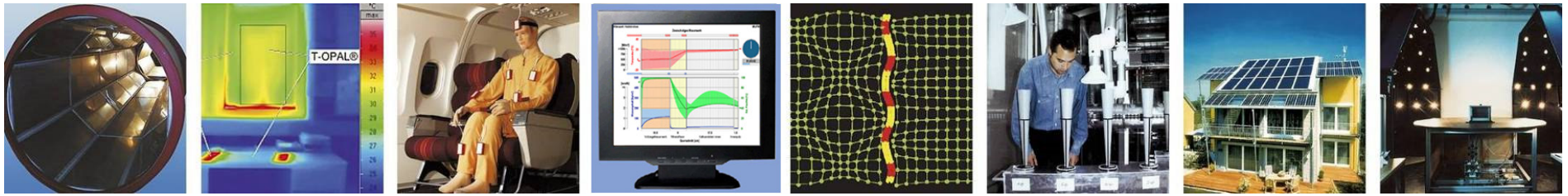

WUFI®

Guideline for the Evaluation and Assessment of hygrothermal Calculation Results

Date: September 2023

Fraunhofer IBP

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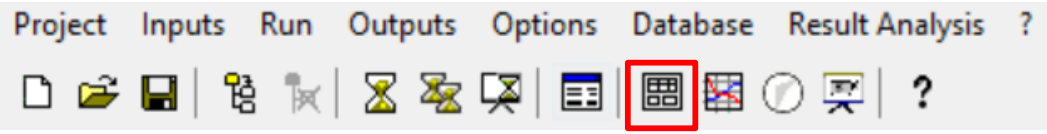
General Proceeding: Evaluation of the Numerical Quality

Important:
First step after the calculation is always to check the numerical quality of the results using convergence failures / balances!

Dialog „Status of last calculation“:

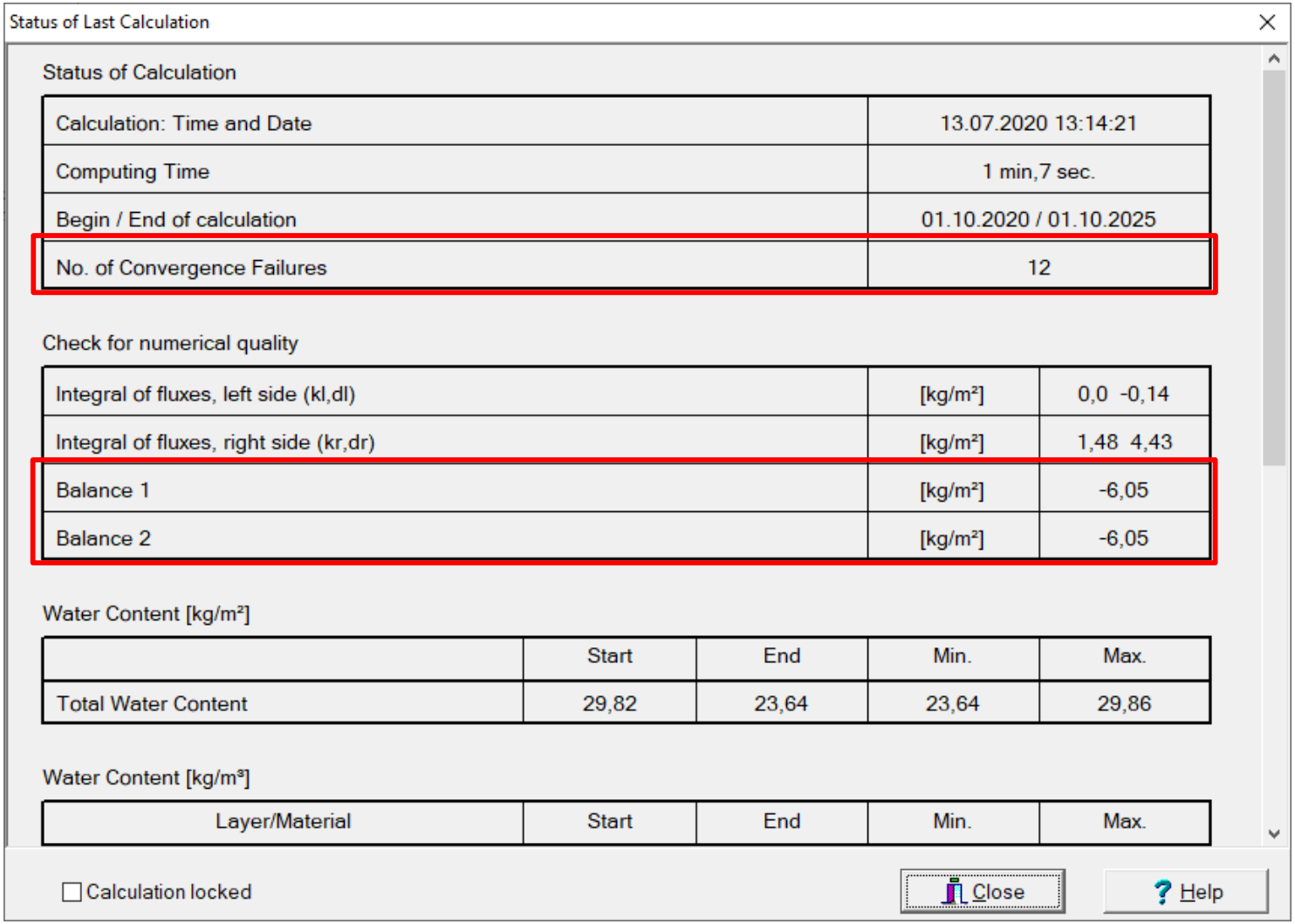
After the calculation of one case, the dialog „Status of last calculation“ opens automatically. This shows a short ***summary of the calculation results*** and ***allows to check the numerical quality*** of the simulation.

