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Performance evaluation of thermal bridge mitigation strategies against the mould growth

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Subject review

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Performance evaluation of thermal bridge mitigation strategies against the mould growth

This study investigates mould/fungi growth risk on two different approaches of thermal bridge mitigation. Thermally insulated balconies and thermally broken balconies in Zero Emission Building (ZEB) are reviewed. Linear thermal transmittance (ψ - value), interior surface temperature and mould/fungi growth risk for five balcony designs is performed. Each design has three variations, two of which have thermal insulation wrap, and a thermal break replacing insulation. Results show thermal breaks outperform all variations. This contradicts the common practice of using thermal insulation wrap. The study also emphasizes EN ISO 13788 inadequacy as comprehensive HAM models are available.

Key words:
thermal bridges, thermal break, surface temperature, temperature factor, mould growth, ZEB, balcony slab

Pregledni rad

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Procjena utjecaja strategija za ublažavanje učinaka toplinskih mostova na rast plijesni

Ovaj rad istražuje rizik rasta i razvoja plijesni/gljivica na dva različita pristupa smanjenja utjecaja toplinskih mostova. Promatrani su balkoni obavijeni toplinskom izolacijom i balkoni sa sustavom prekida toplinskog mosta u ZEB (engl. Zero Emission Building) zgradama. Promatrani su linearna toplinska vodljivost (ψ-vrijednost), temperatura unutarnje površine i rizik pojave plijesni/gljivica na pet različitih slučajeva balkonskih ploča. Svaki slučaj ima tri varijacije, od kojih su dvije obavijene toplinskom izolacijom, a treća varijacija umjesto toplinske izolacije koristi sustav za prekid toplinskog mosta. Rezultati varijacija s prekidom toplinskog mosta nadmašuju ostale varijacije, što je u suprotnosti s uobičajenim pristupom u kojem se koristi obloga od toplinske izolacije. Rad također naglašava neadekvatnost norme EN ISO 13788 zbog sveobuhvatnih HAM (engl. *Heat, Air and Moisture*) modela.

Ključne riječi:
toplinski mostovi, prekid toplinskog mosta, površinska temperatura, temperaturni faktor, razvoj plijesni, ZEB, balkonska ploča

1. Introduction

Indoor Air Quality (IAQ) is very important due to the amount of time spent indoors. The vast majority of Europeans spend 85 – 90 % of their time indoors [1, 2].

Buildings protect people from many outdoor conditions but – they cannot protect occupants from poor air quality inside the building. Mould and fungi in residential buildings have a significant impact on air quality. Fungi and moulds are ubiquitous in the environment, and their spores can easily become airborne, leading to inhalation exposure. This exposure is of particular concern in indoor environments where people spend a significant amount of time [1, 3]. Due to their size, ranging from 2 to 5 m, many fungal spores can easily penetrate deep into the lungs and reach the bronchial tubes. This poses a significant health risk as it can trigger asthma in some individuals [4, 5].

The study [6] highlights that poor insulation and inadequate wall thermal properties increase energy use and risk of mould growth, suggesting better insulation to improve indoor quality. Mould and damp problems are very common in Europe. It is expected that one in every six homes is affected by it [7]. According to [5, 8], almost a quarter of buildings in Northern Europe and North America are contaminated with mould, affecting the health of millions of people through exposure to microbial airborne pollutants such as including spores, fungal fragments, mycotoxins, endotoxins, glucans and mVOCs. Exposure to mould spores and fungal irritants can lead to a range of health problems for occupants, including allergic reactions, hypersensitivity pneumonitis, and infections [9-12].

The literature shows that buildings' indoor environment temperatures are suitable for mould and fungi germination as they develop within a temperature range of 0 to 50 °C [4]. Mould growth becomes more likely as humidity increases. Most mould species find ideal growth conditions at a relative humidity of around 80 %. Even higher humidity levels, typically between 90 % and 96 %, are only favourable for a selected few moulds variety. Thankfully, both temperature and humidity are essential in order to achieve favourable conditions for mould development. Other parameters such as oxygen content, surface roughness, biotic influences, pH value, salt content of the substrate, light and time can also influence germination and mycelium growth.

Winter brings with it a double threat for mould growth, especially in the area of thermal bridges. These areas, where heat flow is increased, cause lower internal surface temperatures compared to the rest of the building envelope. This temperature difference, combined with the typical increase in indoor humidity during the winter, creates a prime environment for mould and fungi to thrive.

The impact of thermal bridges on the transmission heat losses in buildings is significant, studies such as [13] indicate a potential share of up to 30 % in certain cases. However, this high ratio is typically observed only in buildings where the architectural design includes numerous protrusions of the load-bearing structure through the thermal envelope. Study [14] highlights the importance of nZEB (nearly Zero Energy Buildings) standards and thermal bridge impact on transmission heat losses, building material degradation and structural damage.

According to current nZEB regulation and with the upcoming ZEB regulations in the EU, thermal bridges might cause additional problems in the future. In general, the steady-state heat flow through the building component without the influence of the thermal bridge is considered to be one-dimensional, in the direction perpendicular to the wall [15]. However, thermal bridges can disrupt the direction of heat flow and cause additional heat loss. With regards to the energy consumption of buildings, uninterrupted thermal bridges caused by balcony slabs have one of the most significant shares on overall building [16]. These elements cause thermal bridges due to several key factors. Balcony slabs are typically constructed from reinforced concrete, the same material as the primary building slabs or walls. Reinforced concrete has a high thermal conductivity, creating a heat transfer path with low thermal resistance between interior and exterior. Design limitations often do not allow for the balcony to be properly insulated and on top of that balcony slabs have a large, exposed surface area compared to a well-insulated wall.

The practice of installing thermal insulation wrap on protrusions like balconies and roof parapet walls can still be found on Croatian construction sites. Although thermal breaks are known and present on the construction market, the practice of installing them is still not usual. Thermal performance of thermal breaks is still relevant topic in academic community with high research interest [17-22].

The two most common approaches to minimizing thermal bridges in balcony slabs is by applying thermal insulation wrap on all sides of the balcony slabs and a thermal break that does not compromise the load-bearing capacity of the balconies [21-24, 27]. There are also different reinforcement materials for thermal breaks available on the today's market. The impact of different reinforcement material is presented in [17].

The study [28] emphasizes the importance of designing insulation blocks that minimize thermal bridges, which are critical in preventing heat loss and potential moisture issues in building envelopes.

The research in [27] also considers the application of thermal insulation wrap to the internal wall surface in order to minimize the thermal bridging effect caused by the balcony slab. Although the internal surface temperature is higher, the study concludes that the internal insulation does not reduce the heat flux and therefore it does not reduce the thermal bridging effect.

Concrete balconies, which are constructed as a direct extension of the floor slab, create a major thermal bridge. This not only reduces building's energy efficiency but also leads to cold interior surfaces during winter period, which increases the risk of condensation and mould growth [17, 27].

There are many studies that compare thermal performance of uninsulated balcony slabs with thermal breaks [17, 18, 24, 27, 29-35] but very few compare the effectiveness of thermal insulation wrap versus thermal breaks.

When observing the residential buildings with very pronounced thermal bridges, occupants may not know how the thermal bridges affect their monthly bills, but they may feel discomfort caused by mould growth in corners of their rooms, behind furniture or discomfort caused by cold ceiling or floor in case of large areas of thermal bridges. Thermal bridges on balconies slab can affect the indoor wall surface temperature and cause thermal discomfort, or even mould and fungus growth.

The problem of mould and fungus germination on thermal bridges arises from the low temperatures during winter months, which create favourable conditions for their development. Croatian regulations currently mandate the calculation of only the temperature factor (f_{Rsi}) as an indicator of the risk of condensation and mould growth on the surface of building elements. However, the occurrence of mould and fungi germination is relatively common [5, 7, 8] even when the building itself meets the specified factor requirements f_{Rsi}, suggesting a deeper issue that cannot be adequately addressed solely by the f_{Rsi} factor.

In Croatian practice, the most commonly used condition for the factor f_{Rsi} is = 0.7. This value is derived from the DIN 4108-3 [36] standard and is in accordance with Croatian building regulations and technical guidance [37]. For a more detailed calculation, the EN ISO 13788 [38] standard should be considered.

According to Croatian building regulation [37], there is another criterium, but it applies for buildings with water vapour partial pressure higher than 1750 Pa, that have thermal bridges with Ψ– value higher than > 0,15 W/(mK). For those buildings it is necessary to prove that water vapor will not condense on the inner surface of thermal bridges. This demonstration is carried out in accordance with HRN EN ISO 10211:2008 [39] and HRN EN ISO 13788:2002 [38]. Water vapour condensation inside building elements and its evaporation are calculated according to HRN EN ISO 13788:2002.

Though unnecessary for most homes due to the absence of features generating high water vapor pressure (>1750 Pa), this calculation could be valuable tool for addressing moisture problems prevalent in many buildings. Study [40] investigates how modifications like perforations and slits in expanded polystyrene (EPS) affect its water vapor diffusion and thermal conductivity. The findings indicate that while such modifications can enhance water vapor diffusion by up to 42.18 %, they also lead to a 9.02 % increase in thermal conductivity, which could influence the material's insulation performance.

Although mould spores require several days to germinate at given boundary conditions, the historical weather data for Zagreb (continental climate conditions) [41] indicates a significant possibility of both spore germination and subsequent mycelium growth due to consistently low air temperatures with adequate high RH near thermal bridges. Thermal bridge temperatures during winter are insufficient to destroy mould and fungi.

Under suitable conditions of temperature and humidity, cold spores can germinate on or within building materials. Once germination occurs, these spores will continue to grow forming a network known as mycelium, if the surrounding environment remains favourable [42]. It's important to note that this study did not consider the potential inhibitory effect of sunlight on mould growth.

2. Case study

This study examines two methods for reducing thermal bridges in concrete balconies, compared to the traditional approach of continuous concrete extensions. The focus is on how these approaches affect the inner wall surface temperature and its impact on mould and fungi growth.

2D computer simulation is employed in order to analyse five different balcony connection details, each detail has three variations:

- Croatia's most commonly used approach with 5 cm of thermal insulation wrap on all sides of balcony slab although regulations require 8 cm
- Rarely encountered in practice uses thicker layer of thermal insulation wrap (10 cm) as an extreme example for comparison.
- This method employs thermal break built in the concrete slab, instead of thermal wrap.

