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Hygrothermal Performance of Wooden Structures in Combination with Bio-Based Insulation in Future Climates in Belgium

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Abstract

In Europe, 40% of the total energy requirements relates to the energy consumption in the construction sector. The awareness resulted in the use of bio-based materials thanks to their small carbon footprint (Zhao et al. 2017).

The aim of this study is twofold. The first objective is to gain a better understanding of the durability of traditional insulation materials such as mineral wool and PUR versus bio-based insulation (cellulose) in timber frame constructions and CLT constructions. The second objective is to evaluate to which extent this durability depends on various levels of climate change impact we might face based on the future greenhouse gas concentrations.

This study uses the Mould Index as an indicator for possible degradation of the insulation layer. The mould Index is calculated using temperature and relative humidity derived from HAM simulations in Delphin 6.1.4. These simulations are done for different wall assemblies and different climate scenarios for Brussels.

The results show that climate change has a negative effect on the durability of the outer part of the insulation material and that this effect is higher for cellulose than for mineral wool in timber frame construction.

Keywords: bio-based insulation; climate change; CLT; HAM simulations; wood frame construction.

Introduction

The use of bio-based materials gains popularity thanks to their small carbon footprint (Zhao et al., 2017). However, because of the natural origin of bio-based materials, an exposure to unfavourable moisture and temperature combinations could lead to higher concentrations of insects, fungi or bacteria, possibly resulting in mould growth or degradation of the cell structures. On top of that, these materials are able to store moisture over time. Both the moisture buffering capacity and the possible change in pore structure due to mould growth could alter the thermal performance. Since both of these are influenced by moisture, it is important to gain more insight into the moisture content in constructions using these kinds of materials.

Not only is it important to know whether bio-based insulation performs different than their traditional counterparts such as mineral wool or PUR, it is also useful to know how these materials would hold up in the future. Climate projections can be used to gain insight in the hygrothermal performance of different types of insulation materials and wall types for different scenarios greenhouse gas concentrations.

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Previous studies assessed the hygrothermal behaviour and mould growth risk for cross-laminated timber and timber frame construction insulated with cellulose. Kukk et al. (2022) compared HAM simulations to field measurements in cross-laminated timber insulated with mineral wool, PIR and cellulose insulation. Field measurements used to calculated the mould index showed no risk of mould growth at the outside surface of the insulation. However, the relative humidity at this surface was generally lower for walls insulated with cellulose compared to walls insulated with mineral wool or PIR. Vanderschelden et al. (2021) found the mould growth on the inner OSB layer in a timber frame construction to be lower in case of the use of cellulose insulation compared to mineral wool for different air and rainwater leaks.

The aim of this study is twofold: the first objective is to gain a better understanding of the durability of traditional insulation materials such as mineral wool and PUR versus bio-based insulation (cellulose). The second objective evaluates to which extent this durability depends on various levels of climate change impact we might face in function of the future greenhouse gas concentrations.

Methods

Wall assembly

This study starts from two wall configurations: a timber frame wall using mineral wool as insulation material and a CLT wall using PUR as insulation material. This study compares these configurations with a similar build-up, but using cellulose as bio-based insulation material.

Vanderschelden et al. (2021) found the ventilation rate in the cavity crucial for the severity in mould growth. Hence, in this study the ventilation rate in the cavity is varied based on Langmans et al. (2016): ACH 100, 200 and 400 1/h. For these wall configurations, the thickness of the insulating layer is also varied. The different wall types are visualized in Fig. 1.