If several cases have been calculated, this dialog can be called up for each case under „Outputs → Status: Last Calculation“ or via the corresponding button.



General Proceeding: Evaluation of the Numerical Quality

Dialog „Status of last calculation“:



Status of Last Calculation

Status of Calculation

Calculation: Time and Date	13.07.2020 13:14:21
Computing Time	1 min,7 sec.
Begin / End of calculation	01.10.2020 / 01.10.2025
No. of Convergence Failures	12

Check for numerical quality

Integral of fluxes, left side (kl,dl)	[kg/m²]	0,0 -0,14
Integral of fluxes, right side (kr,dr)	[kg/m²]	1,48 4,43
Balance 1	[kg/m²]	-6,05
Balance 2	[kg/m²]	-6,05

Water Content [kg/m²]

	Start	End	Min.	Max.
Total Water Content	29,82	23,64	23,64	29,86

Water Content [kg/m³]

Layer/Material	Start	End	Min.	Max.

Calculation locked

Close

Help

General Proceeding: Evaluation of the Numerical Quality

Number of Convergence Failures:

A ***high number of convergence failures*** indicates a difficult solution of the equations and is usually associated with ***high moisture contents or large amounts of moisture transported***.

The reason for this can be a ***high moisture entry*** or a ***difficult drying***, so e.g. a bad rain protection or vapor-tight layers within the assembly!

Recommendation:

It is often more useful to design the component assembly more favorable than to try to improve the quality of the simulation of the unfavorable component!!

General Proceeding: Evaluation of the Numerical Quality

Describtion of the Convergence Failures:

WUFI® uses an ***iterative process to solve the transport equations***. Sometimes convergence is very slow and WUFI® reaches the maximum allowed number of iterations without the intermediate solutions satisfying the termination criterion..

In this case the iteration is aborted and the result achieved up to that point is compared with somewhat less strict criteria. If these are fulfilled, the result is accepted and WUFI ® continues with the next time step. If the ***criteria are not fulfilled***, WUFI® accepts the result anyway and also continues the calculation, but increases the counter for the ***convergence failures*** by one.

The ***total number of convergence failures*** is a ***first indication regarding the reliability of the results***. However, the fact that a convergence failure was registered says nothing about how large the residual error was when the iteration was aborted.

General Proceeding: Evaluation of the Numerical Quality

Assessment of the Convergence Failures:

It is possible that the ***termination criteria*** were ***only narrowly missed*** and the ***convergence failure*** is therefore ***negligible***, what is usually the case.

However, it is occasionally also possible that ***numerical instability*** has developed and the ***iteration steps*** are moving ***further away from the solution***. Often this is noticeable by water appearing or disappearing in the middle of the component without being induced by the boundary conditions. The result is unmotivated jumps in the water content curves and a poor water balance.

Important:

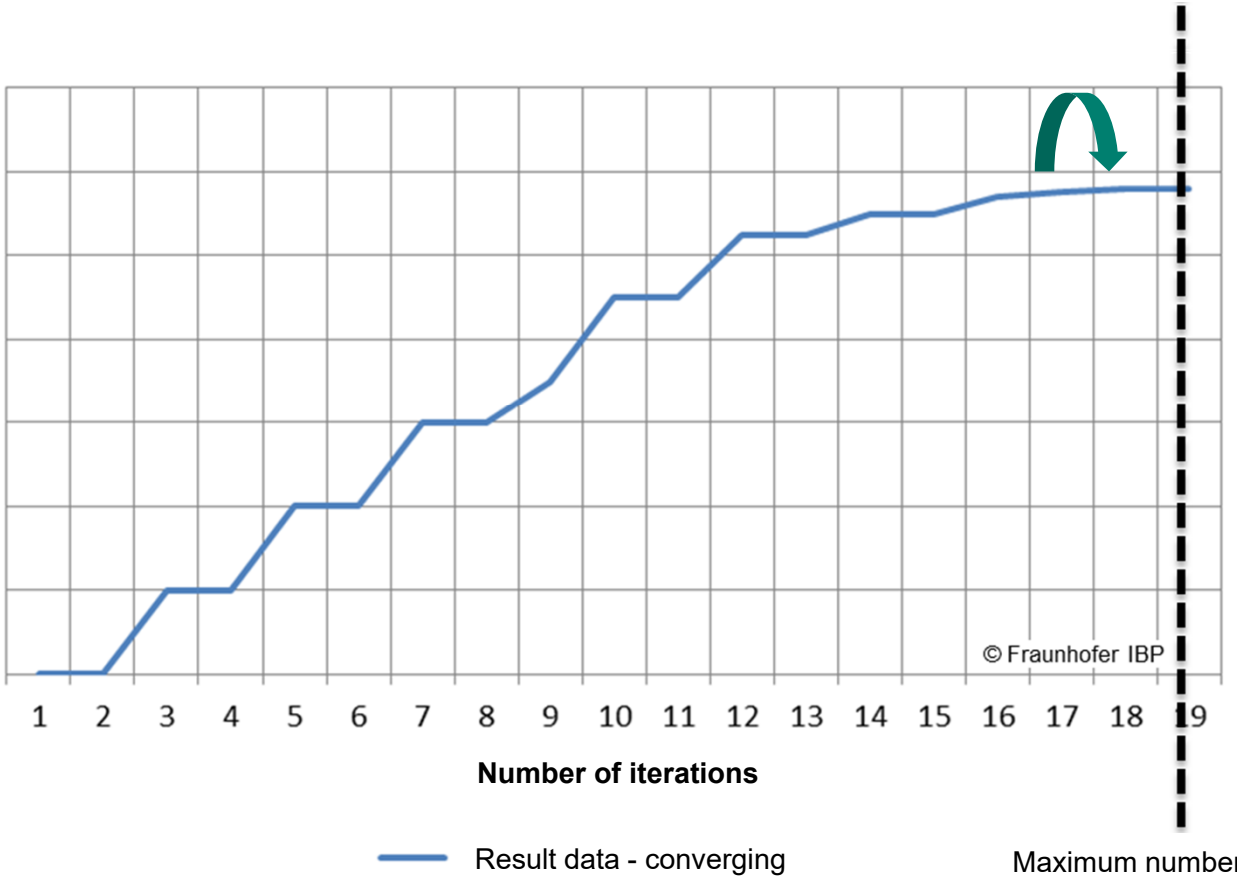
Convergence failures can only be assessed together with the balances!

