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HYGROTHERMAL PERFORMANCE OF NATURE-BASED INSULATION MATERIALS INTEGRATED IN TIMBER-BASED WALL-SYSTEMS

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ABSTRACT:

This study is part of the European research and innovation project Build in Wood and has investigated the hygrothermal performance of nature-based insulation materials in two timber-based wall systems: i) stud wall and ii) externally insulated cross-laminated timber (CLT). Six nature-based insulation materials were selected for the analyses. The analyses conducted have focused on optimization of exterior wall configurations to avoid moisture-related problems, i.e. interstitial condensation and mould growth, in the wall constructions under various climates in Europe. For this purpose, three European locations representing respective geographical parts of Europe and corresponding climate zones, were selected as input for the simulations: Oslo (Northern Europe), Paris (Central Europe), and Barcelona (South Europe), while different exterior and interior claddings were considered. A commercial 1D hygrothermal software, i.e. WUFI Pro 1D, was used for the computation of the hygrothermal performance of the wall systems, while the add-on software WUFI Bio has been further employed for the detailed evaluation of the risk for biodegradation. In total 684 numerical simulations were conducted. The results show the various insulating materials behave differently when integrated in timber-based system. Generally speaking, both wall systems, i.e. stud wall and CLT, function similarly in Oslo, while in Barcelona the CLT was systems show better performance. The climate of Paris is critical for most of the wall configurations. Furthermore, the existence of ventilated air cavity back from the exterior cladding has a positive effect on all assembly configurations, while the high water vapour diffusion resistance of the exterior cladding might be determinant, in a negative way, for the moisture problems in nature-based insulating materials.

KEYWORDS: CLT, Stud wall, Nature-based insulation materials, Hygrothermal performance, Moisture, Mould growth, Interstitial condensation.

1 INTRODUCTION

The European Commission aims at the decarbonization of building sector by 2050, starting the drastic reduction of greenhouse gas emissions (GHG) in the coming years; as of 2030, all new buildings must be zero-emission, while all new public buildings must be zero-emission already as of 2027 [1]. Given that energy efficiency in buildings has been on focus the last decades, the interest has been switched to life-cycle stages before as well as after operation. In particular, the extraction, production and manufacturing of building materials are stages with remarkably high embodied GHG emissions, therefore there is an increasing demand for building materials with low carbon footprint, such as structural timber and nature-based insulating materials, e.g. [2]. Wood-based wall systems have several advantages, such as low carbon footprint, moisture buffering effect etc., while they show durability against mould growth upon proper design [3]. Commercial wood-based insulation materials, e.g. wood fibreboard and wood woolboard, have also gained ground in building applications. In addition, other nature-based building materials such as hemp, cellulose, flax etc. have started getting integrated in building systems, usually as insulation materials. Generally speaking, material selection is a complex equation that considers various parameters, material properties, GHG emissions, availability, cost etc. In particular for insulation materials, durability is an important aspect, so that they can function adequately during operation stage, without increasing the need for replacement, which would have negative consequences for the total GHG emissions. In this study, the hygrothermal performance of innovative nature-based insulation materials integrated in timber-based wall systems is investigated and the risk for moisture damages and degradation is identified.

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2 MATERIAL AND METHODS

2.1 Wall systems and assemblies

Two different exterior wall systems have been employed for the analyses: 1) stud wall and 2) externally insulated cross-laminated timber (CLT) (Fig.1). A short literature review of nature-based insulation materials gave an indication on various insulation types used in the

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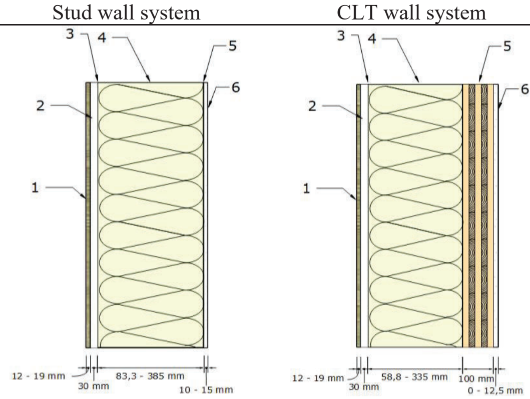
European market. According to [4], there are six different types of nature-based insulation materials: sheep's wool, hemp fibre, flax fibre, wood fibreboard, cellulose, and wood woolboard. In total 22 different products of the six different types of nature-based insulation were identified. One product of each of the six types has been selected for the analyses in this study. The six chosen insulation products are hemp fibre, sheep's wool, flax fibre, wood fibreboard, cellulose and wood woolboard.

