Retrofitting the building envelope of SME industrial buildings: hygrothermal risk assesment

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Abstract

The project 'KMO Reno', focuses on qualitative renovation of small and medium-sized enterprise buildings. The aim is to provide guidelines for retrofitting the building envelope.

In this exploratory study the hygrothermal risk of retrofitting the walls of SME industrial buildings is assessed. The HAM simulation program Delphin is used to analyse the moisture transport in the building envelope. Three facade systems are being studied: cellular concrete panels, insulated wall panels and liner trays.

The risks on interstitial condensation and biological growth are analysed when applying internal insulation. One extra case is studied: cellular concrete with an external insulation. This case is simulated to evaluate the behaviour of the existing moisture content in the wall.

Conclusions show that internal insulation of a cellular concrete wall is not advised. The moisture level in the cellular concrete may be too high and can lead to mould growth and interstitial condensation. The application of internal insulation of a building envelope consisting of insulated metal sandwich panels or insulated liner trays involve a low risk when performed in buildings with a humidity level not higher than ICC2. A cellular concrete wall can be externally insulated without any hygrothermal risk.

Keywords

Energy-efficient retrofit, Delphin, mould growth, internal insulation, SME industrial building, risk assessment

1. Introduction

The energy consumption of the building sector in the developed countries of the European Union represents 40% of their total energy consumption. The importance of non-residential buildings is also relevant: roughly 15% of all constructions are industrial buildings [1].

The majority of the industrial building stock from the years '2000 still meets the structural requirements, but the building envelope is reaching the end of its life span. Meanwhile, there are new requirements that demand an increase in comfort and energy performance. Building envelope heat dissipation is the major component of energy consumption during building usage, about one third of the whole energy consumption. Thus strengthening the building envelope heat retaining property is the key to reduce building energy consumption [2]. The energy efficient renovation of these SME-buildings is new to building professionals. The current lack of theoretical and practical knowledge within construction companies about renovation possibilities of this type of buildings, is leading to a sub-optimal practice. This study wants to play a role in setting up guidelines for the practice of retrofitting SME-buildings.

Renovation of the building envelope with retrofit insulation ensures a thermal improvement but also leads to a modified heat and moisture transport. Important consequences are the changed risk on the forming of condensation or mould growth. As we assume, there will be a higher risk when implementing internal insulation to a vapour tight building envelope such as insulated metal sheet panels. By extension there is little knowledge and experience concerning retrofitting the building envelopes of the described industrial buildings and their hygrothermal risks. In this study hygrothermal

simulations are performed with the Delphin software to analyse the heat and moisture transport in the building envelope. We want to detect the risks of the retrofit options as described below.
All of the simulated models were also built in a lab together with the manufacturers, to test the compatibility of the materials, the technical feasibility, the water-and airtightness.
First the paper presents the method of the simulations, followed by the results. Subsequently recommendations for practice are described, to conclude with the final conclusions.

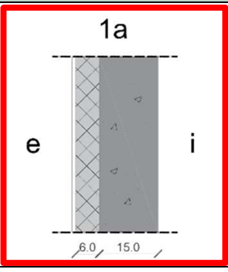
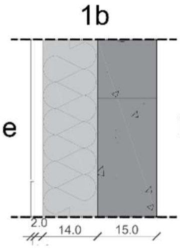
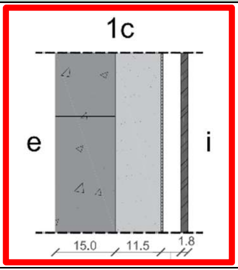
2. Method

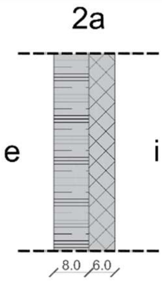
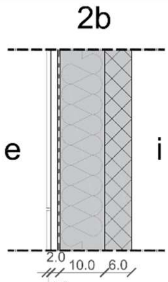
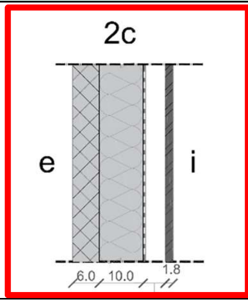
Four cases are numerically simulated to analyse their hygrothermal performance. Below the cases and the defined boundary conditions are described, as well as the performance criteria taken into account.

