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Numerical Analysis and Experimental Verification of the Thermal Performance of Hybrid Cross-Laminated Timber (CLT)-glass Facade Elements

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Structural solutions involving the mechanical interaction of timber and glass load-bearing members showed a progressive increase in the last decade. Among others, a multipurpose hybrid facade element composed of Cross-Laminated Timber (CLT) members and glass panels interacting by frictional contact mechanisms only was proposed ion the framework of the VETROLIGNUM project. While demonstrating enhanced load-bearing and deformation capacity performances under seismic loads, facade elements are known to represent a building component with multiple performance parameters to satisfy. These include energy efficiency, durability, lightening comfort and optimal thermal performance. In this paper, a special focus is dedicated to the thermal performance assessment of CLT-glass facade modules under ordinary operational conditions. Based on the thermal-chamber analysis of small-scale prototypes, reliable Finite Element (FE) numerical models are developed and applied to full-scale VETROLIGNUM solution. Sensitivity analyses are hence carried out to explore the actual thermal performance of these novel hybrid systems.

Keywords: Cross-Laminated Timber (CLT), structural glass, CLT-glass hybrid facade, thermal performance, small-scale experiments, Finite Element (FE) numerical modelling

1. Introduction

In the last decade, there has been a progressive development of load-bearing building components – especially beams – composed of timber and glass (Cruz and Pequeno, 2008; Premrov et al., 2014; Rodacki et al., 2019; Sjöström et al., 2020). Even more attention has been dedicated to curtain wall applications, where wide surfaces must be covered and enhanced load-bearing performances / deformation capacities must be satisfied, especially under extreme design loads such as earthquakes (Neubauer, 2011; Ber et al. 2013; etc.). In most of the cases, however, the explored solutions and design applications still involve a continuous (adhesive and/or mechanical) connection between a given timber frame and the glass infill panels (Fig. 1).


a) b)

Fig. 1 Examples of timber-glass facade solutions: a) typical cross-section of curtain wall detail (*www.stabalux.com*); b) adhesively bonded framed panels according to (Neubauer, 2011).

Among others, it was shown through the VETROLIGNUM project (*www.grad.unizg.hr/vetrolignum*) that structurally efficient Cross Laminated Timber (CLT)-glass hybrid systems can be used in buildings, taking advantage of frictional contact interactions between glass and timber only (Žarnić et al., 2020).

Besides the need of optimal structural performances for these innovative solutions, however, a facade element as a whole should fulfill a multitude of performance requirements, including the thermal response, energy efficiency, usability, etc. In this research paper, a special care is dedicated to the analysis of VETROLIGNUM hybrid facade elements under ordinary thermal loads. The study includes small-scale experimental prototypes and Finite Element numerical analyses. After a first validation of thermo-mechanical models, the attention is moved from the small-scale level to the typical CLT-glass facade module for full-scale applications.

2. Research context and goals

Testing the energy performance and behaviour of innovative load-bearing solutions and components for buildings represents, nowadays, a crucial step of research and design. The facade enclosure is in fact a key factor in defining the energy rating and class of the entire building it belongs, as well as the thermal comfort of occupants. Accordingly, it must satisfy specific performance limits (EU 2010/31). This is also the case of the VETROLIGNUM innovative CLT-glass hybrid facade element, that has been assessed over a 3-years project and is further investigated in this paper. Following the EN ISO 13788 standard, for example, one of the performance parameters to assess is the thermal quality, that can be generally expressed by the well-known temperature factor at the internal surface f_{Rsi}. The simplified calculation approach presented in EN ISO 13788 suggests that:

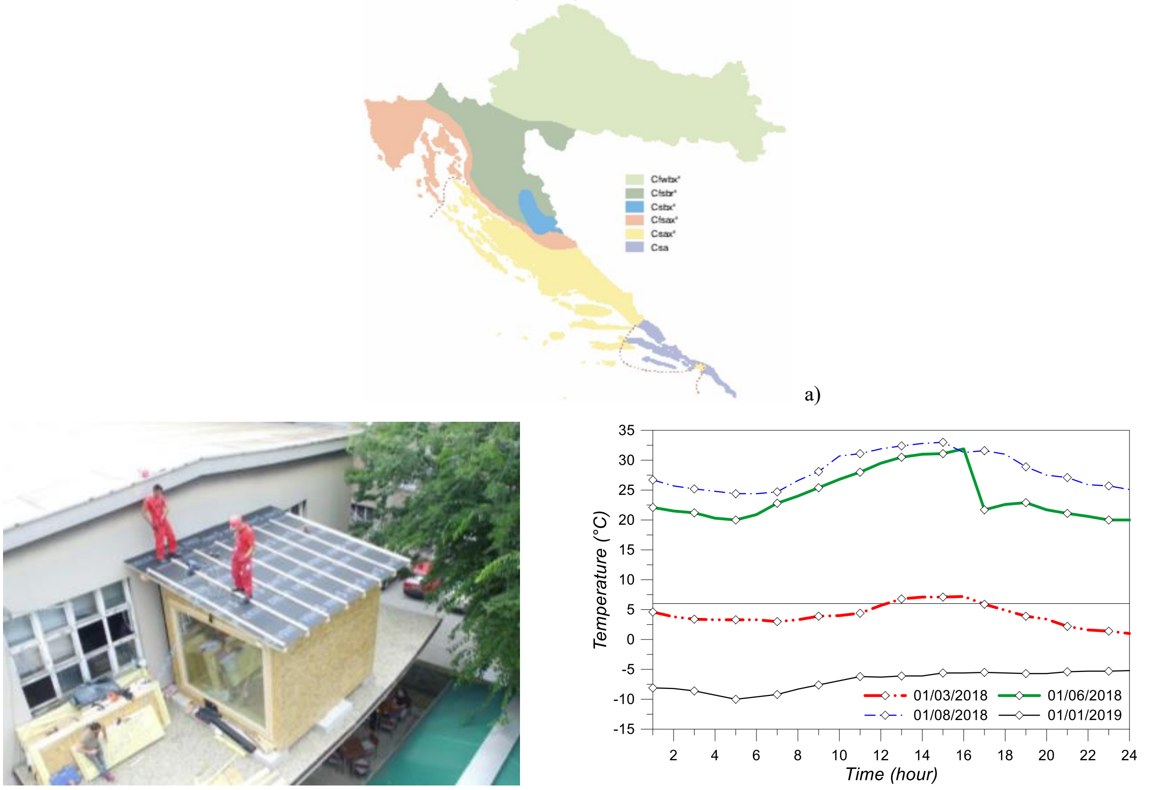
$$f_{Rsi} = \frac{T_{si}-T_{out}}{T_{int}-T_{out}} \tag{1}$$