Stud wall system	CLT wall system



Stud wall system	CLT wall system
1. Exterior cladding	1. Exterior cladding
2. Air gap	2. Air gap
3. Wind barrier	3. Wind barrier
4. Nature based insulation	4. Nature based insulation
5. Vapor barrier	5. CLT element
6. Interior cladding	6. Interior cladding

Figure 1: *Overview of the two wall systems and the corresponding assemblies.*

2.2 Coupled heat and moisture transport (HAM)

A major challenge for all nature-based building materials is their potential vulnerability to moisture. A commercial 1D hygrothermal software i.e., WUFI® Pro 1D [5], has been used for the computation of the hygrothermal performance of the wall systems, with focus on the risk for interstitial condensation. WUFI® Pro is a dynamic simulation tool that accounts for the coupled heat and moisture transport across building components, including latent heat of sorption and heat and moisture storage in building materials, as mentioned by Karagiozis *et al.* [6]. In particular, WUFI® Pro 1D computes the variation of moisture content in each material/layer of building component, while it can provide additionally detailed information about temperature and relative humidity in numerous cross sections of the component and consequently provide the risk of condensation.

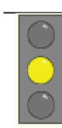
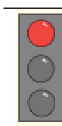
By integrating the results of WUFI Pro into an another (add-on) software of WUFI® family, called WUFI® Bio [7], the risk of mould growth and biodegradation can be classified. The latter is the most crucial parameter for the evaluation of nature-based insulation materials. WUFI Bio provides the mould growth coverage in building materials, expressed in mm. In addition, it includes an empirical model which has been developed by Viitanen [8] and computes the so-called mould index (MI). This index takes values from 0 to 6 and reflects the risk of biodegradation of building materials (Table 1).

Table 1. *Description of mould index (MI) according to Viitanen model [7, 8].*

Mould index	
0:	No growth
1:	Some growth visible under microscope
2:	Moderate growth visible under microscope, coverage more than 10%
3:	Some growth detected visually, thin hyphae found under microscope
4:	Visual coverage more than 10%
5:	Coverage more than 50%
6:	Tight coverage, 100%

For the classification, the 'signal light' is employed by the software (Table 2); the green light shows low or no risk for biodegradation, the yellow light reflects moderate risk and additional control may be needed and the red light reveals high risk for biodegradation and therefore the construction is considered as not acceptable. In this study, three different cross sections of the insulation layer have been checked; exterior, middle, and interior cross section. For each of these cross sections, the bio-hygrothermal analysis has been conducted and the respective results, in terms of 'signal light' are provided, in three positions: i) outer part of insulation, ii) middle part of insulation and iii) inner part of insulation.

Table 2.1. *'Signal-light' classification in WUFI Bio, reflecting the three different evaluations, i.e. green: acceptable, yellow: acceptable under conditions, red: not acceptable [7].*

		Surfaces inside constructions without direct contact to indoor air
	Mould growth (g_m): Mould-Index (MI): Assessment:	< 176 mm/year ≤ 2 Usually acceptable.
	Mould growth (g_m): Mould-Index (MI): Assessment:	$176 < g_m \leq 239$ mm/year $2 < MI \leq 3$ Additional criteria or investigations are needed for assessing acceptability.
	Mould growth (g_m): Mould-Index (MI): Assessment:	> 239 mm/year > 3 Usually not acceptable.

2.3 Exterior and interior climate

To investigate the impact of the exterior climate three European locations representing respective geographical parts of Europe and corresponding climate zones, were selected as input for the simulations: Oslo (Northern Europe), Paris (Central Europe), and Barcelona

(Southern Europe). The climate characteristics for each location are shown in Table 3.