2.1 Description of building envelopes and retrofit scenarios

The project focuses on single storey industrial buildings, constructed using fast construction methods. These buildings are used for industrial and distribution warehouses and retail. The structural frame consists of steel or concrete (beams and posts). The most common types of cladding systems are prefabricated cellular concrete panels, insulated (metal sheet) panels and liner tray systems. Table 1 gives an overview of the different retrofit scenarios for the selected cladding systems. All of the construction methods are proposed with an external insulation with insulated metal sheet panels, an external insulation with mineral wool and an aerated exterior sheeting and an internal insulation.

The cases considered with the highest hygrothermal stress (1c, 2c, 3c) are numerically simulated. One additional case is simulated to evaluate the behaviour of the moisture content already present in the existing wall (cellular concrete) when insulating from the exterior (1a). In total, four cases are simulated (indicated on Table 1 with red squares).

	External insulation (Insulated panel)	External insulation (Mineral wool)	Internal insulation
MODEL 1 Cellular concrete			
Wall configuration from exterior to interior as modelled in Delphin	0.5 mm stainless steel, 60mm polyurethane boards, 0.4 mm stainless steel , 150 mm cellular concrete	Aerated ext. sheeting, 140mm mineral wool, 150 mm cellular concrete	150mm cellular concrete, 115 mm Mineral Wool, vapour barrier *

	External insulation (IP)	External insulation (MW)	Internal insulation
MODEL 2 Insulated panel 6cm			
Wall configuration from exterior to interior as modelled in Delphin	0.5 mm stainless stl, 80mm polyurethane boards, 0.4 mm stainless stl, 0.5 mm stainless stl, 60mm PU boards, 0.4 mm stainless stl	Aerated ext. sheeting, 140mm mineral wool, 0.5 mm stainless stl, 60mm, PU board , 0.4 mm stainless stl	0.5 mm stainless steel, 60mm, polyurethane board , 0.4 mm stainless steel , 100 mm mineral wool, vapour barrier *

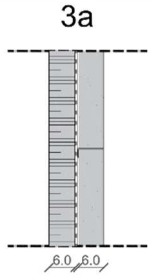
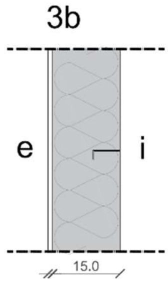
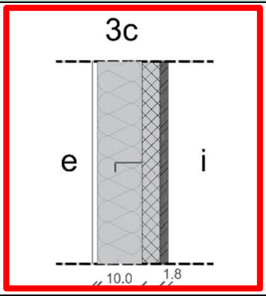
	External insulation	External insulation	Internal insulation
MODEL 3 Liner tray system			
Wall configuration from exterior to interior as modelled in Delphin	0.5 mm stainless stl, 60mm polyurethane boards, 0.4 mm stainless stl, vapour barrier, 60mm mineral wool, 0.75 mm stainless steel	Aerated ext. sheeting, 150mm mineral wool, 0.75 mm stainless steel	0.75 mm stainless steel, ventilated cavity 25mm, 60mm mineral wool, 0.75 mm stainless steel, 40 mm Polyurethane board, 12.5 mm gypsum board

Table 1 Matrix: overview of the insulation retrofits. The red squares mark the scenarios assesed in this paper.

**A modelling simplification is applied to reduce simulation time. In reality after installing, an inner finishing will be placed (such as gypsum board, OSB board, …) with a ventilated service cavity in between. In this model, the cavity and the finishing are not taken into account because this impact is negligible. [9].*

2.2 Hygrothermal simulations

2.2.1 Simulation software: Delphin

The HAM- simulation program Delphin version 5.9.4 [3] is used for the hygrothermal simulations. All of the scenarios are simulated in 1D over a timespan of 4 years. The material data is used from the Delphin material library. In specific cases, alterations are made based on the information of the manufacturer.

2.2.2 Boundary conditions

The orientation of the simulated walls is south-west. This orientation has the most heavy rain load in Belgium.

The external climate data used in the models are the climate data for Essen [3]. These data are most representative for the weather in Belgium within the database of Delphin [10].

