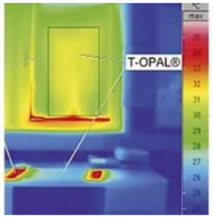
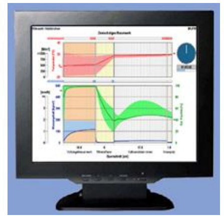
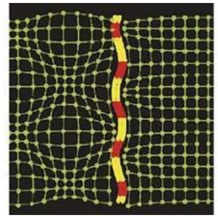




WUFI®

# Guideline for the Calculation of Pitched Roofs

## Date: December 2023

Fraunhofer
IBP

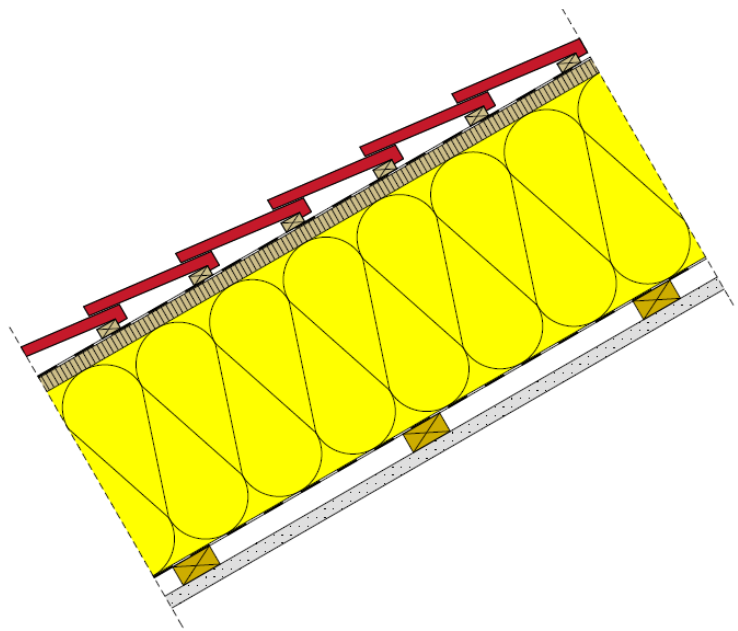
# Content

# Introduction

This guideline explains the procedure of the calculation and evaluation of pitched roofs with a vapour retarder applied on the whole interior surface.

In the first step all necessary input data and the evaluation criteria are described.

The procedure from input to evaluation is then explained using an example case.



# Notes on the Input: Component Assembly

## Component - Assembly/Monitor Positions

### *Roof Cladding with Tiles*

The ventilated roof cladding is replaced in the simulation by effective transfer parameters, e. g. according to Kölsch [1]. So, this is not modelled for the simulation.

### *Underlay / Weather Protection Membrane*

The underlay / weather protection membrane is also not included in the calculation as a component layer but is taken into account as an $s_d$-value in the surface transfer parameters. This leads to practically identical results, but speeds up the calculation significantly compared to taking the roofing membrane into account in the component structure.

### *Underlying Roof Assembly*

The underlying layers are to be entered according to the assembly in the cross section of the insulated cavity.

# Notes on the Input: Moisture Sources

## Component - Assembly/Monitor Positions

*Moisture Source – Infiltration (only needed for structures with wooden parts)*

According to EN 15026 [7], the amount of moisture which enters the construction by convection depending on the air tightness of the envelop always needs to be assessed for wooden structures. In the simulation it is considered using the IBP infiltration model.

The moisture source must be placed at the position in the model where the condensation water will form in practice – usually this is below of the second airtight layer on the cold side of the component.

For roof constructions we recommend the following settings:

- with wooden sheathing: moisture source in the interior 5 mm of the wooden sheathing
- without wooden sheathing: moisture source in the exterior 5 mm of the insulation layer

# Notes on the Input: Moisture Sources

## Component – Assembly/Monitor Positions

*Moisture Source – Infiltration (only needed for structures with wooden parts)*

The source strength is automatically determined depending on the overpressure due to the building's thermal buoyancy (temperature difference between outside and inside as well as specified air space height), the indoor air humidity and the specified airtightness of the building envelope [3].

For more information on using the infiltration source in WUFI®, click here: Guideline for Using the Air Infiltration Source in WUFI®

# Notes on the Input: Orientation / Inclination

## Component - Orientation

*Orientation*

The relevant orientation usually is North where the lowest radiation gains occur. Alternatively, the most unfavourable orientation of the building part can be used for specific projects.

*Inclination*

The inclination of the roof must be specified according to the planned roof inclination.

# Notes on the Input: Surface Transfer Coefficients

## Component – Surface Transfer Coefficients

*Heat Transfer Coefficient on the exterior surface*

The heat transfer coefficient is set according to the following tables (Kölsch [1]); the long-wave radiation parts of the heat transfer coefficients must be set to 0 W/m²K, as the radiation is calculated explicitly.

Usually „normal ventilated“ can be assumed!

| | |
|---|---|
| Strong ventilated | $a_{k,e}$ = 30 [W/m²K] |
| Normal ventilated | $a_{k,e}$ = 19 [W/m²K] |
| Low ventilated | $a_{k,e}$ = 13,5 [W/m²K] |

$a_{k,e}$: convective heat transfer coefficient

| | | | |
|---|---|---|---|
| Strong ventilated | Eaves open without any ventilation grid etc. | Ridge open with a low flow resistance | |
| Normal ventilated | Eaves openings with insect protection grid or eave comb | Ridge closed with ridge / arris role | |
| Low ventilated | Small openings at the eaves | Small openings at the ridge | No counter battens |

# Notes on the Input: Surface Transfer Coefficients

## Component – Surface Transfer Coefficients

*<u>$s_d$-value on the exterior surface</u>*

The underlay / weather protection membrane is considered as $s_d$-value in the surface transfer parameters, instead of modelling it as a layer.

Underlay membranes with $s_d$-values of less than 0.1 m are offered on the market. As this value may increase due to dust and deposits, the $s_d$-value of the underlay membrane should be set at a minimum of 0.1 m in the calculation according to the note in the German Standard DIN 4108-3, Annex A [4].

# Notes on the Input: Surface Transfer Coefficients

## Component – Surface Transfer Coefficients

*$s_d$-value on the exterior surface*

Note for constructions with absorbent underlay materials:

In the case of assemblies with exterior wooden sheathing, an additional $s_d$-value of 0.01 m must be applied to the external surface in order to avoid unrealistically high condensation on the substructure caused by the absence of roof tiles in the simulation.

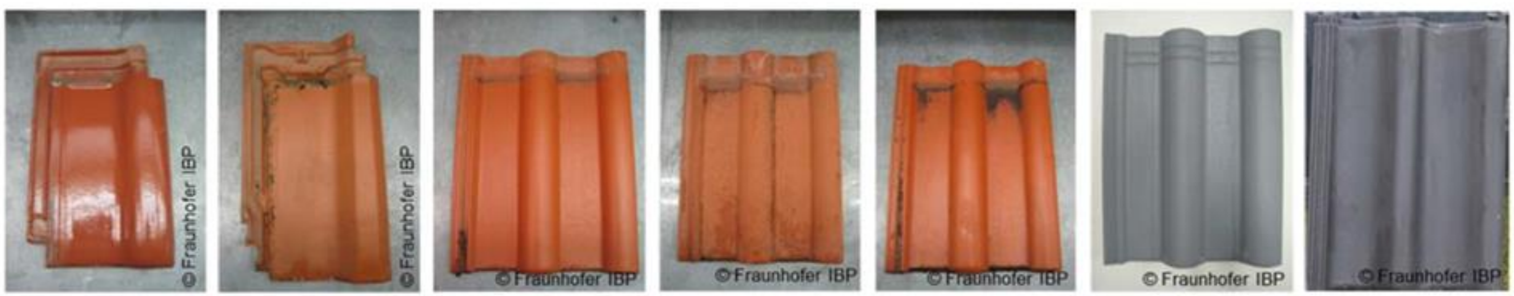
For a more detailed explanation, see Hygrothermal Simulation of ventilated pitched roofs with effective transfer parameters, chapter 8.

## Component – Surface Transfer Coefficients

### *Short-Wave Radiation Absorptivity*

The short-wave radiation absorptivity should be selected depending on the colour of the roof tiles (examples below or in right table) and, if necessary, be reduced according to Kölsch [1] (table on next slide).

| | |
|---|---|
| Red tiles | a = 0.67 – 0.78 |
| Grey tiles | a ~ 0.85 |
| Dark tiles | a = 0.9 – 0.94 |




| Red, high gloss glazed | Brick red | Light red, semi-matt | Light red, matt (weathered) | Natural clay red, matt | Light grey | Black |
|---|---|---|---|---|---|---|
| 0.72 | 0.74 | 0.75 | 0.76 | 0.78 | 0.85 | 0.94 |

# Notes on the Input: Surface Transfer Coefficients

## Component – Surface Transfer Coefficients

*Short-Wave Radiation Absorptivity*

The middle position can be used to evaluate typical conditions, especially if the coldest position (30 cm distance to the eaves opening) is still in the area of the roof overhang.

| | Coldest position | Middle position | Warmest position |
|---|---|---|---|
| Strong ventilated | $a_e = a \cdot 0.7$ | $a_e = a \cdot 0.9$ | $a_e = a$ |
| Normal ventilated | $a_e = a \cdot 0.7$ | $a_e = a \cdot 0.9$ | $a_e = a$ |
| Low ventilated | $a_e = a \cdot 0.75$ | $a_e = a \cdot 0.9$ | $a_e = a$ |

$a_e$: effective coefficient of absorption

Fraunhofer IBP

# Notes on the Input: Surface Transfer Coefficients

## Component – Surface Transfer Coefficients

### *Long-Wave Radiation Emissivity*

The long-wave radiation emissivity depends on the surface condition of the clay / concrete tiles and varies between 0.82 and 0.91.

| | |
|---|---|
| Clay tile, high closs clazed | ε ~ 0.82 |
| Clay tile, matt | ε ~ 0.84 |
| Concrete tile, in general | ε = 0.9 – 0.91 |

In order to take into account the (night-time) overcooling, the explicit radiation balance must always be switched on for roofs due to its large field of view to the sky.

### *Adhering Fraction of Rain*

The roofing is assumed to be waterproof, so the absorption of rainwater must be switched off.

Note: The setting for the $s_d$-value in the boundary condition only affects the diffusion behaviour of the surface and not the liquid water absorption.

# Notes on the Input: Initial Conditions

## Component – Initial Conditions

*<u>Initial Temperature and Moisture:</u>*

A constant initial relative humidity of 80 % and an initial temperature of 20 °C is recommended as a default setting.

If increased build-in moisture contents are known, these can be specified separately for the corresponding layer.

# Notes on the Input: Control

## Control

### *Calculation Period / Profiles:*

It is recommended to start the calculation on October 1st, because the component usually moistens up further in the following winter months before drying to the inside possibly starts in spring. This start date is therefore usually an extra stressing of the component.

The calculation time depends on the time the construction needs to reach steady state conditions. Usually, a calculation time of 5 years is sufficient. In the case of diffusion-open building components, the calculation times tend to be shorter, in the case of diffusion-tight building components, the calculation times tend to be longer.

### *Numerics:*

For the numerical settings, default values can be used.

# Notes on the Input: Climate

## Climate

<u>*Outdoor Climate:*</u>

A climate appropriate for the location of the building should be used.

