comes to durability, due to different issues that may occur during the lifetime of a structure, mainly due to poor detailing and/or lack of knowledge of these materials and products. Consequently, given the scarcity of first-hand data regarding what goes well and what's done wrong, and longevity of timber structure is low-balled by insurance and warranty providers, the latter overprice policies, which in turn renders prohibitive for many customers to build their new project out of wood.

One of the objectives of CATT is to create and gather information on timber structures, both good and bad practice, and to provide useful information for insurance companies to base their judgement on and give prices in line with other materials for timber buildings too. Furthermore, the objective is not only to provide proof timber can be durable, but also to assess when it isn't and what are the countermeasures to be taken to extend the life of wood-based structural and non-structural members.

2.1.2 Sustainability and User experience

Regardless of being natural, with trees sequestering carbon during their growth, the real degree of sustainability of timber constructions is yet to be evaluated precisely. The whole life carbon assessment of these structures is crucial to compare the embodied carbon of these buildings to that of other building materials constructions. Moreover, the durability issue may play a vital role in assessing these figures, with less sustainable, at least at the beginning, materials resulting more environmentally friendly in the long run due to the necessity to maintain and substitute timber decayed elements in inadequately built timber constructions.

In the utilisation of the building, attention must be paid to its serviceability and check if other materials could be better used instead or provide different characteristics to it, not only for its usage, but also for its possible modification of spaces or quality of the experience of the occupants from any point of view.

To summarise, the building must be sustainable before, during, and after, and liveable and functional during.

In this regard, CATT wants to investigate the supply chain of timber constructions, assessing the impact of all elements involved and looking into what differentiate these buildings from others. The aim is also the evaluate users' experience and indoor quality.

2.1.3 Digitisation and Digitalisation

These two topics are at the base of the development of any industry out there. Construction industry will use digital tools, IoT devices, and monitoring campaigns more and more in the years to come. In order to assess the wellbeing of a structure, sensors must be utilised and measurements taken, which then can be used to simulate different scenarios to prepare and act against possible future events before these happen. In the manufacturing and design phases, computer aided and controlled technologies will make production and construction more and more sustainable, with less waste and optimisation both off-site and on-site.

CATT, together with the Centre for Automated Manufacturing, wants to pilot new technologies and partner with industrial stakeholders to develop new ones in order to progress and push the whole timber industry, from seed to building and reuse/recycle, forward.

2.1.4 Outreach and Education

The lack of knowledge in the UK when it comes to wood and timber engineering is palpable, with very few institutions providing specialistic modules in their curricula covering what industry needs to operate in this sector in the best way possible. Many rely on CPDs after graduation or on the experience passed from employee to employee when inserted in the new company. The minority of college or university educated come out work-ready.

CATT is keen to provide education, at any level, for students and professionals wanting to have a career in the field of timber and wood industry and of sustainable built environment. The objective is to deliver up-to-date learning content in different areas, with materials underpinned by research outputs, helping, this way, not only learners, but the whole industry through outreach and dissemination.

Part of these objectives will be pursued using the CATT/CAM building as a living lab, collecting data in different areas directly from it.

3 LIVING LAB

Even if the term "Living lab" has assumed several meanings and has been used in different contexts [6], it is fair to say that the difference between that and a traditional lab is that a living lab doesn't set up tests using a controlled environment, well established boundary conditions, and predetermined loads, actions, or disturbances to see the influence of various aspects on a certain phenomenon.

A living lab takes advantage of ordinary situations, it gathers information from the actual environment to test real life scenarios and see how different approaches work when applied to a situation with unpredictable variables, which are naturally present and constitute the existent operative conditions.

This means a living lab can test a setup with way more external influences than those of a traditional test: usually, in a lab, conditions are established to analyse a specific behaviour when a particular perturbation is applied to the system. In a living lab, nothing, usually, is externally

https://doi.org/10.52202/069179-0555

applied to the system, but naturally occurring events contribute to the variation of settings.
As any test, living labs makes use of sensors and other tools to measure specific quantities. However, as they are bigger in size, greater is the number of sensors too, if compared to a normal test, to be able to get the correct information from the assessed area, which can be a school, a hospital, a factory, or even an entire city. Depending on the characteristics to be evaluated, the desired degree of precision, and the dimensions of the specimen, the capillarity and number of measuring devices could vary from few units to hundreds.
Basically, everything could be transformed into a living lab, depending on the information one wants to extrapolate and from where. Plus, a living lab runs itself: once sensors are placed and the platform starts to collect data, it is just a matter of analysing that data and extract the right information once the sample is wide enough to draw useful conclusions.

