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NUMERICAL MODEL DEVELOPMENT FOR THE OPTIMIZATION OF WOOD COATING ENCLOSURES

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Abstract: *Current tendencies around sustainability linked to building façades encouraged us to develop a new system which, apart from presenting a low environmental impact with relation to both production and waste of material, also allows a continuous savings of energy during the whole building life cycle. In this regard, wood is characterized for being a renewable and ecological resource whose production helps to mitigate the CO released to the atmosphere, cutting down the carbon footprint.*
In this project, different façade solutions will be carefully analyzed, in terms of energy savings, whose exterior layer is made up of a group of identical joined wood strips. Different shapes and configurations will be addressed, taking into account also the global aesthetics of the solution finally adopted. For this purpose, a case study will be carried out by simulating different cross-sectional areas through the THERM v 7.3© software, to obtain the thermal behavior of the material through the estimation of its thermal resistance as a whole.
From these results, a numerical model based in the geometry and thermal properties of timber walls according to the current Spanish regulation will be built. The relationships of the different parameters involved such as, geometries, endurance treatments, etc. will allow us to establish a complete methodology for estimating the thermal resistance of different solutions, in order to obtain a fully optimized wooden enclosure. The wood selected is the so called "Pinus Radiata", *valued for rapid growth and desirable lumber and pulp qualities is a common specimen in the Basque Country.*

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1. INTRODUCTION

Wood is natural material and has been traditionally used widely for great variety of construction applications, not only due to its mechanical properties but also because of its easy-to-work properties [1, 2]. It is also known that it is an environmentally friendly material, as can be considered ecological and renewable. In fact, in the construction field has been demonstrated that wood is a low carbon material, not only as raw material but also in sub-products which require more industrial processes [3-5].
For years, wood has been used to build cottages and detached houses in northern countries, including the external cladding, while in Spain wood has been used mainly for interior flooring, and less frequently to build structures usually hidden inside walls and façades. Here is more common to see walls and enclosures made of bricks, whereas in other countries like Canada or Sweden the houses are built of light-timber-frame solutions, where both internal and external walls configure the building load structure, working as a whole system.
However, wood market is growing up due to its sustainability as raw material but also because it is easy to transport, transform and install in most of construction works, becoming one of the most influential material in order to mitigate the greenhouse effect [6-8]. Besides, it is a local and abundant material.
The hygrothermal behavior of half-timbered facades is due to the combination of different layers, including internal insulation layers. While the type of timber frame solutions in different countries is structurally similar, the way of insulate the enclosure differs from different continents. In Europe, we tend to use ETICS (External Thermal Insulation Composite Systems). These solutions are characterized by closing thicker insulation, using EPS (Expanded Polystyrene), while in North America facade systems are thinner and it is more common to use fiberglass insulation [1].
The EU Framework Programme Horizon 2020 shows a tendency towards less energy consumption through new products which promote energy efficiency. Because of that, for enclosure systems in buildings, a wide variety of insulation products have recently appeared in the market [9].
The most representative phase of the full life cycle in a building represents its overall use, because it consumes energy, mainly through electric supply. There is wide variety of studies around the importance of analyzing the full life cycle; comparing wood made buildings with other materials [10-13].
However, the different disposition of the material and its homogeneity interfere with its correct behavior. That is, the presence of thermal bridges increases energy losses, breaking down the energy efficiency of such enclosures.
The thermal resistance of walls made of different layers is relatively easy to estimate if the slabs are homogenous. In fact, it is easy to calculate through the Spanish Technical Code [14], because it estimates that the heat flows perpendicular to the different surfaces of layers which configure the whole façade system. However, when there are layers with different shapes or angles, the calculation is much more difficult, as it has to take into account the hygrothermal behavior of the façade as a whole [15, 16]. In Figure 1, two different configurations of timber façades whose external layer is made of joined wood strips illustrates a case study.