For Germany:

The hygrothermal reference years (HRY), which were created for 11 locations in Germany as part of a research project [5], are useful here. These locations are representative for the respective climate region. For more information, please refer to the
*WUFI® Help (F1) → Topic: Hygrothermal Reference Years*

The Holzkirchen location is considered critically representative for Germany for many application fields. However, especially when evaluating roofs, locations with less radiation may cause more unfavorable conditions.

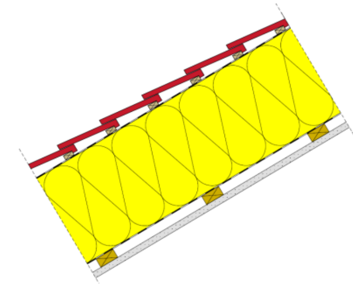
# Notes on the Input: Climate

## Climate

*Indoor Climate:*

By default, we recommend to use the indoor climate with medium moisture load + 5% for design purposes according to German Standard DIN 4103-3 Appendix D [4], EN 15026 [7] and WTA Guideline 6-2 [6].

# Notes on the Evaluation: Mineral Wool Insulation



*<u>Roofs with mineral wool insulation and underlay membrane</u>*

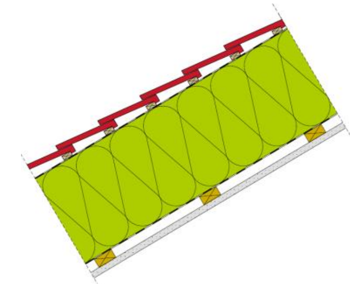
These assemblies do not have any moisture-sensitive materials in the standard cross-section (insulated cavity). Below the roofing felt, due to the higher diffusion resistance compared to the insulation, temporarily increased moisture or condensation may occur.

The amount of condensation occurring below the roofing felt is used for result evaluation. For this purpose, the maximum water content in [kg/m³] in the outer area of the mineral wool insulation is evaluated. A distinction is made here between insulation materials with an internal moisture storage function and those with a measured moisture storage function. For more detailed information, please refer to the <u>Guideline for assessing condensation problems in hydrophobic material fiber</u>.

As a general limit value, the condensation water quantity of 200 g/m² specified in EN ISO 13788 [8] is recommended (conversion required). Above this quantity, there is a risk of condensation running off.

# Notes on the Evaluation: Wood Fibre Insulation

*Roofs with wood fibre insulation and underlay membrane*



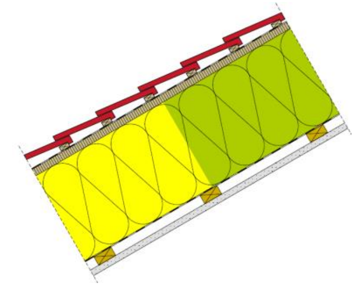
For assemblies with wood fibre insulation between the rafters, an evaluation of the wood moisture in the wood fibre insulation is performed.

For this purpose, the wood moisture content is evaluated in [% by mass] in the outer centimeter of the wood-fiber insulation in the settled state. The settled stage has reached if the course of the water content does not change inbetween the years any longer.

For evaluation purposes, the general limit value of 18 % by mass from DIN 68800 [2] can be used, which may be exceeded by a maximum of 20 % by mass for up to three months a year. Alternatively, the manufacturer can guarantee the maximum moisture content for which his product can be used.

# Notes on the Evaluation: Wooden Sheathing

*Roofs with insulation and wooden sheathing*

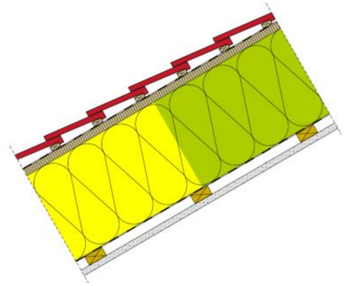


For assemblies with exterior wooden sheathing, the insulation between the rafters (mineral wool or wood fibre) is evaluated according to slide 18+19.

For the evaluation of the wooden sheathing, the course of the wood moisture content in [% by mass] in the wooden sheathing in the settled state is used. The value of 20 % by mass for wood and 18 % by mass for wood-based materials specified in DIN 68800 [2] is recommended as the limit value. If this limits are kept, no further evaluation is necessary.

If the wood moisture exceeds the limit value according to DIN 68800 [2], an evaluation according to the WTA Guideline 6-8 [9] also can be carried out for solid wood. This allows a more precise evaluation considering the temperature and humidity conditions.

# Notes on the Evaluation: Wooden Sheathing



*Roofs with insulation and wooden sheathing*

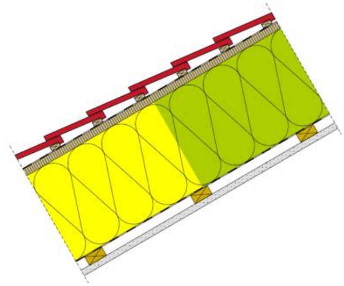
Evaluation according to DIN 68800 [2]

Critical moisture conditions regarding damage to the wood can occur, if the moisture content limits of 20 % by mass for wood and 18 % by mass for wood-based materials are exceeded over a long period.

However, this limit value includes high safety margins and, in contrast to the WTA guideline 6-8 [9], no specifications are made for the evaluation area. In the case of thin wooden sheathings, the entire section of the sheathing shall be evaluated, otherwise the most critical 1 cm thick section should be used in accordance with the WTA evaluation.

If the wood moisture remains below the limit values (see above), no further evaluation is necessary.

# Notes on the Evaluation: Wooden Sheathing



*Roofs with insulation and wooden sheathing*

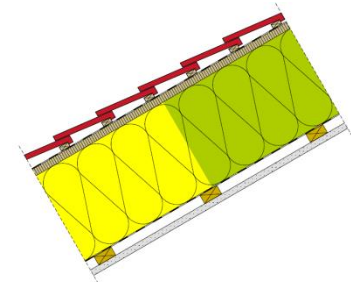
Evaluation according to WTA Guideline 6-8 [9]

If the limit value for wood of 20 % by mass according to DIN 68800 [2] is exceeded, also an evaluation according to the WTA 6-8 [9] can be carried out. Here, the evaluation of wood structures is carried out based on temperature-dependent limit values for the relative pore air humidity in a 1 cm thick layer at the critical position of the wood. This allows a more accurate and realistic evaluation.

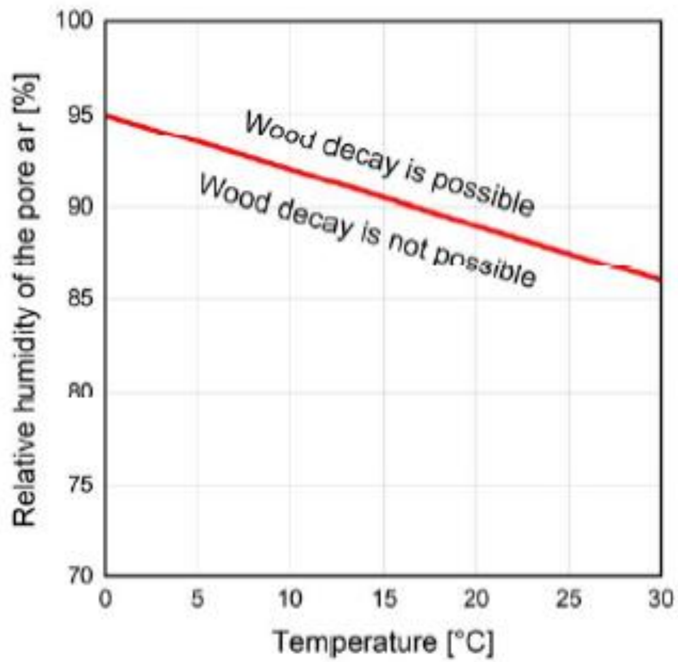
Please note: This evaluation can not be used for wood-based materials, as other limit values for rotting processes may apply here.

# Notes on the Evaluation: Wooden Sheathing

*Roofs with insulation and wooden sheathing*



Limit curve for wood decay depending on temperature (x-axis) and relative humidity (y-axis) according to WTA 6-8 [9].
At conditions below the red limit line, wood decay is not possible in solid wood.



# Literature


[1] Kölsch, Ph.: Hygrothermal simulation of ventilated pitched roofs with effective transfer parameters. 01/2017. (Guideline for the simulation of ventilated pitched roofs with effective transfer parameters)

[2] DIN 68800-2: Holzschutz – Teil 2: Vorbeugende bauliche Maßnahmen im Hochbau. Beuth Verlag, February 2022.

[3] Zirkelbach, D.; Künzel, H.M.; Schafaczek, B. und Borsch-Laaks, R.: Dampfkonvektion wird berechenbar – Instationäres Modell zur Berücksichtigung von konvektivem Feuchteeintrag bei der Simulation von Leichtbaukonstruktionen. Proceedings 30. AIVC Conference, Berlin 2009.

[4] DIN 4108-3: Klimabedingter Feuchteschutz, Anforderungen, Berechnungsverfahren und Hinweise für Planung und Ausführung. Beuth Verlag, October 2018.

[5] Research Report: Energieoptimiertes Bauen: Klima- und Oberflächenübergangsbedingungen für die hygrothermische Bauteilsimulation. IBP-Bericht HTB-021/2016. Durchgeführt im Auftrag vom Projektträger Jülich (PTJ UMW). July 2016.

[6] WTA Guideline 6-2/E: Simulation of heat and moisture transfer. December 2014.

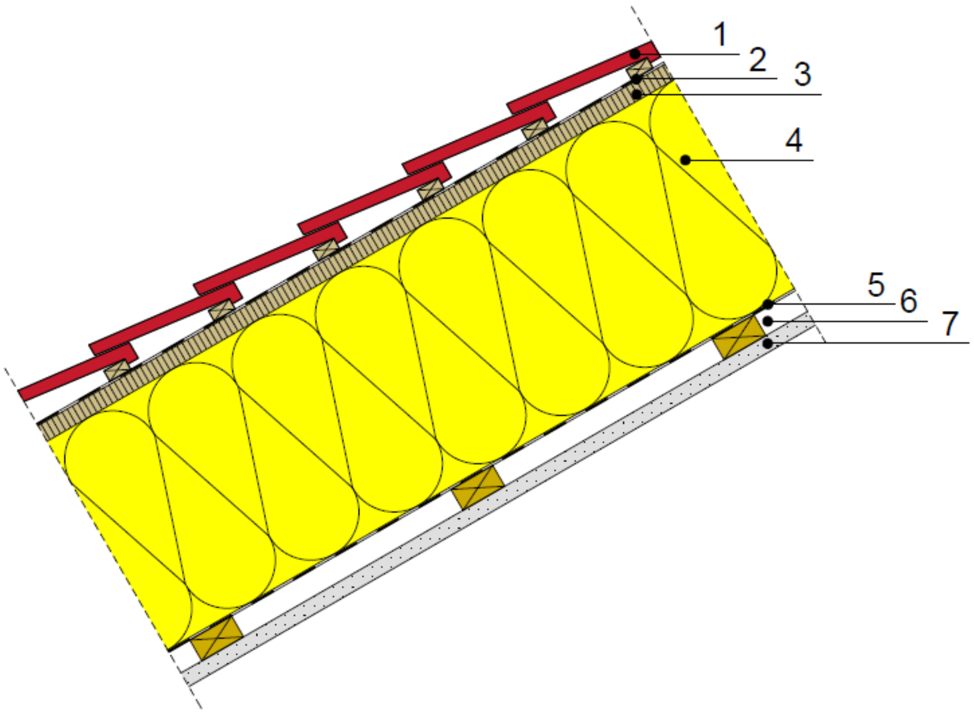
[7] EN 15026: Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation. Beuth Verlag, December 2023.

[8] EN ISO 13788: Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods. Beuth Verlag, May 2013.