Table 3. *Climate characteristics of the chosen locations for the numerical simulations – Oslo, Paris and Barcelona [5].*

	Oslo	**Paris**	**Barcelona**
Mean air temperature [°C]	6.8	10.9	16.3
Max. air temperature [°C]	29.3	36.3	34.3
Min. air temperature [°C]	-14.8	-8.9	-1.0
Mean air relative humidity [%]	73.1	80.6	66.8
Max. air relative humidity [%]	100.0	100.0	99.0
Min. air relative humidity [%]	15.0	19.0	13.0
Mean wind speed [m/s]	2.7	2.6	4.1
Normal rain [mm/year]	604.7	817.4	513.3
Counter radiation [kW/m^2*year]	2 641.4	2 851.5	not available
Mean cloud index [-]	0.67	0.67	not available

For the interior climate, the European standard EN ISO 13788 was used [9]. In particular, the indoor air temperature was assumed constant at 20°C, a humidity class of 3 has been considered. This class, among the five available (1-5), reflects better the moisture production in residential buildings, which is the majority of existing building stock in Europe. while the initial relative humidity across the wall systems have been set at 50%, which reflects dry state of the building materials. All the cases have been solved for 10 years period.

2.4 Thermal transmittance (U-value) of assemblies

The national building regulations in the three selected countries Norway, France and Spain, have set different requirements regarding the thermal transmittance in exterior walls. The chosen U-values for the wall systems in the three locations are: Oslo, 0.18 W/m^{2}K; Paris, 0.23 W/m^{2}K; Barcelona, 0.35 W/m^{2}K.

2.5 Categorization of hygrothermal numerical simulations

The hygrothermal numerical simulations were organised in 'Groups' for better overview:

- Group A – Wall systems with wooden panel (picea abies) as exterior cladding and gypsum board (standard density, ρ = 720 kg/m^3) as interior cladding. The CLT case has been additionally studied exposed, without the gypsum board as interior cladding.
- Group B – Wall systems with wooden panel as exterior cladding and two different interior panels: a) gypsum board of high density (ρ = 1 153 kg/m^3) and b) a plywood panel. The latter has been used only in the stud-wall system but not in combination with the CLT cases.
- Group C – Wall systems with various panels (two different types of cement-based board and wooden panel with fire retardant) as exterior cladding and gypsum board (standard density) as interior cladding. In particular, three boards were employed: a) a cement-based board with low density, ρ = 1 150 kg/m^3 b) a cement-based board with high density, ρ = 1 650 kg/m^3, and c) a solid wooden panel with fire retardant.

All the abovementioned cases have been computed having considered both limited-ventilated air cavity back from the exterior cladding and fully ventilated air cavity. In total, around 600 simulations have been performed.

3 RESULTS

3.1 Group A – Wall systems with wooden panel as exterior cladding and gypsum board (standard density) as interior cladding

3.1.1 Oslo

In stud wall systems (Fig. 2), all insulation materials have shown no remarkable moisture problems when used in a stud wall system with a wooden panel as exterior cladding and a gypsum board of standard density, i.e. ρ = 720 kg/m3. The materials that have showed the best performance, regardless the orientation nor the natural convection in air cavity, has been the wood woolboard followed by the flax fibre and cellulose (the last two have shown some minor issues at the edges of the insulation layer).

In contrast, the materials that have shown some issues, but only in the worst orientation and when assuming limited natural convection (ACH = 1h-1) are:

i) the sheep's wool and hemp fibre, which have shown risk for mould growth during a few weeks in summer, when the reverse of moisture transport occurs due to increase of partial air pres-sure outdoors. This is a common problem in Scandinavian exterior wall systems due to the presence of vapor retarder on the inner side of insulation layer, which causes temporal (sea-sonal) blockage of water vapor when the moisture transport is reversed.
ii) the wood fibreboard that shows risk of condensation on the cold side of insulation layer when the wall is exposed to the orientation with most wind and driving rain.

These materials have shown no moisture problems in all other wall orientations. Furthermore, when the air cavity back from the exterior cladding is fully ventilated by natural convection, no moisture problem has been identified (Fig. 3).