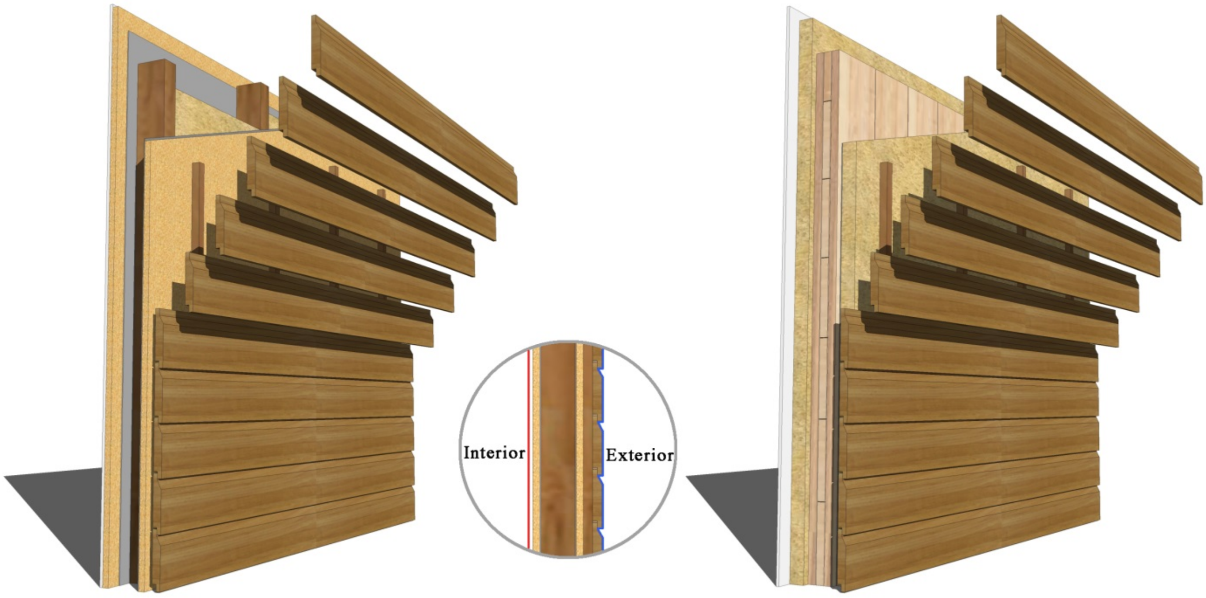

Figure 1. Timber-frame (left) and Cross-laminated timber façade (right)

On the left, a single configuration so called timber-frame whereas on the right a so called cross-laminated timber. In Table 1, the main characteristics defining these two enclosures are shown.

TF FAÇADE	e [m]	λ [W/m·K]
Wood	0.0300	0.180
Air cavity without ventilation	0.0250	0.180
Particle board (ρ<1200 kg/m^3)	0.0190	0.230
Glass wood insulation	0.1000	0.031
PE (Polyethylene) sheet	0.0002	0.160
OSB panel (ρ<650 kg/m^3)	0.0190	0.130
Laminated plasterboard (*)	0.0100	0.250
(*) ρ=750-900 kg/m^3		
Transmittance and thermal resistances		
U = 0.2480 W/m^2·K		
R = 4.0317 m^2·K/W		
Rsi = 0.130 m^2·K/W		
Rse = 0.040 m^2·K/W		

CLT FAÇADE	e [m]	λ [W/m·K]
Wood	0.0200	0.180
Air cavity without ventilation	0.0250	0.180
Glass wood insulation	0.0550	0.031
CLT (Cross Laminated Timber)	0.0810	0.180
PE (Polyethylene) sheet	0.0002	0.160
Glass wood insulation	0.0500	0.031
Laminated plasterboard (*)	0.0100	0.250
(*) ρ=750-900 kg/m^3		
Transmittance and thermal resistances		
U = 0.2380 W/m^2·K		
R = 4.1979 m^2·K/W		
Rsi = 0.130 m^2·K/W		
Rse = 0.040 m^2·K/W		

Table 1. Main characteristics for the two solutions façades, TF (left) and CLT (right)

In Figure 2, the two different solutions simulated with the THERM v7.3© software are shown, to estimate more accurately the thermal resistance of both enclosures.