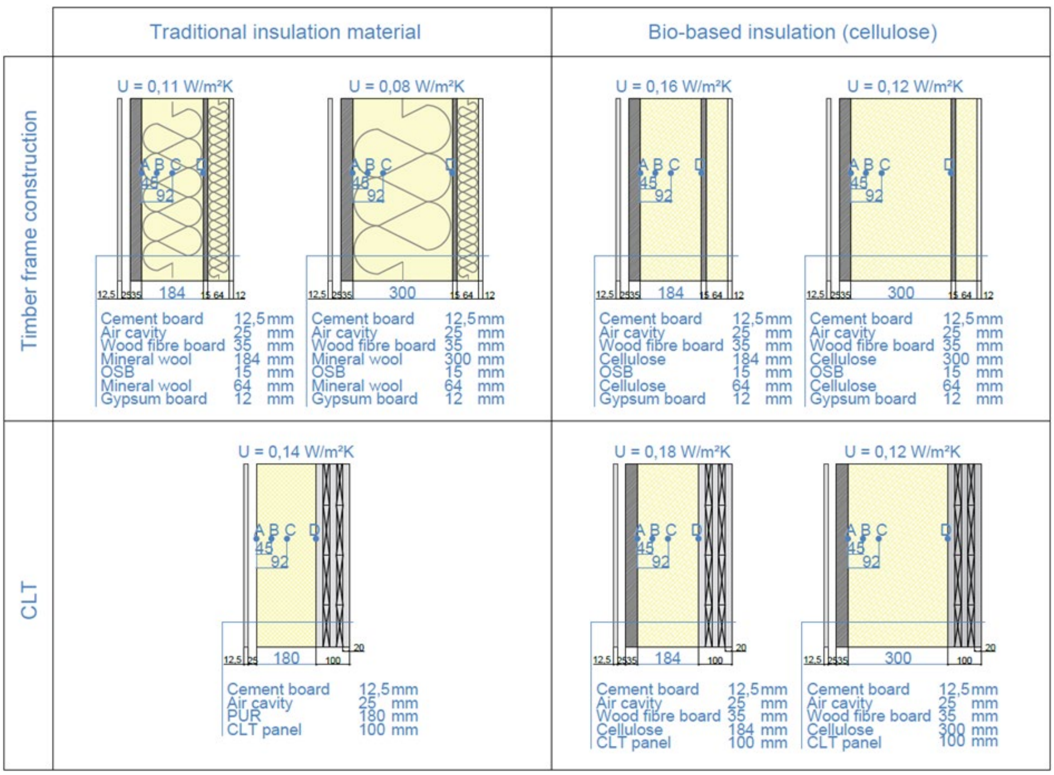

Fig. 1
Cross-section of wall types

HAM simulations

Heat, air and moisture 1D simulations are done in Delphin 6.1.4.

Almost all materials of the wall types are selected from the built-in Delphin database but, the adhesive used in the CLT panel is selected from materials experimentally tested by Ghent University. All hygrothermal properties used in the simulations are reported in Table 1.

Material	ID	ρ kg m-3	χπ ϑ kg-1 K-1	λ W m-1 K-1	μ -	Aw kg m-2 s-1/2	Θ80 kg m-3	Θsat kg m-3
Façade cladding								
Cement board	654	1158,7	1188	0,313	26,4	0,014	70,9	283,6
Air cavity	16	1,3	1050	0,138	0,4	0	0	1000
Insulation materials								
PUR	194	37	1500	0,022	65,0	0,0001	0,001	945,0
Mineral wool	730	37,0	840	0,032	1,00	0	0,1	900,0
Cellulose	580	55,216	2544	0,048	2,05	0,563	6,3	780
CLT construction								
Aluminium facer (in case of PUR)	1763	200,0	1700	0,390	> 3E+6	-	4,85E-5	0,002
Wood fibre board (in case of cellulose)	435	250,0	2100	0,050	5,00	0,012	31,8	408,2
Spruce tangential	713	393,7	1843	0,106	487,7	0,005	59,8	728,1
Spruce radial	712	393,7	1843	0,112	487,7	0,012	59,8	728,1
MUF adhesive	*	425,0	1245	0,079	36,5	0,00	72,6	590,2
Timber frame construction								
Wood fibre board	435	250,0	2100	0,050	5,00	0,012	31,8	408,2
OSB	650	595,0	1500	0,130	165,00	0,002	95,7	847,0
Gypsum board	839	1054,5	1335	0,311	11,67	0,066	7,2	461,0
Wood fibre board	435	250,0	2100	0,050	5,00	0,012	31,8	408,2

Table 1

Hygrothermal properties of the selected materials. "ID" is the identification code used in the Delphin software material database. (*) indicates that the material properties derived from experiments

The rain exposure coefficient is set to 0,7. A water source of 1% of the rain flux (ASHRAE 2016) is assigned to the inner surface of the air cavity to take rain leakage through the façade cladding into account.