In CLT wall systems (Fig. 2 and 3), similarly to the stud wall, the wood woolboard and the flax fibre has shown the best performance, i.e. no moisture problems regardless the level of ventilation in the air cavity and the use (or not) of gypsum board on the interior side of the CLT. All the other four insulation products, i.e. sheep's wool, hemp fibre, wood fibreboard and

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cellulose, require that the air cavity is ventilated by natural convection to avoid showing condensation problems and mould growth in a few years after the use of the building.

Figure 2: *Risk of mould growth in the insulation layer in Group A wall systems in Oslo, when the air cavity is limited ventilated.*

Figure 3: *Risk of mould growth in the insulation layer in Group A wall systems in Oslo, when the air cavity is well ventilated.*

3.1.2 Paris

In case of Paris (Fig. 4 and 5), natural convection back from the exterior cladding is essential in order to avoid moisture damages in the insulation layer. This has been observed both in stud wall systems as well as in the CLT walls without gypsum board on the interior side. When the CLT is covered by gypsum board, the results are considered generally as not acceptable for all the six materials, regardless the level of natural convection in the air cavity.

The only insulation material that has shown a moderate hygrothermal performance in stud wall system when there is limited natural convection in the air cavity, it's the wood woolboard. However, even this material has shown moisture problems in the worst orientation (West for Paris) when integrated in a stud wall system, while when used in CLT wall systems, the moisture diffusion resistance of interior cladding contributes positively.

For all other insulation products, ventilation in air cavity by natural convection contributes drastically to avoid biodegradation in stud wall systems, while in CLT walls there is the additional prerequisite of low water vapor diffusion resistance on the interior surface (no gypsum board).

Figure 4: *Risk of mould growth in the insulation layer in Group A wall systems in Paris, when the air cavity is limited ventilated.*

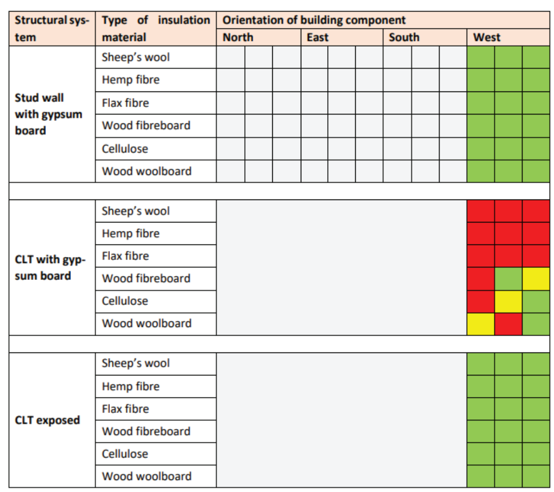

Figure 5: *Risk of mould growth in the insulation layer in Group A wall systems in Paris, when the air cavity is well ventilated.*

3.1.3 Barcelona

The wood woolboard has been the only insulation material showing no moisture problems regardless the type of wall system and the level of natural convection in the air cavity (Fig. 6). The source of problems for the other five insulation materials when used in the stud wall system is the presence of water vapor tight layer at the interior side of insulation, e.g. vapor retarder, vapor-tight interior cladding. This because in hot and humid climates, such as Barcelona's, the moisture flow is expected to take place from outdoors to indoors for the longest part of the year (in contrast to colder climates like Oslo). A solution is to use a vapor retarder at the exterior side of the insulation layer in order to block the moisture transport from outdoors. It should be mentioned that this issue remains in the stud wall systems even when the air cavity is considered as fully ventilated (Fig. 7).

Figure 6: *Risk of mould growth in the insulation layer in Group A wall systems in Barcelona, when the air cavity is limited ventilated.*

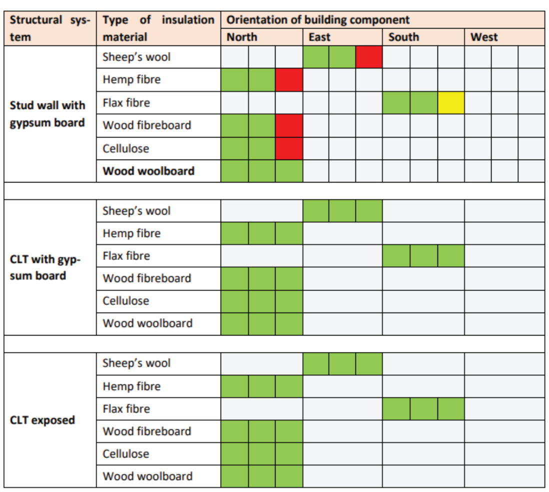

Figure 7: *Risk of mould growth in the insulation layer in Group A wall systems in Paris, when the air cavity is well ventilated.*