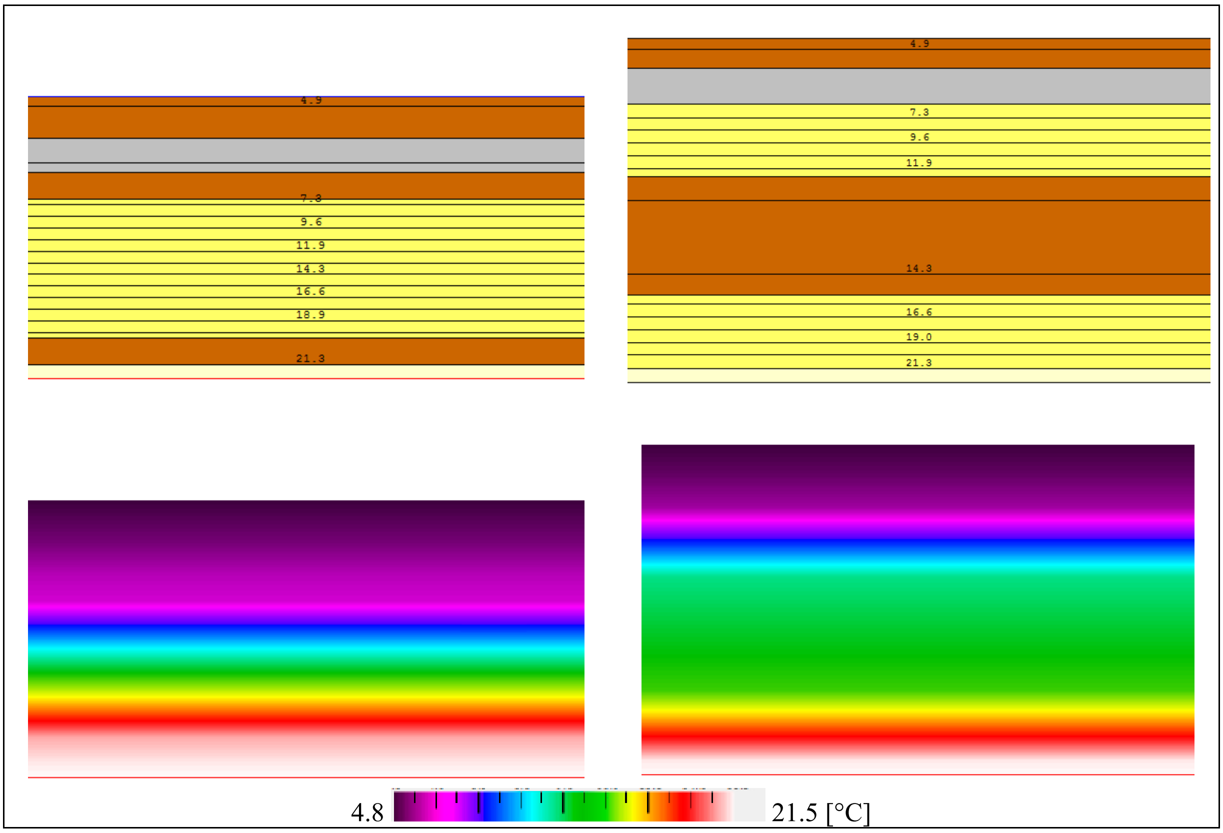

Figure 2. Simulation of both solutions through THERM v 7.3 ©, TF (left) and CLT (right)

When the different section planes are not constant, the estimation became more difficult as it is necessary to model it through specific software, as the simulation derives in three dimensional models. However, in the construction field it is quite common the use of guides to make easier and simplify the calculation process.

If the configuration of different wood façades is analyzed, it is usual to see posts, boards, insulation panels and wood cladding strips, disposed in horizontal and vertical positions. Most of them are cube forms, which make easier the estimation of the thermal resistance without turn to specific software.

However, the exterior cladding made of joined wood strips means a great handicap. The strips have chamfers in order to block water when it is raining, so the strips are not totally plain and their sections show different angles. Because of that, it is difficult to estimate the thermal resistance of this particular layer.

Besides, from the architectural point of view, wood can cover a wide variety of geometries, as it is very adaptable, and allows investigating other different cladding forms.

In this study, different solutions based on joined wood strips disposed to protect the external layer of façades will be analysed. This external face of the cladding system is neither continuous nor totally plain, in order to protect the enclosure from the rain, being a necessary design for preventing water entrance. It is well known that when water enters inside walls and

it is not allowed to go out or there is not ventilation between the different surfaces, moisture could appear, which is really painful not only to wood but also to other construction materials [17, 18].
Conversely, the interior surface of the joined strips is totally plain to make easier the union with the rest of façade system layers and structure. As the rest of elements forming the whole enclosure solution, the external cladding has to transfer its load to the floor in a vertical way.