with T_{si} the temperatures of internal wall surface, T_{int} the internal air temperature and T_{out} external air temperature respectively. The internal surface temperature strictly depends on the features of the structure to investigate, and can be sensitive especially to thermal bridges causing multidimensional heat flow. Another relevant parameter is represented by the internal surface resistance, that depends on convection and radiation coefficients, on the air movements in the room, on the air and surface temperature distribution in the room and on the surface material properties. Accordingly, refined and time consuming numerical models of a given room as a whole would be necessarily required, to account for several aspects like the thermal resistances of the surrounding envelopes, the environmental temperature, the air distribution in the room and its geometry. However, simplified calculation methods or input values recommended by existing guideline documents can be used for preliminary estimates.

The temperature factor f_{Rsi} should be generally close to the unit to represent optimally insulated buildings. In any case, values at least equal to $f_{\mathrm{Rsi}} \geq 0.75$ are commonly accepted to ensure the occurrence of mould growth and surface condensation in dwellings. This is in line with several National guidelines and recommendations, with minimum values equal to $f_{\mathrm{Rsi}} \geq 0.52$ (France), or $f_{\mathrm{Rsi}} \geq 0.65$ (Netherlands) and $f_{\mathrm{Rsi}} \geq 0.7$ for Germany (Kalamees, 2006) .

Besides the envelope features, however, the reference f_{Rsi} minimum value is in fact related to climate conditions and climate changes. Accordingly, new building envelopes and systems should be able to properly satisfy a set of thermal performance requisites that become even mor restrictive as far as the climate conditions modify. Following a past Köppen's classification for the Croatian region (see (Zanor et al., 2005) and Fig. 2a), for example, the largest National part was detected to have a moderately warm rainy climate, with mean monthly temperature in the coldest month of the year above -3°C and below 18°C. The highest mountain regions only (with > 1.200 m of altitude) were recognized to have a snowy, forest climate, with the mean temperature in the coldest month below -3 °C. In the continental mainland, finally, the hottest month of the year was usually detected in a mean temperature lower (and in the coastal area higher) than 22 °C.

Such a literature study, as in most of other cases, actually underestimates the real climate conditions of several regions. Within the VETROLIGNUM project, as a result, field ambient measurements have been recorded over a period of 3 years. Special care was spent for outdoor parameters of technical interest (Fig. 2b), giving evidence of a progressive enforcement of extreme temperatures both in winter and in the summer season. Typical temperature records, see the examples in Fig. 2c), were collected up to -10°C and >32°C, for repeated episodes. Given such a severe climate scenario, and assessed the structural efficiency of the CLT-glass hybrid elements for load-bearing envelopes, this current paper numerically explores the thermal performance of the same innovative solution. At this stage, the support is derived by small-scale thermal chamber testing of CLT-glass prototypes (Faculty of Civil Engineering in Rijeka, Croatia) and by ambient measurements from the Live Lab in Zagreb University (Fig. 2c). The thermal chamber measurements are first used to validate a reliable Finite Element (FE) numerical model for thermal assessment purposes. The same FE modelling approach is then transferred to a full-scale VETROLIGNUM prototype. FE thermal estimates and EN ISO calculation methods (i.e., Eq.(1)) are then taken into account for preliminary estimates and comparisons.



a)

b)

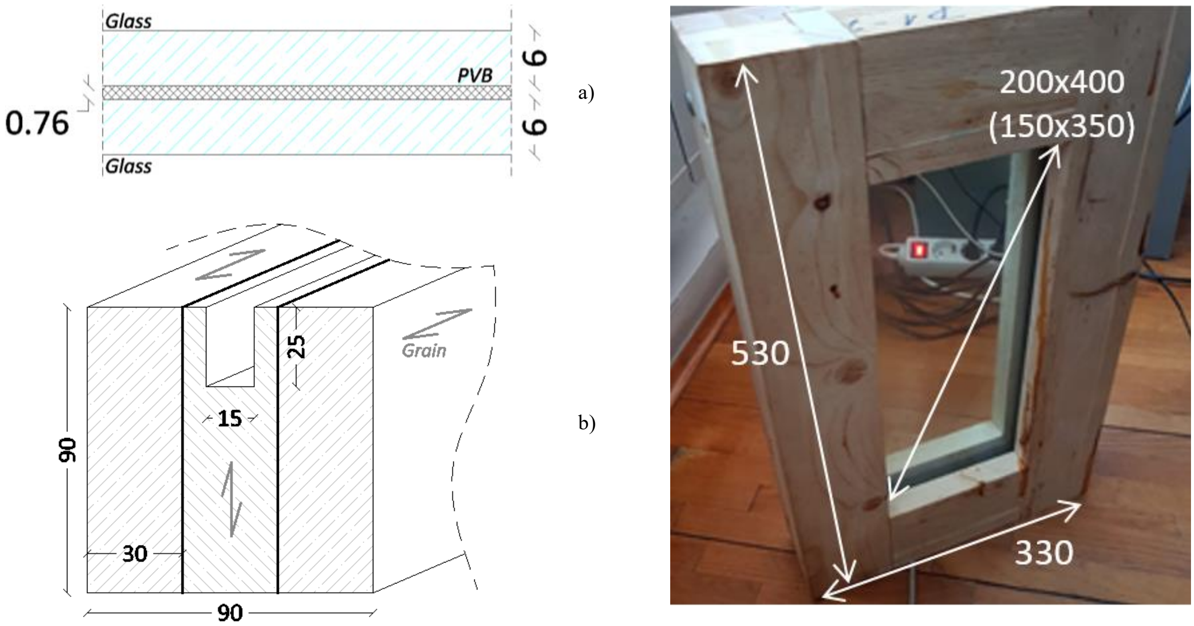
c)

Fig. 2 Ambient measurements: a) Köppen's classification of Croatian climate (reproduced from (Zanor et al., 2005)), with b) Live Lab installation and c) example of outdoor temperatures (selection).