4 CATT AS A LIVING LAB PROJECT

4.1 MOTIVATIONS

The main reason behind the Living Lab implementation is to provide the evidence base to support the need to deliver a better, more sustainable built environment. As previously reported, the construction industry and building operations combined are responsible for the biggest slice of carbon emissions and energy consumption in the world, meaning that reversing the trend passes through more sustainable practices in these areas.
This means to adopt sustainable materials and technologies and to build less energivorous buildings. The former means to use natural materials, that, at least, but not only, from a structural point of view, usually means timber. In the UK, however, given the recent policies to reduce the use of flammable materials in construction, the general lack of expertise in timber engineering, and a broad distrust of wood, especially by insurance companies and warranty providers, the spread of timber structures struggles to take off. The insurance question is the one that would benefit the most from living lab approaches within timber buildings: monitoring the actual performance of the structure, especially the load-bearing elements, will give the actual picture of timber durability, providing real data that could change the perception of this material and simultaneously lower the insurance costs, which is the main reason for reconsideration for many costumers willing to have a timber building. The living lab approach will give the opportunity to learn from possible mistakes, inform policy makers, designers, manufacturers, and building companies, and in general will enable the creation of conditions for better, more reliable, and long-lived buildings of this type in the future.
The second aspect, namely, the less energy demanding building piece, can gain from the living lab approach too: the monitoring of the building can challenge the effectiveness of the design solutions adopted, informing the suitability of materials, correct performance of the details, and in general help, once more, to build better timber buildings, with better materials and better details.

4.2 METHODOLOGY

As mentioned, given the lack of skills in the UK and the necessity to change the construction industry, implementing more and more bio-based products in future and retrofitted buildings, CATT's mission is to bridge the gap, providing educational solutions for both professionals and students.
In doing so, the CATT/CAM building, together with other case studies and projects, will be used to create research-based, up-to-date learning content through a living lab approach.
The methods that will be implemented to address the four objectives outlined in 2.1 will be:

4.2.1 Durability and Warranty

The building will be used to test directly the possible issues a timber building can experience, plus measure several properties over time, such as mechanical properties and insulation performance, to give a more complete picture of the construction and its behaviour year after year.
To do this, sensors will be deployed to measure real-time quantities, both inside and outside the building, to compare internal and external conditions and get the best image of the building performance, especially in terms of humidity and moisture, and temperature. Periodic measurements on structural elements will be made to ascertain their properties remain in a suitable range over time [7]-[10]. Measurements like these, or those involving sensors, will be replicated on other buildings to get statistically relevant results and formulate better theses, with attention to the influence of different boundary conditions [11].
In the workshop, laboratory tests may be carried out to simulate different environmental conditions, and outside natural weather could be used in a "controlled" fashion to assess the behaviour of different timber products outside or to evaluate the protection capabilities of different solutions, especially those not yet covered in literature [12], [13].
The major part, if not all, of the data gathered will be used to inform insurance and warranty providers in order for them to understand better the material and related products, and what actually are the things to look more carefully at when stipulating a policy, instead of focusing solely on the fact that the building to be insured is made of timber, and so will eventually rot or burn. Moreover, the proof will be able to inform designers and constructors on non-working details or concepts, moving towards more reliable and durable solutions.

4.2.2 Sustainability and User experience

Life-Cycle Assessment (LCA) and Whole Life Carbon Analysis (WLCA) have already been used successfully to analyse the effective sustainability of timber structures [14]-[18]. However, a shared strategy is still missing, especially to compare timber figures with other materials. CATT's supply chain mapping will be used to do LCA

and WLCA to assist in the establishment of a methodology to assess the actual impact of timber constructions and judge their actual carbon storage capacity when compared to other forms of construction. This exercise will be repeated for other buildings to find a consistent and reliable method to address the issue.
Given the outputs of the first objective, the ability to deliver a more durable timber-built environment will act as an amplifier for sustainability, with less maintenance and replacement needed for timber elements resulting in longer storage of carbon within the buildings.
In addition, relying on the experience gathered from other researches in literature [19], [20], the user experience and comfort will be monitored to address the optimal use of air conditioning and heating system in an environment with exposed wood elements, being wood a hygroscopic material. This part will be covered with direct involvement of occupants with surveys and workshops [21], but other means might be used in the future to analyse other aspects and/or get rid of the human judgement/perception from the equation [22]-[24].