2. MATERIALS AND METHODS

The external cladding of timber framed façades is the part which usually differs in section, due to discontinuousness in shape. There are different solutions of joined wood strips. The geometry of the external cladding has strong influence in the conductivity, as the thickness is not the same along the external face. Getting to know the global conductivity of the external side, makes it easier to calculate the thermal resistance of the façade, as its discontinuousness comes from the vertical direction.
For the thermal resistance estimation, the THERM v 7.3© software was used, as a 2D finite-element heat-transfer analysis tool. The calculus description of the software is explained next [19]: THERM's steady-state conduction algorithm, CONRAD [20], is a derivative of the public-domain computer program TOPAZ2D [21, 22]. THERM's radiation view-factor algorithm, VIEWER, is a derivative of the public-domain computer program FACET [23]. It contains an automatic mesh generator that uses the Finite Quadtree algorithm [24], checking solutions for convergence and automatically adapts the mesh as required using an error-estimation algorithm based on the work of Zienkiewicz and Zhu [25, 26].
THERM's calculation routines evaluate conduction and radiation from first principles. Convective heat transfer is approximated through the use of film coefficients obtained from engineering references [27, 28]. This program allows estimating the conductivity of different solutions. The inputs are the conductivity of the raw material and the environment boundary conditions.
In this study, four solutions made of joined wood strips were selected. For these cases, the total length of each strip is 12 and 15 centimetres, being the total thickness 2 and 3 centimetres respectively.
In order to simplify the estimation of different joined wood strips solutions for the external cladding of façades, THERM is used to know the R-value of the system at first. From this, form and size will be analysed in order to estimate, through a numerical simplified model, the thermal resistance of the solutions depending on their geometry.
As can be seen in Figure 3, the detailed geometry definition corresponding to four models of joined wood strips (W1, W2, W3 and W4) respectively, are depicted. In order to illustrate the numerical process, on the one hand the definition of the main geometry parameters such as thickness (total, constant and equivalent), length (constant and discontinuous) together with perimeters (relative and total), associated to each model is depicted. On the other hand, as boundary conditions, the internal external temperatures and convective coefficients are also shown [14]. Step (#1) means the first iteration and (#2) the second iteration.