General Proceeding: Evaluation of the Numerical Quality

Definition of the Convergence Failures:

All numerical solution methods represent "only" an approximate solution.

Convergence criterion = acceptable deviation between two iteration steps



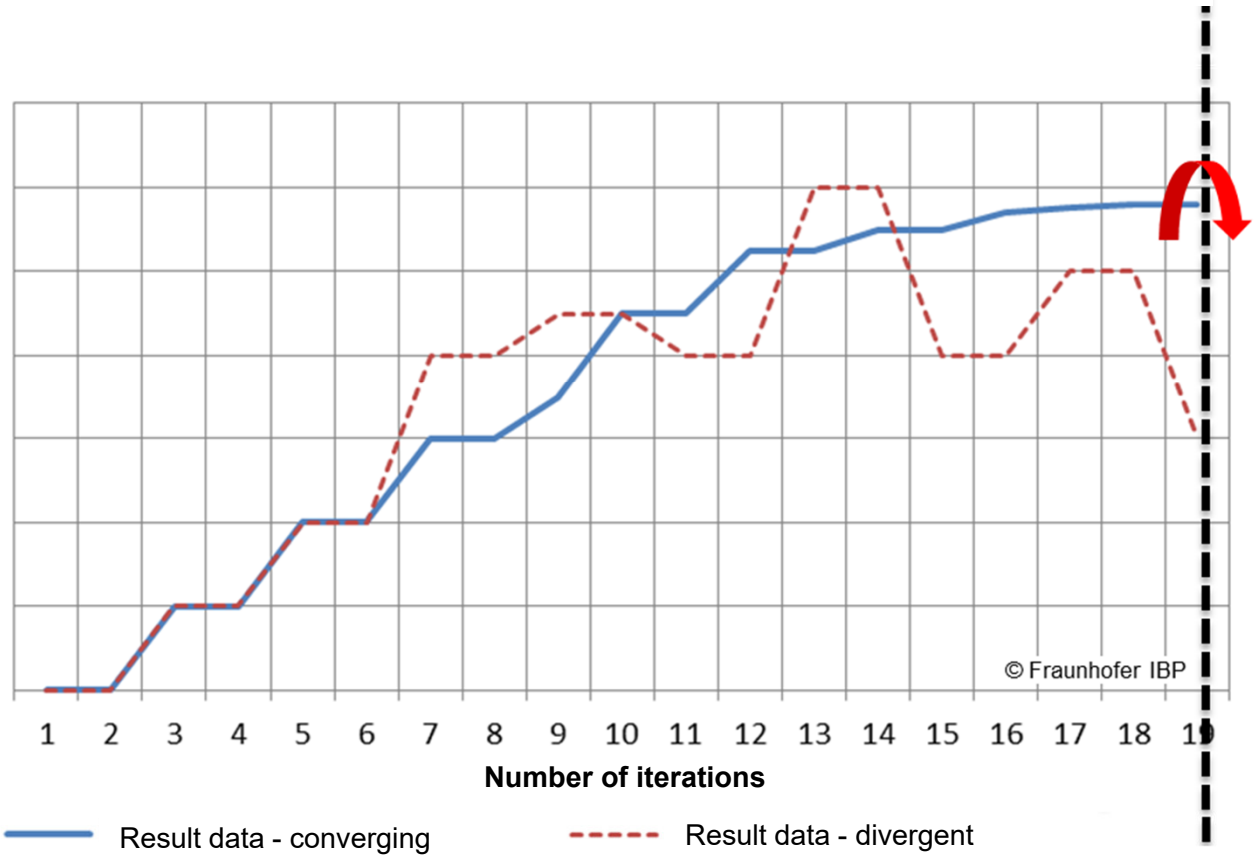
No convergence failure

The convergence criterion is undercut before or at the maximum number of iteration steps!

General Proceeding: Evaluation of the Numerical Quality

Definition of the Convergence Failures:

All numerical solution methods represent "only" an approximate solution.