4.2.3 Digitisation and Digitalisation

Information from measuring the building and from the supply chain mapping will be captured within a BIM model, which will be used in the teaching activities, with the different information being used in different contexts to help teaching different topics.
In the future, the digital strategy could then be broadened to include other goals, such as:

- Understand the building from an operational perspective, enabling consumption optimisation [25];
- Have a 3D image of the measurements allowing the visualisation of the conditions and to interrogate whether different measurements are interrelated;
- Run simulations on the building using non-standard scenarios, stress-testing the system.
-

4.2.4 Outreach and Education

Finally, the above will be used, as already mentioned, to inform the outside, namely, all the areas directly or indirectly involved with the timber industry, to push the material forward, help finding better solutions to old and new problems, build more reliable constructions, and develop new technologies. This will be done in partnership with every layer of the sector, from forest to landfill, for CATT to act like glue joining together all these different entities.
More importantly, the data gathered, research undertaken, and knowledge acquired will be used in all the different programmes CATT will deliver to upskill and reskill today's professionals, or to train the future ones [26]. The educational offer will be strongly based on a learning-by-doing approach, with evidence-based content being the backbone of the teaching activities [27].

4.3 LIVING LAB RELATED PROJECTS

4.3.1 Stora Enso partnership

Stora Enso is world leader in the supplying of mass timber products. The company provided the CLT panels for the building, and started a research partnership with the Centre.
48 Wiiste sensors (Figure 2) have been installed in different locations of the building. These sensors are able to monitor the moisture content of the CLT panels at determinate depths using coated screws that work as the pins of a moisture meter. The uncoated part of the screws, namely, the tip, is the measuring part, so that different length screws can measure different parts of the panel. The sensors are all set to measure the moisture content of the inner and outer layer. Furthermore, the sensors allow also the gathering of temperature and humidity data inside the building.
The information collected will be compared to that gathered by a weather station placed on top of the building to assess the correlation between external weather and internal conditions.

Figure 2: *Moisture measuring Wiiste sensors: side (top) and frontal (bottom) view (credits Wiiste Oy).*

4.3.2 Measuring Mass Timber

Together with the architects' firm dRMM, CATT (via ENU) has submitted a proposal to fund a project that will focus on Whole Life Carbon (WLC) and Quality of Life Methods for mass timber buildings. The CATT will act as one of five case studies, and the project itself will use the information gathered with the Supply Chain Mapping (SCM) to contribute to the creation of data bank to demonstrate whole-life value of timber structures. The outline of the advanced proposal is:

- Whole Life Carbon (WLC) assessment: combining the latest industry best practice guidance for assessing

https://doi.org/10.52202/069179-0555

carbon in general and specifically for timber buildings. Defining core input requirements, challenges in data collation and comparing outcomes against business as usual and best practice datasets/benchmarks (e.g., RIBA 2030, LETI)

- Post-Occupancy Evaluation: monitoring relevant essential activity components of the RIBA's POE & BPE Primer, with an emphasis in terms of assessing Quality of Life and user satisfaction. Additional monitoring of internal air quality & thermal comfort to support any qualitative feedback. Comparing outcomes against national and building POE specific datasets.
- Fundamental project information: essential information for each building, to contextualise each case study project's WLC and POE outcomes in terms of their unique circumstances (e.g., date constructed, project build cost, detail on the building's use and client/occupiers, suppliers of mass timber systems, etc.).

4.4 DIGITAL SOLUTIONS

During the construction phase, the companies shared information through a level 2 BIM model to coordinate activities and check whether any modification to the original plan had an impact on any other already schedule undertaking.

The importance of this digital approach is that everyone is sharing the same design space and can know right away what is going on in the other operations, which optimise productivity and increase safety.

From a Living Lab perspective, the digital model can be used to collate data about different aspects of the building: a BIM model can be used not only to plan, but each element within the model can be populated with information regarding several aspects, such as supply chain (e.g., manufacturer, origin of materials, or ubication of production site), performance (e.g., U-value, sound absorption, or structural grade) sustainability (e.g., CO_2 equivalent). This way, a comprehensive tool can be generated and used as a library containing all the information about the building.

The next step is to use the model to create a digital twin. The new model takes advantage of part of the information stored in the BIM model and augment this with information about mechanical, electrical, and plumbing (MEP) systems, such as consumptions and performance. This approach helps to understand if the designed performance is met by the actual building.