3. Preliminary validation of FE numerical models towards small-scale experiments

3.1. Materials and methods for thermal chamber setup

For the purpose of testing the effect of temperature on glass and wood, a reference prototype of global dimensions *B*= 330mm × *H*= 530mm (200×400mm the net are of the glass panel, plus external frame) was preliminary investigated in a thermal chamber setup.



a)

b)

c)

Fig. 3 Small-scale specimens: a) nominal cross-section detail for laminated glass and b) CLT frame members, with c) final assembly (dimensions in mm).

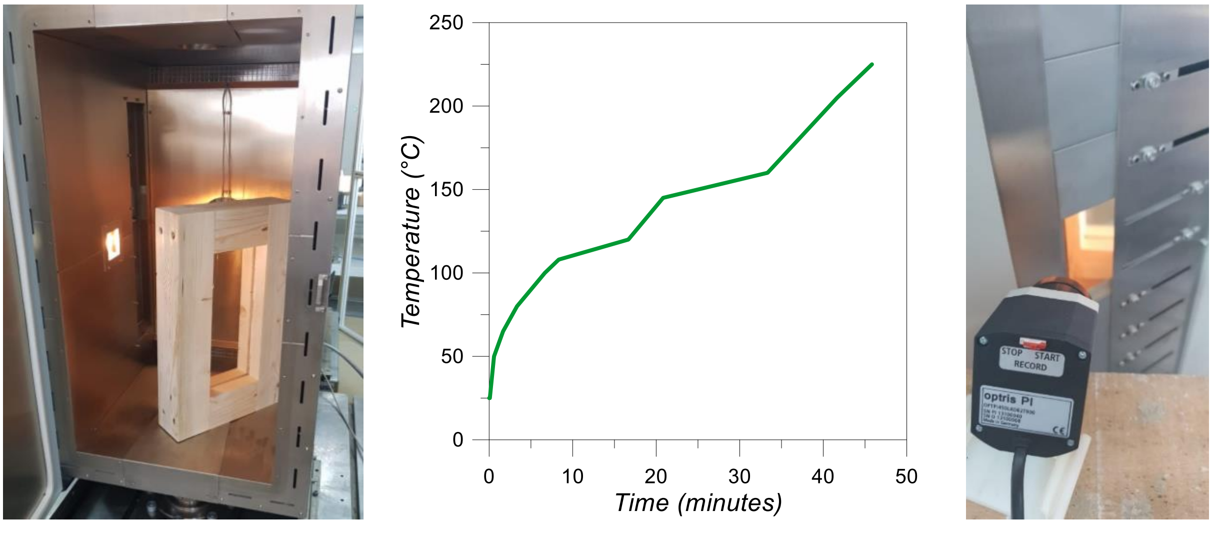
Given that the thermal chamber in use for the pilot experiment was characterized by limitations in size and allowable temperatures, namely:

- internal dimensions: 450 × 550 × 850 mm,
- available temperatures: -80 to +250°C (liquid nitrogen required for sub-zero temperatures),

the final size of the specimen was restricted by the thermal chamber itself, and thus resulted in a small-scale prototype that is not representative of real window / facade elements. Otherwise, the same prototype allowed to verify the accuracy of numerical methods, and thus to extend the same modelling strategy and assumptions to full-scale components.

More in detail, the glass panel (12.76mm in thickness) was obtained by lamination of 6mm glass layers and a 0.76mm thick Polyvinyl Butyral (PVB®) foil, see Fig. 3a). The frame members were then made of CLT with resistance class C24 (spruce), according to the EN 338: 2016 standard. The members in use were cut in accordance with Fig. 3b), that is from a three-layer, 8.4m long and 2.95m wide CLT plate (StoraEnso, *www.storaenso.com*) whose section was made of 30mm thick lamellae with "non-visible" machining quality (EN 16351:2015). As usual, a formaldehyde-free polyurethane adhesive was used to bond together the slats, and all the timber members were realized with an identical cross-section (b= 90mm × h= 90mm the nominal size). In accordance with the VETROLIGNUM design concept, the laminated glass panel was positioned in continuous slots (25mm high) realized along the timber members, see Fig. 3b). Accordingly, a reduced surface of glass was directly exposed to thermal loading (150×350mm). Frictional contact interactions only were taken into account at the CLT-to-glass interface, without the use of other interposed materials or mechanical fasteners. The four wooden members were finally bolted together by means of bolts, so as to produce a continuous frame for glass (Fig. 3c).

At the time of the pilot experiment, see Fig. 4a, the CLT-glass sample was hence positioned in such a way that it could be uniformly exposed to the chamber temperature. After 20-25 minutes, the latter was measured in the order of ≈180° C and further increased up to ≈230°C (Fig. 4b). The thermal performance of timber and glass components was thus monitored with the support of a thermal camera (Fig. 4c).



a) b) c)

Fig. 4 Small-scale CLT-glass prototype: a) test setup, b) imposed temperature-time history and c) thermal camera.