Convergence Failure (Criterion not reached !!)

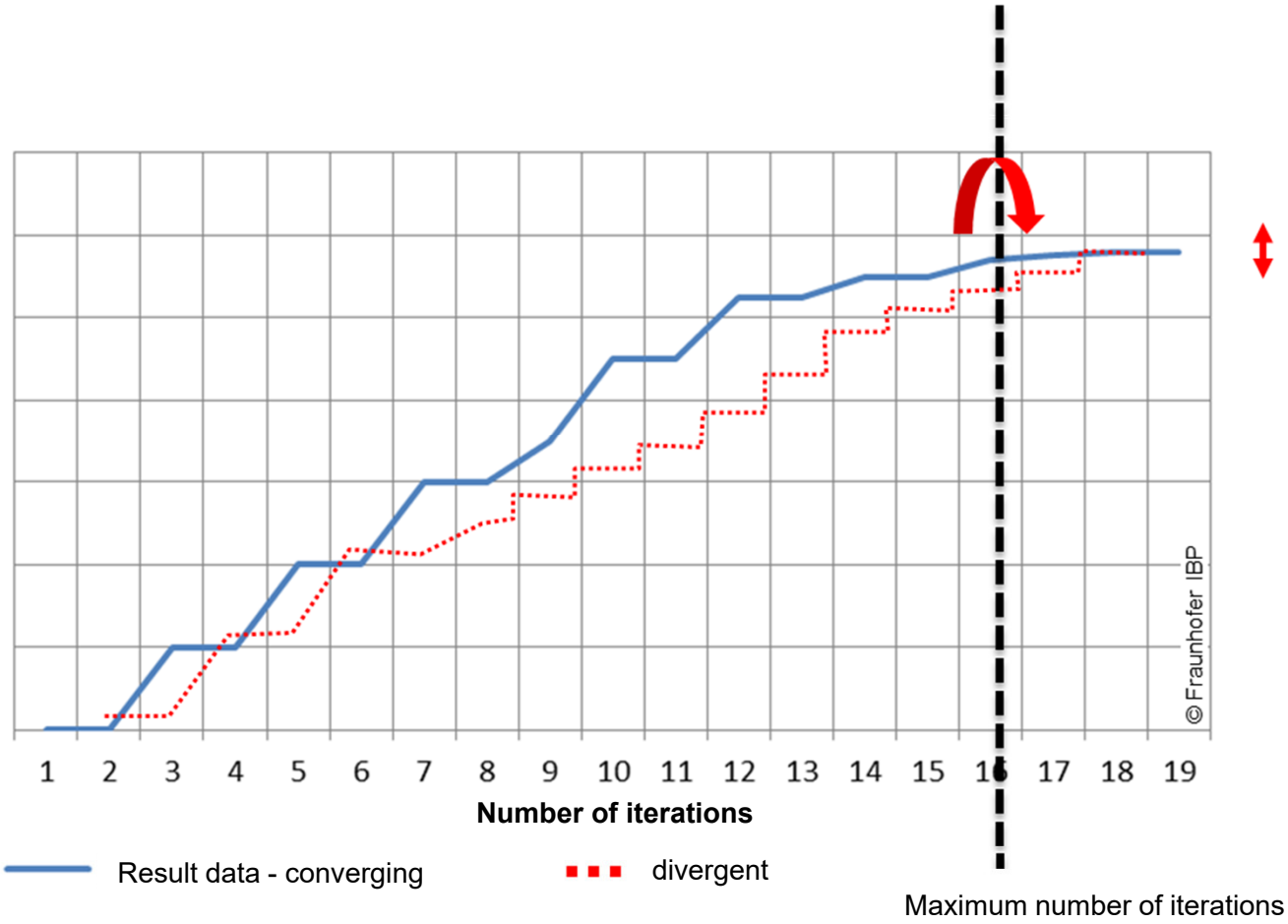
Convergence criterion is clearly missed after maximum number of iteration steps (possibly diverging).

⇨ usually clear difference in balances!

General Proceeding: Evaluation of the Numerical Quality

Definition of the Convergence Failures:

All numerical solution methods represent "only" an approximate solution.



Convergence criterion just missed!! Nevertheless convergence failure!

Converging result, but convergence criterion not reached!

⇨ No or small difference in balances!

General Proceeding: Evaluation of the Numerical Quality

Evaluation of the balances:

Balance 1: Change in the total water content

Balance 2: Sum of moisture fluxes through the surfaces and released by sources

Amount of moisture in [kg/m²] over the **total calculation period**,
i.e. longer calculation period usually leads to numerically larger balance differences.
(negative: drying, positive: moisture accumulation)

Differences in balance:

Due to numerical errors or inaccuracies, moisture in the assembly “appeared” or “disappeared” in the component

- ***Differences in balances*** should remain ***as small as possible***!
- If the differences in balances are ***small compared*** to the total amount of water taken up or dried out, or compared ***to the total water content***, these usually have a ***negligible influence*** (also depends on the type of construction!).
- ***Significant*** relative and absolute ***differences in the balances***: ***result unreliable***!!

General Proceeding: Evaluation of the Numerical Quality

What to do in case of convergence failures / differences in balances?