In order to reach a stabilized behaviour, simulations are performed over 34 consecutive years of which the first 4 years are used as conditioning period and therefore discarded in the results (see also section 2.3). Prior to running the simulations, the assemblies are discretized in a grid where the largest element is no larger than 13 mm wide and the smallest element is 1 mm thick.

Climate data

For the climate data, this study locates the different wall types in Brussels (50.8°N; 4.3°E) (BE) with a south-west facing orientation. The indoor air temperature is computed from the outdoor air temperature based on EN 15026 (CEN 2007) and WTA 6.2 (WTA 2014). The indoor relative humidity is also computed based on WTA 6.2 indoor climate model for 'increased moisture load (plus 5%)' (WTA 2014).

To gain insight in the change of hygrothermal behaviour due to possible climate change in the future, four different climate datasets were analysed: historically measured data from Brussels

(1972-2005) and three different climate projections for 2066-2099 each taking into account a different Representative Concentration Pathway (RCP) (Vandemeulebroucke et al., 2022a,b,c). The different RCP scenarios include a strong mitigation scenario (RCP 2.6), an intermediate scenario (RCP 4.5) and an extreme high emission scenario (RCP 8.5). The values 2.6, 4.5 and 8.5 represent the radiative forcing in W/m^2 by the end of the 21st century (van Vuuren et al., 2011). The climate data originate from the ALARO-0 RCM (Giot et al., 2016) driven by the CNRM-CM5 GCM (Termonia et al., 2018).

Fig. 2 gives the distribution of the annual mean temperature, annual relative humidity and annual precipitation for the different climate scenarios in Brussels.

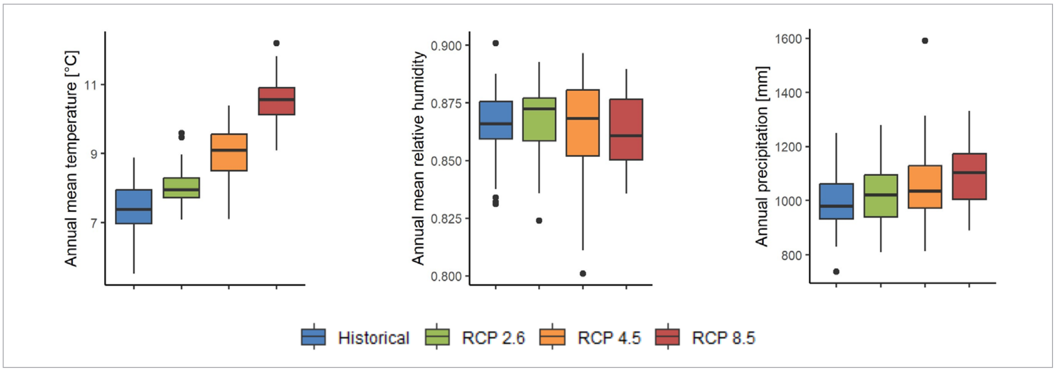

Fig. 2

Annual mean temperature (left), annual mean relative humidity (middle) and annual precipitation (right) for the different climate scenarios (Historical, RCP 2.6, RCP 4.5 and RCP 8.5) in Brussels

Mould growth

The damage mechanism that is evaluated in this study is mould growth.

The mould growth risk is evaluated according to the improved VTT-model (Viitanen & Ojanen, 2007), which defines a mould index (MI), depending on the temperature and relative humidity values of the investigated surfaces. The MI ranges from 0 to 6. The growth rate and description of these indexes are summarized in Table 2. The improved VTT-model also takes four mould sensitivity classes into account depending on the type of material: very sensitive, sensitive, medium resistant and resistant. The insulation materials analysed belong to a different sensitivity class. However, to have a better basis for comparison and since the locations analysed are adjacent to wooden elements (wood fibre board, OSB board and spruce), the decision was made to consider them all to be in mould sensitivity class 'Sensitive' and decline class "Almost no decline" (C_{eff} = 0,1). An exception was made for CLT construction insulated with PUR insulation; sensitivity class "Medium resistant" was taken into account.