[9] WTA Guideline 6-8: Feuchtetechnische Bewertung von Holzbauteilen – Vereinfachte Nachweise und Simulationen. August 2016.

# Example: Pitched Roof with Mineral Wool and Wooden Sheathing

Based on the example of a pitched roof with mineral wool insulation and wooden sheathing, the procedure for the input and the evaluation is described.




1 Roofing and Battens
2 Weather Protection Membrane
3 Wooden Sheathing
4 Insulation
5 Vapour Retarder
6 Installation Layer
7 Gypsum Board

# Example: Assembly

*Assembly (from outside to inside):*

| | | |
|---|---|---|
| • Red Concrete Tiles | | |
| • Weather Protection Membrane ($s_d$ = 0.01 m) | | |
| • Wooden Sheathing (Softwood) | 0.025 | m |
| • Mineral Wool (heat cond.: 0.04 W/mK) | 0.24 | m |
| • Moisture-Variable Vapour Retarder (Intello Plus) | 0.001 | m |
| • Air Layer | 0.02 | m |
| • Gypsum Board | 0.0125 | m |

# Example: Boundary Conditions

*Boundary Conditions:*

- Pitched roof (30° to the North)
- Red concrete tiles
  (a = 0.67; ε = 0.9)
- Normal ventilated roof (middle position)
- Outdoor climate: Holzkirchen
- Indoor climate: medium moisture load + 5 %
  according to EN 15026
- Air tightness of the envelope: $q_{50}$ = 3 m³/m³h
- Stack Height: 5 m

# Example: Evaluation Matrix

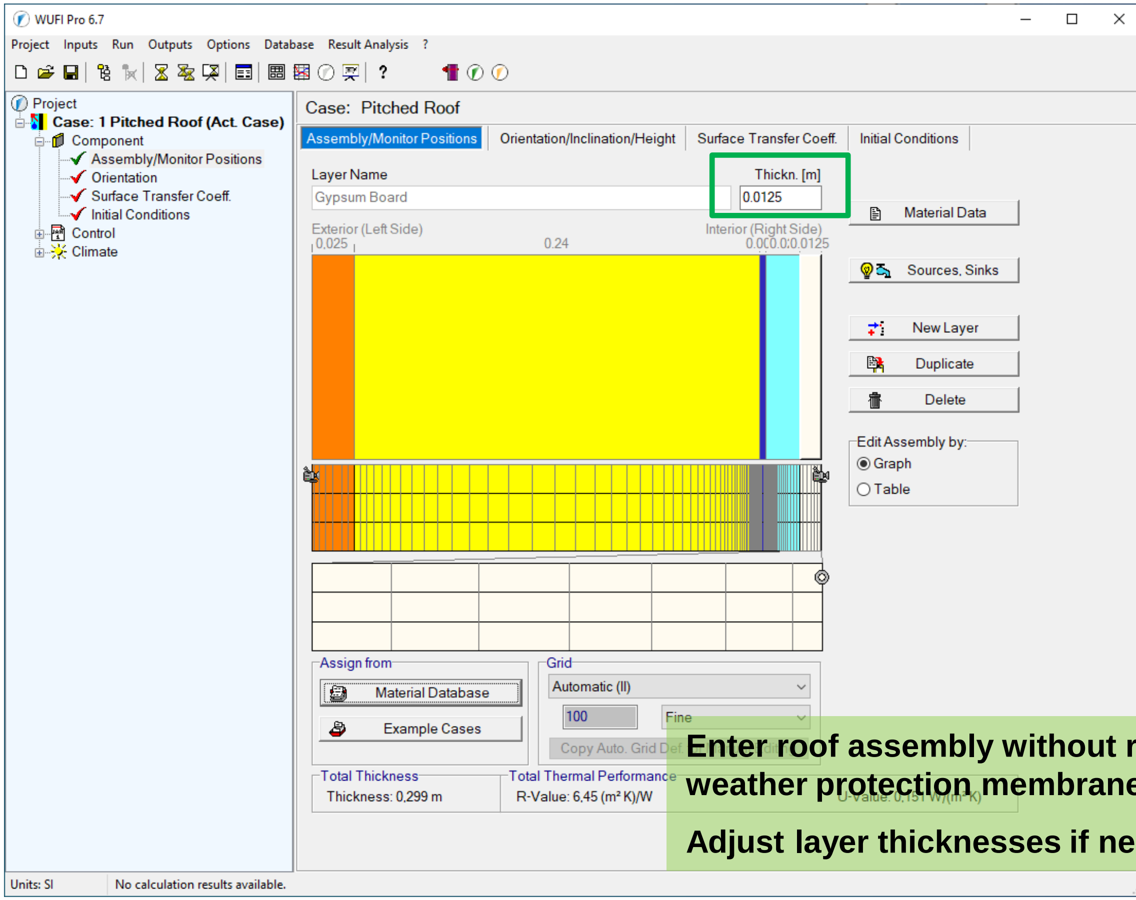
*Evaluation Matrix:*

The following matrix shows the evaluation criteria relevant to this design.

| | **Criteria** |
|---|---|
| 1) Numerics | Low balance differences? |
| | Few or no convergence failures? |
| 2) Evaluation parameters | Total water content settled? |
| | Amount of condensation in the insulation layer? |
| | Risk of wood decay in the wooden sheathing?<br>(limit values according to DIN 68800-3 or WTA 6-8) |

# Example: Input – Component Assembly

*Input:* Component - Assembly / Monitor Positions



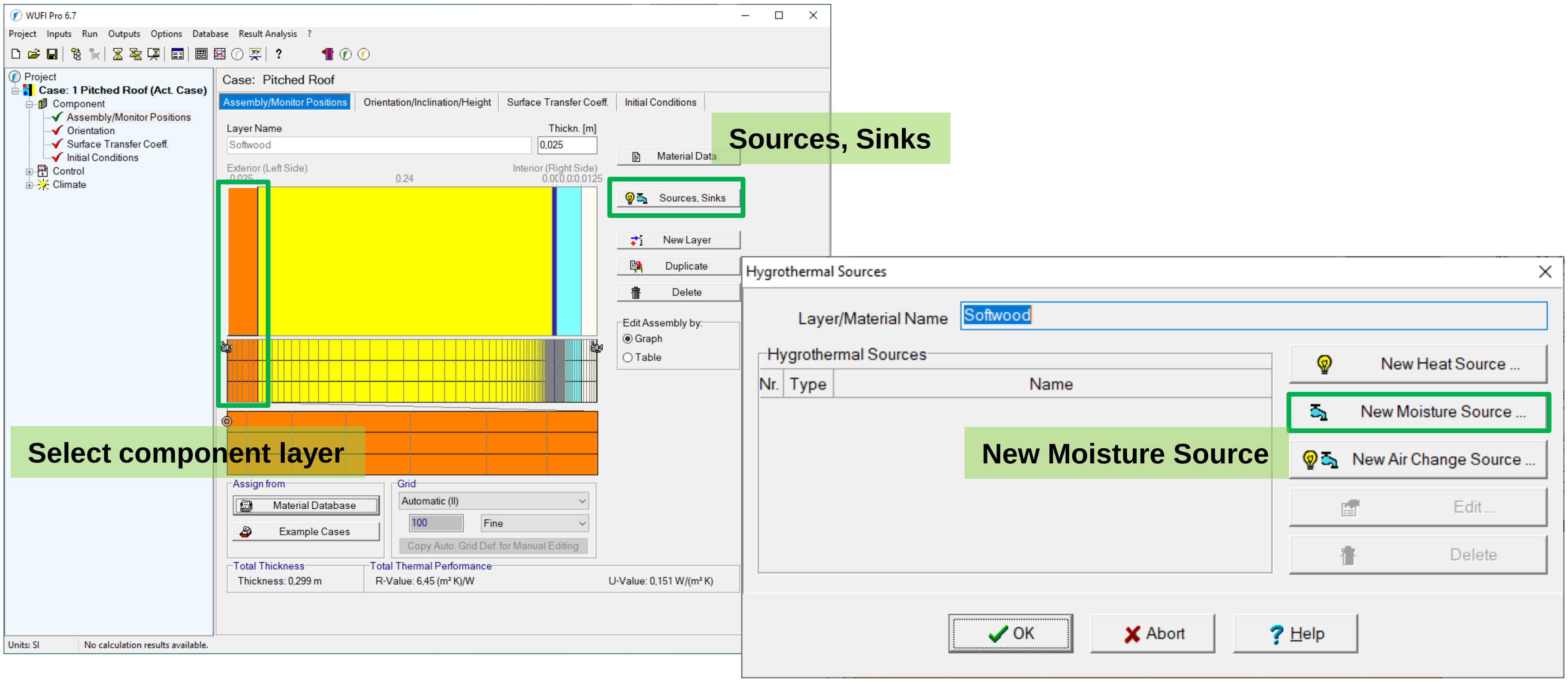

**Enter roof assembly without roofing tiles and weather protection membrane**

**Adjust layer thicknesses if necessary**

# Example: Input - Infiltration Source

*Input:* Component - Assembly / Monitor Positions

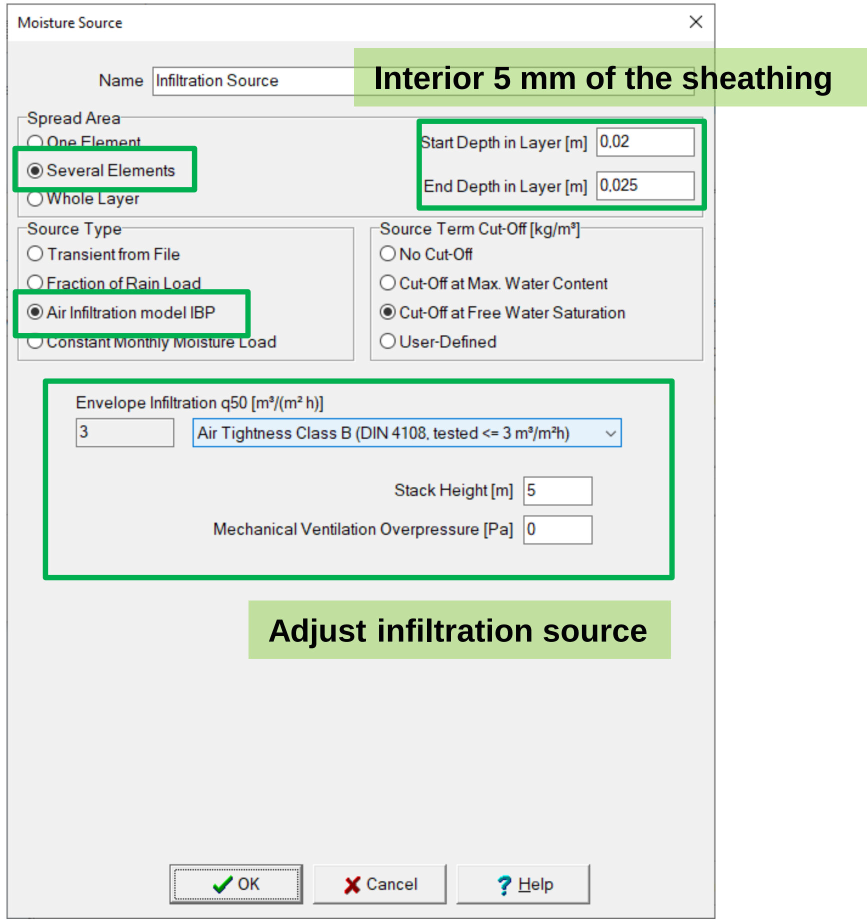
Infiltration source in the wooden sheathing according to EN 15026.