Select a finer grid:

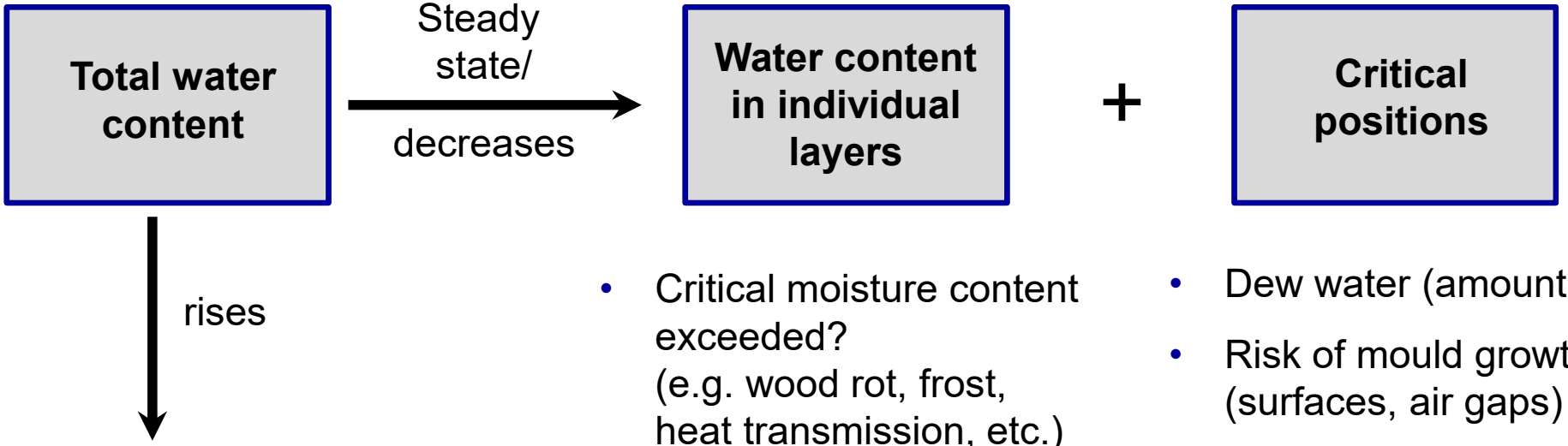
Normally, the use of the automatically generated grid is sufficient. In ***exceptional cases***, however, an ***even finer grid structure may be required***.

To do this, you can select „user-defined“ and enter the desired number of grid elements, which will then be distributed over the component by the automatic grid generator.

Switch on adaptive time step control:

If the adaptive time step control is enabled, WUFI® automatically switches to ***shorter time steps*** as soon as numerical problems are identified. The numerical problematic calculation step is repeated with shorter time steps; if necessary, these time steps are further subdivided. ***In many cases***, a ***calculation*** which produces numerous convergence failures or a poor numerical balance ***can be improved***.

General Proceeding: Principle of Evaluation „coarse to fine“:



1. Extend calculation period
2. Start with higher initial water content
3. In case of long-term increase:
   Construction fails due to accumulation of moisture

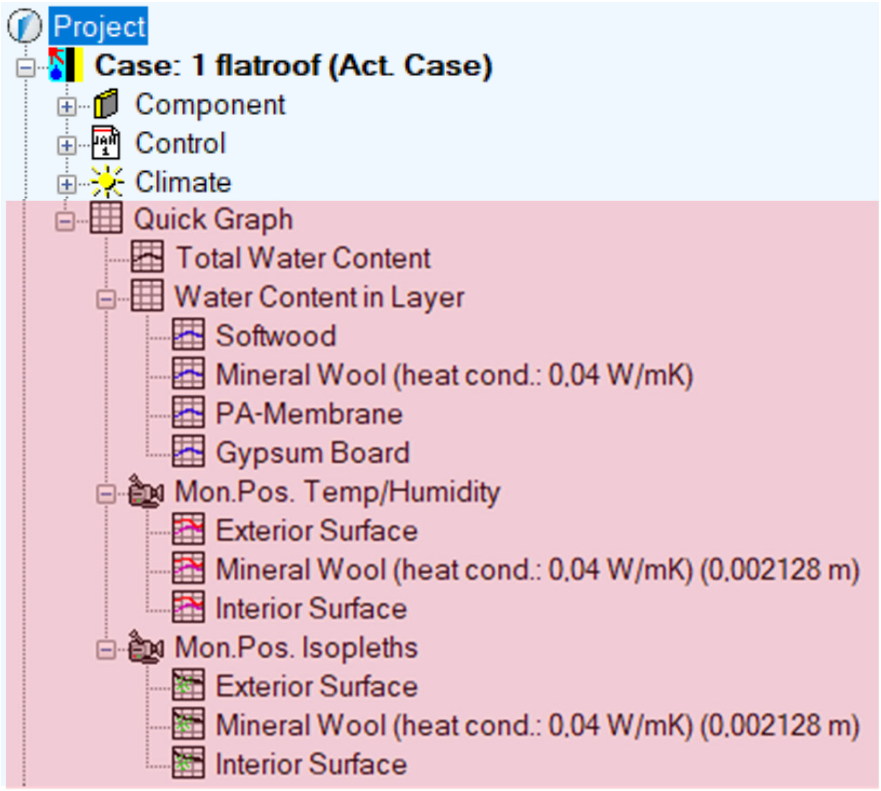
- Critical moisture content exceeded?
  (e.g. wood rot, frost, heat transmission, etc.)
- Increases over many years → accumulation by redistribution

- Dew water (amount?)
- Risk of mould growth (surfaces, air gaps)
- Wood decay
- Risk of frost damage
- Corrosion
- etc.