Table 2

Mould growth index (Viitanen, 2007)

Index	Growth rate	Description
0	No growth	Spores not activated
1	Small amounts of mould on surface (microscope)	Initial stages of growth
2	< 10% coverage of mould on surface (microscope)	-
3	10% - 30% coverage of mould on surface (visual)	New spores produced
4	30% - 70% coverage of mould on surface (visual)	Moderate growth
5	> 70% coverage of mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

Mould growth will only occur on the outer faces of the materials. However, the mould index is also used as an indicator for other possible damage mechanisms due to moisture. As moisture content is expected to be the highest in the outer area of the insulation layer, this study also evaluates the mould index at additional points near the outside surface. These specific locations are based on the RH.

Results

Relative humidity in assembly

Since the relative humidity is one of the factors impacting the mould index, the selection of depths at which the mould index is analysed is based upon the relative humidity throughout the construction. Fig. 3 gives the relative humidity throughout the entire depth of the construction in 2099 (the last year of the simulation period)with RCP 8.5 as climate model and an ACH of 100 1/h for mineral wool and cellulose insulation.

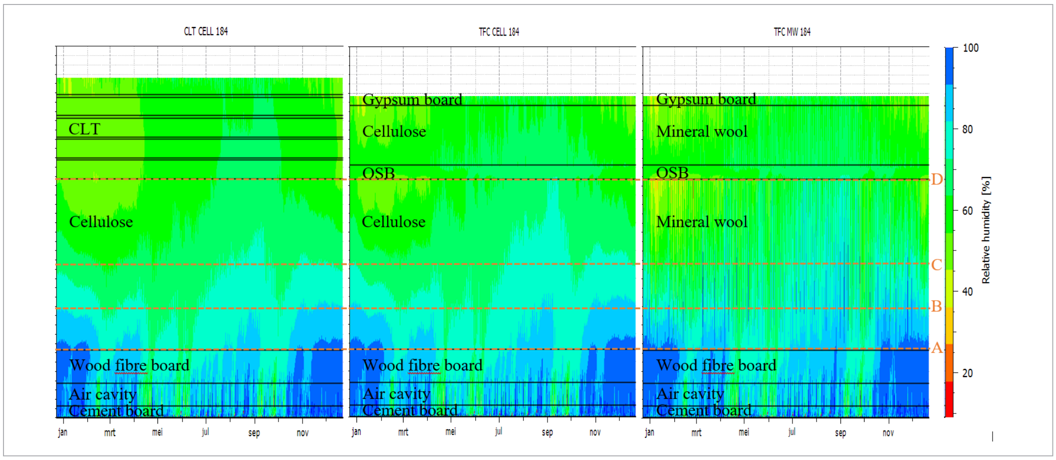

Fig. 3

Relative humidity in a CLT wall insulated with cellulose (left), in a timber frame wall insulated with cellulose (middle) and in a timber frame wall insulated with mineral wool (right) for year 2099 (RCP 8.5), ACH of 100 1/h

Based upon this Fig. 3, the relevant locations are chosen to be the outside surface of the insulation (location A), 45 mm measured from the outside surface of the insulation layer (location B), 92 mm measured from the outside surface of the insulation layer (location C) and the inside surface of the insulation layer (location D). In case of a CLT construction, where there is no need to apply a wood fibre board, location A is still chosen to be at the outside surface of the insulation material.