# Example: Input - Infiltration Source

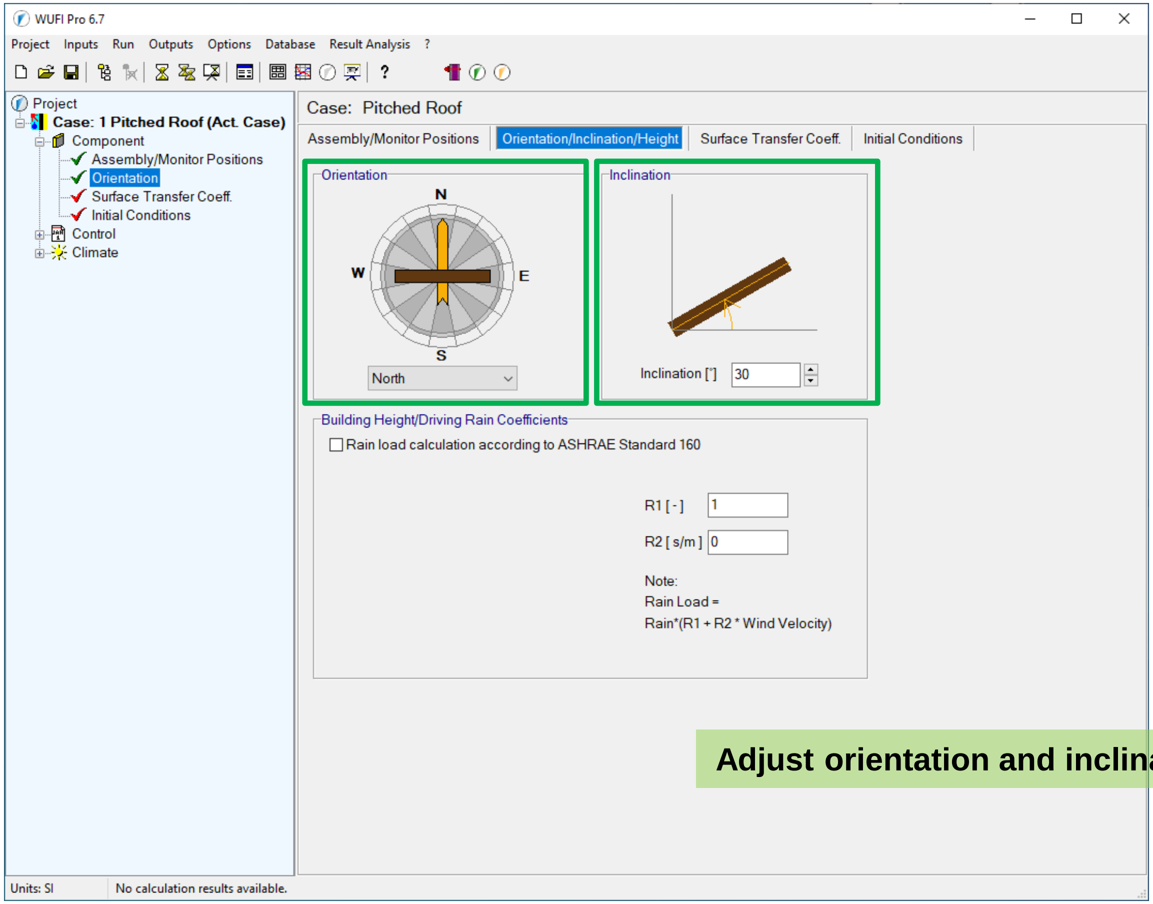
*<u>Input:</u>* Component - Assembly / Monitor Positions

Moisture Source in the interior 5 mm of the wooden sheathing.



# Example: Input – Orientation / Inclination

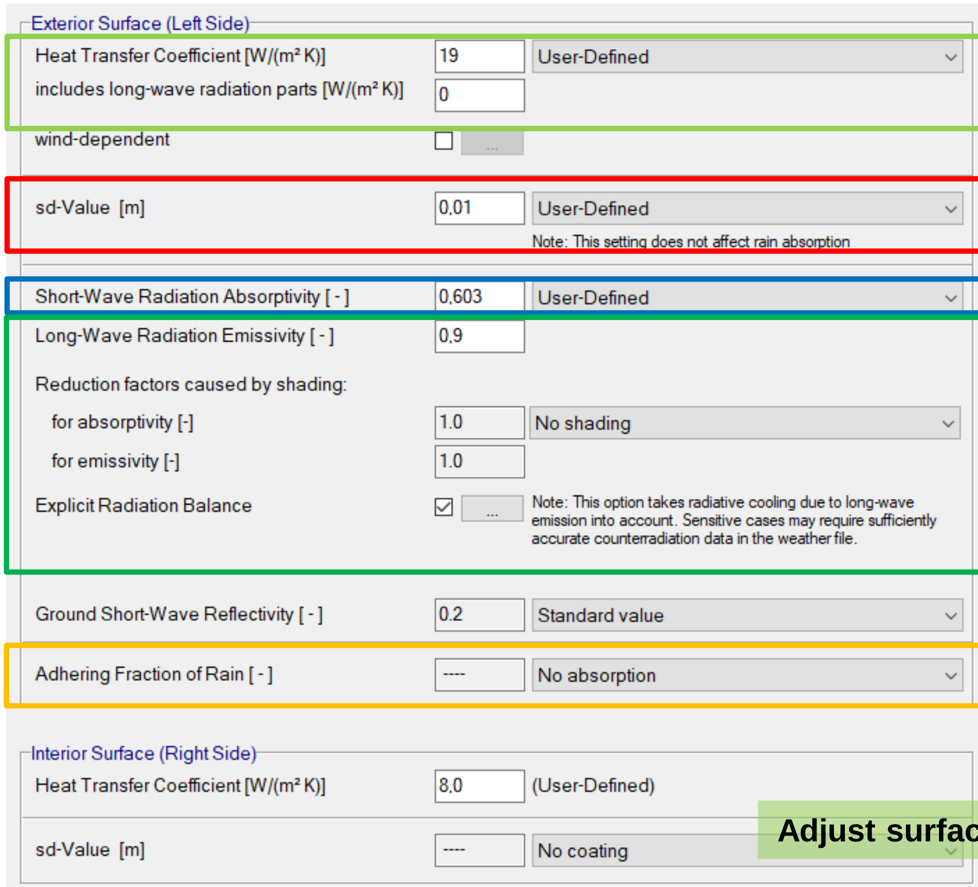
*Input:* Component - Orientation




Adjust orientation and inclination

# Example: Input - Surface Transfer Coefficients

*<u>Input:</u>* Component – Surface Transfer Coeff.




**Heat Transfer Coefficient**
**für a normal ventilated roof = 19 W/m²K**
**Note: long-wave radiation parts set to 0!**

**$s_d$-value of the weather protection membrane**

**Colouring of the roofing for middle position**
**($a_e$ = a · 0.9 = 0.67 · 0.9 = 0.603)**

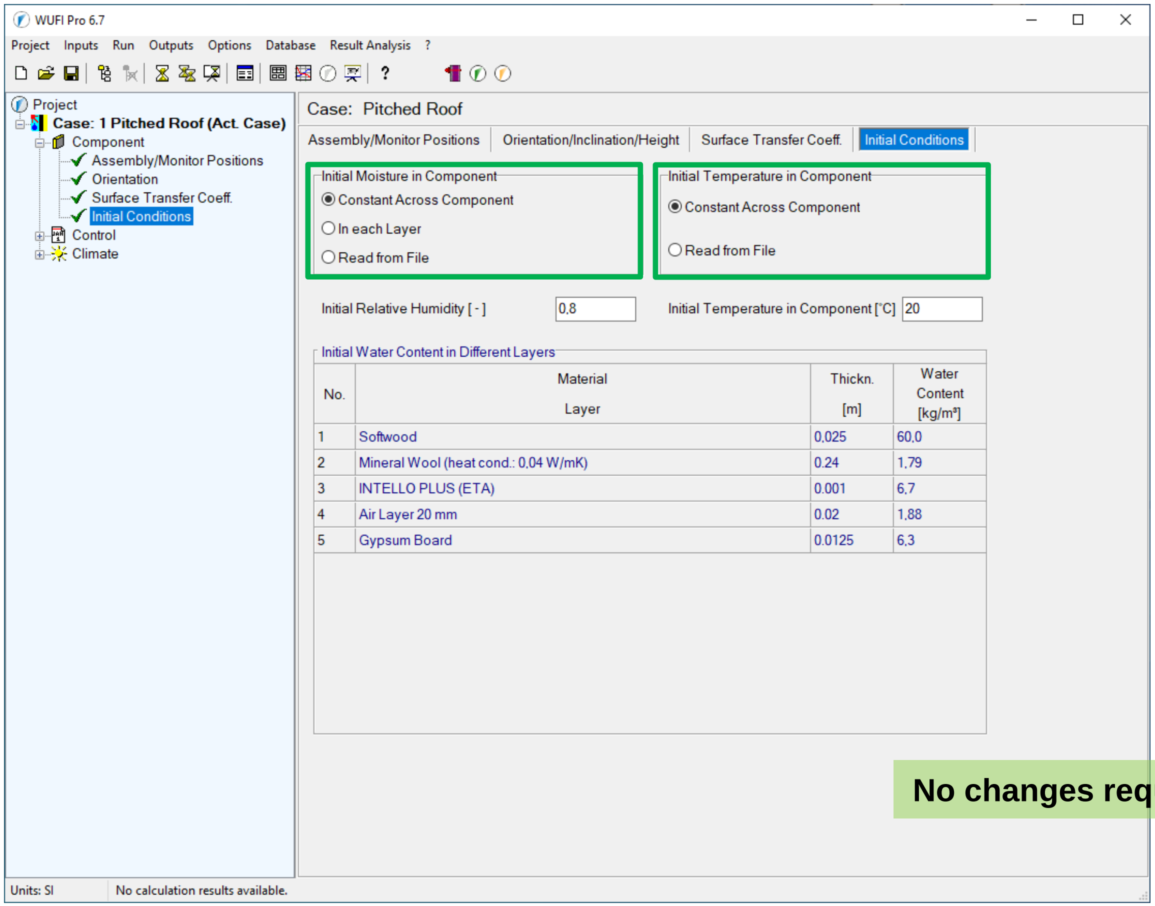
**Use Explicit Radiation Balance (ε = 0.9)!**
**No shading**