Tools for Result Evaluation – Quick Graphs

Quick overview over the calculation results:

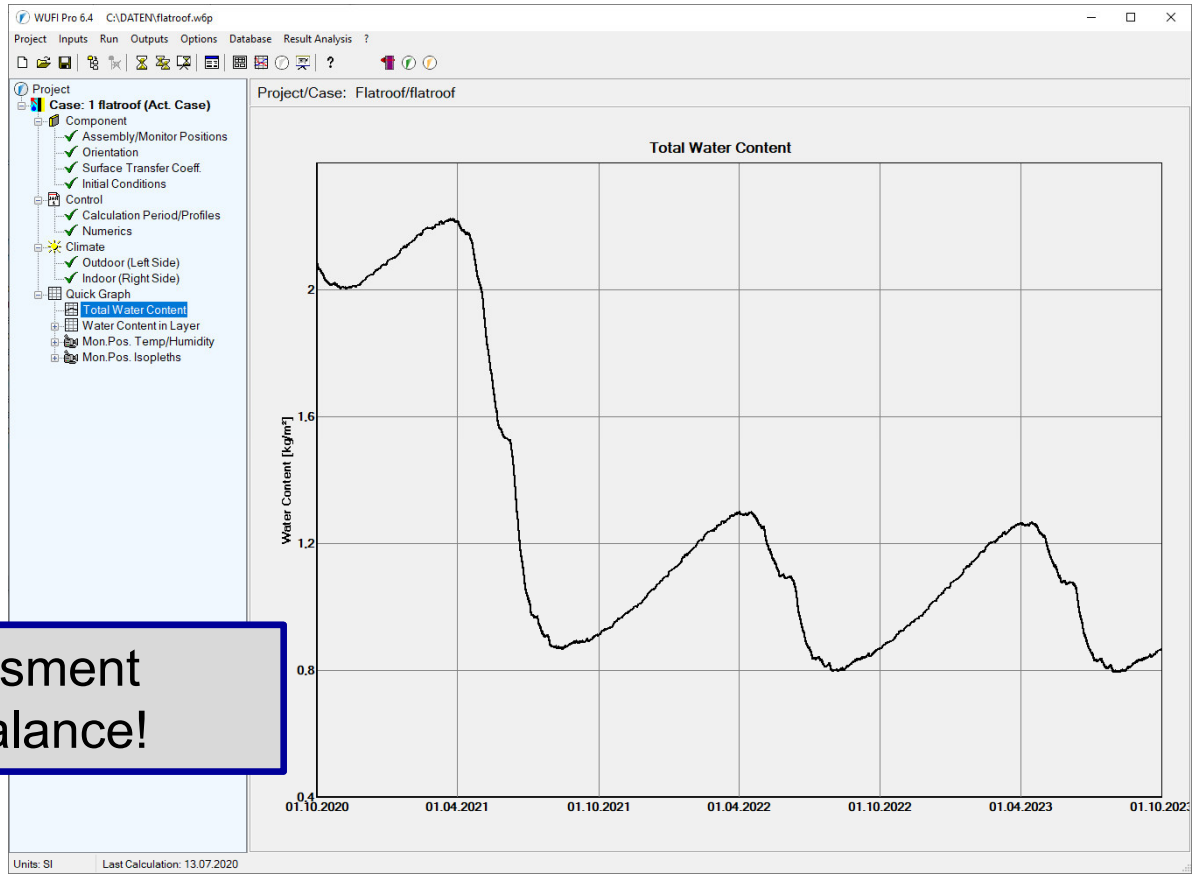
- The quick graphs allow aequick overview of the calculation results
- Displayed in the order of practical evaluation:
  - Total water content
  - Water content in the individual material layers
  - Temperature and relative humidity at the monitor positions
  - Isopleths at the monitor positions



Tools for Result Evaluation – Quick Graphs

Total water content in [kg/m²]

- Water content of a component per m² component area
  (thicker constructions tend to contain more moisture than thin ones)