However, when the insulation materials are used in CLT walls, the hygrothermal performance becomes better. In particular, sheep's wool, flax fibre and wood woolboard show no moisture damages regard-less any other requirement. The other three materials, i.e. hemp fibre, wood fibreboard and cellulose, have shown biodegradation on their exterior parts when the air cavity is limited ventilated. By ensuring natural convection in the air cavity the risk of interstitial condensation will be drastically decreased both in stud wall and in particular in CLT wall systems, where no insulation material would show moisture problem.

3.2 Group B – Wall systems with wooden panel as exterior cladding and various panels (gypsum board of high density and 3-ply cross-laminated timber panel) as interior cladding

3.2.1 Oslo

The change of type of gypsum board, i.e. higher density, in the stud wall systems in Oslo (Fig. 8 and 9) hasn't showed any impact on the hygrothermal performance of the insulation materials. The findings are identical with the ones in the Group A, where the wood woolboard, the flax fibre and cellulose have showed the best performance. In contrast, the other three materials, i.e. sheep's wool, hemp fibre and wood fibreboard have shown moisture problems, either on the interior part of insulation layer (sheep's wool and hemp fibre) or at the exterior part of insulation layer (wood fibreboard). These problems disappear when the air cavity back from the exterior cladding is fully ventilated by natural convection (Fig. 9).

However, in particular for hemp fibre and wood fibreboard the already problematic hygrothermal performance in the stud wall systems becomes slightly worse when the plywood has been used as interior cladding. The change of interior cladding hasn't affected the other four materials. It is worth to mention that even in this case, i.e. 3-ply cross-laminated as interior cladding, all insulation materials have shown no moisture problems when the air cavity back from the exterior cladding is fully ventilated.

Figure 8: *Risk of mould growth in the insulation layer in Group B wall systems in Oslo, when the air cavity is limited ventilated.*

In the CLT wall systems (only the gypsum board has been considered as alternative here), only the wood woolboard has shown no biodegradation. The flax fibre has also shown good performance but there are some moisture problems on the outer part of the insulation

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layer. All the other four materials have shown unacceptable hygrothermal performance. The natural convection in the air cavity would reduce drastically the risk for biodegradation and make all CLT wall systems acceptable.

Figure 9: *Risk of mould growth in the insulation layer in Group B wall systems in Oslo, when the air cavity is well ventilated.*

3.2.2 Paris

The change of type of gypsum board, i.e. higher density, in the stud wall systems in Paris (Fig. 10 and 11) hasn't showed any remarkable impact on the hygrothermal performance of the insulation materials. The wood woolboard is the only insulation material with acceptable performance, while all other materials have shown high risk of biodegradation. The use of the plywood as interior panel has made the performance even worse, even for the wood woolboard which in this case cannot be considered as acceptable. Similar situation in the CLT wall systems where all insulation materials have shown high risk for biodegradation.

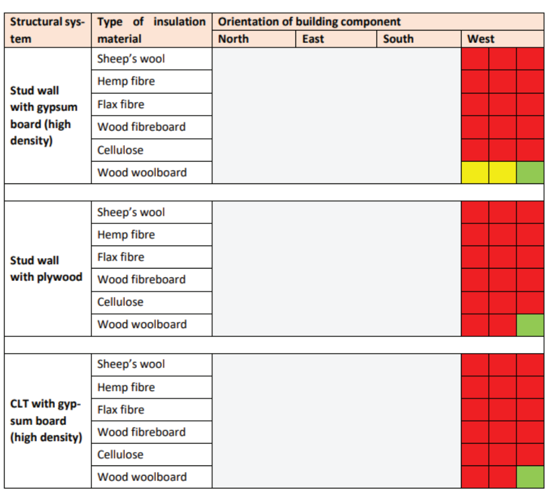

Figure 10: *Risk of mould growth in the insulation layer in Group B wall systems in Paris, when the air cavity is limited ventilated.*

All these results refer to the case of limited natural convection in the air cavity back from the exterior cladding (Fig. 10). The increase of air exchanges in the cavity will affect positively all the insulation materials, both in the stud wall and CLT systems resulting in acceptable hygrothermal performance (no risk for biodegradation) for all of them (Fig. 11).