**No Rain Water Absorption!**

**Adjust surface transfer coefficients!**

# Example: Input - Initial Conditions

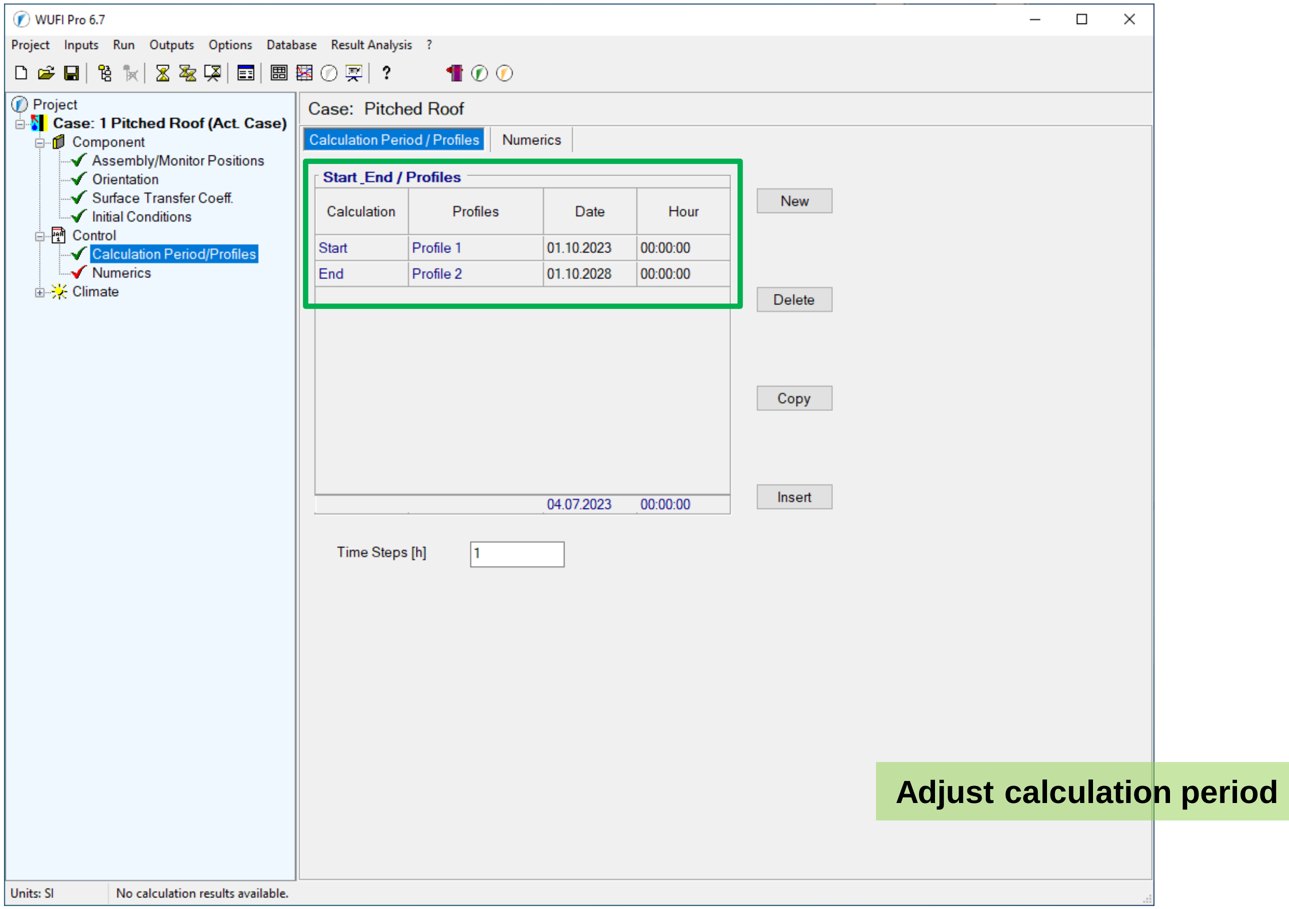
*Input:* Component – Initial Conditions




**No changes required**

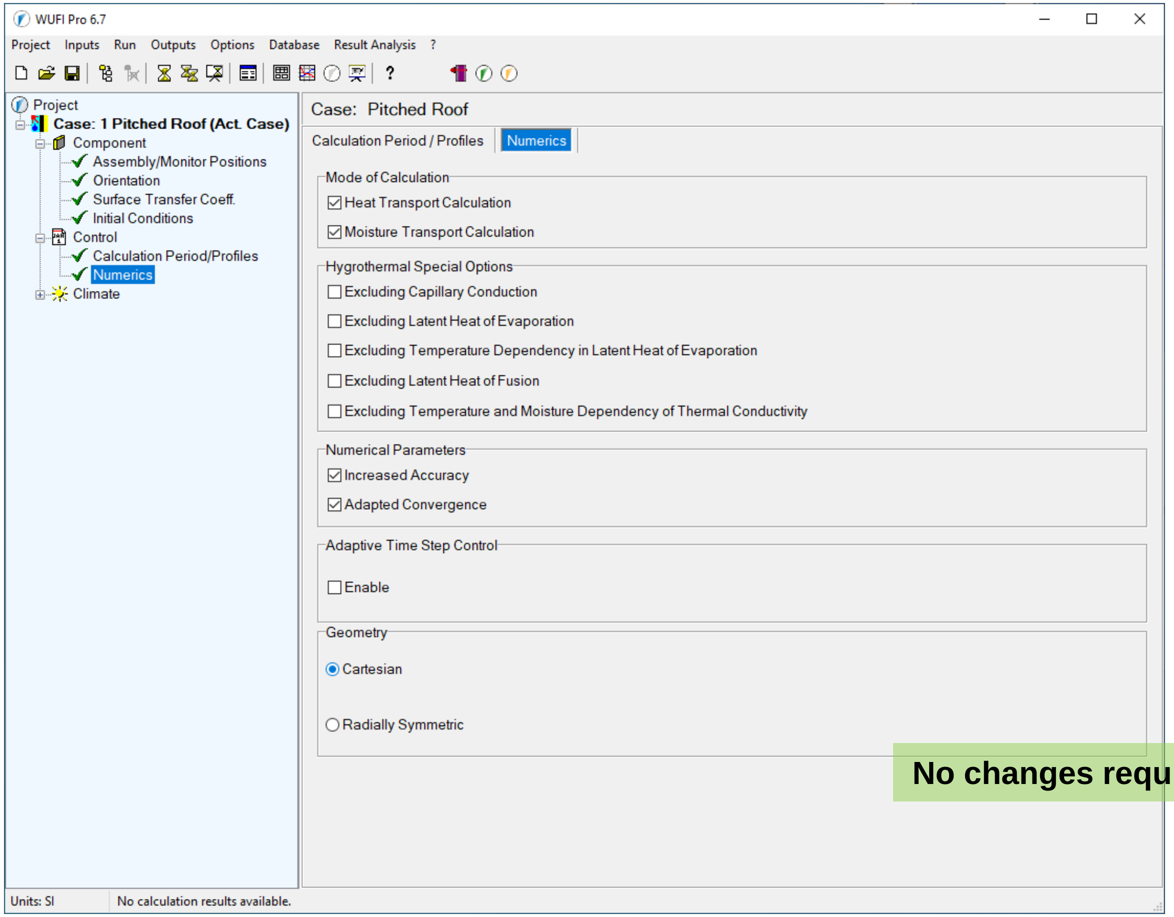
# Example: Input - Calculation Period

*Input:* Control – Calculation Period / Profiles



# Example: Input - Numerics

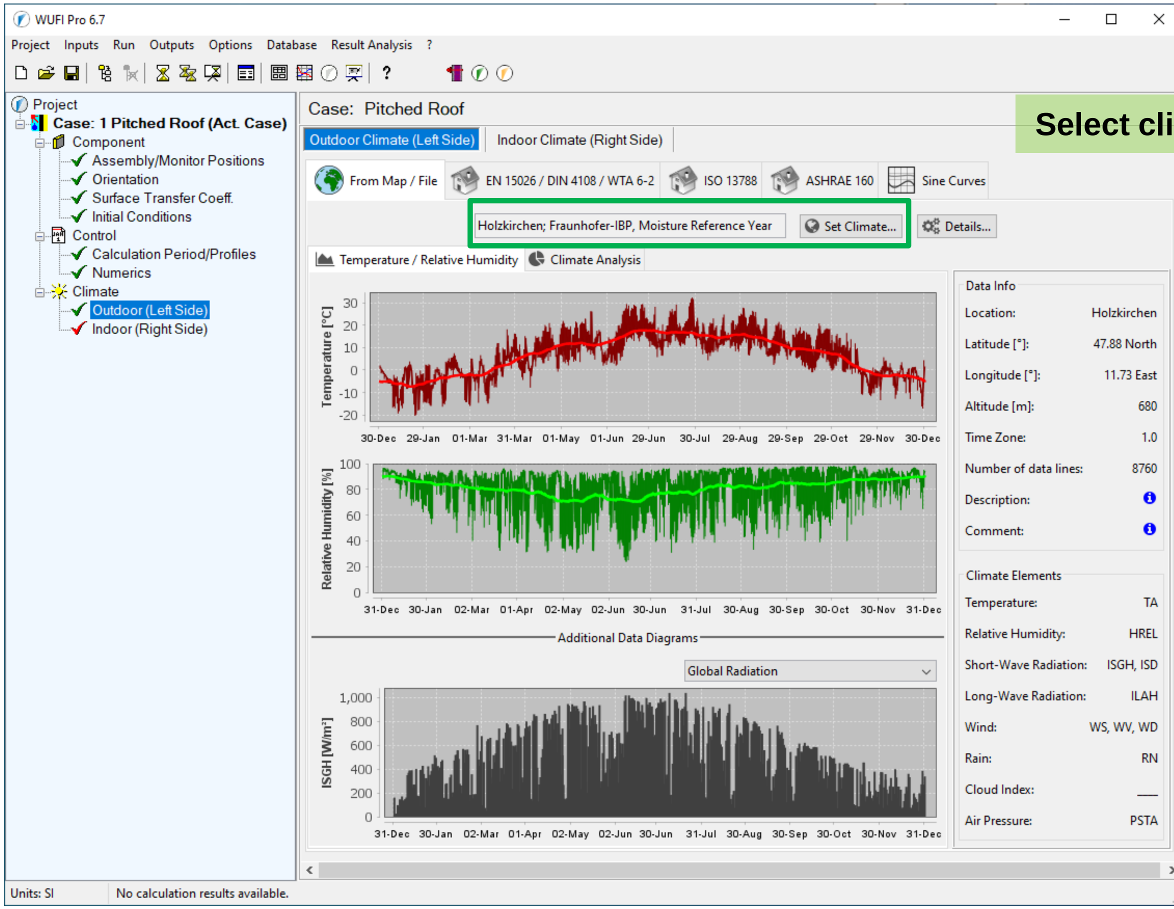
## *Input:* Control – Numerics




**No changes required**

# Example: Input - Outdoor Climate

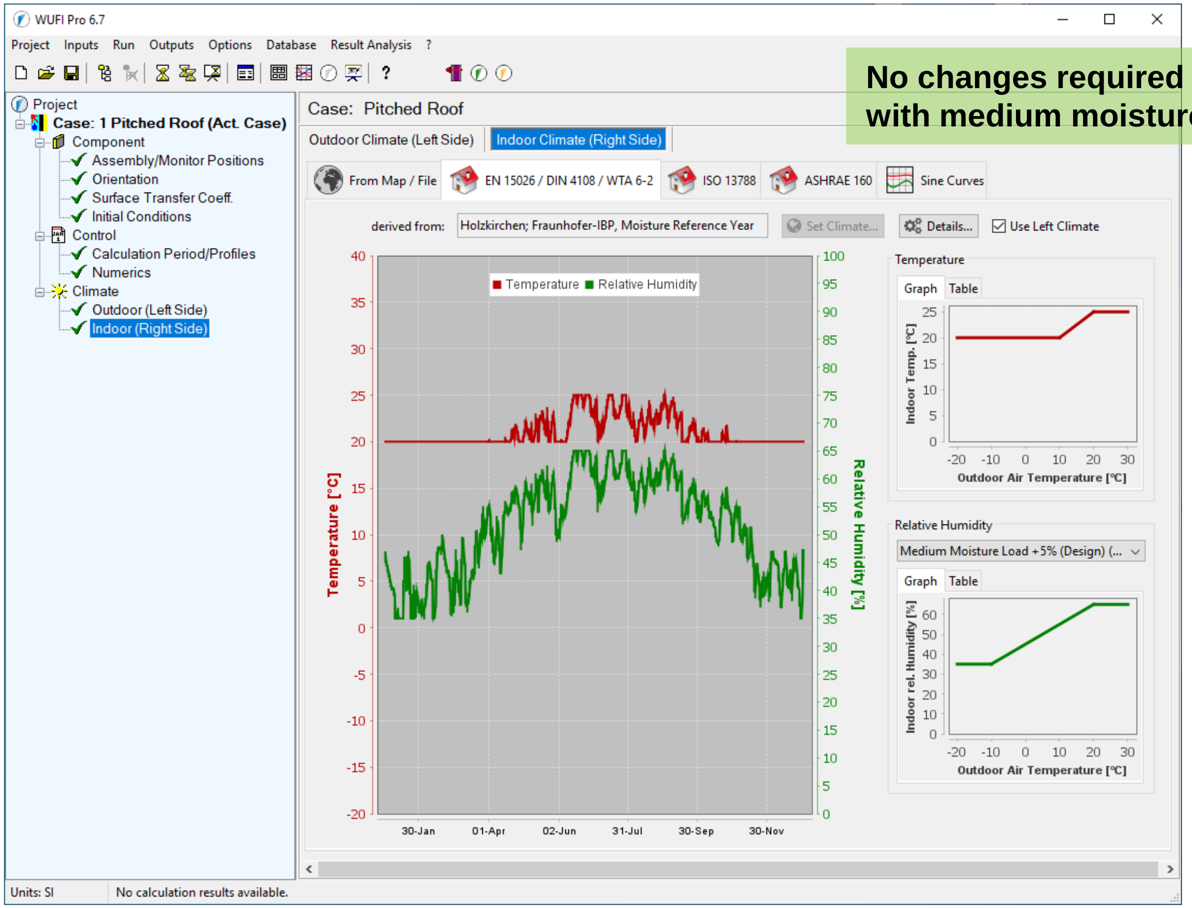
*Input:* Climate – Outdoor (Left Side)