When defining the internal climate data, assumptions have to be made, because no relevant data was ever measured in SME buildings in Belgium. Two different temperature zones are defined in relation to normal activities in the building and the Belgian climate. Temperature zone 1 and 2 have temperatures between 16-25°C respectively 20-25°C depending on the outdoor temperature. According to NBN EN ISO 13788 (annex A) [4] , the indoor climate files for the two temperature zones are generated. This model allows the calculation of an indoor climate based on ambient temperature.

With regard to the interior relative humidity, there is equally a lack of relevant measured data within SME buildings in Belgium. Therefore the Belgian classification of Indoor Climate Classes (TV215) [5] is used to divide the different humidity levels according to the activities within the building. The calculation is based on the outdoor temperature. Table 1 lists the different Climate Classes.

Indoor Climate Class	buildings	Yearly mean indoor vapour pressure pi (Pa)	Mean vapour pressure difference during 4 weeks (pi – pe) (Pa)
ICC I	storage areas, churhes, garages	$1100 \le p_i \le 1165$	$< 159 - 10.\ \theta_e$
ICC II	Schools, shops, offices, gymnasium, dwellings	$1165 \le p_i < 1370$	$< 436 - 22.\ \theta_e$

ICC III	Small dwellings, flats, hospitals, restaurants, theatres	1370 ≤ p_i < 1500	< 713 – 22. θ_e
ICC4 IV	Swimming pools, breweries, laundries, printing companies	p_i ≥ 1500	> 713 – 22. θ_e

Table 2: The Indoor Climate Classes linked to types of buildings (See [5])

To calculate the interior relative humidity in both temperature zones, the values of the highest limit for every Indoor Climate Class are used. Within the scope of this paper, the Indoor Climate Class ICC4 will not be taken into consideration for the retrofit options.

These calculations lead to 6 different climate files for the indoor relative humidity related to the temperature zone: these different parameters are used for the hygrothermal simulations.

Indoor Climate Classes	Temperature zones 20-25°C (mean indoor relative humidity)	Temperature zones 16-25°C (mean indoor relative humidity)
ICC 1	(1) φ_i = 0,42	(4) φ_i = 0,50
ICC 2	(2) φ_i = 0,48	(5) φ_i = 0,58
ICC 3	(3) φ_i = 0,59	(6) φ_i = 0,71

Table 3 : mean indoor relative humidity for the temperature zones and the Indoor Climate Classes.

2.2.3 Performance criteria

The risk on **interstitial condensation** is assesed by calculating the overhygroscopic moisture within the building components. This is the mass of moisture related to a relative humidity higher than 95% per element volume [3]. In the simulations performed, the condensation on the cold surface of the insulation is examined. A limit value of 0.2 kg/m² is determined as maximum level of condensation according to the Belgian guideline as stated in TV215 (see [5]).

The risk on **mould growth** is evaluated with Viitanen Mould Model [6]. The model can be used to evaluate the mould risk on a surface of material samples or inside structures in changing temperature and relative humidity conditions. The mould risk is described with mould index M which is calculated from hourly temperature and relative humidity values. Mould riks can get values from 0-6. Table 4 gives an overview of the definitions of the Mould index M.

The original VTT-model (Hukka & Viitanen 1999) is restricted to wood only (pine and spruce). Later this model was updated by including prediction methods to simulate mould growth on other building materials, such as concrete, wood based materials, insulation materials (Ojanen et al. 2010) [7] . Figure 1 shows the sensitivity classes according to the building materials. All of the models in this paper are simulated with the sensitivity class 'medium resistant' according to the materials.

0 No growth
1 Small amounts of mould on surface (microscope),
2 Several local mould growth colonies on surface,
3 Visual findings of mould on surface, <10% coverage
4 Visual findings of mould on surface, 10%-50 % coverage (visual), or <50% coverage of mould (microscope)
5 Plenty of growth on surface, >50% coverage (visual)
6 Heavy and tight growth, coverage about 100%

Table 4: Definition of Mould index (M) according to Hukka & Viitanen (1999)

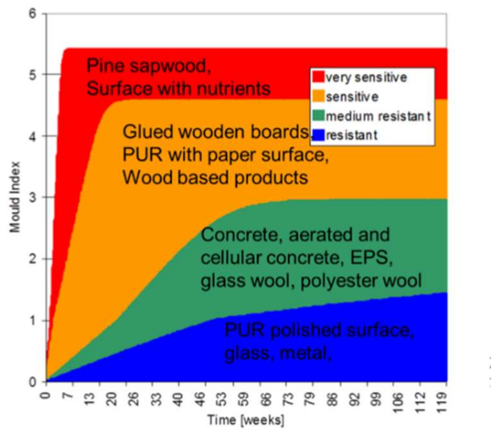


Figure 1 . Mould sensitivity classes for different materials [8]