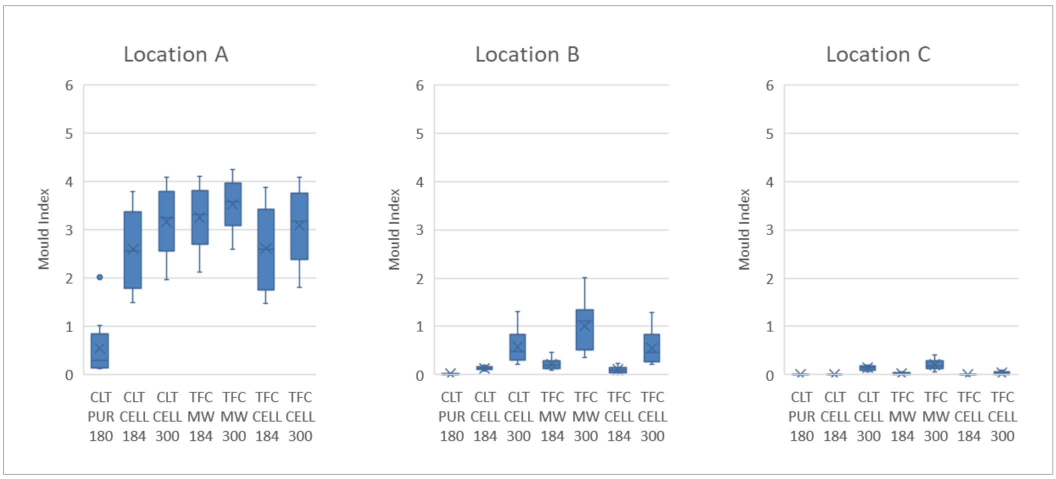

Fig. 4

Mould index for the different wall types at locations A, B and C. The first line states the type of load bearing structure (CLT = Cross Laminated Timber, TFC = Timber Frame Construction), the second line gives information about the insulating layer (PUR = Polyurethane, MW = Mineral Wool, CELL = Cellulose) and the third line gives the thickness of the insulating layer in mm

Mould index for different wall configurations

For each wall configuration and locations A, B and C in the insulation, the boxplots of Fig. 4 give the distribution of the mould index for the differ climate scenarios and ACH in the ventilated air cavity. For location D (the inner surface of the insulation layer), the mould index was never higher than 0,07 and is therefore not shown in Fig. 4.

The highest mould index is found in location A. At this location, the mould index is the highest for timber frame construction insulated with 300 mm mineral wool. The mould index is the lowest for a CLT wall with PUR insulation. This is no surprise as the PUR insulation is the only material with a sensitivity class of “Medium resistant”. If the sensitivity class “Sensitive” was assigned to the PUR insulation, this mould index would become the highest. Meaning that the conditions at the outer part of insulation are the least favourable in case of PUR insulation.

At location B, the mould index is low for all wall configurations, but the thickest insulation layers have a higher mould index. This can be explained by the fact that for thicker insulation layers, the average temperature at location B is lower, leading to a higher relative humidity.

The same effect is (to a lesser degree) also noticed at locations A and C.

For the timber frame construction, in case of mineral wool the mould index is higher than for cellulose since the vapor diffusion resistance is lower and cellulose reduces humidity peaks by buffering them over its thickness.

As can be seen in **Fig. 4**, there is only visible mould for location A (the outside surface of the insulation layer). As the mould index is the main damage indicator in this study, in the next chapters only location A will be discussed.

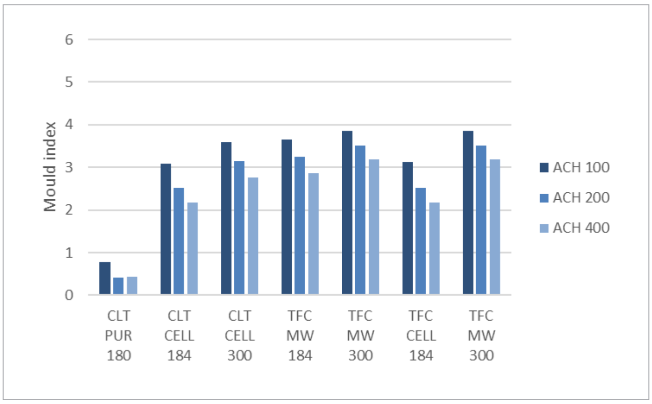

Fig. 5

Average mould index of the different climates at location A for the wall types with different ACH

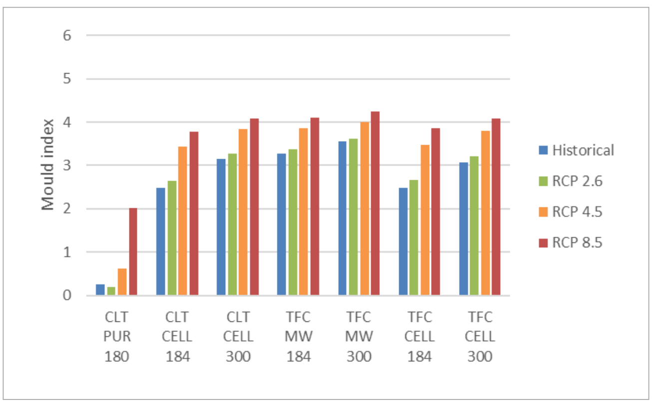

Fig. 6

Mould index at location A for the different wall types with ACH 100 1/h for different climate scenarios

Mould index in function of the ventilation rate in the air cavity

Fig. 5 shows the average mould index at location A for the different ventilation rates in the air cavity. The values shown are the average for the four climate scenarios. In line with the findings of Vanderschelden et al. (2021) the mould index decreases for higher ventilation rates in the air cavity.