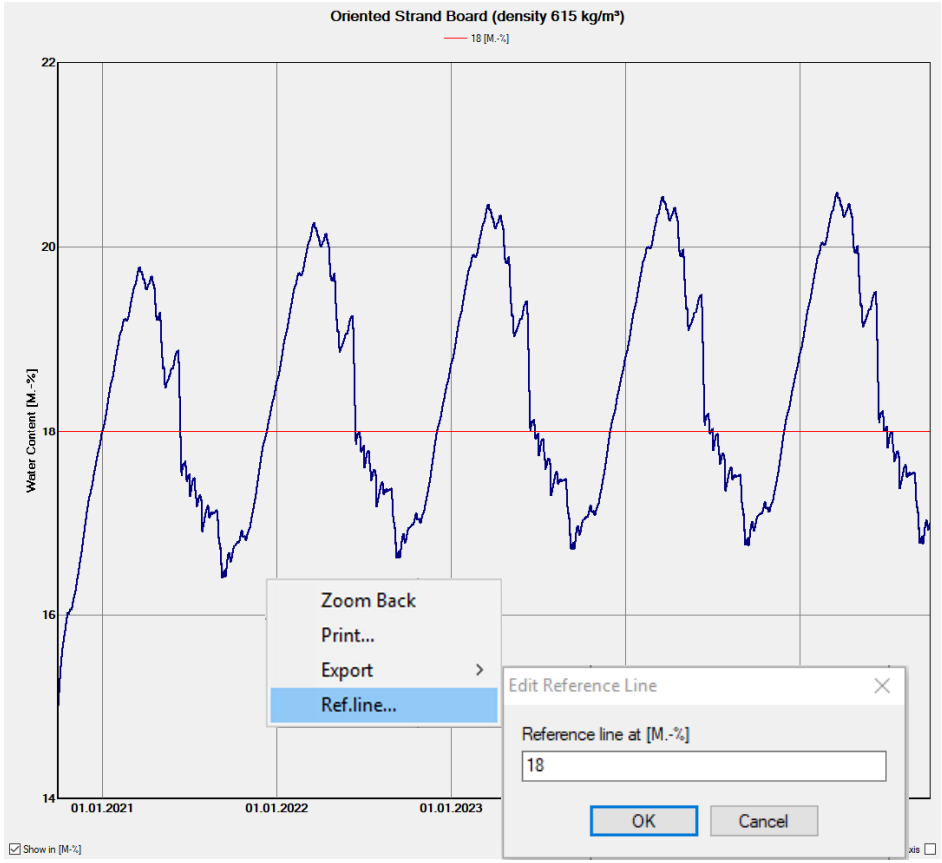


Qualitative assessment
of the moisture balance!

Tools for Result Evaluation – Quick Graphs

Water content in layer in [kg/m³] or [M.-%]

- Qualitative assessment of the moisture balance of individual materials / layers
- Quantitative assessment of the moisture level achieved
- Thick layers may be subdivided to assess critical areas of thick material layers



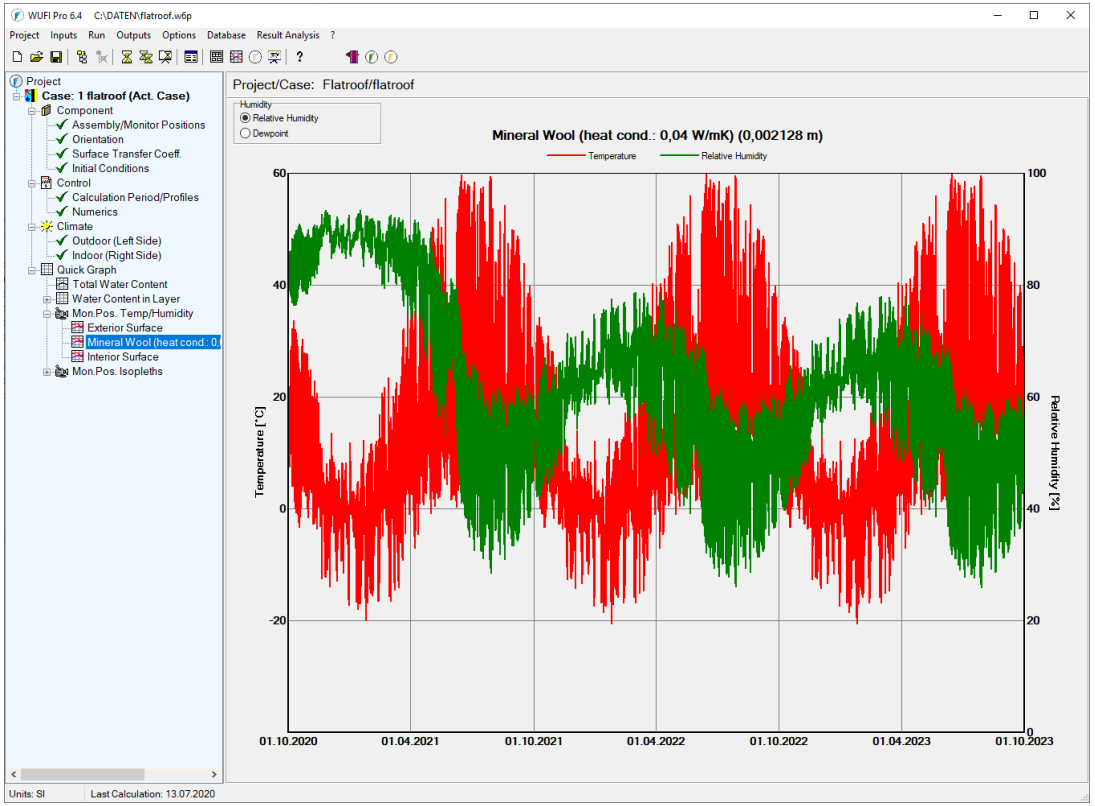
- Evaluation regarding e.g.:
  - Wood decay
  - Frost damage
  - Transmission heat losses
  - etc.