For both mould growth and intersitital condensation, a limit state is defined. In this study the limit of mould growth is set at index 3: Visual findings of mould on surface, <10% coverage (visual), or <50% coverage of mould (microscope) [9]. However, the assesment should be considered as a basis for comparison of the different scenarios. The risk assesment models are used relatively to give an indication of the higher or lower potential risk in the simulated retrofit scenarios

3. Results

All of the retrofit scenarios chosen from the matrix, as described in 2.1.3 are simulated within the six different boundary conditions as described in 2.2.2 Table 5 lists the results of the simulations.

		Temp 20-25	Temp 16-25	Temp 20-25	Temp 16-25
		Mould index	Mould index	Interstitial Condensation	Interstitial condensation
Model 1A	ICC 1	0	0	0 kg/m²	0 kg/m²
	ICC 2	0	0	0 kg/m²	0 kg/m²
	ICC 3	0	0	0 kg/m²	0 kg/m²
Model 1C	ICC 1	>3	>3	>0,2 kg/m²	>0,2 kg/m²
	ICC 2	>3	>3	>0,2 kg/m²	>0,2 kg/m²
	ICC 3	>3	>3	>0,2 kg/m²	>0,2 kg/m²
Model 2C	ICC 1	0	0	0 kg/m²	0 kg/m²
	ICC 2	Max 0,025	Max 0,2	0 kg/m²	<0,2 kg/m²
	ICC 3	3	3	<0,2 kg/m²	<0,2 kg/m²
Model 3C	ICC 1	0	0	0 kg/m²	0 kg/m²
	ICC 2	Max 0,010	Max 0,13	0 kg/m²	0 kg/m²
	ICC 3	Max 0,6	2,5	0 kg/m²	<0,2 kg/m²

Low risk Medium risk High risk

Table 5: Overview of the results: mould index and interstitial condensation

3.1 Material 1: Cellular concrete

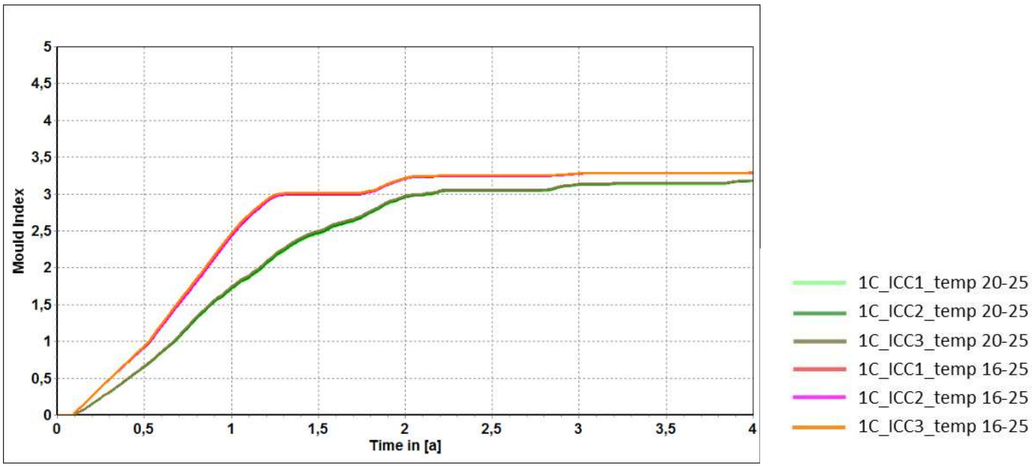
3.1.1 Model 1 A: Cellular concrete with external insulation (insulated panels)

There is no risk of any biological growth according to the VTT mould model. The mould index is 0 in all of the cases.

In this model the simulation does not show any condensation.