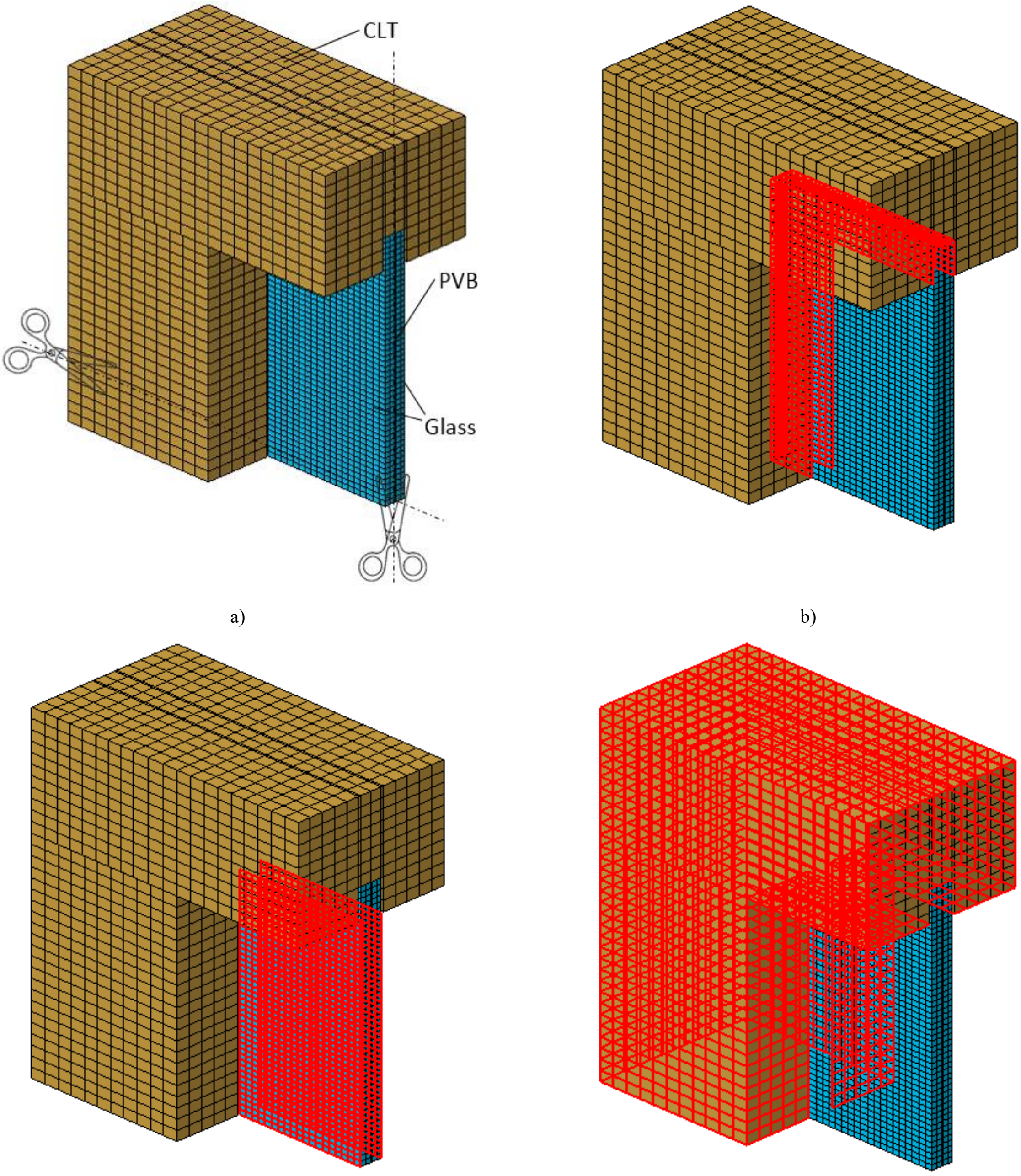
3.2. Preliminary FE validation: methods and assumptions

In accordance with the schematic drawings of the small-scale prototype in Fig. 3, 1/4th the nominal geometry was numerically reproduced, with appropriate boundary conditions for symmetry (Fig. 5a). The reference FE model consisted of 8-node brick elements (*heat transfer* elements, DC3D8 type from ABAQUS library (Simulia)), with a total number of 13,500 elements and 55,000 DOFs.

The FE model globally consisted of three mechanically interacting components (the laminated glass panel and two orthogonal CLT members). Following the experimental assemblage step, their reciprocal interaction was numerically reproduced via surface contacts. For the CLT-to-glass interface (Fig. 5b), a surface-to-surface mechanical behaviour was used. Similarly, the orthogonal CLT members were rigidly connected at the intercepting section ("tie" rigid constraint avoiding possible relative displacements and rotations).

A transient heat-transfer simulation was carried out in ABAQUS, by imposing the actual temperature-time history derived from thermal chamber measurements (Fig. 4b) to the FE assembly of Fig 5a).

As such, specific surface thermal interactions were defined for the surfaces under thermal exposure. All the external surfaces of glass (Fig. 5c) and timber (Fig. 5d) were subjected to thermal loading. This assumption, while not representative of an actual thermal exposure for real windows, was chosen to reproduce the boundary conditions of the thermal chamber setup. Based on past literature efforts (see for example (Bedon, 2018; Bedon and Louter, 2018; EN 1991-1)), *surface radiation* and *surface film* interactions were defined for glass and timber. The convection coefficient for all the faces under thermal exposure was set equal to 23W/m^{2}K (EN ISO 10077-2). Emissivity coefficients for glass and timber, at the same time, were defined in 0.95 and 0.8 respectively.



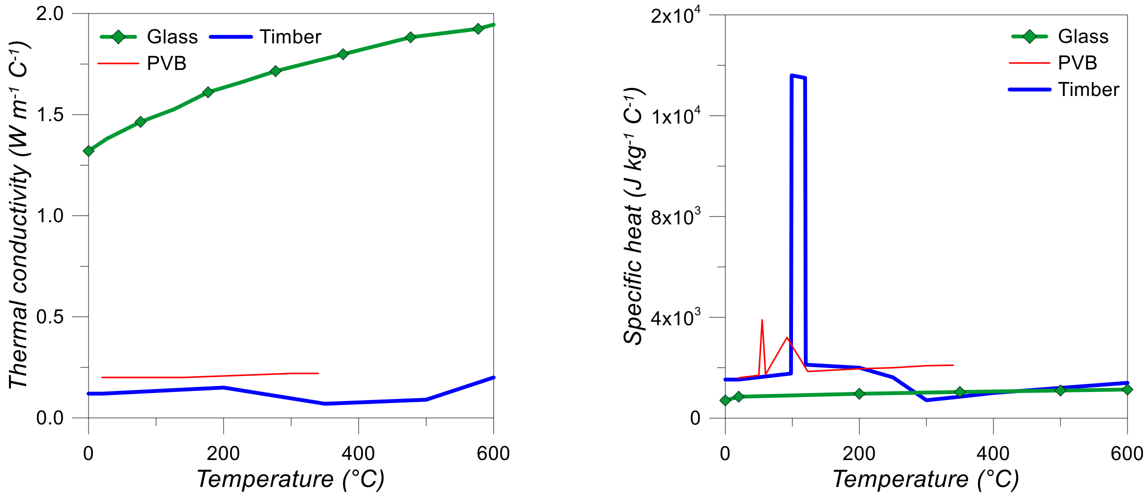
a) b) c) d)

Fig. 5 Small-scale FE model (ABAQUS): a) geometry and b) CLT-to-glass contact surfaces, with exposed regions for c) glass and d) timber.