Select climate file

# Example: Input - Indoor Climate

*Input:* Climate – Indoor (Right Side)



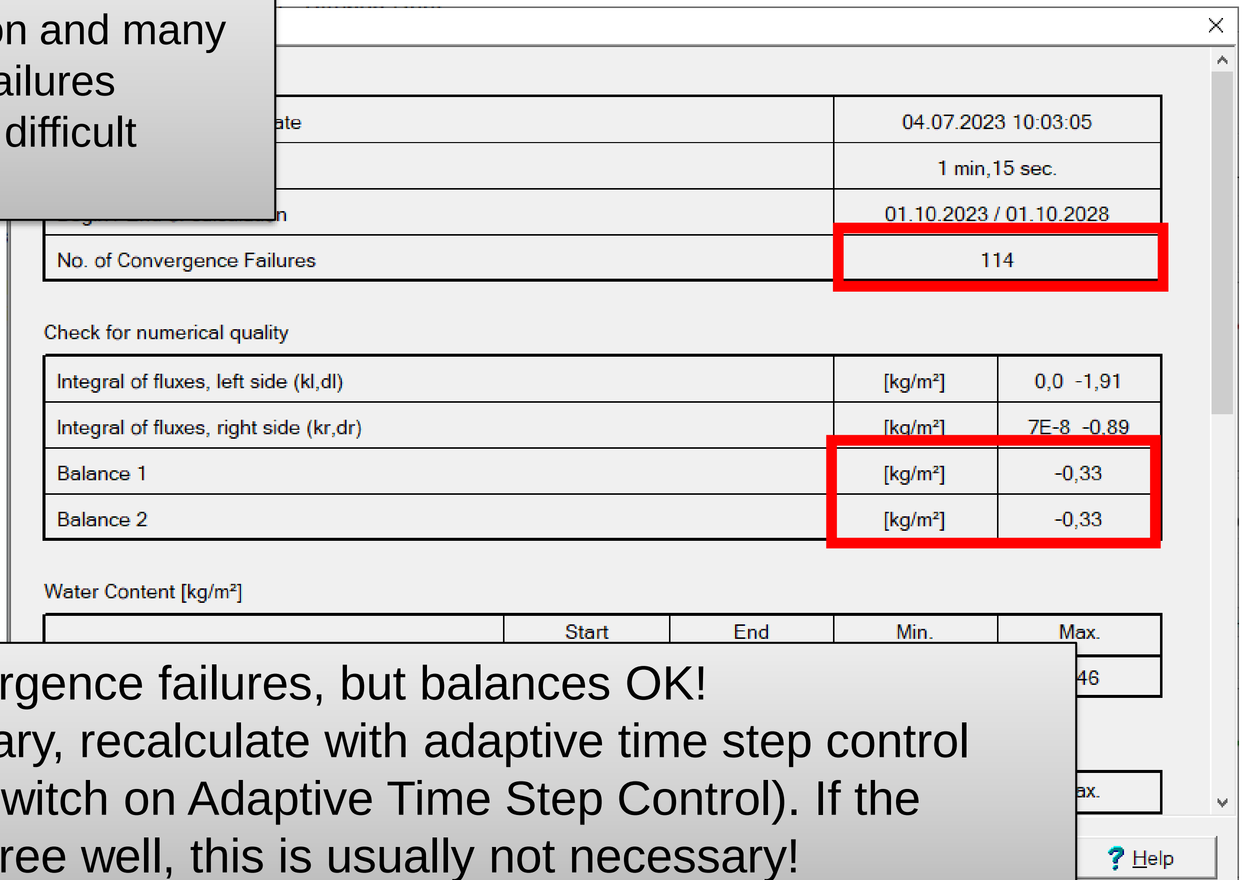

**No changes required for indoor climate with medium moisture load + 5 %**

# Example: Evaluation – Numerics

*__Evaluation:__* Numerics

For more information on the evaluation of the numerical quality, see "[Guideline for the Evaluation and Assessment of hygrothermal Calculation Results]".

__Note:__
Slow calculation and many convergence failures indicate rather difficult convergence.




Many convergence failures, but balances OK!
→ if necessary, recalculate with adaptive time step control (numerics: switch on Adaptive Time Step Control). If the balances agree well, this is usually not necessary!

# Example: Evaluation – Numerics

*Evaluation:* Numerics – with Adaptive Time Step Control

Status of Last Calculation

Status of Calculation

| | |
|---|---|
| Calculation: Time and Date | 04.07.2023 10:18:04 |
| Computing Time | 1 min,23 sec. |
| Begin / End of calculation | 01.10.2023 / 01.10.2028 |
| No. of Convergence Failures | 0 |

Check for numerical quality

| | | |
|---|---|---|
| Integral of fluxes, left side (kl,dl) | [kg/m²] | 0,0 -1,91 |
| Integral of fluxes, right side (kr,dr) | [kg/m²] | 7E-8 -0,9 |
| Balance 1 | [kg/m²] | -0,33 |
| Balance 2 | [kg/m²] | -0,33 |

Water Content [kg/m²]

| | Start | End | Min. | Max. |
|---|---|---|---|---|
| Total Water Content | 2,05 | 1,74 | 1,27 | 2,45 |

| Min. | Max. |
|---|---|

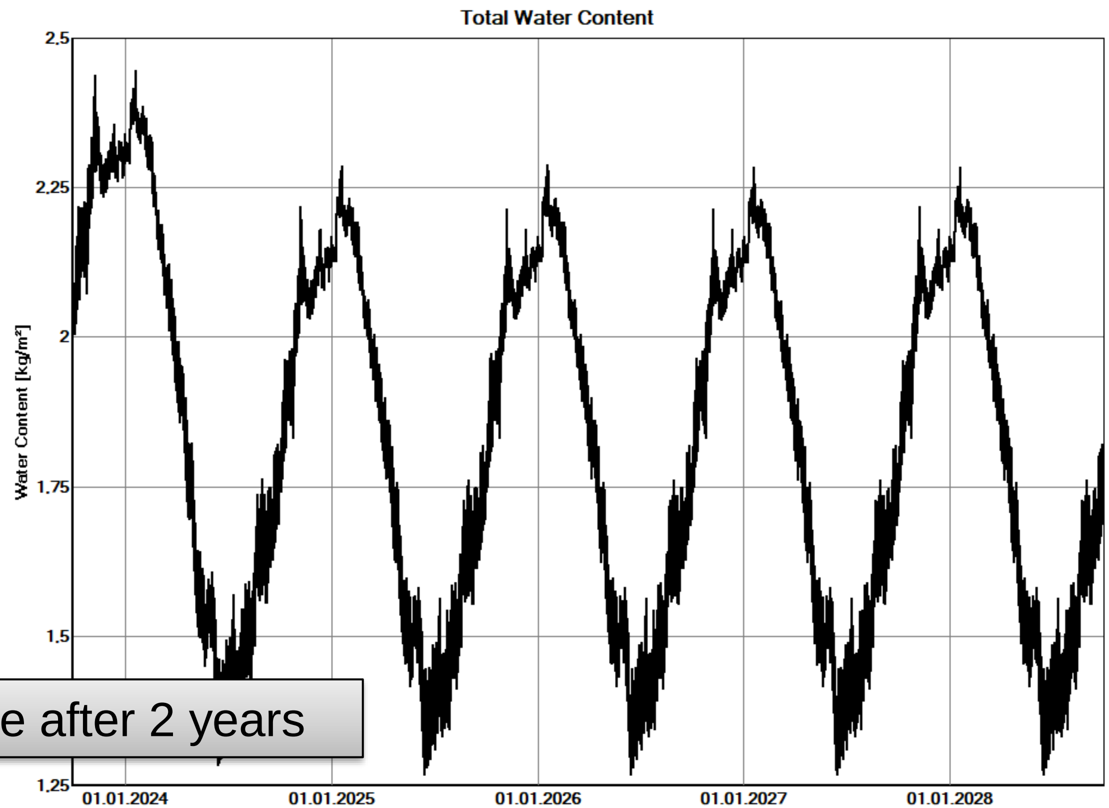
☐ Calculation locked

Close   ? Help

**No convergence failures and no balance differences!**

# Example: Evaluation – Total Water Content

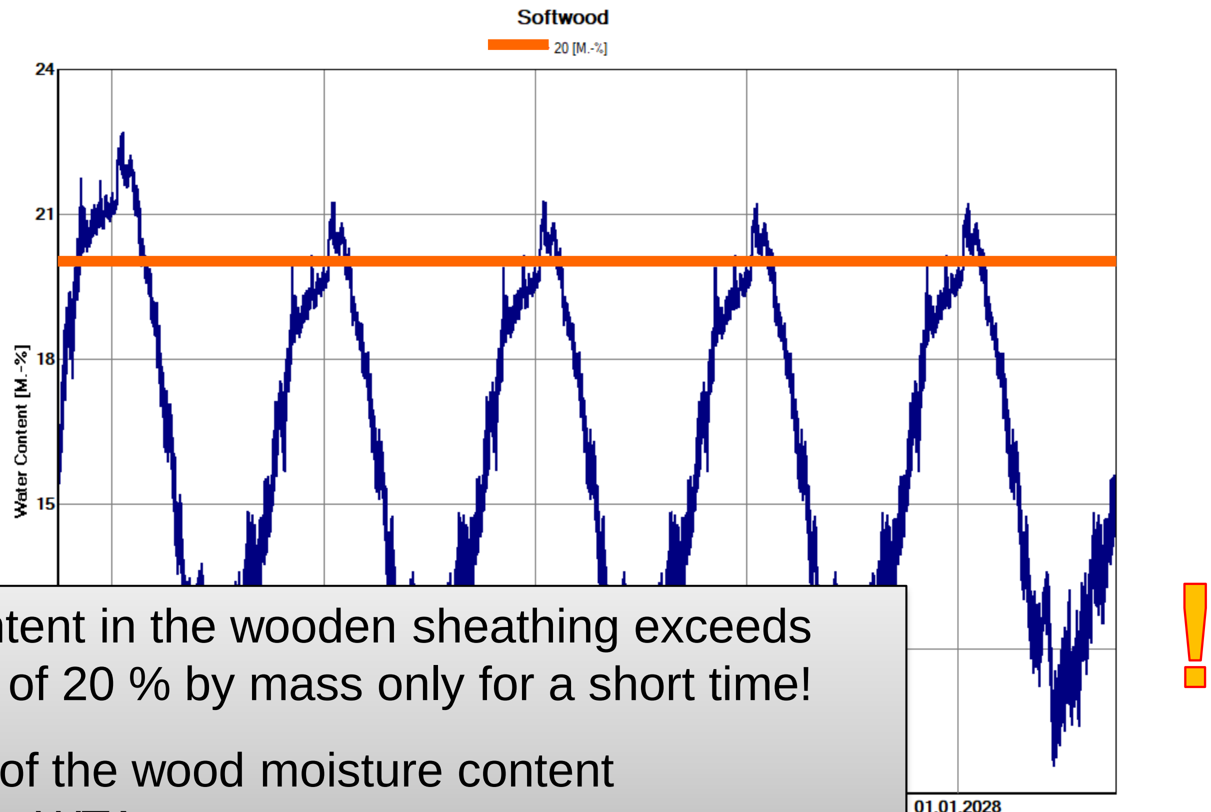
*Evaluation:* Total Water Content




Steady state after 2 years

# Example: Evaluation – Wooden Sheathing

*<u>Evaluation:</u>* Moisture Content in the Wooden Sheathing
– according to German Standard DIN 68800