The third, and more interesting, step, from a Living Lab perspective, is to use the digital twin to gather data from sensors. This approach allows for the direct estimation of localised performance of the building, enabling immediate action against any possible problem, or the ability to track the evolution of the construction over time, to check performance is maintained throughout. Another advantage of this is the possibility to use up-to-date information to run simulations, both for different from usual scenarios and for different characteristics of the buildings, namely, different materials or MEP systems, to study the building from any desired perspective and address specific problems.

At the present stage, the array of sensors currently deployed is not allowing us to take full advantage of this tool, but, given the goal we set ourselves, the will is to increase the amount of sensors and to expand the current range of monitored characteristics, making the adoption of this technology very likely, if not necessary, in the future.

Furthermore, as previously mentioned, these solutions are of interest for building maintenance and operations, which means not only research and learning activities can be based on this, but also analyses on costs and consumptions can benefit from the digital twin. Therefore, not only the CATT team, but the NMITE's Estate team is interested in this technology and will collaborate on this project too.

5 CONCLUSIONS AND FUTURE STEPS

In this paper, the current operations regarding the implementation of a living lab within the CATT/CAM building of NMITE are presented. The living lab approach is discussed together with the projects that will take advantage of said approach. Finally, digital solutions to be implemented are depicted.

The methodology illustrated is, for now, just a methodology, apart from the moisture in CLT sensors and the supply chain mapping. Nevertheless, the direction shown is clear and the targets set are well-defined and implementable over time with the correct resources secured.

In the future, further measurements and monitoring should be carried out, such as structural health monitoring or thermal performance assessment of the envelope, to not only augment the base knowledge of the building, but also to provide further information on the actual behaviour of such buildings, with an emphasis on durability. The information collated, together with that already gathered, will inform the educational programme providing first hand evidence. The LCA and supply chain mapping will provide evidence of the sustainable procurement approaches taken toward the derivation of a more standardised methodology to evidence the actual sustainability of timber buildings. Digital solutions are also considered as an approach for transparency and visualisation to convey in a more powerful and incisive way concepts regarding timber constructions, capable of assisting with the gathering of data and its interpretation, particularly as the level of sensors and measurements grows and becomes more complex.

REFERENCES

[1] Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., Harradence, F., et al.. Gemini Principles. (CDBB_REP_006), 2018. https://doi.org/10.17863/CAM.32260

[2] Guglielmo C., Nitesh M.. Circular Business Models for the Built Environment. In Arup & BAM, 2017.

[3] Ellen MacArthur Foundation. Intelligent Assets: Unlocking the Circular Economy Potential, 2016. https://emf.thirdlight.com/link/1tb7yclizlea-116tst/@/preview/1?o

[4] United Nations Environment Programme. 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi, 2022.

[5] Giddings J.. Mass Timber: Challenges & Potential Solutions - Summary report of the ASBP's Timber Accelerator Hub. The Alliance for Sustainable Building Products, 2022.

[6] Leminen S. Q&A. What Are Living Labs? Technology Innovation Management Review, Vol. 5(9), pp 29–35, 2015. http://timreview.ca/article/928

[7] Palma P., Steiger R.. Structural health monitoring of timber structures – Review of available methods and case studies. Construction & Building Materials, Vol. 248, 118528, 2020. https://doi.org/10.1016/j.conbuildmat.2020.118528

[8] Alarcón M., Soto P., Hernández F., Guindos P.. Structural health monitoring of South America's first 6-Story experimental light-frame timber-building by using a low-cost RaspberryShake seismic instrumentation. Engineering Structures, Vol. 275, part B, 2023. https://doi.org/10.1016/j.engstruct.2022.115278

[9] Wang J., You H., Qi X., Yang N.. BIM-based structural health monitoring and early warning for heritage timber structures. Automation in Construction, Vol. 144, 2022. https://doi.org/10.1016/j.autcon.2022.104618

[10] Larsson C., Abdeljaber O., Bolmsvik Å., Dorn M.. Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building. Engineering Structures, Vol. 268, 114726, 2022. https://doi.org/10.1016/j.engstruct.2022.114726

[11] Kukk V., Kers J., Kalamees T., Wang L., Ge H.. Impact of built-in moisture on the design of hygrothermally safe cross-laminated timber external walls: A stochastic approach. Building and Environment, 226-109736, 2022. https://doi.org/10.1016/j.buildenv.2022.109736

[12] Evans, P. D., Matsunaga, H., Preston, A. F., Kewish, C. M.. Wood Protection for Carbon Sequestration - a Review of Existing Approaches and Future Directions. Current forestry reports, Vol. 8, pp 181-198, 2022. https://doi.org/10.1007/s40725-022-00166-x