Regarding the characterization of materials in use, different thermo-physical properties were taken into account for glass, PVB and C24 spruce, see Fig. 6. More in detail, reference input properties and their variation with temperature were taken from (Tong, 1994; Cardenas et al. 2016; Bedon, 2017; Debuyser et al. 2017) in the case of glass and PVB, while recommended values reported in EN 1991-1 were used for timber. The presence of CLT lamellas with different grain orientation (as in Fig. 3) was disregarded for the thermal characterization of timber, as also in accordance with literature studies that prove the homogeneous thermal behaviour of wood (see for example (Chang et al., 2019)).

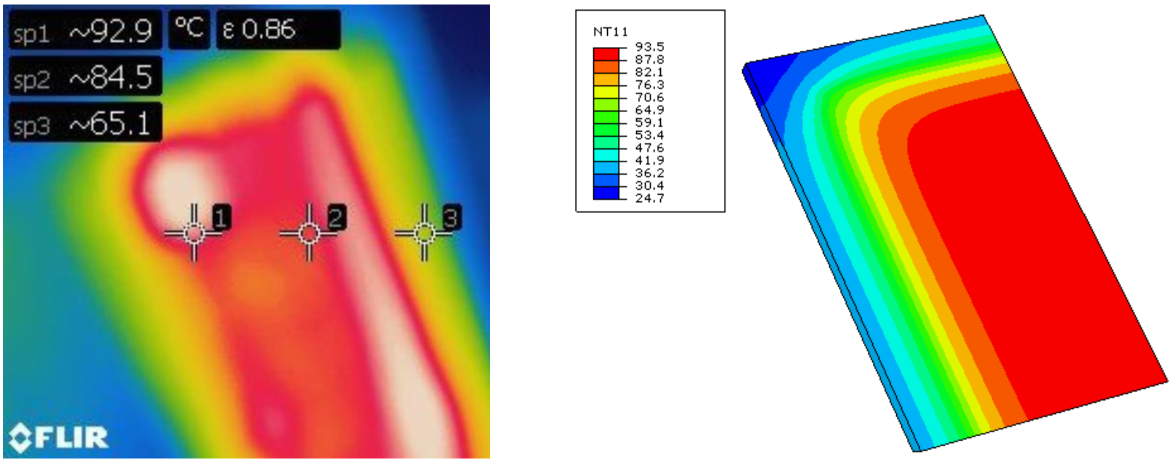
Given that the goal of the study herein reported was the thermal performance assessment only, the actual variation of mechanical properties with temperature was temporarily disregarded, because not relevant for the performed simulations. Similarly, density and emissivity variations with temperature were neglected. Similarly, the grain orientation of lamellas composing the typical CLT cross-section was found to do not affect the prediction of thermal analyses.

The attention of thermal analyses was hence focused on the analysis of temperature evolution and distribution in the load-bearing members, for the imposed boundary conditions. When possible, FE estimates were compared with the corresponding test predictions. In Figs. 7a) and b), a typical temperature correlation can be shown between the small-scale prototype and the corresponding FE model.
A rather close correlation can be perceived between thermal camera estimates (in evidence, the glass panel) and the corresponding FE predictions. The presence of timber frame members can be recognized in temperature contour plots by the presence of lower temperatures, with respect to the central region of glass with direct thermal exposure.



a) b)

Fig. 6 Thermo-physical characterization of glass, PVB and timber: a) conductivity and b) specific heat.



a) b)

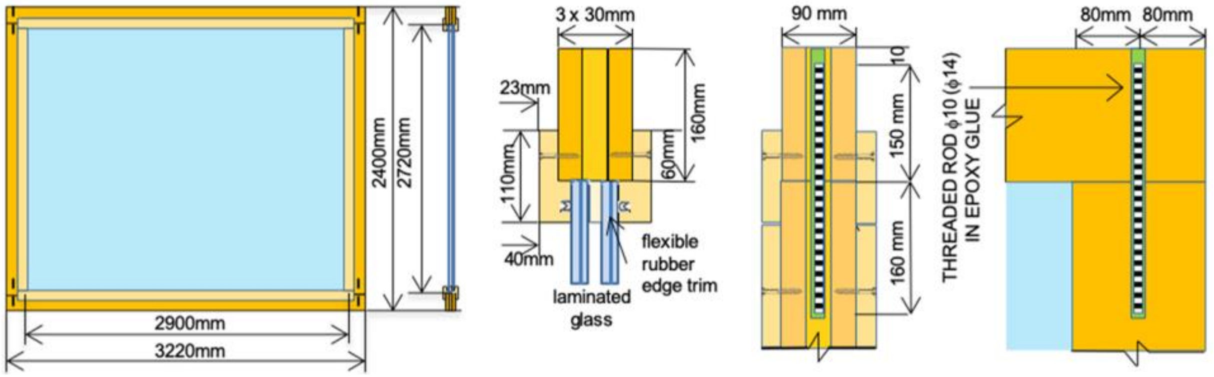
Fig. 6 Small-scale CLT-glass analysis: a) example of the typical thermal camera acquisition (glass in evidence) and b) corresponding FE estimation (with CLT frame and mesh pattern hidden from view; temperature values in °C).