3.1.2 Model 1 C: Cellular concrete with internal insulation

The risk on mould growth when insulating a cellular concrete wall with an internal insulation of mineral wool is evaluated in the VTT mould model. Figure 2 compares the simulated maximum mould index for the six different cases. the pink, orange and red lines show the cases in the temperature zone 16-25°C (within the different indoor climate classes (ICC1, 2, 3). The different green lines show the cases in the temperature zone 20-25°C (within ICC1, 2, 3). The green lines are packed together in one green line, the red, pink and orange line are packed together in one orange line.The graph indicates that this retrofit scenario will have the risk of visual mould growth (M > 3) after 2 years. The cases within the temperature zone 16-25°C will have a higher risk on mould growth. The indoor humidity has a lower impact on the hygrothermal risk of the different cases.



Figue 2: Comparison of simulated mould index for model 1C with the different parameters.

Figure 3 compares the overhygroscopic moisture mass measured on the coldest (outer) surface of the insulation for the six different cases. The blue lines are packed together in one blue line (ICC 1, 2 and 3 in temp.zone 20-25°C), the red, pink and orange line are packed together in one red line (ICC 1, 2 an 3 in temp.zone 16-25°C)...

All of them are exceeding the maximum level of condensation (0.2 kg/m²). This retrofit option is not recommanded due to the high risk on interstitial condensation.

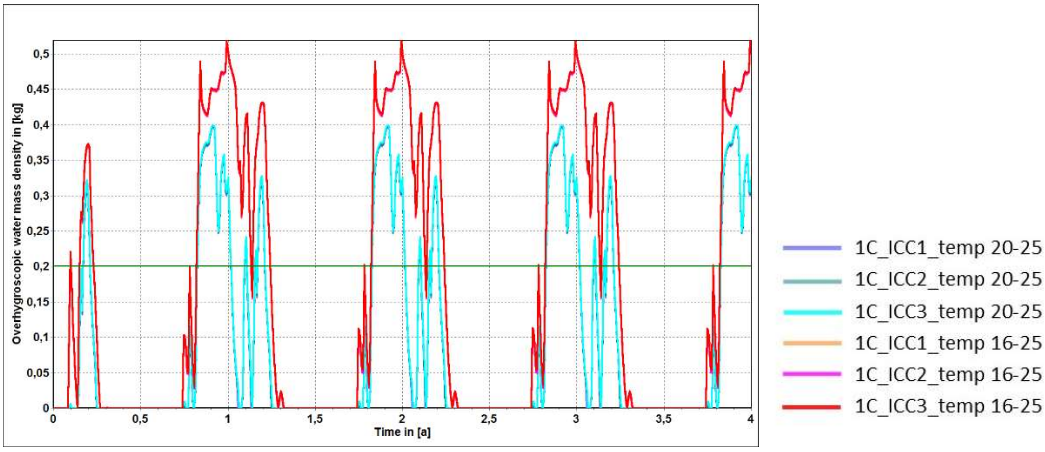


Figure 3: Overhygroscopic moisture mass for the cases for model 1C with the six different parameters. The green horizontal lines indicates the limit value 0.2 kg/m²

The main cause for the high levels of humidity is the rain load from the exterior. The diminution of the rain load can lead to lower hygrothermal risk:

(a) Application of hydrophobic treatment is an efficient option to improve rain protection of the exterior surface. This option is numerically simulated for the ‘worst case’ meaning the parameters according the indoor climate class ICC3 and temperature zone 16-25°C. The results: no interstitial condensation, and low risk of mould growth however with an upward trend (index 0.14 after 4 years). On the cold surface of the insulation a great reduction of the relative humidity is perceivable in figure 4 (black line) compared to the worst case (blue line). At the same time there is a high reduction of the total overhygroscopic moisture over the total thickness of the wall as seen in figure 5 (black line, compared to blue line in the graph). The addition of a hydrophobic render has its drawbacks, such as the diminution of the vapour permeability. Further research is needed and falls beyond the scope of this paper.

(b) Adding a watertight rain screen is a very efficient way of keeping the cellular concrete dry. This could be done by adding an exterior cladding system with a ventilated cavity. To simulate this option, a simplification is done: instead of adding a cladding system and an air cavity, the properties of the outer layer of the cellular concrete is changed into a watertight layer. This simplification helps reduce the simulation time in Delphin. The model is tested with the same parameters as described above. The outcome is that no interstitial condensation is formed and the mould index is 0. As seen in figure 4 and 5, the surface humidity on the cold surface of the insulation have dropped (red line) compared to the hydrophobic model (black line) and the total overhygroscopic has decreased. This option is relatively seen, the best option for model 1C.