The details are based on the design of a building constructed in Croatia. In Figure 1, layers of the wall, roof and intermediate slab construction are listed.

Materials such as rendering, vapor retardant layers, waterproofing, as well as finishing layers like cement screed and tiles on the external side of the models have negligible influence on the thermal bridge properties, are not listed in Figure 1, as they do not significantly affect the heat flow under the steady-state conditions used for the calculation A comprehensive description of each detail and its variation is described below.

Detail 1a (Figure 2) presents external wall with 5 cm thermal insulation wrap around balcony slab. Detail 1b (Figure 3) is variation of Detail 1a, the difference is in the thickness of thermal wrap where Detail 1b has 10 cm of thermal wrap. Detail 1c (Figure 4) has thermal break TB3 instead of thermal wrap.

Detail 2a (Figure 5) presents external wall with 5 cm thermal insulation wrap around balcony slab. Glass doors are placed above the balcony slab, while there is an external wall below balcony slab. Detail 2b (Figure 6) is variation of Detail 2a where thermal wrap thickness is increased to 10 cm. Detail 2c (Figure 7) has thermal break TB3 instead of thermal wrap. Detail 2 shows the incorrectly installed balcony doors but is commonly used in Croatia.

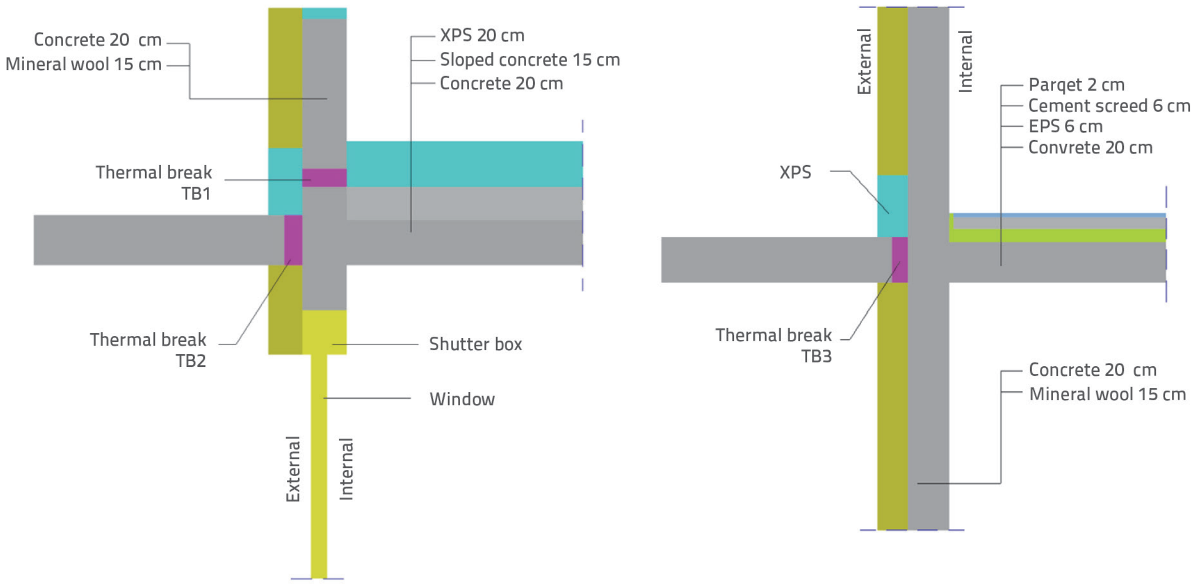

Figure 1. Example of detail variations with layers

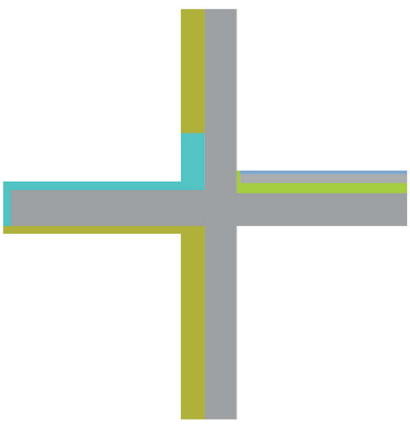

Figure 2. Detail 1a, cladding thickness 5 cm

Figure 3. Detail 1b, cladding thickness 10 cm

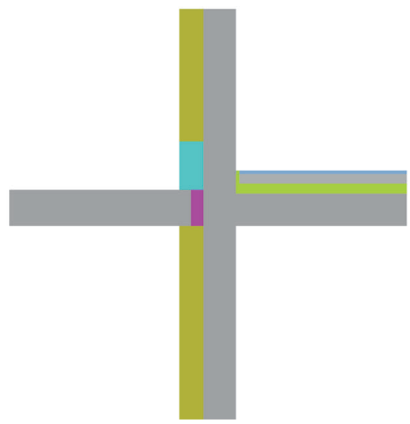

Figure 4. Detail 1c, thermal bridge break TB3

Figure 5. Detail 2a, cladding thickness 5 cm

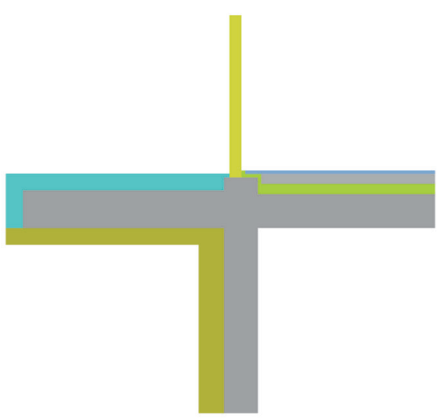

Figure 6. Detail 2b, cladding thickness 10 cm

Figure 7. Detail 2c, thermal bridge break TB3

Detail 3a (Figure 8) presents external wall with 5 cm thermal insulation wrap around balcony slab. The external wall is above balcony slab, while below is external wall, box for blinds and window. Detail 3b (Figure 9) is variation of Detail 3a with increased thermal wrap thickness to 10 cm. Detail 3c (Figure 10) uses thermal break TB3 instead of balcony slab thermal wrap.

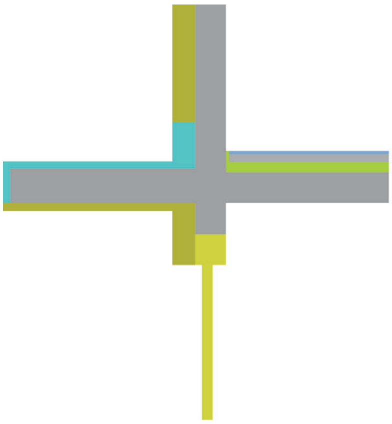

Figure 8. Detail 3a,cladding thickness 5 cm

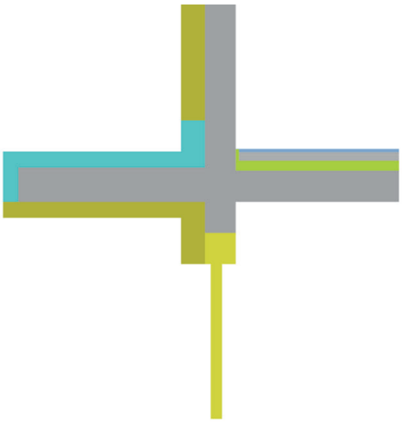

Figure 9. Detail 3b, cladding thickness 10 cm

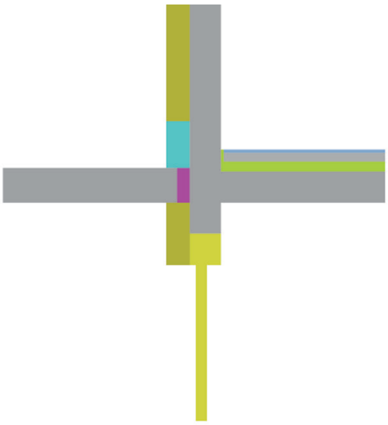

Figure 10. Detail 3c, thermal bridge break TB3

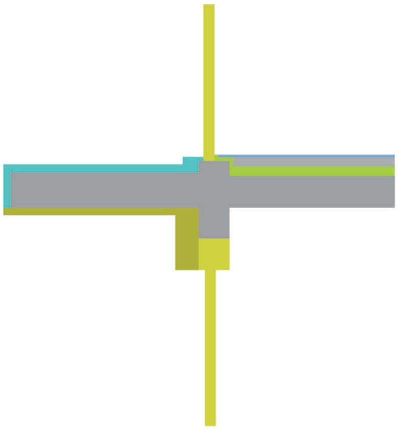

Figure 11. Detail 4a, cladding thickness 5 cm

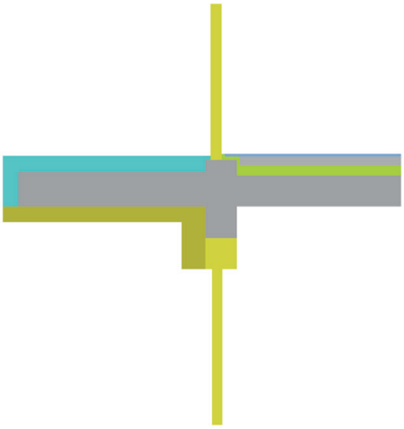

Figure 12. Detail 4b, cladding thickness 10 cm

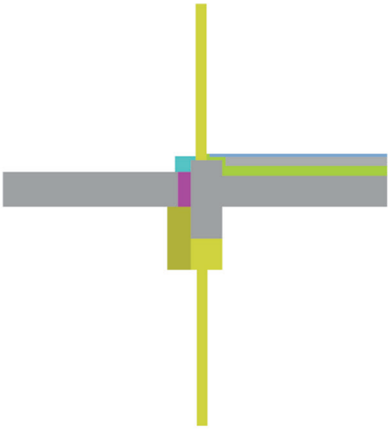

Figure 13. Detail 4c, thermal bridge break TB3

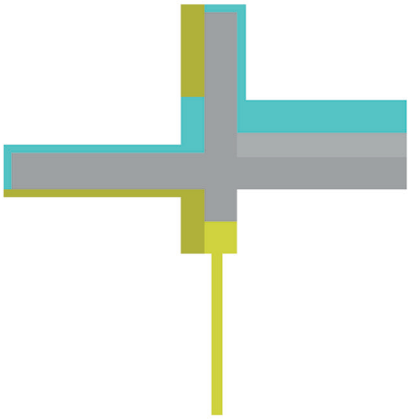

Figure 14. Detail 5a,cladding thickness 5 cm

Figure 15. Detail 5b, cladding thickness 10 cm

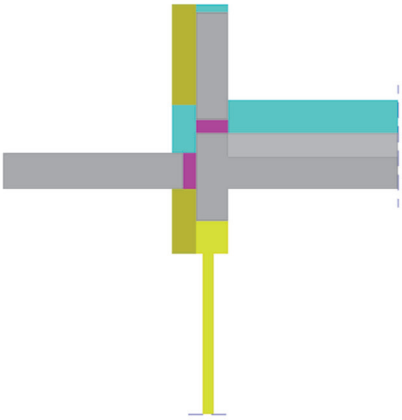

Figure 16. Detail 5c, thermal bridge break TB1 and TB2

Detail 4a (Figure 11) presents external wall with window and door that lead to the balcony. The balcony slab is wrapped with 5 cm of thermal wrap. Detail 4b (Figure 12) is variation of Detail 4a, where thermal wrap thickness is increased to 10 cm. Detail 4c (Figure 13) has installed thermal break TB3 instead of thermal wrap. Detail 4 shows the incorrectly installed balcony doors but is commonly used in Croatia.