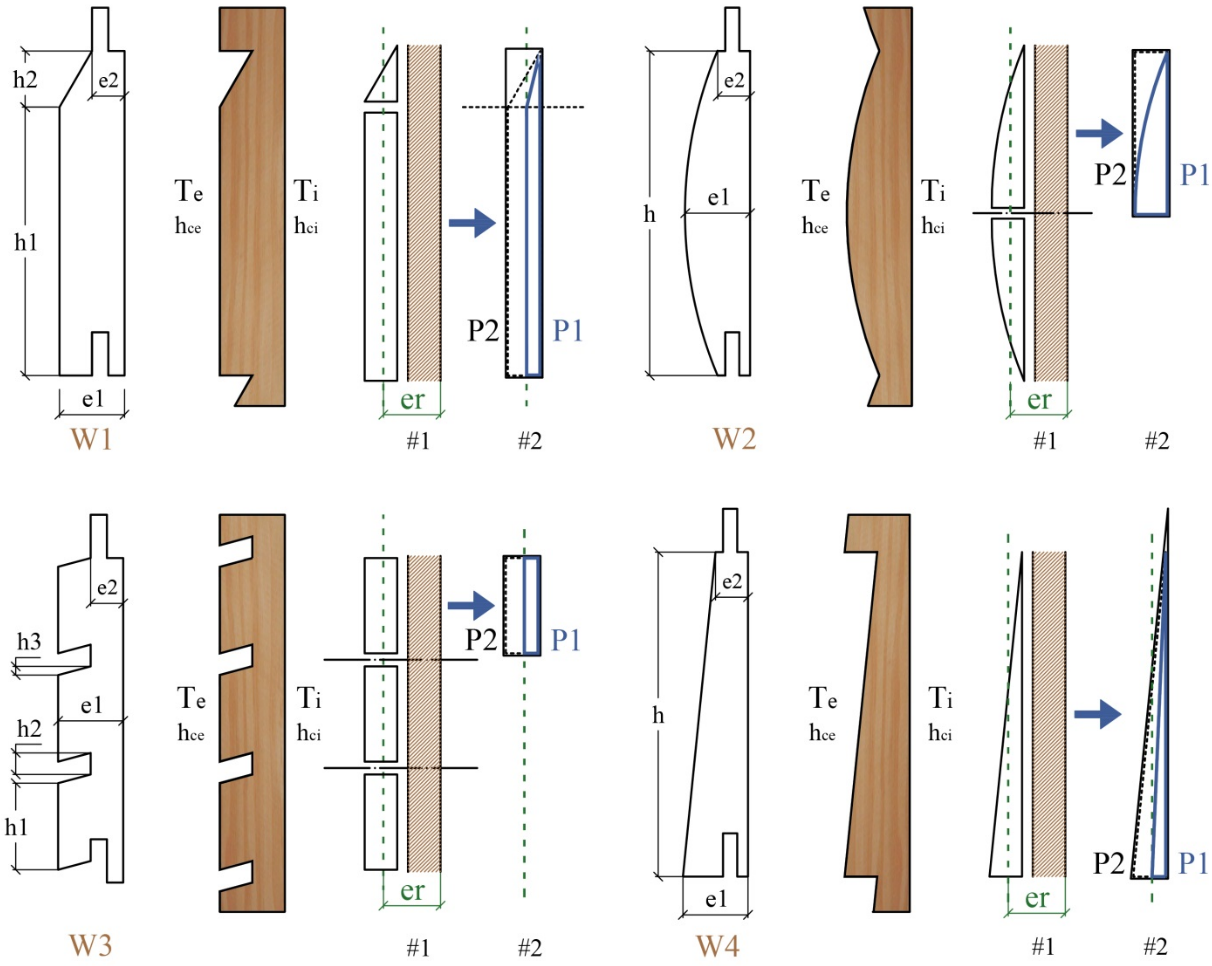

Figure 3. Joined wood strips domain for the four cases studied; Numerical model definition

The wood selected is the so called "Pinus Radiata", specie of pine native to the Central Coast of California and Mexico, being the most widely planted pine in the world, valued for rapid growth and desirable lumber and pulp qualities which is a common specimen in the Basque Country.

3. RESULTS AND DISCUSSION

Table 2 summarizes the calculation procedure step by step, until the achievement of a thermal resistance closer to the THERM software results for the four cases studied, including then the Energy Error Norm (EEN) provided by the software as a result of the iterations (limited to a maximum value of 1 %), and the numerical error (ε), associated to the model for each one of the four cases considered. The correction factor (C) is the ratio P1 to P2 defined in order to obtain an error lower than 4 %.

	W1	Value	W2	Value	W3	Value	W4	Value
#1	λ	0.1500	λ	0.1500	λ	0.1500	λ	0.1500
	h1	0.0930	h	0.1200	h1	0.0100	h	0.1200
	h2	0.0270	e1	0.0200	h2	0.0300	e1	0.0200
	e1	0.0200	e2	0.0100	h3	0.0040	e2	0.0100