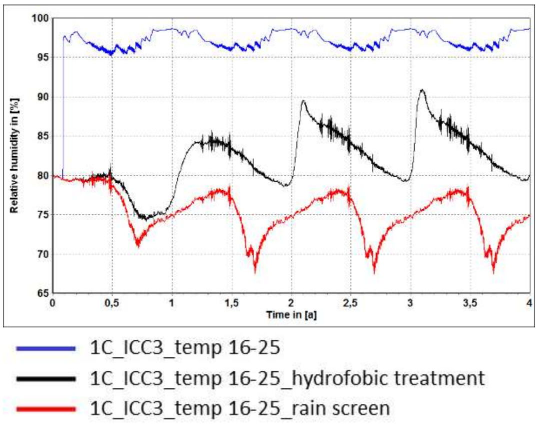


Figure 4: relative humidity on the cold surface of the insulation.

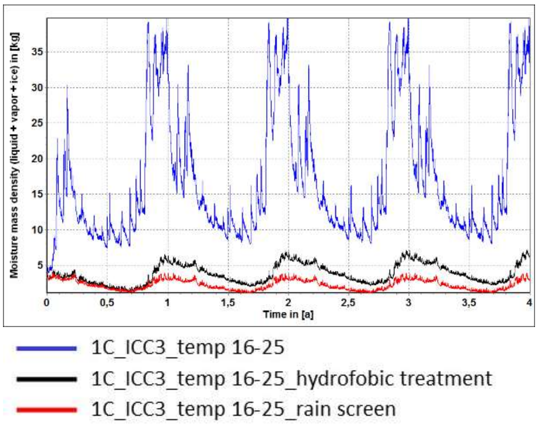


Figure 5: entire overhygroscopic moisture for the total thickness of the wall.

3.2 Material 2: insulated wall panels

3.2.1 Model 2 C: Insulated panels with additional internal insulation

Mould index: Model 2C

Figure 6 compares the simulated maximum mould index for the six different cases. The red line shows the mould index of the model within the indoor climate class ICC3 in the temperature zone of 16-25°C. The blue line is the mould index for the model in climate class ICC3 in the temperature zone of 20-25°C. The green line shows the mould index for this model in the indoor climate class ICC 2 within a temperature zone of 16-25°C. The other lines of the different cases are not visible on the graph, because the mould index is almost zero. The graph shows that there is a risk of visual mould growth for the cases in the indoor climate class ICC3 after 2.5 to 3 years. The humid conditions of this indoor climate will facilitate the biological growth on the cold surface of the insulation layer. The risk in climate class ICC2 within the temperature zone 16-25°C is low (max mould index = 0.2). The risk of biological growth in climate class ICC1 and ICC2 (temp 20-25°C) is 0. .

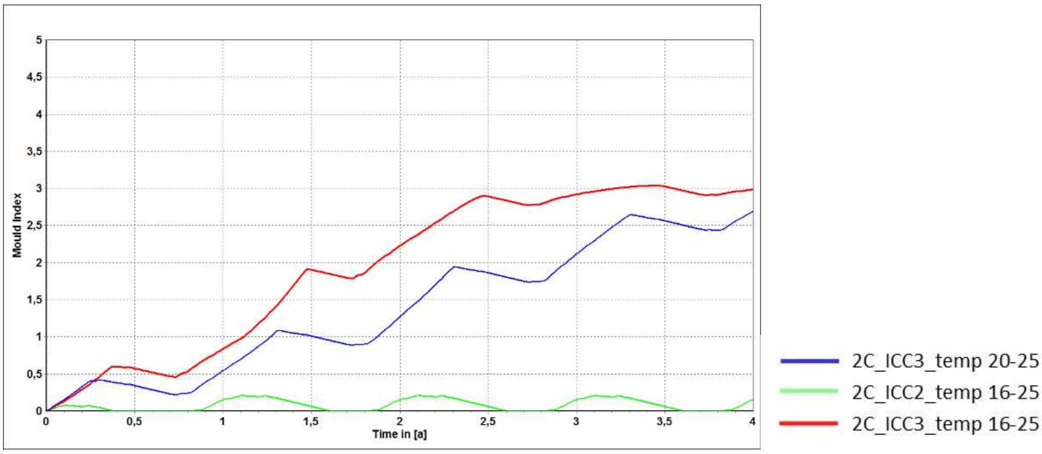


Figure 6: Comparison of simulated mould index for model 2C with the different parameters.