Detail 5a (Figure 14) shows external wall with canopy slab and roof parapet wall. On the external wall there is a box for blinds and a window. The canopy slab and roof parapet wall are wrapped in thermal insulation. Detail 5b (Figure 15) is a variation of Detail 5a, where thermal insulation wrap is increased to 10 cm. Detail 5c (Figure 16) uses thermal break TB2, while the roof parapet wall has added thermal break TB1.

Table 1. Surface heat transfer coefficient

Heat flux direction	Boundary	*h* [W/m²K]
Horizontal	Exterior	25.0
	Interior	7.69
Upwards	Exterior	25.0
	Interior	10.0
Downwards	Exterior	25.0
		5.88

Finishing layers are not in the models (Figure 1 - Figure 16) as they have negligible impact on the thermal bridge.
This paper investigates two alternative methods of thermal bridge mitigation in concrete balconies, on continuous concrete extensions. The study focuses on – value, internal surface wall temperatures, dimensionless temperature factor (f_{Rsi}) and their impact on mould and fungi growth.
The numerical analysis was carried out by CRORAL [43], a computer software for calculation of the two-dimensional steady state heat transfer and temperature distribution in the cross-section. The software was developed on University of Zagreb at the Faculty of Civil Engineering in the Department of Materials and is validated according to EN ISO 10211 [39] and EN ISO 10077-2 [44]. In order to be classified as a two-dimensional steady-state high precision method, given conditions had to be fulfilled:
- the difference between temperatures calculated with CRORAL and listed in EN ISO 10211 had to be lower than 0.1 °C
- the difference between heat flow calculated with CRORAL and listed in EN ISO 10211 had to be lower than 0.1 W/m
- the difference between calculated with CRORAL and listed in EN ISO 10077-2 had to be lower than 3 %

Using the provided details (Figure 2 to Figure 16), values f_{Rsi} were calculated employing the most common method in Croatia (Section 2.2.). Additionally, stricter criteria taken for cases with high water vapor pressure (>1750 Pa) was considered where both, internal and external temperatures were variated to encompass a wide range of climatic conditions in Croatia.
A final comparison was conducted using the Sedlbauer model, which utilizes isotherms. This analysis revealed the impact of exposure duration to external temperatures on mould and fungal germination.

2.1. Thermal bridge calculation

Ψ-value is calculated according to equation (1) [39]:

$$\psi = L_{2D} - \sum_{i=1}^{n} U_i \cdot l_i \qquad (1)$$

where:
- L_{2D} - thermal coupling coefficient obtained from two-dimensional calculation of the component separating the two environments being considered [W/(mK)]
- U_i - hermal transmittance of the one-dimensional component, i, which separates the two environments being considered [W/(m²K)]
- l_i - length over which the value applies U_i [m]
- n - number of one-dimensional components.

Table 1 summarizes the surface heat transfer coefficients which are taken according to EN ISO 6946 [45].

2.2. Temperature factor calculation

The standardized climate conditions defined in DIN 4108-3 [36] specify a temperature of 20 °C and 50 % relative humidity. Under these conditions, the dew point temperature is T_{DP} = 9.3 °C. if the minimum surface temperature ($T_{si,min}$) of a building element is higher than 9.3 °C, condensation will not occur on the surface. However, it is important to note that condensation is not the only factor influencing mould growth.
Favourable conditions for mould germination typically arise around 80 % relative humidity. In the standardized climate scenario (20 °C and 50 % relative humidity), this critical humidity level is reached at a surface temperature of approximately 12.6 °C. These two limit temperatures (9.3 °C and 12.6 °C) are used to calculate the factor f_{Rsi} for the room-side surface according to DIN 4108-3 [36], considering the standardized boundary conditions of -5 °C outside temperature and 20 °C indoor temperature. Based on this calculation, the minimum f_{Rsi} required factor to prevent mould growth is f_{Rsi} = 0.7.
Temperature factor of the internal surface wall is calculated according to equation (2) [39]:

$$f_{Rsi} = \frac{T_{si,min} - T_e}{T_i - T_e} \qquad (2)$$

where:
- $T_{si,min}$ - internal surface temperature obtained through numerical calculation of 2D thermal bridge [°C]
- T_i - internal air temperature [°C]
- T_e - external air temperature [°C].

Table 2. Material properties used for calculations

Material	λ [W/mK]	μ
Reinforced concrete	2.6	80
Cement screed	1.6	80
EPS	0.04	70
XPS	0.04	80
Ceramic tiles	1.3	200
Shutter box	0.6	100000
Mineral wool	0.04	1
Window frame	0.13	100000
Parquet	0.13	60
Thermal break TB1	0.177	80
Thermal break TB2	0.119	80
Thermal break TB3	0.166	80

This calculation method, along with the specified criterion of f_{Rsi} 0.7 is widely employed in Croatia.
More detailed calculation method involves determining the factor f_{Rsi} for each month based on the average monthly external temperature instead of using a fixed value of f_{Rsi} = 0.7 while also considering saturation pressure (p_{sat}). The month with the highest factor is identified as the critical month ($f_{Rsi,max}$), and the condition $f_{Rsi} > f_{Rsi,max}$ is applied.

The minimum allowable saturation pressure $p_{sat}(T_{si})$ is calculated as [38]:

$$p_{sat}(T_{si}) = p_i / 0,8 \qquad (3)$$

where:
0.8 presents the critical humidity of 80 % at which mould development occurs as stipulated by EN ISO 13788 and p_i- total indoor vapor pressure [Pa].

2.3. Material properties

Thermal breaks TB1, TB2 and TB3 are used in this study, each with a unique purpose for mitigating thermal bridging in various building elements (Figure 1). Thermal break TB1 is specifically employed for roof-wall parapets, while TB2 is utilized for concrete canopy slabs. Finally, TB3 is implemented for balcony slabs. The thermal conductivity of a thermal break is influenced by its material composition and design, which must also ensure adequate load-bearing capacity for the structural integrity of the building.
Material thermal conductivity and water vapor resistance factor values used for calculations are taken according to [37, 46] and are shown in Table 2.
U_w- values in Table 2 are taken according to DIN 4108, Beiblatt 2 [47]. This approach is considered acceptable by Schild [48] in situations where specific window properties are unavailable during the design phase. Schild [48] justifies this method by suggesting that the overall window U– value can be approximated by calculating a simplified model. This model would consist of blocks with equivalent thickness to the actual window frame, assigned a thermal resistance (R - value) identical to the real window's glazing [49].

3. Thermal performance results

Figure 17 to Figure 31 show temperature distribution, minimal surface temperature location, U- values and dimensions used for Ψ- value calculation for detail variations corresponding to the Figure 2 to Figure 16.
Just by analysing the cross-section temperature distribution, there is a notable difference between details with thermal insulation wraps and thermal breaks. Thermal brake incorporates a thermal discontinuity in the canopy slab, significantly reducing heat transfer through it. This discontinuity leads to a lower heat flux across the building element resulting in higher internal surface temperatures.
Details with thermal breaks incorporate a discontinuity in the canopy and balcony slab, significantly reducing heat transfer through it. This discontinuity leads to a lower heat flux across the building element, resulting in higher internal surface temperature. Figure 32 to Figure 36 show graphical representation of numerical calculation. When analysing and comparing the results of computation one should compare the same details and different variations. Details with thermal break have favourable results with lower Ψ– values and higher internal surface temperatures resulting in lower energy consumption and lower mould growth risk while achieving higher thermal comfort. It has to be noted that 10 cm of thermal insulation wrapping the balcony slab is a lot and is rarely seen in practice due to additional cost and alignment between inside and outside floor height, which means lower thermal wrap thickness will result in even worse results and bigger differences.