Figure 11: *Risk of mould growth in the insulation layer in Group B wall systems in Paris, when the air cavity is well ventilated.*

3.2.3 Barcelona

In the stud wall systems in Barcelona (Fig. 12 and 13), the use of higher density gypsum board (with additional higher water vapor diffusion resistance) have shown higher risk for biodegradation compared to the respective Group A cases (gypsum board of standard density). This is rather expected because, as analysed in Group A above, the moisture transport by diffusion takes place towards indoors for the largest part of the year and therefore an increase in water vapor diffusion resistance at the inner part of the insulation layer would result in higher degree of vapor blockage and consequently higher mould growth. The only insulation material that has not been affected by the change of the type of the gypsum board and has shown as good hygrothermal performance as with the gypsum board of standard density (Group A) is the wood woolboard.

The use of plywood as interior cladding in the stud wall systems hasn't changed the overall picture; the wood woolboard has shown acceptable hygrothermal performance, while all other five materials have shown risk for biodegradation, either in parts of the insulation layer, i.e. in sheep's wool, wood fibreboard and cellulose, or throughout the entire layer, i.e. in hemp and flax fibre.

Remarkable but expected, the consideration of fully ventilated by natural convection air cavity back from the exterior cladding (Fig. 13) has only partly contributed positively in the cases of stud walls in Barcelona, in contrast for example to Paris. In particular, the inner parts of the insulation layers have still shown moisture problems due to the predominant water vapor flow to indoors.

Figure 12: *Risk of mould growth in the insulation layer in Group B wall systems in Barcelona, when the air cavity is limited ventilated.*

Figure 13: *Risk of mould growth in the insulation layer in Group B wall systems in Barcelona, when the air cavity is well ventilated.*

In Barcelona, the CLT wall systems have generally shown better hygrothermal performance than the stud walls. Even when the ventilation in the air cavity is limited, only three insulation materials have shown moisture problems: hemp fibre, wood fibreboard and cellulose. These problems appear only at the outer part of the insulation layer. The other three materials, i.e. sheep's wool, flax fibre and wood woolboard, have shown no risk for biodegradation when integrated in CLT wall systems. Last but not least, by ensuring fully ventilated air cavity the risk for biodegradation vanishes even for the hemp fibre, wood fibreboard and cellulose and all insulation materials can be considered as acceptable.

3.3 Group C – Wall systems with various panels (two different types of cement-based board and wooden panel with fire retardant) as exterior cladding and gypsum board (standard density) as interior cladding

3.3.1. Oslo

All insulation materials have shown poor overall hygrothermal performance when integrated into stud wall systems, regardless the type of exterior cladding. However, when the air cavity is fully ventilated by natural convection, flax fibre primarily followed by sheep's wool and hemp fibre have shown acceptable performance, when the exterior cladding is the wooden panel with the fire retardant. No wall configuration with cement board as exterior cladding can be considered as acceptable.

The CLT wall systems have shown similar moisture problems as the stud walls. When the cement board (either type, i.e. density) is used as exterior cladding, all insulation materials have shown high risk for biodegradation. When the air cavity is fully ventilated and the wooden panel with fire retardant is used as exterior cladding, the sheep's wool, the hemp fibre and the flax fibre have shown good hygrothermal performance, with minor moisture issues on the cold side of insulation. No wall configuration with cement board as exterior cladding can be considered as acceptable.