Interstitial condensation: Model 2 C

Figure 7 shows the overhygroscopic moisture mass measured on the coldest (outer) surface of the insulation. As we can see in the graph none of the measured overhygroscopic moisture is exceeding the limit value of 0.2 kg/m². The blue line shows the condensate for the indoor climate class ICC3 in temp.zone 20-25°C, the orange illustrates the condensate for the indoor climate class ICC3 in temp.zone 16-25°C. All of the other cases have negligible interstitial condensation.

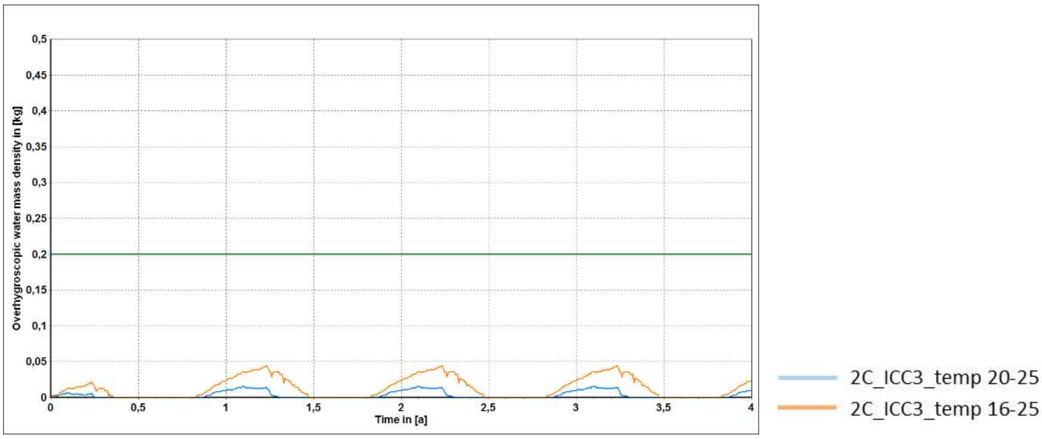


Figure 7: Overhygroscopic moisture mass for the cases of model 2C with the six different parameters. The green horizontal lines indicates the limit value.

3.3 Material 3: Liner trays

3.3.1 Model 3 C: External profile sheeting – insulation –liner trays – interior insulation

Mould index: Model 3C

In figure 8 the graph shows that model 3C is not yet reaching towards the level of risk of visual mould growth, when implemented in the indoor climate class ICC3 in the temperature zone 16-25°C, but has an upward trend (black line). The humid conditions of this interior climate will however facilitate the biological growth on the cold surface of the interior insulation. The risk in climate class ICC3 within the temperature zone 20-25°C is lower but also had an upward tendency (after 4 year max mould index = 0.6) (red line). The risk in ICC 2 within temperature zone 16-25°C is low (blue line max mould index= 0. 13).In climate class ICC1 and ICC 2 (temp 20-25°C) the risk is very low to 0.