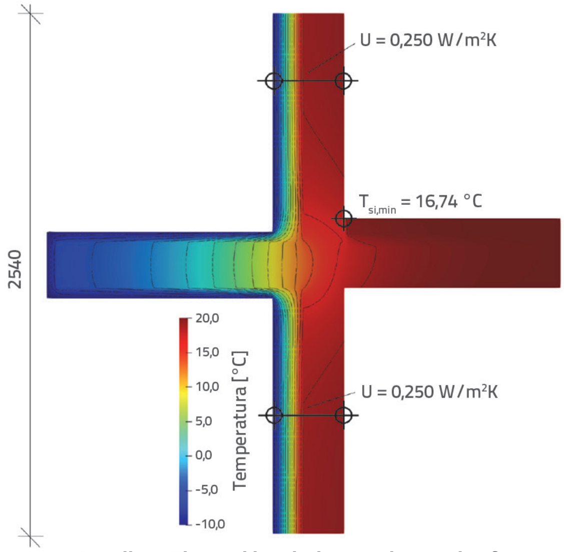

Figure 17. Detail 1a: Thermal insulation coating made of 5 cm

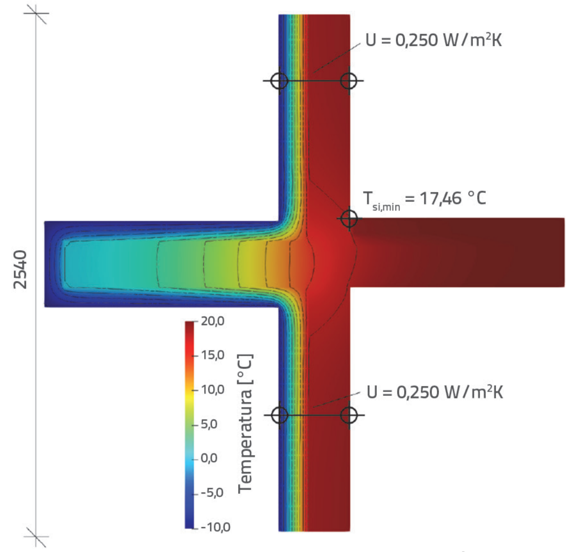

Figure 18. Detail 1b: Thermal insulation coating made of 10 cm

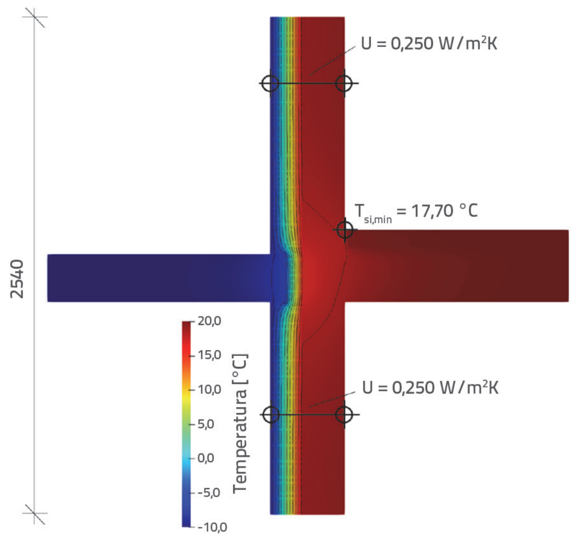

Figure 19. Detail 1c: Thermal bridge break TB3

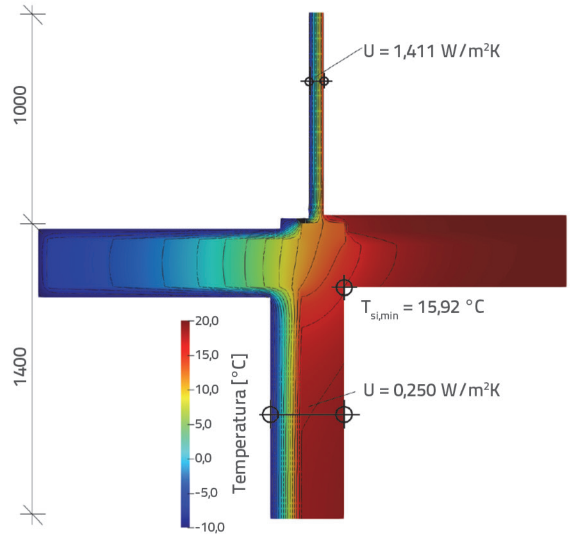

Figure 20. Detail 2a: Thermal insulation coating made of 5 cm

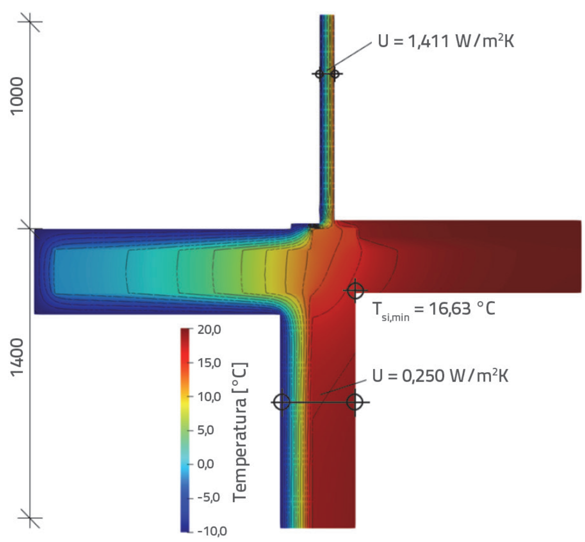

Figure 21. Detail 2b: Thermal insulation coating made of 10 cm

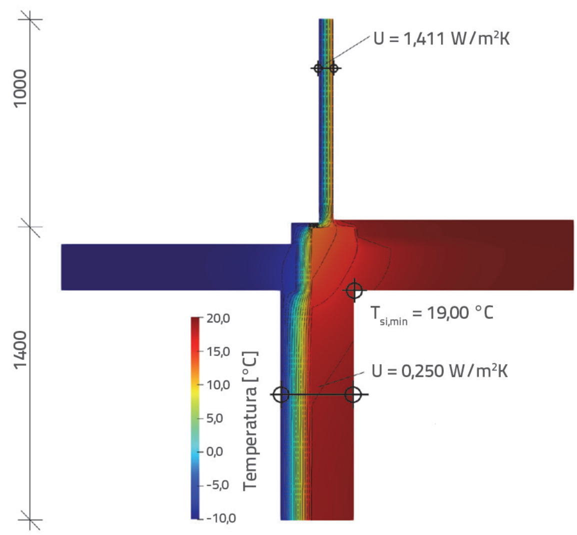

Figure 22. Detail 2c: Thermal bridge break TB3

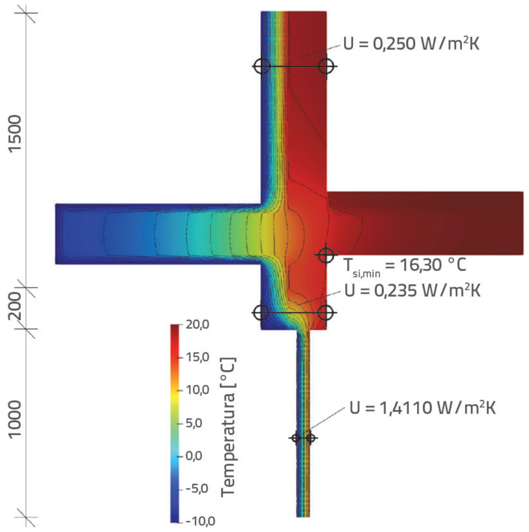

Figure 23. Detail 3a: Thermal insulation coating made of 5 cm

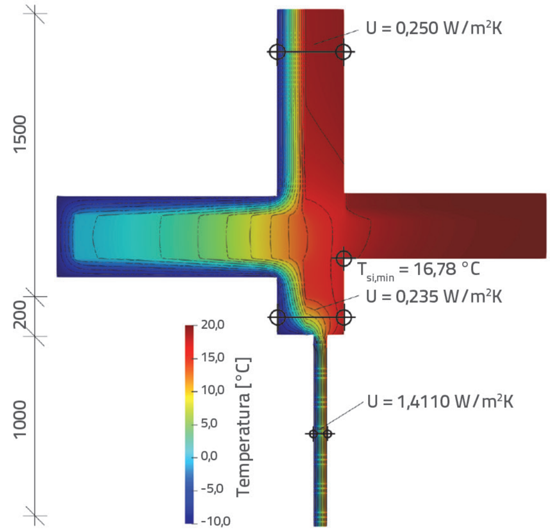

Figure 24. Detail 3b: Thermal insulation coating made of 10 cm

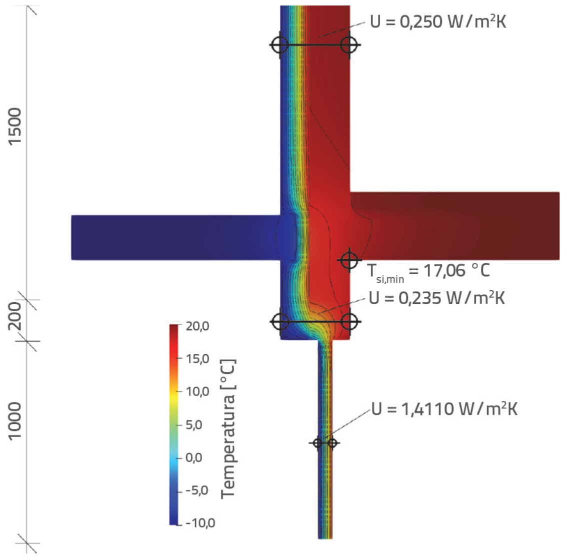

Figure 25. Detail 3c: Thermal bridge break TB3

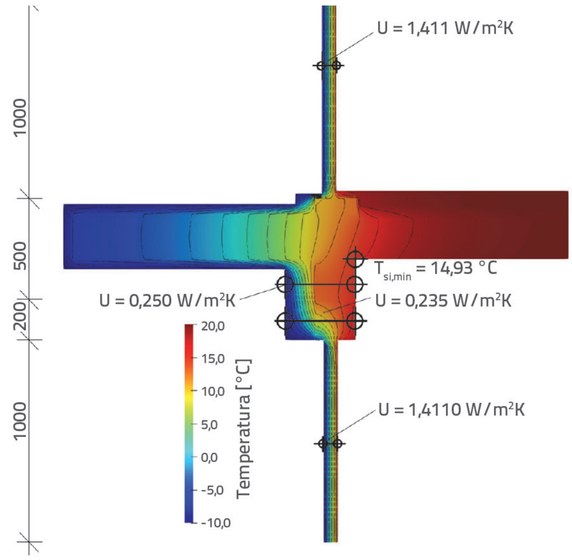

Figure 26. Detail 4a: Thermal insulation coating made of 5 cm

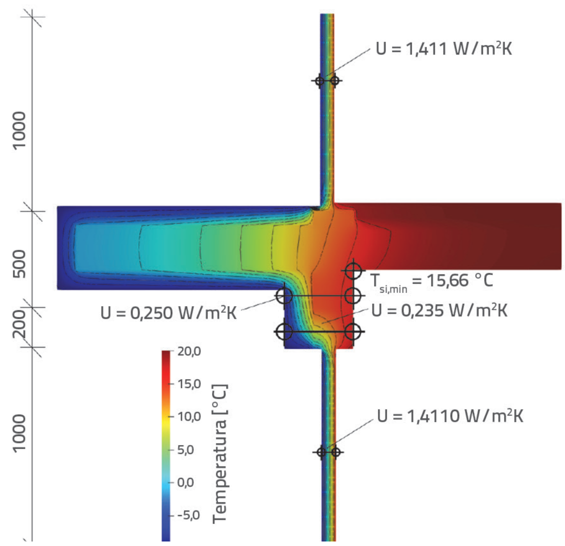

Figure 27. Detail 4b: Thermal insulation coating made of 10 cm

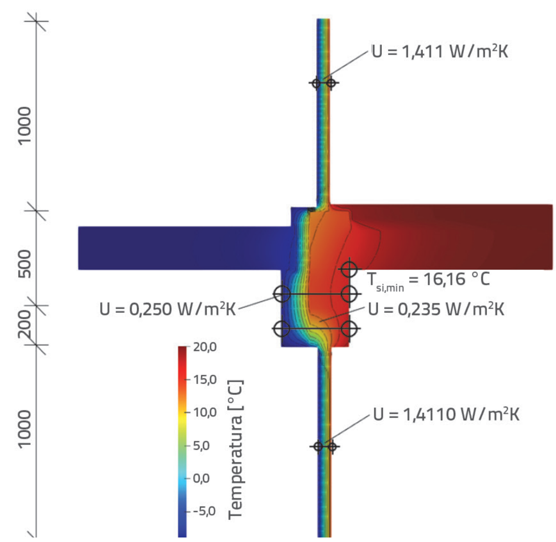

Figure 28. Detail 4c: Thermal bridge break TB3

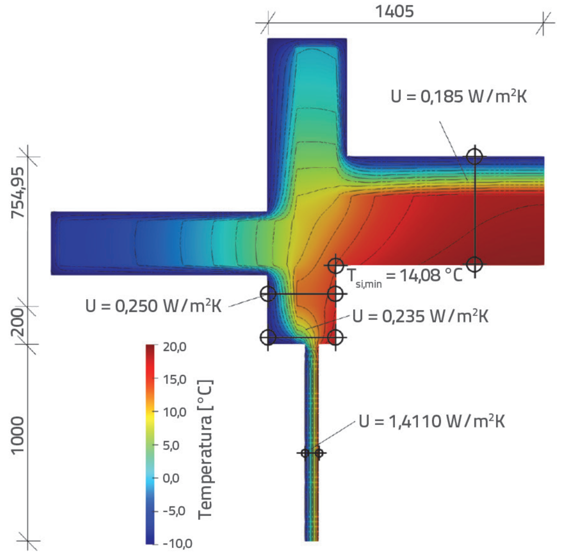

Figure 29. Detail 5a: Thermal insulation coating made of 5 cm

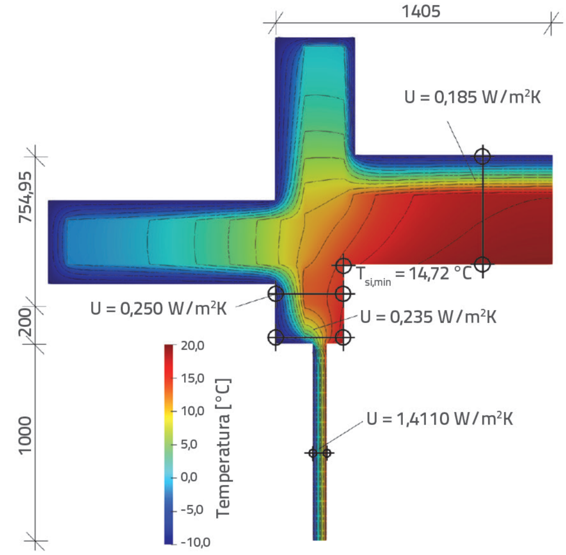

Figure 30. Detail 5b: Thermal insulation coating made of 10 cm

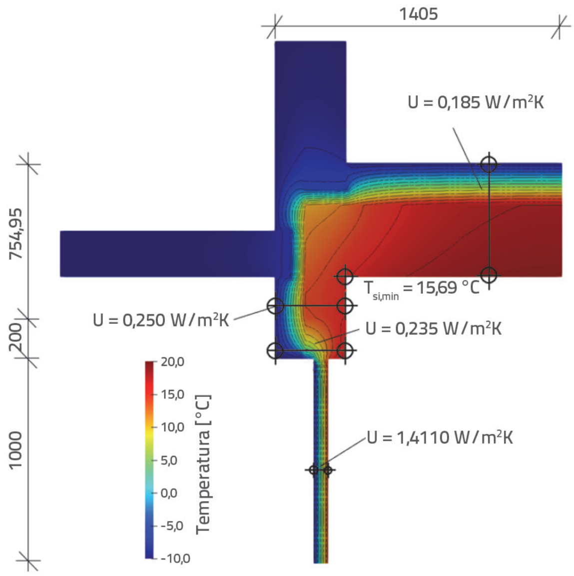

Figure 31. Detail 5c: Thermal bridge break TB1 i TB2

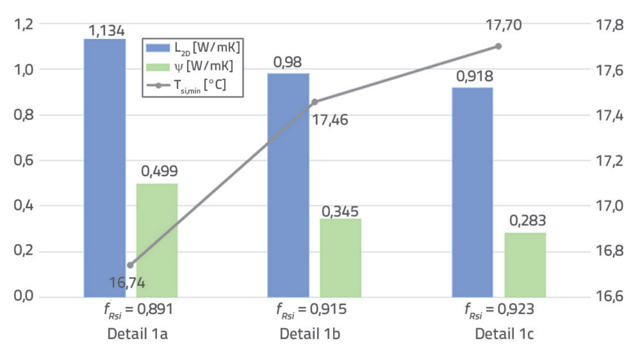

Figure 32. Results for Details 1a, 1b, and 1c

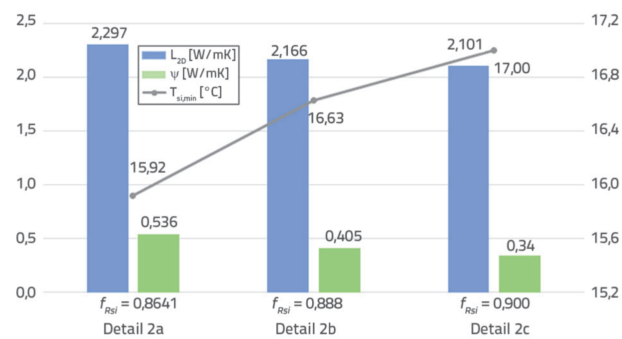

Figure 33. Results for Details 2a, 2b, and 2c

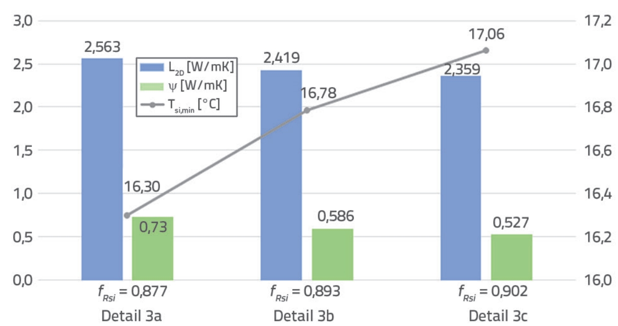

Figure 34. Results for Details 3a, 3b, and 3c