Figure 14: *Risk of mould growth in the insulation layer in Group C wall systems in Oslo, when the air cavity is limited ventilated.*

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Figure 15: *Risk of mould growth in the insulation layer in Group C wall systems in Oslo, when the air cavity is well ventilated.*

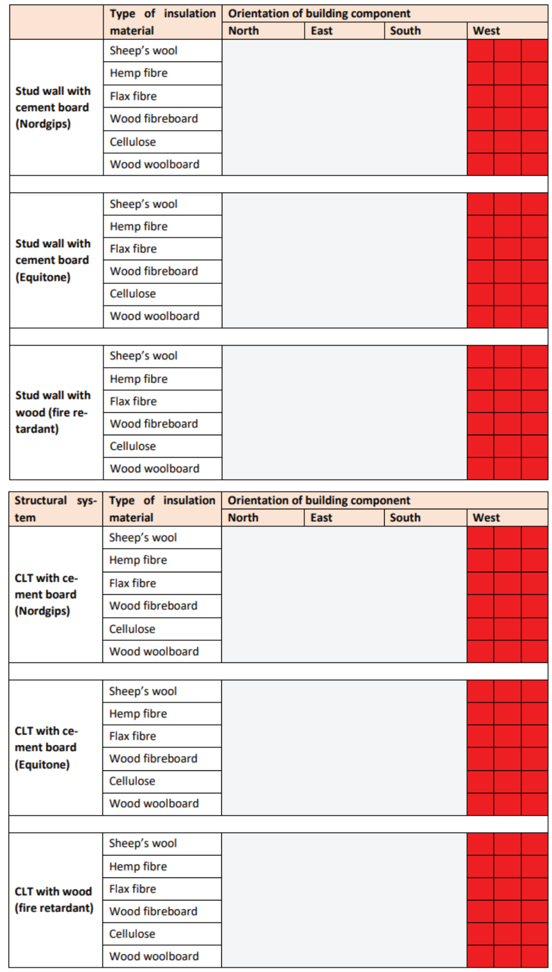


Figure 16: *Risk of mould growth in the insulation layer in Group C wall systems in Paris, when the air cavity is limited ventilated.*

3.3.2 Paris

In Paris, none of the wall configurations can be considered as acceptable, neither stud walls nor CLT walls. All the insulation materials have shown high risk of biodegradation, which can lead to the conclusion the cement board and the wooden panel with fire retardant (with a very high water vapor resistance) are not optimal choices foe getting combined with the specific nature-based insulation materials. The degree of natural convection in these case hasn't had any (positive) impact on the results.

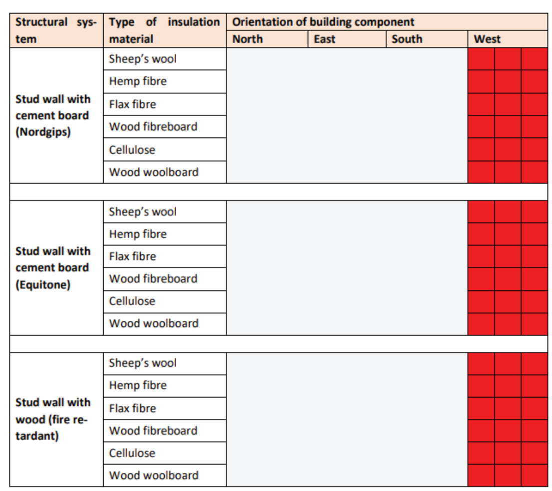
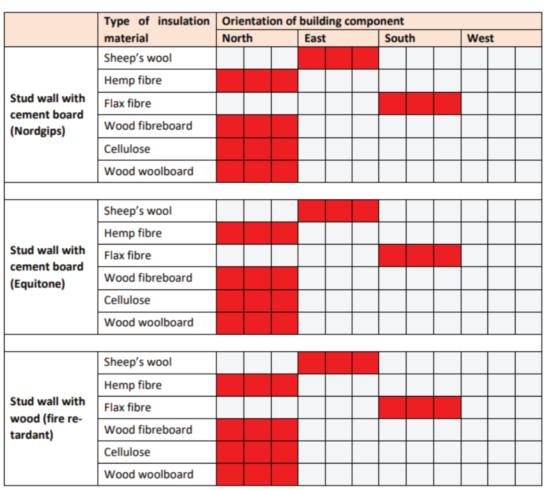


Figure 17: *Risk of mould growth in the insulation layer in Group C wall systems in Paris, when the air cavity is well ventilated.*

3.3.3 Barcelona

In Barcelona, none of the insulation material have shown acceptable hygrothermal performance when integrated into stud wall systems, regardless the type of exterior cladding, i.e. cement board or wooden panel with fire retardant. The impact of natural convection in the air cavity is negligible.The CLT wall systems have shown better hygrothermal performance, but only when the wooden panel has been used as exterior cladding and the air cavity is considered as fully ventilated. In this case, the flax fibre and the wood woolboard have shown no risk for biodegradation, while the sheep's wool have shown some local moisture problems at the inner side of the insulation layer. All cases with cement board as exterior cladding cannot be considered as acceptable.