	e2	0.0100	Seg/2	0.0611	e1	0.0200	Ac	0.0012
	Ac	0.0019	Ac	0.0012	e2	0.0100	At	0.0006
	At	0.0001	As	0.0008	Ac	0.0002	Xc	0.0050
	Xc	0.0050	Xc	0.0050	At	0.0000	Xt	0.0133
	Xt	0.0133	Xs	0.0160	Xc	0.0050	Yc	0.0600
	Yc	0.0135	Yc	0.0600	Xt	0.0133	Yt	0.0400
	Yt	0.0090	Ys	0.0450	Yc	0.0150	Xg	0.0078
	Xg	0.0056	Xg	0.0094	Yt	0.0013	Yg	0.0533
	Yg	0.0132	Yg	0.0540	Xg	0.0058		
					Yg	0.0138		
	er	0.0151	er	0.0155	er	0.0154	er	0.0156
	R1	0.1333	R1	0.1333	R1	0.1333	R1	0.1037
	R2	0.1007	R2	0.1033	R2	0.1028	Rsi	0.1300
	Rw	0.1261	Rw	0.1183	R3	0.0667	Rse	0.0400
	Rsi	0.1300	Rsi	0.1300	Rw	0.1064		
	Rse	0.0400	Rse	0.0400	Rsi	0.1300		
					Rse	0.0400		
	R	0.2961	R	0.2883	R	0.2764	R	0.2737
	U	3.3777	U	3.4682	U	3.6176	U	3.6536
	ε	-2.73%	ε	-4.02%	ε	-7.43%	ε	-3.60%
#2	P1	0.2476	P1	0.1311	P1	0.0908	P1	0.2457
	P2	0.2620	P2	0.1400	P2	0.1	P2	0.2600
	C	0.9450	C	0.9365	C	0.9083	C	0.9449
	R	0.2798	R	0.2700	R	0.2511	R	0.2586
	U	3.5742	U	3.7035	U	3.9829	U	3.8665
	THERM		THERM		THERM		THERM	
	R	0.2882	R	0.2772	R	0.2573	R	0.2642
	U	3.4698	U	3.6075	U	3.8865	U	3.7850
	EEN	0.73%	EEN	0.81%	EEN	0.82%	EEN	0.78%
	ε	2.92%	ε	2.59%	ε	2.42%	ε	2.11%