When comparing L_{2D} values, Detail 4a and 4b have the highest value due to two windows with high *U*– values.

Figure 36 shows the results of the Details 5a, 5b and 5c. In those details there are two major thermal bridges, one is the roof parapet wall connection to roof and external wall, while the other is canopy slab connection to the external wall.

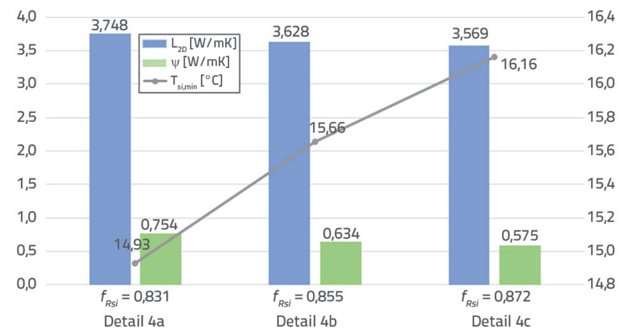

Figure 35. Results for Details 4a, 4b, and 4c

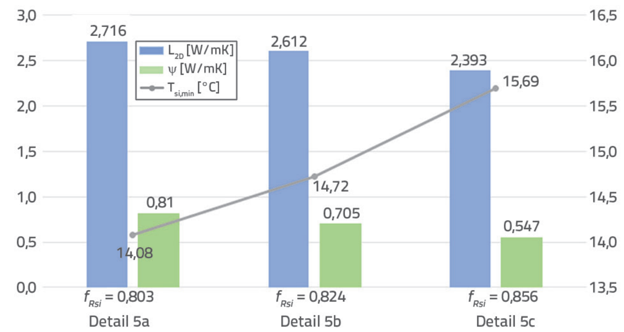

Figure 36. Results for Detail 5a, 5b, and 5c

Internal surface wall temperatures between details 1 to 4 and their belonging variants have minimal differences.

When comparing Ψ– values, the highest value belongs to Detail 5a. Thermal breaks in Detail 5c have the biggest impact among the calculated details in this study.

On a case to case basis, the difference in Ψ– values between thermal wrap and thermal breaks are 9 to 43 %. The biggest difference is between Detail 1a and 1c because there are no additional thermal bridges caused by window, door or roof wall parapet elements that might cause additional thermal bridges and therefore reduce the impact of thermal break.

While increasing the thermal wrap thickness to 10 cm in Detail 1b resulted in a 30 % reduction in – values, incorporating a thermal break in Detail 1c achieved an even greater improvement of 43 % lower Ψ– values.

The differences between variations with 5 cm thermal wrap and thermal break for details 1 to 4 in internal surface temperatures are around 1 °C. The biggest difference is found between Detail 5a and 5c where the difference is almost 2 °C.

As can be observed form the research results, all details fulfil the given condition 0.7. Even the Detail 5a, which has 5 cm of thermal wrap and lowest surface wall temperature of all analysed configurations has value well over 0.7, resulting of f_{Rsi}=0.803.