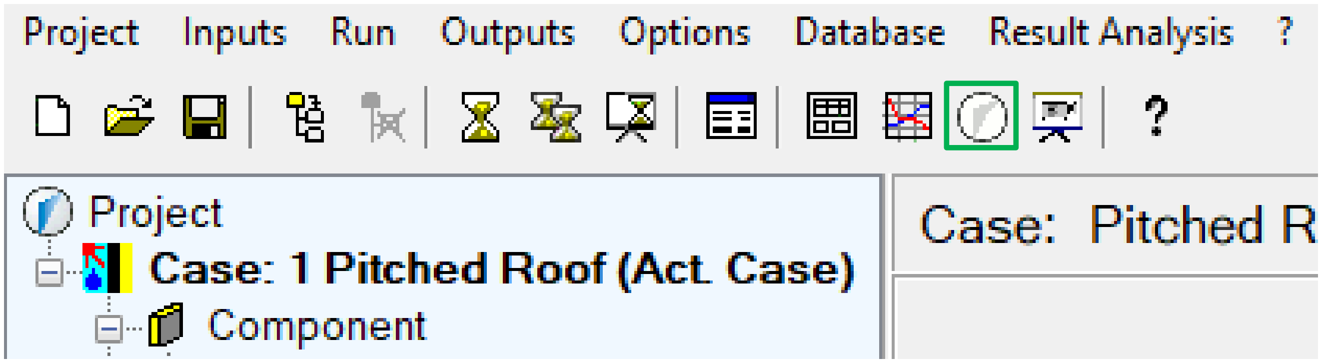

The water content in the wooden sheathing exceeds the limit value of 20 % by mass only for a short time!

→ Evaluation of the wood moisture content according to WTA

# Example: Evaluation – Wooden Sheathing

*Evaluation:* Moisture Content in the Wooden Sheathing
– according to WTA 6-8

Open WUFI Graph



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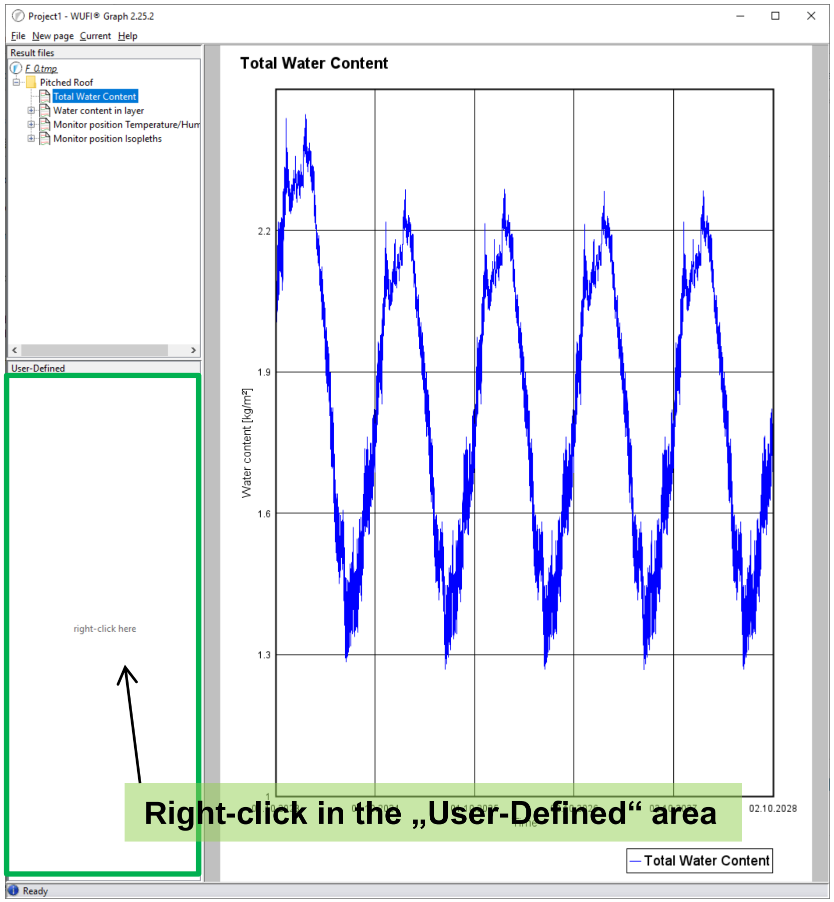

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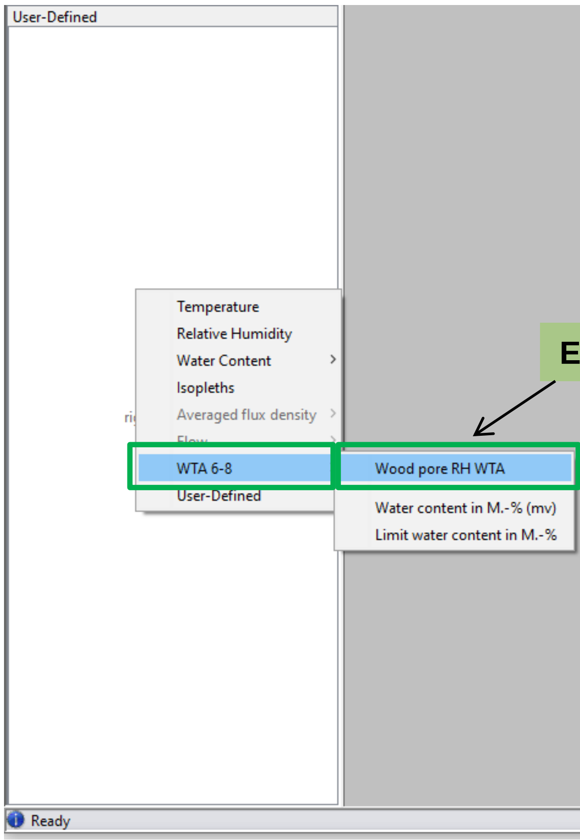


**Evaluation of the wood pore RH according to WTA**

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*Evaluation:* Moisture Content in the Wooden Sheathing
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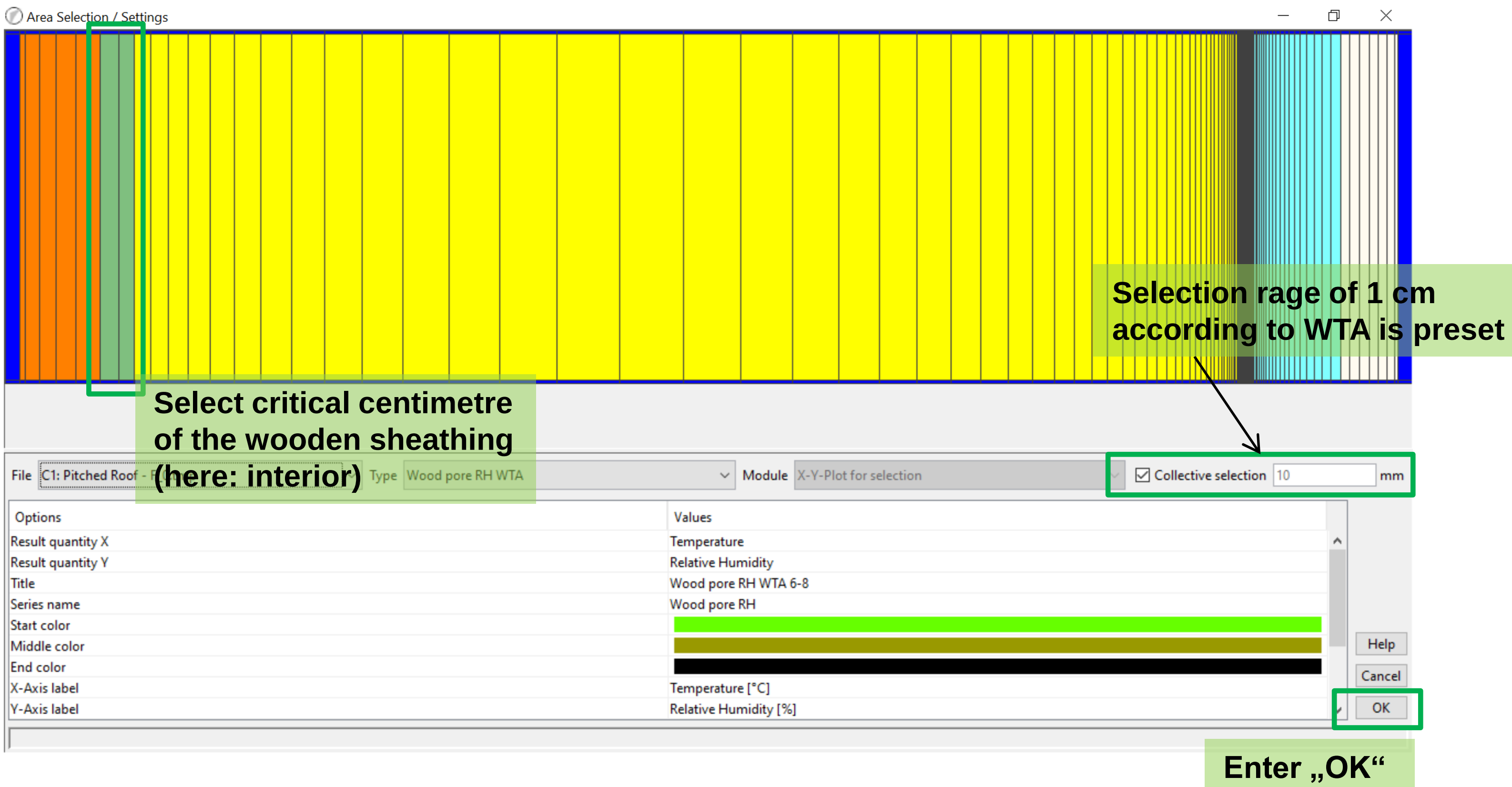