Table 2. Definition of the Numerical model for the joined wood strips

In Figure 4, the temperature distribution over the different configurations is depicted, considering different sizes (length and thickness) for the four of them.

As the boundary conditions, the climate conditions of Vitoria in the Basque Country are selected as is considered the coldest city of the three capitals. The exterior temperature is 4.6 °C and the interior 22 °C, which is the comfort temperature. The convective coefficient for the exterior is 25 W/m^2 K, while the interior is 7.69 W/m^2 K. Those values have been taken from the Spanish Building Technical Code [14] which provides superficial resistance values for the internal and external air, according to the direction and position of the heat flux.

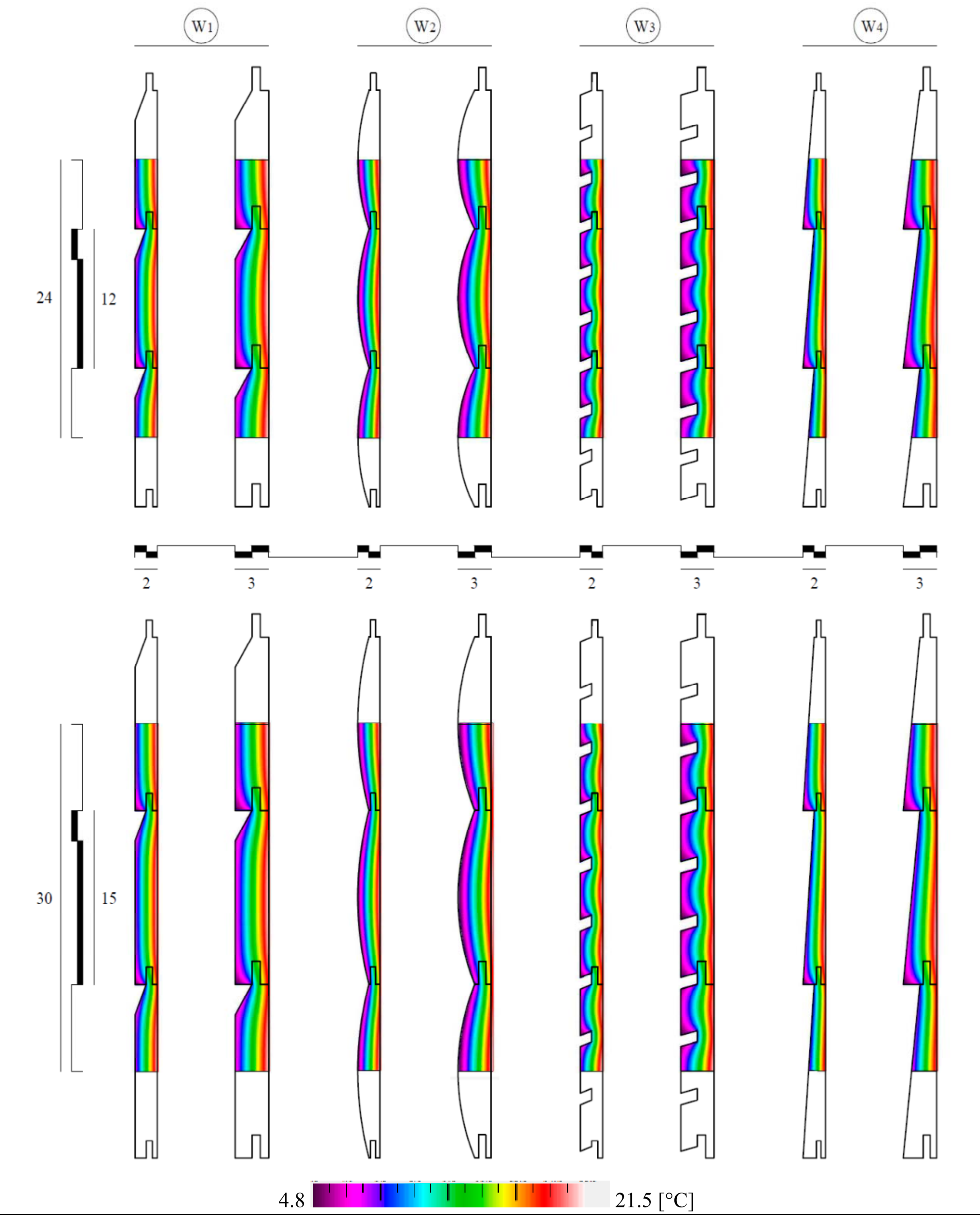

Figure 4. Temperature distribution for the solutions for different length and thickness (cm)

Aiming to obtain the value of the convective coefficient, the inverse of the air thermal resistance is considered. If convective coefficients are compared, the exterior is bigger than the interior one because of the influence of wind among other variables.
To the numerical model two parameters have taken into consideration, the section area of each strip and their perimeter. At first, the area is analyzed to take a relative value of thickness. This thickness is related with the conductivity of the material and is less than the total real thickness of strips. In this case, the thermal resistance is cut down due to the reduction of section in some points, and it is calculated as if the section were continues but smaller at the same time. That is called equivalent section, in this project.
When the thermal resistance calculated is compared with the THERM software results, it can be seen an error in most cases in favour of the simplified numerical model. In order to approach the results, a correction coefficient is set out. In this case, the perimeter is analyzed taken into account the compactness of the different solutions. The closer is the relative thickness to the total one, the bigger is the coefficient. The coefficient is always less than one and the results cannot be more favorable than the software estimation, as the results are closer to real state.
In total there are sixteen solutions presented in Table 3. A comparative test between the results obtained with the numerical model and the THERM software was performed.

	h [cm]	e = 2 cm	e = 3 cm
W1	12	2.92	3.52
	15	2.43	2.92
W2	12	2.59	2.91
	15	1.84	1.61
W3	12	2.42	2.00
	15	3.61	3.32
W4	12	2.11	3.08
	15	1.38	2.02

Table 3. Numerical model error ε [%] for different length and thickness of the wood strips

As it can be seen in the last table, every error values are in positive and the maximum registered is around 4%. The positive value implies that the thermal resistance of the solution set out with the numerical model is smaller than the thermal resistance calculated through the THERM software, which is closer to reality. In other words, the simplified numerical model is penalized in order to verify that it fulfills the minimum requirements.
The numerical model of the second solution (W2) presents the lowest errors, in general. That could be for two reasons, symmetry and compactness. However, it is not the best solution against the rain as the water can run over a great part of the external surface before breaking its path. Because of that the cut of the surface in perpendicular makes easier the blockage of moisture which can influence heavily the life cycle of the façade.
The restriction of rain water entrance, usually accompanied by wind, makes difficult the energy efficiency evaluation as the external surface is not completely continuous. However

wood has a number of advantages. On the one hand it is a hygroscopic material so it releases and captures humidity balancing the environment statement which helps to achieve the comfort conditions. On the other hand it is ecological, renewable and considered as low carbon material being one of the best materials to promote sustainability, not only related to environment but also to the market [7, 10, 11, 29].
In terms of thermal efficiency, the results are rather different. That is the best design against rain does not have to be the best one in terms of insulation. The thermal resistance of each solution can be seen in Table 4. According to this, the first solution (W1) seems to be the most insulated whereas the third one (W3) is supposed to be the worst option.