The question then arises, if all details fulfilled the f_{Rsi} condition with ease, why is mould and fungi in indoor environments occurring in practice in cases of analogous details when insulation wrapping is applied, and one may also ask why the issues with mould growth are so common? To be able to answer these questions one needs to go deeper into the hygrothermal analysis and into the spore germination and mycelium growth models. The described analysis was carried out in this research in the following chapters.

4. Hygrothermal models

According to EN ISO 13788 [38], to check the development of mould on the surface of a building element, only one method is defined and acceptable, there are no other alternative methods in this area. The method given in standard [38] is based on Glaser method. There are many drawbacks to Glaser's method, such as not combining heat and moisture transport and stationary condition assumption. Other drawbacks to Glaser method can be found in [4, 50].

4.1. Temperature factor criterium

Calculation that considers indoor air temperatures (T_i), and relative humidity (Rh) are defined for the building's location (Zagreb, Croatia), which is under continental climate conditions. These calculations are based on designed temperatures, designed relative humidity, and daily average temperatures ($T_{e,davg}$), (Table 3 - Table 5) is performed. Other variation with monthly average temperatures ($T_{e,mavg}$), (Table 6) is also performed.

The saturation vapor pressure ($p_{sat,i}$) is determined using the indoor surface temperature (T_{si}) according to Appendix E of EN ISO 13788. The total indoor vapor pressure (p_i) includes the influence of relative humidity increased by 5 % (Table 3 - Table 6).

The minimum allowable surface temperature($T_{si,min}$) is derived from the minimum allowable saturation vapor pressure $p_{sat}(T_{si})$, according to Appendix E of EN ISO 13788 (Table 3 -Table 6)

The temperature of -10 °C represents the Zagreb's minimum daily average winter air temperature for the period from 1991 to 2020 reduced by two standard deviations [41] and is set as minimal calculation temperature.

Table 3. Minimum criteria for f_{Rsi} indoor temperature T_i = 20 °C

$T_{e.davg}$ [°C]	T_i [°C]	Rh_i [%]	p_i [Pa]	$p_{sat}(T_{si})$ [Pa]	$T_{si.min}$ [°C]	f_{Rsi} [-]
-10	20	65 %	1519	1899	16.7	0.89
-5	20	65 %	1519	1899	16.7	0.87
0	20	65 %	1519	1899	16.7	0.83
5	20	65 %	1519	1899	16.7	0.78

EN 16798-1:2019 [51] recommended indoor temperatures during the heating season and divided them into four categories, but they all have the same upper limit temperature that is equal to T_i = 25 °C. Similar temperature (25.5 °C) is set as upper temperature of comfort by ASHRAE Standard 55 [52].

Researcher performed a study [53] in Croatia where they measured IAQ (Indoor Air Quality). Measured air temperatures during the heating seasons were near the mentioned 25 °C.

Guided by that information, additional simulation was conducted. For the same details as the upper analysis, another variation of previously shown boundary conditions is made. Internal air temperature is raised to 22 °C (Table 4) and 24 °C (Table 5). Maximum of 24 °C was selected in order to cover more homes.

Table 4. Minimum criteria for f_{Rsi} indoor temperature T_i = 22 °C

$T_{e.davg}$ [°C]	T_i [°C]	Rh_i [%]	p_i [Pa]	$p_{sat}(T_{si})$ [Pa]	$T_{si.min}$ [°C]	f_{Rsi} [-]
-10	22	65 %	1718	2147	18.6	0.89
-5	22	65 %	1718	2147	18.6	0.88
0	22	65 %	1718	2147	18.6	0.85
5	22	65 %	1718	2147	18.6	0.80

Table 5. Minimum criteria for f_{Rsi} indoor temperature T_i = 24 °C

$T_{e.davg}$ [°C]	T_i [°C]	Rh_i [%]	p_i [Pa]	$p_{sat}(T_{si})$ [Pa]	$T_{si.min}$ [°C]	f_{Rsi} [-]
-10	24	65 %	1938	2423	20.6	0.90
-5	24	65 %	1938	2423	20.6	0.88
0	24	65 %	1938	2423	20.6	0.86
5	24	65 %	1938	2423	20.6	0.82

The calculated temperature factor criteria based on assumed temperatures (Table 3 -Table *5*) are too strict and cannot be met by buildings with thermal insulation wrap or those with thermal break.

An analysis of historical temperature data for Zagreb revealed that the monthly average external temperature of – 10 °C is too low, leading to unrealistic f_{Rsi} criteria.

To address this issue, more realistic temperatures were obtained from historical data [41], and a temperature coefficient was calculated based on this information. Calculations were performed for each month of the year with monthly mean temperatures ($T_{e,mavg}$) to determine the critical factor value (Table 6).

The critical month for the selection is January, and the maximum allowable value of the temperature factor on the internal surface is $f_{Rsi, max}$ = 0.844.

Despite lowering the f_{Rsi} criterion values to $f_{Rsi, max}$ = 0.844, details with thermal insulation remain non-compliant with the f_{Rsi} > $f_{Rsi, max}$, condition indicating high risk of mould germination and condensation. In contrast, details incorporating thermal breaks satisfy the criteria due to the elevated surface temperature resulting from the thermal bridge interruption.

These models offer more realistic criteria, but the monthly time interval is excessive. Historical data indicates the presence of below-average temperatures lasting for several days or even weeks, along with extremely low temperatures that also need to be considered.

4.2. Isopleth model

EN ISO 13788 [38] accepts occasional, minor condensation on surfaces like bathroom windows and tiles. This is acceptable as long as the moisture does not soak into the material and measures are taken to prevent it from spreading to nearby materials that can be damaged by moisture.

Table 6. Calculation on the temperature factor on the inner surface (f_{Rsi})

Month	1	2	3	4	5	6	7
	$T_{e.mavg}$ [°C]	T_i [°C]	Rh_i [%]	p_i [Pa]	$p_{sat}(T_{si})$ [Pa]	$T_{si.min}$ [°C]	f_{Rsi} [-]
January	-1.2	20	65 %	1519	1899	16.7	0.844
February	2.3	20	65 %	1519	1899	16.7	0.813
March	7.4	20	65 %	1519	1899	16.7	0.737
April	12.7	20	65 %	1519	1899	16.7	0.546
May	16.8	20	65 %	1519	1899	16.7	-0.035
June	20.8	20	65 %	1519	1899	16.7	5.139
July	22.1	20	65 %	1519	1899	16.7	2.577
August	23.4	20	65 %	1519	1899	16.7	1.974
September	18.4	20	65 %	1519	1899	16.7	-1.070
October	12.6	20	65 %	1519	1899	16.7	0.553
November	8.9	20	65 %	1519	1899	16.7	0.702
December	2.0	20	65 %	1519	1899	16.7	0.816

As mentioned before, Glaser method has its drawbacks that need to be considered while dynamic hygrothermal models are available that provide much better insight in heat and moisture transfer that could determine water content in building materials. Temperatures and water content of materials across the cross section can then be used as inputs for spore germination and mould growth models.

Further analysis of 2D problems observed in this research is based on EN ISO 13788 [38] as a steady state, while the results will be plotted against existing spore germination and mould growth models.

The assumption accepted in this research is that the mould growth problems occur in winter period and that the absolute humidity is constant across the room, i.e. in the middle of the room and just besides the external wall. For example, in case of design conditions with a room air temperature of 20 °C and a relative humidity *Rh* = 60 %, when that air comes into contact with the colder thermal bridge, the air temperature near the bridge will drop to match the thermal bridge's surface temperature, while the absolute humidity (*A*h) remains constant independently of air temperature. However, as the air temperature cools down near the thermal bridge, Rh will off course increase. When Rh rises above certain point, it creates favourable conditions for mould growth and, in extreme cases, even condensation on the surface of the thermal bridge.

With known relative humidity (*Rh*), absolute humidity can be calculated according to equation (4) [54]:

$$Ah = \frac{6{,}112 \cdot e^{\left[\frac{17.67 \times T}{T + 243.5}\right]} \cdot Rh \cdot 2{,}1674}{273{,}15 + T} \text{ [g/m}^3\text{]} \quad (4)$$

Of course, the opposite is also valid, since warmer air can hold more moisture, if the relative humidity remains constant at i.e. 60 % when the temperature increases, the absolute humidity needs to rise.

Boundary conditions for internal air temperature is taken according to [38] which is considered to be heated and it equals to T_i = 20 °C. Also, cases with higher temperature air (22 °C and 24 °C) are also considered, while the relative humidity (Rh_i) remained constant.

To account for annual variations in external temperatures in Croatia, simulations were conducted for an arrange of representative winter conditions. Zagreb experiences occasional dips to -10 °C, but more typical winter temperatures are a bit higher. This temperature value represents the Zagreb's average winter daily air temperature for the period from 1991 to 2020 reduced by two standard deviations [41]. To be more precise, simulation is adjusted for range of temperatures that can also be applied to a wider range of Croatia and to more often experienced temperatures. Simulation is performed for external temperatures of -5 °C, 0 °C and 5 °C.

Current methods for calculating mould risk in walls (f_{Rsi}) rely on either constant conditions or monthly average humidity levels based on occupancy type.

To understand how building materials and surface condition influence mould growth, researchers [55] have proposed using isopleth systems in computer models. These isopleths would be applicable for two main categories of materials, based on data gathered from thermal bridge calculation. Results are shown for 2 substrate categories:

Category I: Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, material for permanent elastic joints [55];

Category II: Biologically adverse recyclable building materials such as renderings, mineral building material, certain wood as well as insulation material not covered by I [55].

Absolute humidity is calculated according to (4), assuming the air temperature of 20 °C, 22 °C, 24 °C and 60 % Rh. Based on the previously calculated absolute minimal surface temperature (Figure 36), Detail 5 emerged as the most critical detail for further investigation. Within Detail 5, Detail 5a (Figure 29) exhibited the lowest temperature, while Detail 5c (Figure 31) presented the most favourable outcome. Therefore, the analysis will focus on these two specific details.

Table 7 (Detail 5a) and Table 8 (Detail 5c) show the air and wall surface temperatures along with the corresponding relative humidity, for the given air temperature and humidity, where:

- Rh_i - relative humidity for internal air temperature
- Ah - absolute humidity of air for respective T_i and Rh_i
- $T_{si,min}$ - internal air temperature near wall surface acquired from numerical calculation of thermal bridges (Figure 29 and Figure 31)
- Rh_{si} - relative humidity of air near internal surface wall calculated for respective Ah and $T_{si,min}$.