Impact of different climate projections

For all climate scenarios analysed, the mould index is the highest for an ACH of 100 1/h. **Fig. 6** shows the average mould index at location A for the four climate scenarios for ACH 100 1/h.

The **Fig. 6** shows that a higher mitigation scenario leads to a lower mould index compared to higher emission scenarios. This is probably due to the temperature increase and/or the precipitation increase which are beneficial for mould growth. This conclusion is valid regardless of the construction type (including the type of insulation material).

Focusing on timber frame construction, the mould index for cellulose is lower than mineral wool. However, with increasing emission scenarios, the difference between the bio-based and traditional insulation materials becomes smaller. The difference in mould index between mineral wool and cellulose insulation almost completely vanishes for the highest emission scenario. This is caused by the fact that this climate scenario has a bigger impact on the mould index for cellulose insulation than for mineral wool. For example, in a timber frame construction with an insulation thickness of 300 mm, when looking at the climate scenario RCP 8.5 compared to historical climate, the average mould index for all ACH's combined, increases with about 32% when insulated with mineral wool while this mould index increases with more than 60% for cellulose insulation. The same trend, to a lesser extent, is found for CLT construction insulated with cellulose with an increase of about 52% for an insulation thickness of 300 mm and an increase of 82% for an insulation thickness of 184 mm.

The impact the RCP 8.5 climate has on this mould index is the biggest for a timber frame construction insulated with 184 mm cellulose (an increase of more than 88%). However, the biggest impact of RCP 8.5 is found for CLT construction insulated with PUR (more than 7,5 times higher compared to historical climate data). This is due to the low values for historical climate data.

Discussion

The results of this study show that climate change is increasing the risk of mould and potentially other degradation with similar underlying mechanisms. This is the case for all insulation materials, but the effect of climate change is more important for the bio-based material cellulose. In order to reduce the risk of degradation (and hence to increase the durability of the structure), this effect of climate evolution has to be taken into account when designing the wall build-up. This does not necessarily mean that the worst case assumptions regarding climate change have to be applied, but it is useful to understand the risks related to climate change.

This study provides a first look of what these design considerations can be based upon. A limitation is however that this study only accounts for rainwater ingress into the ventilation cavity. Poor workmanship or imperfections during construction are not taken into account. A poorly executed weathering seal, imperfections at the location of the air sealant or insufficient rain protection during construction could respectively cause rain infiltration, infiltration of humid indoor air or built-in moisture. Further study is needed to evaluate the impact of such imperfections.

Other limitations of this study are related to the selected wall build-ups: Only cladding finish was applied to the different wall types. Other façade finishings such as masonry or plaster could lead to different results since these have different ventilation rates in the air cavity. Previous research has shown that lower ventilation rates lead to an increased risk for mould growth in timber frame constructions (Vanderschelden et al., 2021). The actually used finishing may also affect the amount of rain leakage through the air cavity.

For this study, the only bio-based insulation material analysed is blown-in cellulose. Future research could look into the influence of implementing different types of bio-based insulation materials. However, at the moment only a handful bio-based materials are available in the material database of Delphin for HAM-modelling, hampering the development of a reliable hygrothermal analysis.

Conclusions

The conclusions of this study are only applicable to the climate in Brussels and with one specific wall orientation. The results may be different in other circumstances.

This study provides a first insight into the impact climate change may have on the durability of wooden constructions with traditional and bio-based insulation materials. It shows that climate change has a negative effect on the durability of the outer part of the insulation material and that this effect is higher for cellulose than for traditional insulation materials such as mineral wool or PUR.

Further research is however necessary to take into account other aspects (such as water and air leakage, façade cladding and built-in moisture) potentially impacting the durability of the used materials in various circumstances.

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