4. Numerical thermal analysis of full-scale CLT-glass facade elements

4.1. Reference geometry

Following Section 3, a similar FE numerical approach was taken into account and further extended, towards the investigation of thermal performances for full-scale CLT-glass facade elements according to the VETROLIGNUM study.

Based on the technical drawings reported in Fig. 7, the reference facade element consists of two double laminated glass sections (fully tempered glass, 10mm thick layers, with 1.6mm Ethylene-Vinyl Acetate (EVA®) interlayer). The interposed cavity (s= 12.8mm its thickness) is sealed by a continuous, flexible rubber edge trim (see Fig. 7b), while CLT timber members are used to create a continuous bracing frame. The reference system agrees with the facade prototypes that have been structurally assessed in (Žarnić et al., 2020).



a) b) c)

Fig. 7 Full-scale CLT-glass facade element (figure reproduced from (Žarnić et al., 2020) with permission from Elsevier): a) front view, b) glass-to-CLT frame connection detail (cross-section) and c) timber corner joint.

Besides the use of similar material properties and the qualitative good agreement with the geometrical details of the small-scale prototype described in Section 3, a careful consideration was spent for the analysis of realistic temperature exposures in facades.

4.2. Modelling assumptions

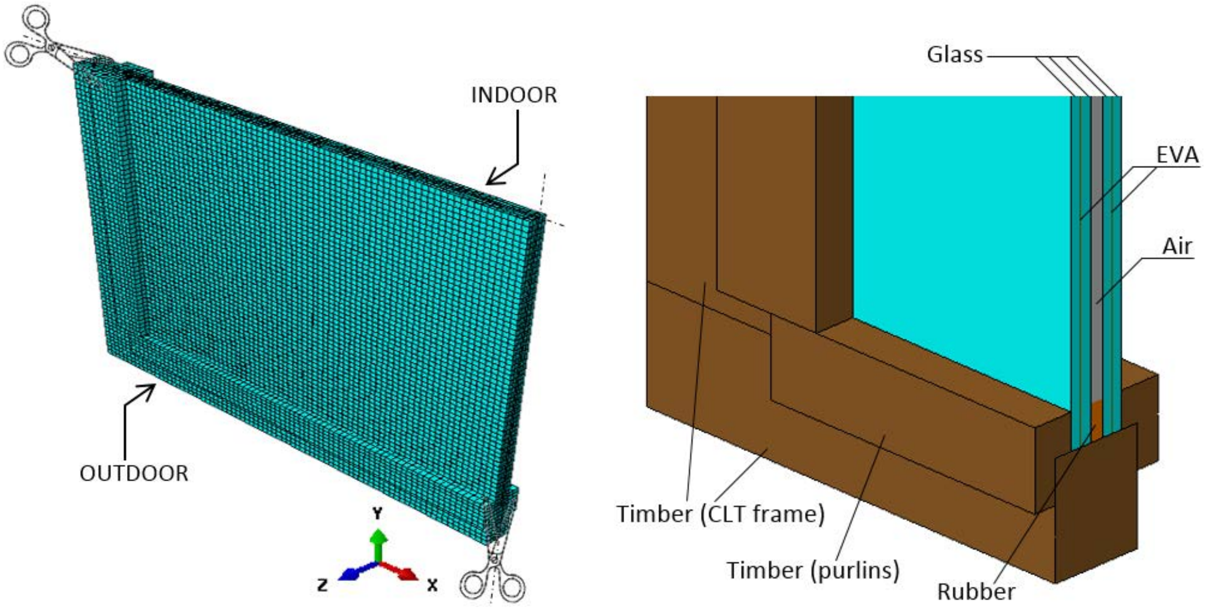
As in Section 3, the reference FE assembly representative of th full-scale system in Fig. 7 consisted of a set of 8-node, *heat transfer* brick elements (DC3D8 type from ABAQUS library), and included the description of the nominal geometry for:

- the laminated glass sections (two panels with 10.10/1.6 nominal section);
- the interposed air cavity (s= 12.8mm);
- a continuous, rubber edge trim facilitating the glass panels to keep their position (detail of Fig. 7b);
- the CLT frame members;
- and additional timber purlins providing a slot for the activation of frictional mechanisms along the edges of glass (see Fig. 7b).

Taking advantage of geometrical symmetry, the FE modelling was focused on 1/4th the nominal module of Fig. 7. The use of symmetry restraints allowed to enhance the computational cost of simulations.
Differing from Section 3, the typical analysis consisted of a steady state heat transfer simulation, under pre-defined thermal boundaries. Based on EN ISO 10077-2:2017 provisions, the reference restraints were taken into account:

- Relative Humidity: 50%;
- External (outdoor) condition: T= 0°C, film coefficient (outdoor surfaces of timber and glass)= 23 W/m^{2}K;
- Internal (indoor) condition: T= 20°C, film coefficient (timber and glass)= 8.02 W/m^{2}K.

The performance of the CLT-glass facade module was hence assessed by evaluating few key performance indicators, such as the overall U-value, the corresponding linear thermal transmittance ψ-value and the expected temperature distribution / limit values under the imposed gradient ΔT (for condensation risk assessment), with a focus on the minimum surface temperature on glass (T_{min}). The latter, according to Eq.(1), is in fact directly responsible of the temperature factor at the internal surface f_{Rsi}, and thus of the overall thermal comfort for occupants.



a) b)

Fig. 8 Reference FE model for the thermal assessment of full-scale CLT-glass facade elements: a) global assembly (1/4th the nominal geometry) and b) detail view, with hidden mesh (ABAQUS).

The imposed thermal scenario, in particular, was found to be well representative of real field measurements available from the Live Lab in Fig. 2, and average indoor conditions for a traditional building. For FE purposes, as in the case of transient analyses on small-scale prototypes, the thermal characterization of materials was carried out based on nominal thermo-physical parameters provided by design standards and literature references (Table 1).

Table 1: Input thermal properties in use for FE modelling (ABAQUS).