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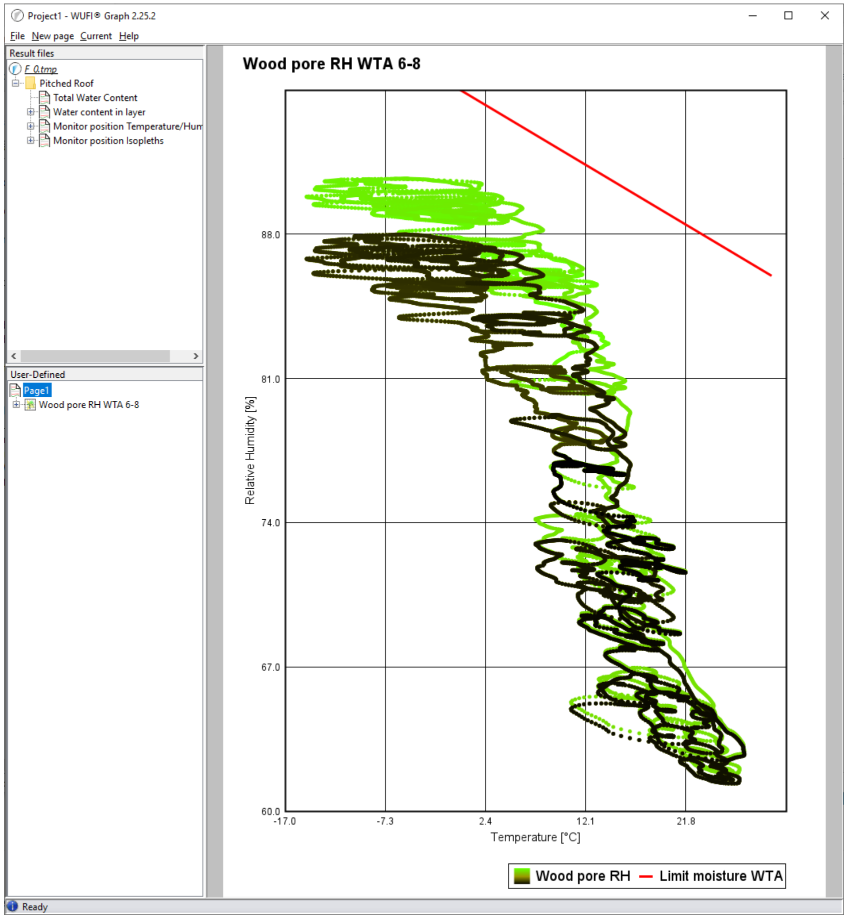
*Evaluation:* Moisture Content in the Wooden Sheathing
– according to WTA 6-8



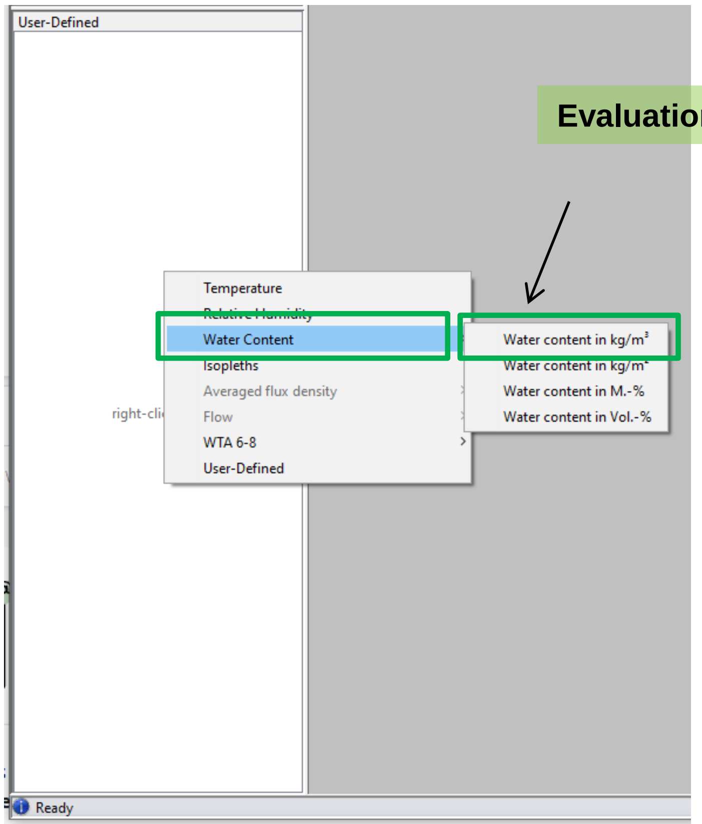

The relative pore air moisture in the interior centimetre of the sheathing doesn´t exceed the limits according to WTA.

→ no damage by wood decay

# Example: Evaluation – Amount of Condensation

*Evaluation:* Amount of condensation in the mineral wool insulation

→ Evaluation of the water content in the outer centimetre of the insulation



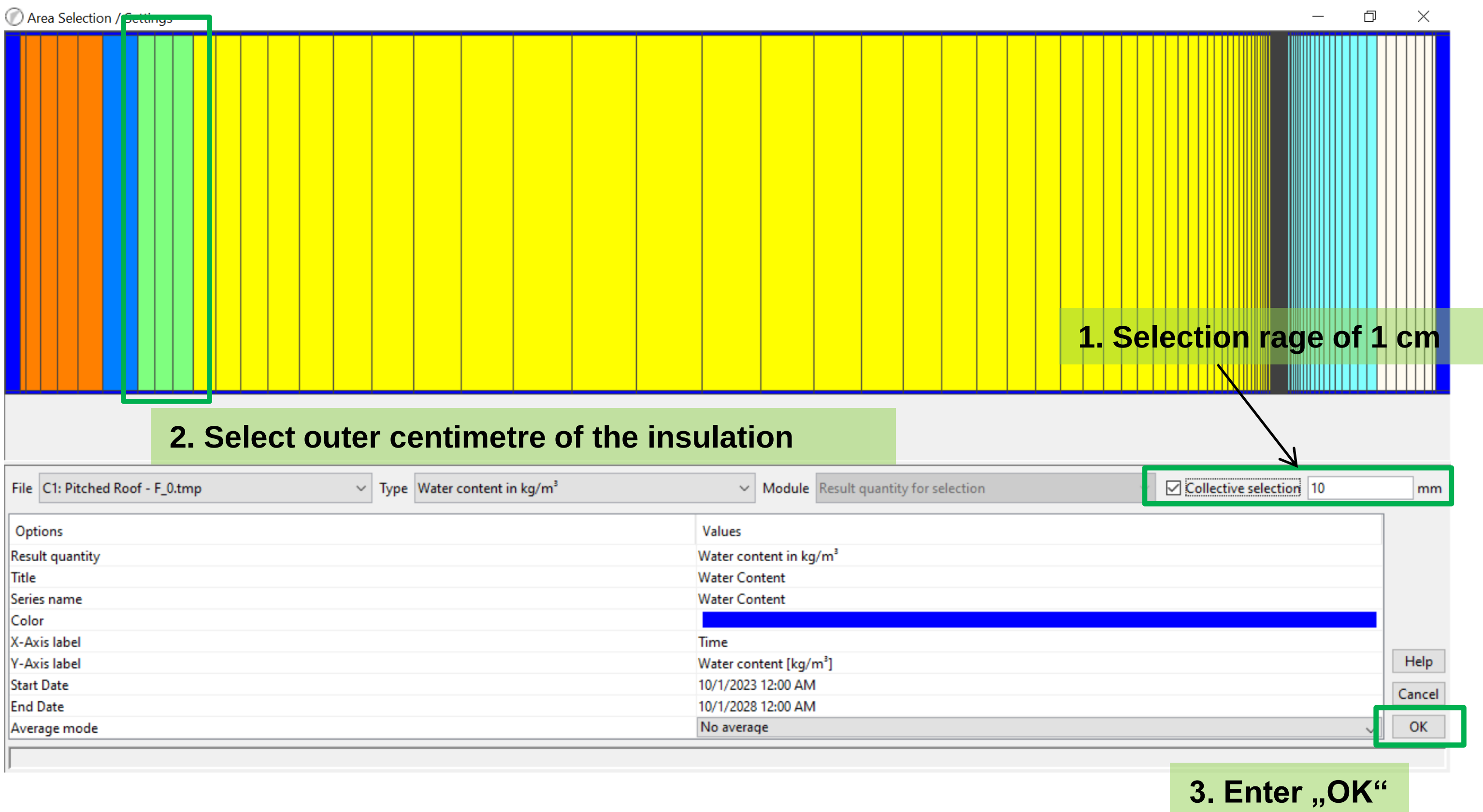

**Evaluation of the water content in kg/m³**

Note:
For mineral fibre insulation with measured moisture storage function, a different evaluation method can be used.
See: „Guideline for assessing condensation problems in hydrophobic mineral fiber“.

# Example: Evaluation – Amount of Condensation

*Evaluation:* Amount of condensation in the mineral wool insulation

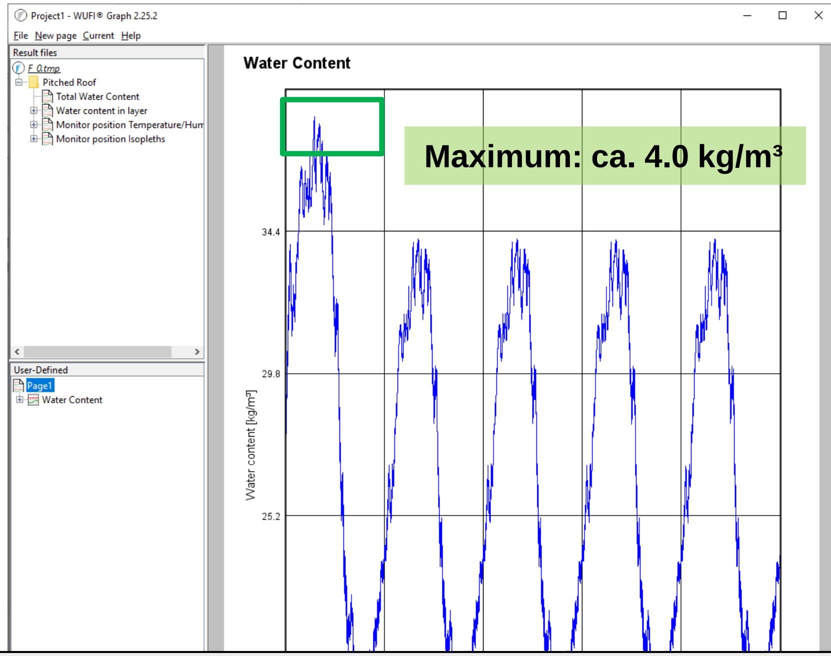
→ Evaluation of the water content in the outer centimetre of the insulation



# Example: Evaluation – Amount of Condensation

*Evaluation:* Amount of condensation in the mineral wool insulation

→ Evaluation of the water content in the outer centimetre of the insulation




Maximum water content = 4.0 kg/m³

4.0 kg/m³ * 0.01 m (layer thickness) = 0.040 kg/m² = 40 g/m²

→ Condensation remains clearly below the limit value of 200 g/m²

# Example: Evaluation – final Evaluation

*Final Evaluation:*

| | Criteria | Evaluation |
|---|---|---|
| 1) Numerics | Low balance differences? | ✓ |
| | Few or no convergence failures? | ✓ |
| 2) Evaluation parameters | Total water content steady-state? | ✓ |
| | Amount of condensation in the insulation layer? | ✓ |
| | Risk of wood decay in the wooden sheathing? (limit values according to DIN 68800-3 or WTA 6-8) | ✓ |

⬇

Construction unproblematic from the moisture point of view!