Table 7. Temperatures and humidity data for thermal insulation wrapping case (Detail 5a)

Thermal insulation wrapping (5 cm)					
T_e [°C]	T_i [°C]	Rh_i [%]	Ah [g/m³]	$T_{si.min}$ [°C]	Rh_{si} [%]
-10	20	60	10.37	14.08	86
-5				15.07	81
0				16.05	76
5				17.04	72

Table 8. Temperatures and humidity data for thermal break case (Detail 5c)

Balcony with thermal break					
T_e [°C]	T_i [°C]	Rh_i [%]	Ah [g/m³]	$T_{si.min}$ [°C]	Rh_{si} [%]
-10	20	60	10.37	15.69	78
-5				16.40	74
0				17.11	71
5				17.84	68

Calculated data is combined with Sedlbauers [4] mould and fungi growth diagram, given results are shown on Figure 37. Data is plotted on a chart to assess whether the conditions are favourable for mould spore germination. Mould spores will only germinate if the temperature and Rh exceed a certain threshold in a sufficient continuous period in time. Once the germination occurs, the growth phase begins. Temperature and Rh data are plotted on a separate chart dedicated to mycelium growth. This chart allows determination of specific growth rate for each combination of temperature and humidity.

Charts show generalized isopleth system for spore germination which is valid for all fungi of hazardous class A (above) and B/C (below). Detailed explanation of the classes of fungi is provided in reference [4]. The Lowest Isopleth for Mould (LIM) indicates the minimum level of biological activity within mould hazard classification. The corresponding number of days represents the

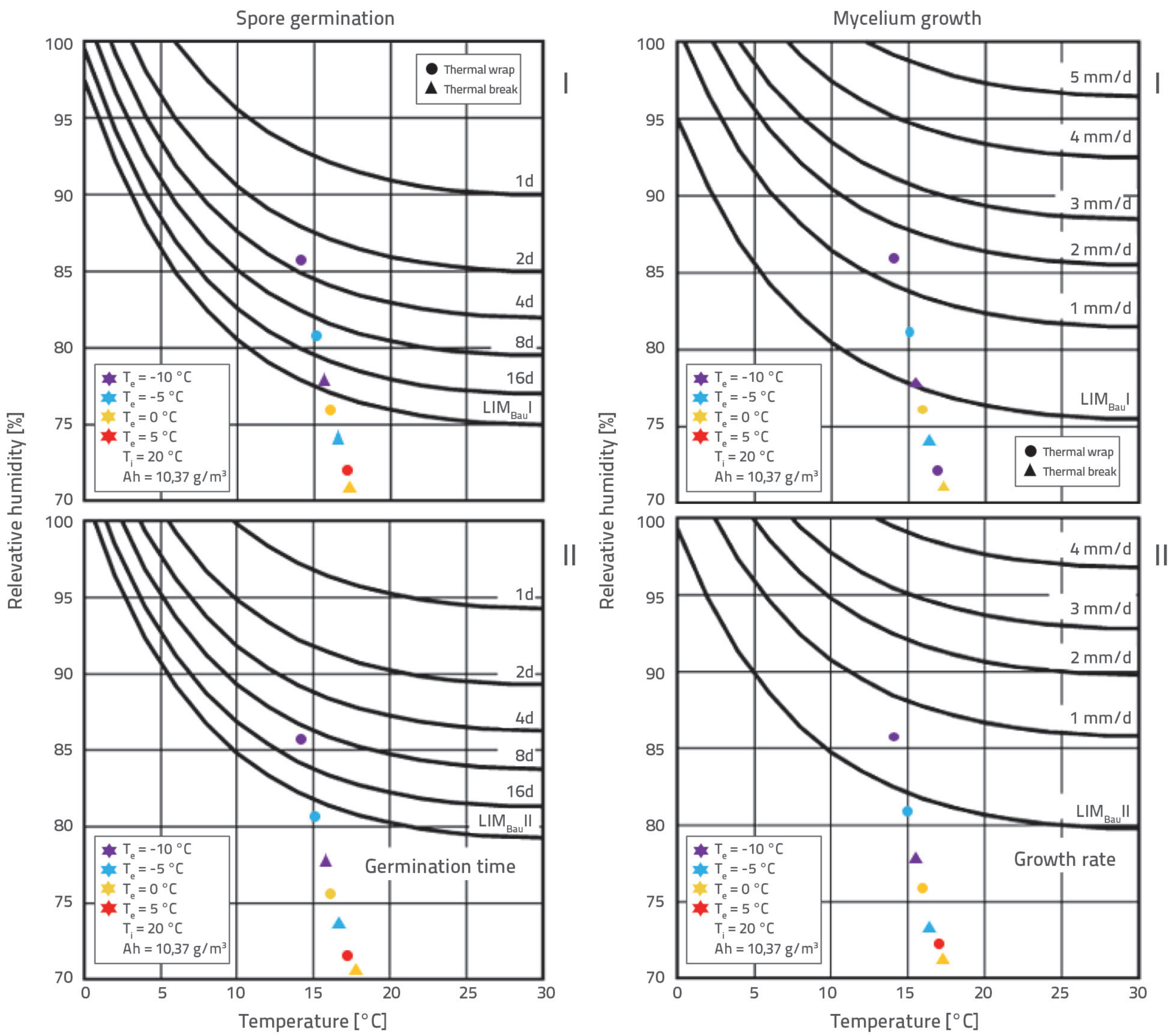

Figure 37. Spore germination and mycelium growth for details 5a and 5c

Table 9. Temperatures and humidity data for thermal insulation wrapping case (Detail 5a)

Thermal insulation wrapping (5 cm)					
T_e [°C]	T_i [°C]	Rh_i [%]	Ah [g/m³]	$T_{si.min}$ [°C]	Rh_{si} [%]
-10	22	60	11.65	15.86	86
-5				16.67	82
0				17.66	77
5				18.65	73

Table 10. Temperatures and humidity data for thermal break case (Detail 5c)

Balcony with thermal break					
T_e [°C]	T_i [°C]	Rh_i [%]	Ah [g/m³]	$T_{si.min}$ [°C]	Rh_{si} [%]
-10	22	60	11.65	17.39	78
-5				18.11	75
0				18.83	72
5				19.55	69

Table 11. Temperatures and humidity data for thermal insulation wrapping case (Detail 5a)

Thermal insulation wrapping (5 cm)					
T_e [°C]	T_i [°C]	Rh_i [%]	Ah [g/m³]	$T_{si.min}$ [°C]	Rh_{si} [%]
-10	24	60	13.06	17.29	89
-5				18.28	84
0				19.26	79
5				20.25	75

Table 12. Temperatures and humidity data for thermal break case (Detail 5c)

Balcony with thermal break					
T_e [°C]	T_i [°C]	Rh_i [%]	Ah [g/m³]	$T_{si.min}$ [°C]	Rh_{si} [%]
-10	24	60	13.06	19.10	80
-5				19.82	76
0				20.54	73
5				21.26	70

timeframe it takes for the first signs of mould growth to appear at that level [4]. The Lowest Isopleth for Mould (LIM) marks the minimum level of mould activity within a hazard class. The corresponding number in mm/d indicates the expected rate of mould growth at that level [4]. LIM is the theoretical line on which spore germination time is infinitely big or the growth rate is 0 mm/d.

The type of building material significantly impacts the type of microbes that can grow on it. Different microbes have specific requirements for water and nutrients.

Charts to follow (Figure 37 to Figure 39) show different mould development and speed of growth based on results presented in Table 7 and Table 8, visually illustrating the impact of different thermal bridge mitigation approach (represented by dots and triangles) and environment temperatures (distinguished by colours). Some evidence shows that water content is the most determining factor of microbial growth on building materials [8], but more research is needed in order to improve the understanding and predicting of microbial growth on building materials.

Calculated temperatures (Table 7 and Table 8) are higher than dew point temperatures, but mould fungi do not require liquid water in order to grow. It is visible from the results presented (Figure 37) that cases of thermal bridges where wrapping with thermal insulation was applied have a higher chance of mould and fungi growth. Figure 37 indicates spore germination will occur on details with 5 cm of thermal wrap when external temperatures are lower than -5 °C.