	Load-bearing component			Interposed cavity	
Property	Glass	EVA	Timber	Rubber	Air
Conductivity λ [W/mK]	0.8	0.19	0.3	0.1	0.028
Emissivity ε [–]	0.95	/	0.8	/	/

A special care was paid, in the latter case, for the air volume enclosed within the cavity between the laminated glass panels, that was properly described in the form of conductivity. The latter assumes that the interposed cavity is perfectly sealed along the glass edges, and can be also extended to the VETROLIGNUM prototype (with frictional contacts with the timber frame, and a continuous flexible rubber edge trim to enclose the cavity). The required *surface film* and *surface radiation* thermal interactions were defined on the internal and external surfaces of the outer glass panes and timber components, according to the boundary conditions earlier described. Symmetry conditions were accounted to reproduce the thermal performance of 1/4th model as a part of a full-scale facade element.

5. Numerical investigation

5.1. Steady-state thermal analyses and parametric study

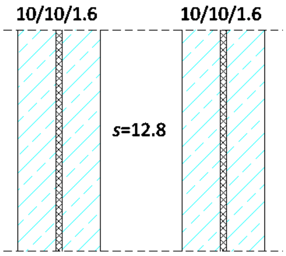
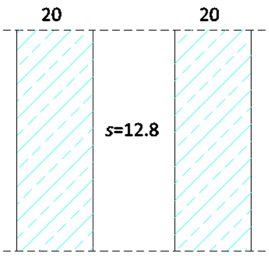
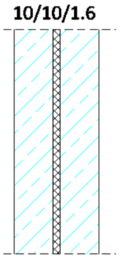
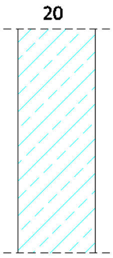
The thermal assessment performance was carried out on the reference FE model schematized in Fig. 8 (herein labelled as “P1 model”), under an imposed thermal gradient of ΔT= 20°C. Major FE outcomes are proposed in Table 2 in terms of U-total estimates, Ψ-values and also max/min internal temperatures for glass ($T_{si,max}$ and $T_{si,min}$). In addition, Fig. 9 shows the typical temperature distribution in glass and in a portion of the timber frame members (with a focus for the corner joint region).

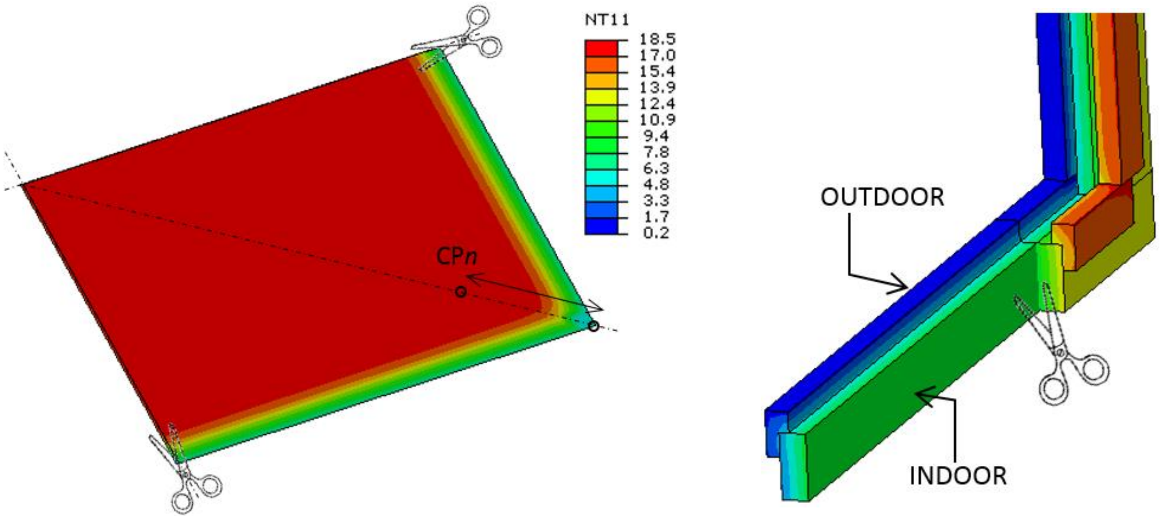
Further parametric results are also proposed in Table 2, as obtained for CLT-glass facade modules having the same overall dimensions of the P1 system (as well as an identical timber frame member concept layout), but some key variations in the composition of the glass panel, namely represented by:

- P2= the presence of a double monolithic glass element (20mm in thickness each), with interposed air cavity (s= 12.8mm) and rubber gasket according to Fig. 7b; or
- P3= a single laminated glass panel (10.10/1.6) with EVA interlayer; or
- P4= a single monolithic glass panel (20mm in thickness).

While the typical temperature distribution observed in the parametric study was found to agree with Fig. 9a), major outcomes from the FE simulations were found in the overall thermal performance of the CLT-glass module (Table 2).

Table 2: Numerical thermal performance assessment (ABAQUS, dimensions in mm).

	Parametric FE models (P_n) for the assessment of CLT-glass facade elements			
	Double laminated EVA	Double monolithic	Single laminated EVA	Single monolithic
	P1 model	*P2*	*P3*	*P4*
				
U-total [W/m^{2}K]	1.826	1.880	7.236	6.928
ψ -value [W/mK]	0.5285	0.5626	3.9815	3.7763
Imposed ΔT [°C]	20	20	20	20
$T_{si,max}$ [°C]	16.60	16.76	/	/
$T_{si,min}$ [°C]	9.15	9.10	/	/