[13] Ayanleye S., Udele K., Nasir V., Zhang X., Militz H.. Durability and protection of mass timber structures: A review. Journal of Building Engineering, 46, 103731, 2022. https://doi.org/10.1016/j.jobe.2021.103731

[14] Pomponi F., D'Amico B.. Holistic study of a timber double skin façade: Whole life carbon emissions and structural optimisation. Building and environment, Vol.124, pp 42-56, 2017. http://dx.doi.org/10.1016/j.buildenv.2017.07.046

[15] Hart J., D'Amico B., Pomponi F.. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. Journal of industrial ecology, Vol.25 (2), pp 403-418, 2021. https://doi.org/10.1111/jiec.13139

[16] Dong Y., Qin T., Zhou S., Huang L., Bo R., Guo H., Yin X.. Comparative Whole Building Life Cycle Assessment of Energy Saving and Carbon Reduction Performance of Reinforced Concrete and Timber Stadiums - A Case Study in China. Sustainability (Basel, Switzerland), 2020, Vol.12 (4), 1566, 2020. https://doi.org/10.3390/su12041566

[17] Morris F., Allen S., Hawkins W.. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. Building and Environment, Vol. 206, 108285, 2021. https://doi.org/10.1016/j.buildenv.2021.108285

[18] Stocchero, A., Seadona, J. K., Falshaw, R., Edwards, M.. Urban Equilibrium for sustainable cities and the contribution of timber buildings to balance urban carbon emissions: A New Zealand case study. Journal of Cleaner Production, Vol. 143, pp 1001-1010, 2017. https://doi.org/10.1016/j.jclepro.2016.12.020

[19] Mazutti J., Londero Brandli L., Lange Salvia A., Fritzen Gomes B. M., Damke L. I., Tibola da Rocha V., dos Santos Rabello R.. Smart and learning campus as living lab to foster education for sustainable development: an experience with air quality monitoring. International Journal of Sustainability in Higher Education, Vol. 21-7, pp 1311-1330, 2020. http://dx.doi.org/10.1108/IJSHE-01-2020-0016

[20] Ascione F., Borrelli M., De Masi R. F., Vanol G. P.. Nearly zero energy target and indoor comfort in Mediterranean climate: Discussion based on monitoring data for a real case study. Sustainable Cities and Society, Vol. 61, 2020. https://doi.org/10.1016/j.scs.2020.102349

[21] Ebbesson E.. Towards a co-creation framework based on citizens' dreams of future mobility. Transportation Research Interdisciplinary Perspectives, Vol. 16, 2022. https://doi.org/10.1016/j.trip.2022.100686

[22] Dong W., Do E., Lee B. S., Cohn J.. Quantifying worker interactions and characterizing worker performance through ubiquitous IoT. Pervasive and Mobile Computing, Vol. 87, 2022. https://doi.org/10.1016/j.pmcj.2022.101702

[23] Piselli C., Pisello A. L.. Occupant behavior long-term continuous monitoring integrated to prediction models: Impact on office building energy performance. Energy, Vol. 176, pp 667-681, 2019. https://doi.org/10.1016/j.energy.2019.04.005

 https://doi.org/10.52202/069179-0555

[24]Eon C., Morrison G. M., Byrne J.. The influence of design and everyday practices on individual heating and cooling behaviour in residential homes. Energy Efficiency, Vol. 11, pp 273–293, 2018. https://doi.org/10.1007/s12053-017-9563-y
[25]Bursill J., O'Brien L., Beausoleil-Morrison I.. Multi-zone field study of rule extraction control to simplify implementation of predictive control to reduce building energy use. Energy and Buildings, Vol. 222, 110056, 2020. https://doi.org/10.1016/j.enbuild.2020.110056
[26]Ridley-Ellis D., Nolte S.. The educational needs of the timber industries – report of an online survey by the centre for timber engineering, 2006. https://www.napier.ac.uk/-/media/worktribe/output-249416/cteedusurveyapr2006pdf.ashx
[27]Mortesen A., Tupenaite L., Naimaviciene J., Kanapeckiene L., Amado M., Hamburg P., Taylor R. H.. Improving transnational education in timber construction by the use of project-based learning approach: as evaluated by teachers and students. Baltic Journal of Real Estate Economics and Construction Management, Vol. 7, 1, pp 228-244, 2019. https://doi.org/10.2478/bjreecm-2019-0014