	h [cm]	e = 2 cm	e = 3 cm
W1	12	0.2911	0.3480
	15	0.2882	0.3428
W2	12	0.2780	0.3305
	15	0.2772	0.3280
W3	12	0.2643	0.3041
	15	0.2573	0.2943
W4	12	0.2651	0.3107
	15	0.2642	0.3093

Table 4. Thermal resistance [m^2·K/W] for different length and thickness of the wood strips

4. CONCLUSIONS

This study has been carried out aiming to enhance the assessment of the thermal resistance for commercial joined wood strips. Four different solutions were analyzed; the most efficient shape is the first one (W1), which has more material and less discontinuousness on average than the rest whereas the third solution (W3) is the least efficient one, taking into account the same total thickness.
If sections are compared to the thermal resistance, the difference between the above mentioned solutions is of about 7.5 %. In case of section vs. conductivity, the difference is even so higher, of about 10% approximately.
The second and the third solutions (W2, W3) present the least area in section. When comparing section vs. thermal resistance for both cases, the difference is proportional, around 5%. However, the second solution (W2) represents the most difficult approach as it is necessary to know the length of the whole segment.
Finally, solution (W4) has less material than (W3) although is more efficient because its thermal resistance is slightly higher. That demonstrates that the design has a strong influence on efficiency, even considering the same total thickness.
The study was carried out taking into account the effect of variations in thickness and length; on the one hand, the thicker the wood strips, the higher the difference between solutions in terms of thermal resistance. However, the external cladding is usually thin because its main

function is wrongly considered to be only the climate protection. On the other hand, the shorter the wood strips, the higher the thermal resistance offered.

The simplified numerical model is close to the real scenario as has been shown here, being the error values lower than 4 %. This method allows a relatively easy estimation of the thermal resistance of particular solutions without the higher requirements of finite elements software. Besides, it makes easier the comparison between different configurations, as the calculations are simplified, so both material optimization and energy efficiency are possible. In fact, they are nowadays some of the most relevant issues in terms of sustainability which is the main objective of this research, trying to reduce the carbon footprint generated by other traditional fossil fuels consumption and preserve our environment.

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NOMENCLATURE

Ac:	Square Area [m^2]
At:	Triangle Area [m^2]
As:	Curved Area [m^2]
C:	Correction factor related to the compactness (= P1/P2)
CLT:	Cross Laminated Timber
e:	Thickness [m]
e1	Total thickness [m]
e2:	Constant thickness [m]
er:	Equivalent thickness [m]
EEN:	Energy Error Norm [%]
EPS:	Expanded Polystyrene
ETICS:	External Thermal Insulation Composite Systems
h:	Length [m]
h1:	Constant length 1 [m]
h2:	Discontinuous length 2 [m]
h3:	Discontinuous length 3 [m]
hc	Convective coefficient [W/m^2 K]
OSB:	Oriented Strand Board
PE:	Polyethylene
P1:	Relative perimeter [m]
P2:	Global perimeter [m]
R:	Total thermal resistance [$m^2 \cdot K/W$]
R1:	Global resistance (= $e1/\lambda$) [m^2 K /W]

R2: Relative resistance (= er/λ) [m^2 K /W]
R3: Global resistance (= e2/λ) [m^2 K /W]
Rw: Wood thermal resistance [m^2 K /W]
Rsi: Internal superficial resistance [m^2 K /W]
Rse: External superficial resistance [m^2 K /W]
Seg/2: Half length of the segment [m]
T: Temperature [ºC]
TF: Timber Frame
U: Transmittance (= 1/R) [W/m^2 K]
Xc, Yc: Gravity center coordinates corresponding to the square area [m]
Xt, Yt: Gravity center coordinates corresponding to the triangle area [m]
Xs, Ys: Gravity center coordinates corresponding to the curved area [m]
Xg,Yg: Gravity center coordinates corresponding to the total area [m]

Greeks
λ: Thermal conductivity [W/m·K]
ρ: Wood density [kg/m^3]
ε Numerical model error [%]

Subscripts
e Related to external
i Related to internal

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