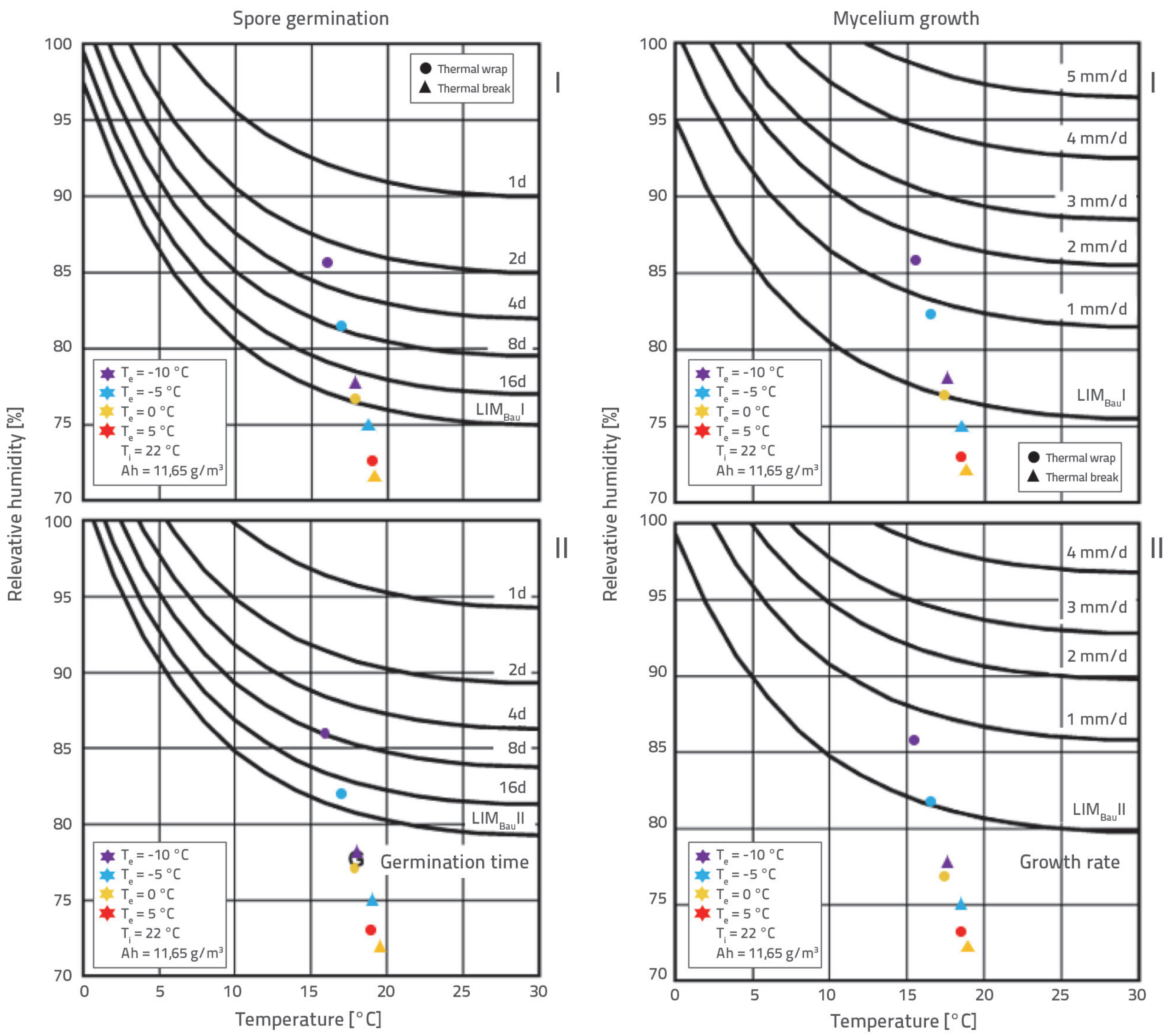

Figure 38. Spore germination and mycelium growth for details 5a and 5c

Details with thermal break are out of the danger and spore germination will not occur.

Researchers in study [56] have found limitations not covered by the Sedlbauer isopleth model. They have concluded that delays during unfavourable conditions might cause drying out the spores which is not included in the study. Germination and mould growth are by themselves a reason for concern, which should be prevented in the first place. According to Martens [57], continuous exposure to *Rh* of 55 % or lower for at least one month can kill active fungi.

For the same details as the upper analysis, another variation of previously shown boundary conditions is made. Internal air temperature is raised to 22 °C (Table 9., Table 10. and Figure 38) and 24 °C (Table 11., Table 12. and Figure 39). Maximum of 24 °C was selected in order to cover more homes.

With increased internal air temperature to 22 °C, chart shows bigger risk of spore germination. Cases with thermally insulated balcony slabs will have higher chance of spore germination and faster mycelium growth, especially when external temperatures lower than 0 °C. Increasing heating does not stop or slow down spore germination and mycelium growth. In example, 5 cm thick thermal insulation wrapping (Figure 38, purple dot) will be endangered with spore germination if the external air temperature is -10 °C and lasts for approx. 3 days and in these conditions continue, the mycelium growth rate will be 1.5 mm/day in case of category I substrate. On other hand, the case with thermal break (Figure 38, purple triangle) and same external conditions (-10 °C) and category I substrate, sits on the LIM isopleth which means that the spore germination time is infinitely big and mycelium growth is 0 mm/day.

It can be concluded from Figure 38 that details with thermal breaks have of course higher chance for spore germination and mould growth than the case with 20 °C but are still out of critical area but still out of danger.

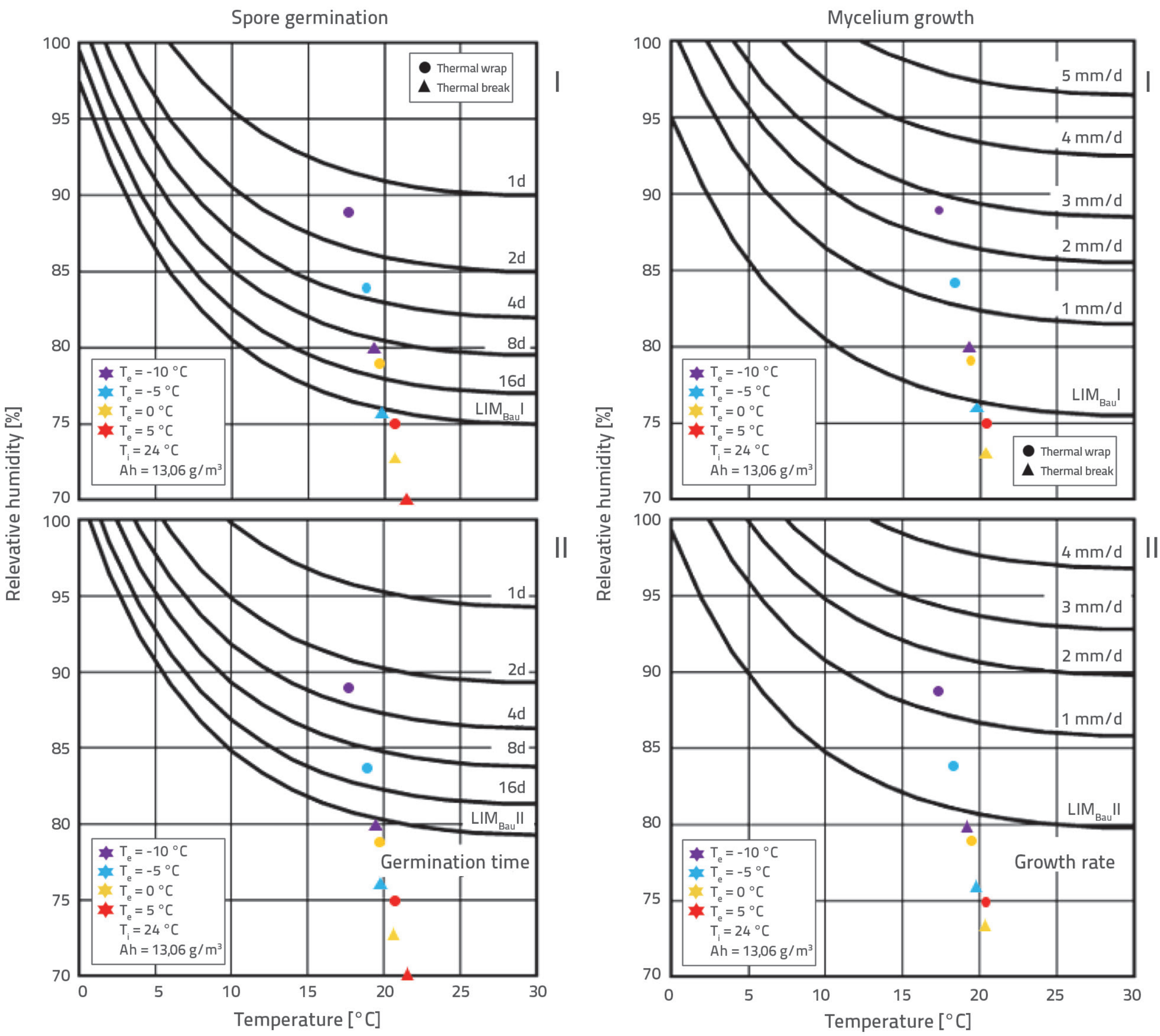

Figure 39. Spore germination and mycelium growth for details 5a and 5c

With the increase of internal air temperature, the trend of higher spore germination and mould growth risk continues to increase. In cases with 5 cm thermal insulation wrapping, spore germination will occur within a day and a half (Figure 39). Cases with thermal break also entered the critical area, but the time needed for spore germination is much longer, i.e. it takes between 8 and 16 days under the severe external conditions of -10 °C for spore germination in case of category I substrate. It is important to note that again all cases meet the requirements for minimum values of the f_{Rsi} factor showing that this factor alone is not sufficient enough to indicate spore germination.

5. Conclusion

This study investigates the impact of two thermal bridge mitigation approaches in continuous concrete balcony extensions: traditional thermal insulation wraps and a thermal break system. 2D computer simulation in CRORAL software was employed on five different balcony connection details, focusing on their effect on – values, inner surface wall temperatures and potential mould/fungi growth risk.

The superiority of thermal breaks over thermal wrap for thermal bridge mitigation is observed. While thicker insulation (cases with 10 cm) improved performance compared to cases with 5 cm, they still performed worse than thermal break details. Furthermore, increasing thermal wrap thickness beyond 5 cm can lead to inefficient material use and potential construction challenges.

The simulations revealed significant differences in surface temperature, particularly for details with slab and roof wall parapets (Detail 5a and 5c). the detail with insulation exhibited a 48 % higher Ψ– value and nearly 2 °C lower surface temperature compared to the thermal break detail. While both approaches f_{Rsi} met the threshold of 0.7, the impact of the 1.6 °C surface

temperature difference on spore germination and mycelium growth risk is explored.
Initially, a very strict criterion was established based on an extreme winter temperature of -10 °C.
However, even with various thermal bridge mitigation techniques employed, none of the cases met this requirement because the calculation relied on average month low temperatures, and -10 °C is unrealistically low for Zagreb.
A more realistic approach used the average monthly winter temperature of - 1.2 °C, resulting in revised criterion of 0.844. Even with this adjustment, thermally wrapped cases still failed to meet the criteria. However, cases with thermal breaks achieved compliance due to their higher surface temperatures.
Mold and fungi germination process does not require a whole month so shorter periods of time with favourable conditions also need to be considered as well as the element material.
Isopleth model considers material properties, surface temperature, relative humidity and time interval with favourable conditions for mould/fungi germination.
The variation with 5 cm insulation displayed high risk of mould/fungi growth during winter at standard temperature of 20 °C. Literature suggests residents are heating their homes to higher temperatures, but analysis shows rising air temperatures will only increase risk of mould/fungi growth. Thermal brake variation did not enter critical risk area until indoor air temperature was raised to 24 °C.
These findings suggest that value alone is insufficient to assess mould and fungi growth risk, particularly in scenarios with indoor temperatures higher than 20 °C. Standard boundary conditions are focused on water vapor condensation and are based on outdated Glaser method. Both mould/fungi growth risk and thermal bridge performance need to be considered during the design process in order to create healthier indoor environments.

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