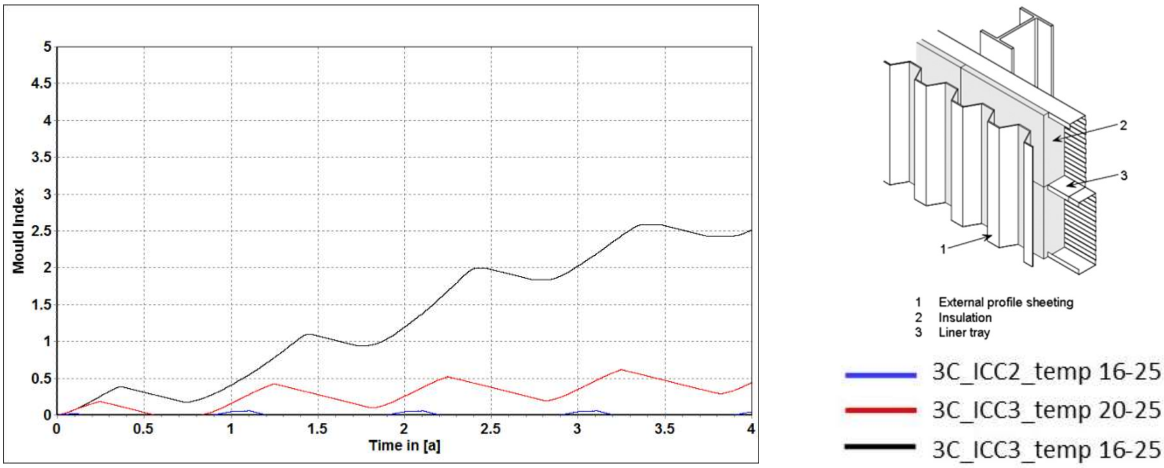


Figure 8: Comparison of simulated mould index for model 3C with the different parameters.

Interstitial condensation: Model 3 C
No interstitial condensation is formed in this model.

4. Discussion and recommendations for practice

Based on this study, some conclusions can be made on retrofitting SME buildings. However, a few remarks need to be considered. In all of the models, the setup was done to represent the 'worst case'. This concerns the orientation of the wall, the upper boundary of the climate classes, …. On the other hand simplifications are carried out because of the 1D approach of the models. The mode of attaching the panels to the wall (plugs, glue mortar,…) is not considerd is this study, as well as air leakages due to bad craftmanship or deterioration over the years, of the existing wall.

Model 1A: cellular concrete with external insulation

When insulating a cellular concrete wall with external insulation, the hygrothermal stress is low. The sandwichpanels both insulate and protect the original wall from rainfall. Of course good workmanship when placing the panels is of great importance. The remaining moisture in the wall will dry out towards the interior. Preferably no interior finishing is placed at the interior surface of the wall to encourage this process.

Model 1C: Cellular concrete with internal insulation

When insulating a cellular concrete wall with internal insulation, the risks on both biological growth and interstitial condensation are real. The main cause for the high levels of humidity is the rain load from the exterior. Technical recommendations for practice are:

(a) Application of hydrophobic treatment is an efficient option to improve rain protection of the exterior surface
(b) Adding a watertight rain screen is a very efficient way of keeping the cellular concrete dry. This could be done by adding an exterior cladding system with a ventilated cavity.
(c) To limit the risk of mould growth it is discouraged to use wood based products for the placement the interior insulation. We refer to the sensitivity classes of materials within the VTT mould model as described above (see [7]).

Model 2C: Insulated panels with additional internal insulation

Retrofitting an envelope consisting of insulated sandwich panels with internal insulation is not recommended when the indoor relative humidity of the building is situated in the indoor climate class ICC3.. The risks on biological growth exists. On the subject of interstitual condensation, we can conclude that the level of moisture is negligible in the three different climate classes. An analysis of the exisiting building skin before insulating, is recommended. The air leakages throught the joints of the liner trays are not taken into account in the wall configuration for the simulation. However, the assumption is that these will only positively influence the risk on damage, because the moisture evaparation of the eventual condensation will be facilitated towards the exterior.

Model 3C: External profile sheeting -insulated linter trays with - interior insulation

The scenario of insulating a wall on the interior, built with insulated liner trays and a metal sheet exterior cladding only has minimal potential hygrothermal risk when realized in a building with activities belonging to the indoor climate class ICC 3 and with temperatures oscillating between 16°C and 25°C. For the temperatures between 20°C-25°C, i.e. use for offices, a real chance of the growth of visual mould could be considerd over the long haul.

5. Conclusions

Results of these hygrothermal simulations indicate that:
(a) a retrofit approach of internal insulation of a cellular concrete wall is not advised without an additional rain protection. The moisture level in the cellular concrete may be too high and can lead to mould growth and interstitial condensation.
(b) the application of internal insulation of a building envelope consisting of insulated metal sandwich panels involves a low risk. This is, when performed in buildings with a humidity level not higher than

ICC2 (< average vapour pressure 1370 Pa),
(c) internal insulation within an existing building envelope of insulated liner trays involves a low risk. The upper boundary of the humidity level is also ICC2.
(d) A cellular concrete wall can be externally insulated without any hygrothermal risk.

6. Acknowledgements

This research is funded by Flanders Innovation and Entrepreneurship (VLAIO). This support is gratefully acknowledged. TETRA HBX.2016.0120 : "KMO RENO- A renovation guide for SME-buildings"

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