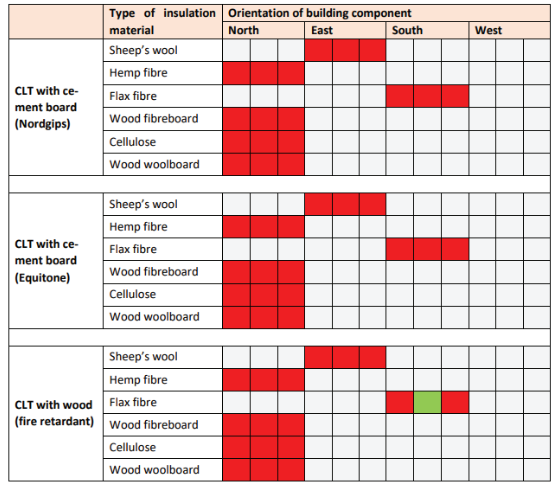
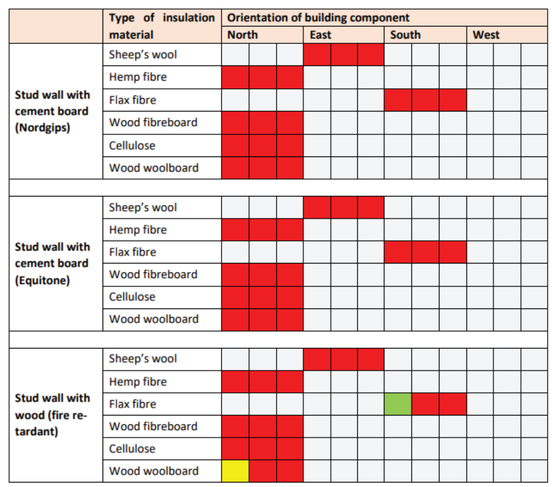


Figure 18: *Risk of mould growth in the insulation layer in Group C wall systems in Barcelona, when the air cavity is limited ventilated.*



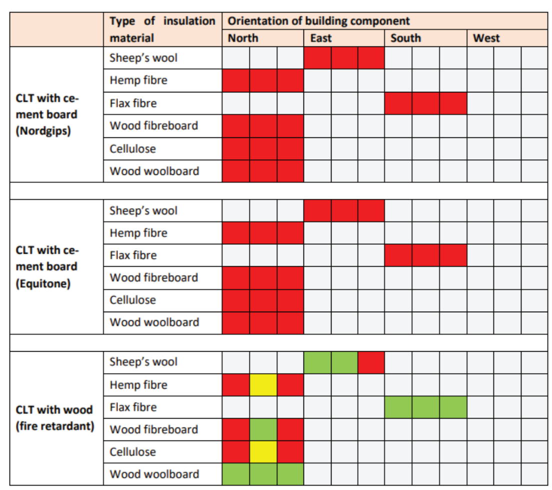


Figure 19: *Risk of mould growth in the insulation layer in Group C wall systems in Barcelona, when the air cavity is well ventilated.*

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4 CONCLUSIONS

The following points summarize the most important findings from the hygrothermal analyses:

- Wood woolboard has shown good hygrothermal performance when integrated in different timber-based wall systems in different climates.
- Flax fibre, followed by sheep's wool and hemp fibre can also be considered as acceptable in some cases.
- Natural convection in the air cavity back from the exterior cladding contributes to drastic reduction of the moisture problems in most of the cases.
- Cement-based board should be avoided in wall systems with nature-based materials.
- Paris has a challenging climate for nature-based insulation materials.
- In Barcelona, CLT wall systems have shown less moisture problems than stud walls.

5 AKNOWLEGDEMENTS

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