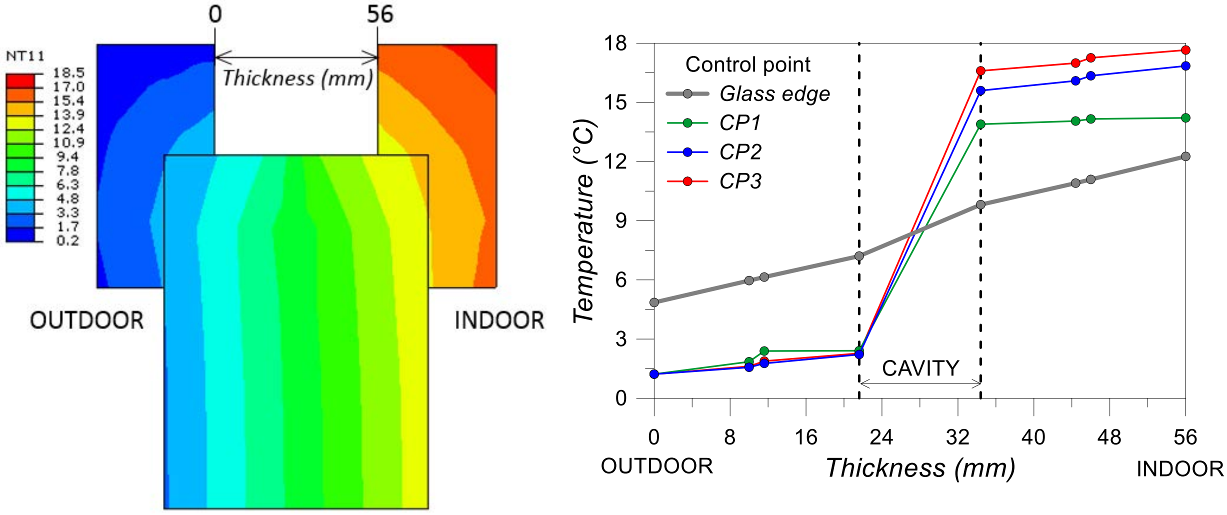
a)

b)

Fig. 9 FE thermal performance assessment of full-scale CLT-glass facade elements (P1 model). Expected distribution of temperature a) in the internal glass panel (external side) and b) timber frame (ABAQUS, values in °C).

Based on a more refined assessment of temperature distributions in timber and glass components, in Fig. 9a) it can be easily detected the region of glass in which contact with timber modifies its thermal response.

To this aim, Fig. 10a) shows the typical temperature distribution in the frame cross-section (CLT members and purlins), while Fig. 10b) offers a more detailed representation of temperatures in the thickness of glass. As far as the glass components are in contact with the frame of Fig. 10a), the temperature distribution at the glass edges corresponds to the “Glass edge” plot in Fig. 10b). In the same figure, the CP1, CP2 and CP3 control points are representative of temperature distributions in the glass thickness. According to the contour plot of Fig. 9a), these CP*n* values are selected on the diagonal of glass panel, at a distance of 50mm, 90mm and 150mm respectively from the corner.



a) b)

Fig. 10 FE thermal performance assessment of full-scale CLT-glass facade elements (P1 model). Temperature distribution: a) in the frame cross-section and b) in the thickness of glass, with a focus on the corner region (ABAQUS, values in °C).

5.2. Some considerations about the thermo-hygrometric verification of the CLT-glass facade element

Besides the lack of field experiments for full-scale prototypes, the knowledge of temperature distributions according to Fig. 10b) allows to draw some preliminary consideration for thermal assessment purposes. Given that the region of glass edges and corners are the most sensitive to potential condensation risks, more in detail, the corresponding temperatures are taken into account.

To avoid condensation, the minimum surface temperature (T_{min}) on the internal face of glass (i.e., inside the cavity volume) has to be higher than the dew point temperature (T_{dp}) for air conditions occurring inside the panel, that is:

$$T_{min} \geq T_{dp} = f(RH,T) \tag{2}$$

The minimum measured surface temperature, see Table 2 and Fig. 10b), was calculated in 9.15°C (frame region), or higher. According to European standards, the reference T_{dp} value for the examined boundary conditions should be checked based on moke up experiments including the continuous monitoring of temperature and humidity values inside the cavity. A similar approach, for example, was proposed in (Zobec et al., 2002) for a novel curtain wall system, and represents a key design step for glass envelopes in general, especially with regard to the detailing of framing members and sealants. Conservatively, the calculation is carried out in the worst conditions for the cavity volume, that is an air temperature of 9°C and RH=80%. The corresponding T_{dp} is estimated in 5.7°C. Consequently, the examined CLT-glass facade element (even in the critical regions of connection with the timber frame members), suggests appropriate performances, that will be further explored in the next stages of the project.

Another relevant parameter is represented by the minimum surface temperature on the indoor face of glass (i.e., temperature estimates in Fig. 10b), for a position of 56mm). In this latter case, for indoor conditions of 20°C and 50% of Relative Humidity, the recommended reference value is T_{dp}= 6°C, thus the limit condition is again optimally satisfied.

Some final considerations cane be spent for the temperature factor f_{Rsi}. Following standard provisions, the calculation of the surface temperature factor should be carried out during the winter season. In addition, the maximum monthly value of temperature factor should be calculated, so as to define the minimum value of the overall thermal resistance that a given building envelope should offer to avoid surface condensation risk.

As far as Eq.(1) is taken into account for the numerically investigated CLT-glass system, it is found that:

$$f_{Rsi} = \frac{T_{si}-T_{out}}{T_{int}-T_{out}} = 0.613 \tag{3}$$

and

$$f_{Rsi} > f_{Rsi,min} = f\left(\mathrm{T_{si,min}}, p_{sat}\right) = 0.285 \tag{4}$$

the calculated limit value to satisfy.

6. Conclusions

According to the literature, structural solutions involving the mechanical interaction of timber and glass load-bearing members proved to offer efficient mechanical performances in buildings, even under extreme design loads. Among others, the multipurpose hybrid facade element composed of Cross-Laminated Timber (CLT) members and glass panels interacting by frictional contact mechanisms only was proposed in the framework of the VETROLIGNUM project. In this paper, a special focus has been thus dedicated to the thermal performance assessment of the same system, given that geometrical and mechanical details also reflect on the thermal comfort of occupants.

Based on the thermal chamber testing of small-scale CLT-glass prototypes, a preliminary FE numerical model was validated, so as to capture the temperature distribution in the components. The same FE modelling approach was then transferred to the VETROLIGNUM full-scale system, with a focus on key performance parameters for its thermal behaviour and indicators. Besides the lack of full-scale ambient measurements for such a system, the preliminary calculation proved that thermal efficiency can be satisfied. At the same time, the numerical estimates emphasized the critical regions of the CLT-glass facade element, thus providing useful suggestions for the field experimental measurements to carry out in the Live Lab facility.

7. Acknowledgements

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