Tools for Result Evaluation – Quick Graphs

Monitor positions – Temperature and relative humidity

- Qualitative assessment of the moisture behavior
- Quantitative assessment of the achieved moisture level

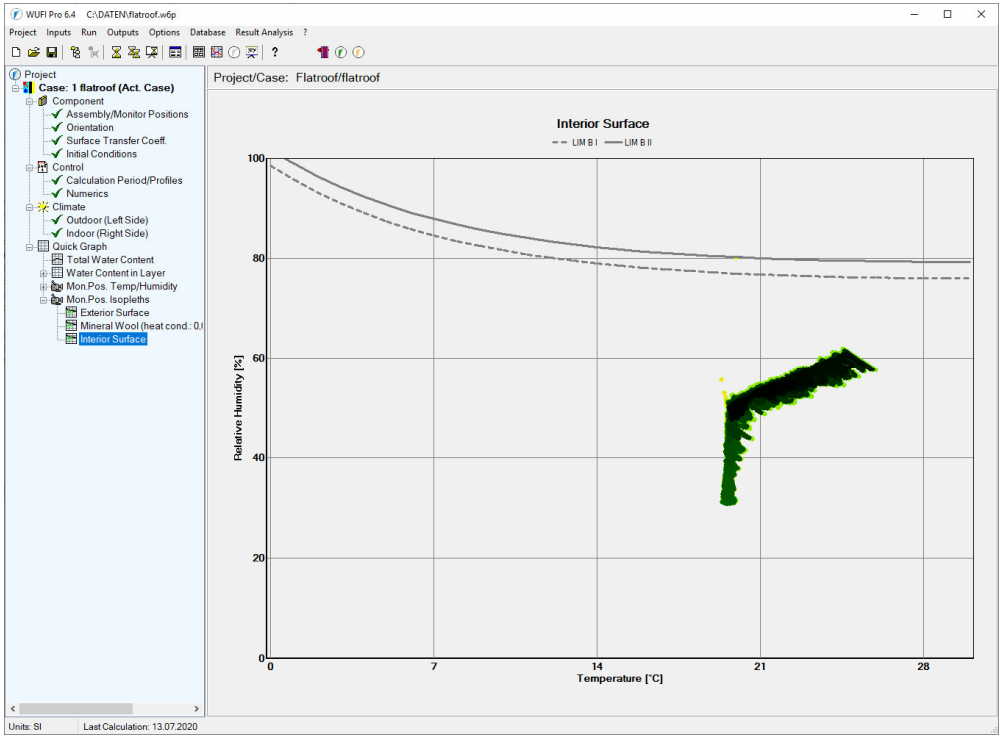
- Evaluation regarding e.g.:
  - Condensation water
  - Mould growth
  - Frost damage
  - Risk of corrosion
  - etc.



Tools for Result Evaluation – Quick Graphs

Monitor positions – Isopleths

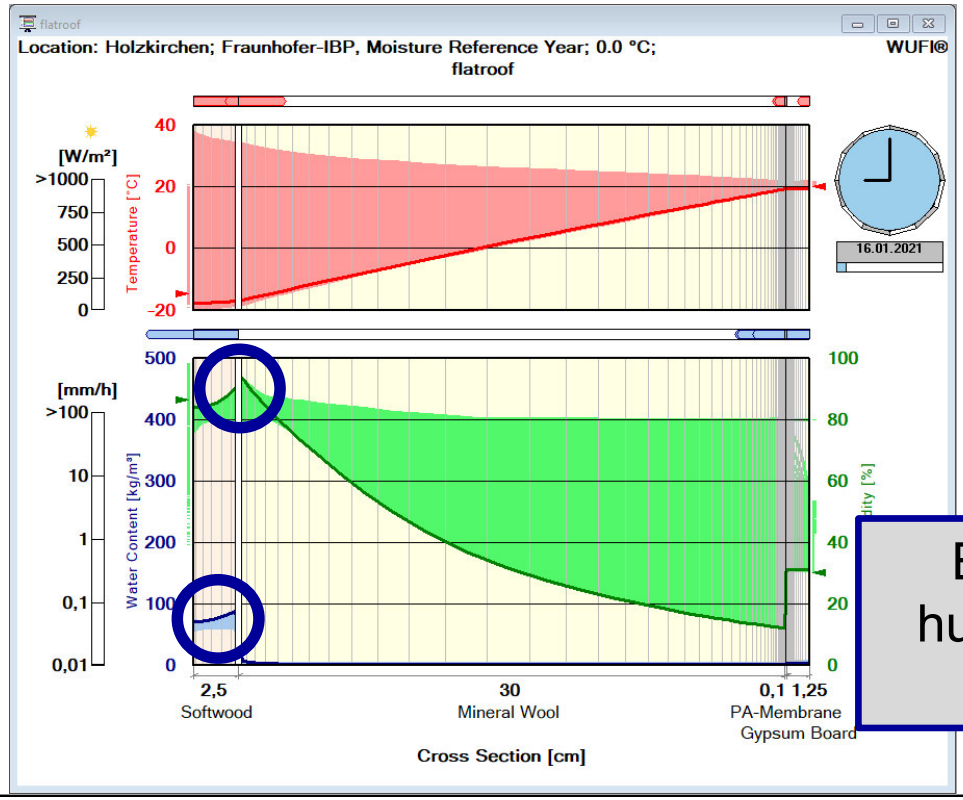
- Visualisation of the occurring combinations of temperature and relative humidity
- Qualitative color gradient of the points from yellow (start of calculation) to black (end of calculation)
- Exceeding the LIM curves on the inner surface: possible risk of mould growth → further evaluation with WUFI® Bio required
- Evaluation of critical limits concerning strength loss or durability if available



Tools for Result Evaluation – WUFI® Animation

Presentation of the calculated profiles as a movie:

- Sequence of the hourly calculated profiles for temperature, relative humidity and water content as a motion picture
- Clear representation of the transport and storage processes
- Easy identification of critical positions



Extreme values in the relative humidity and water content often indicates critical positons.

Tools for Result Evaluation – WUFI® Animation

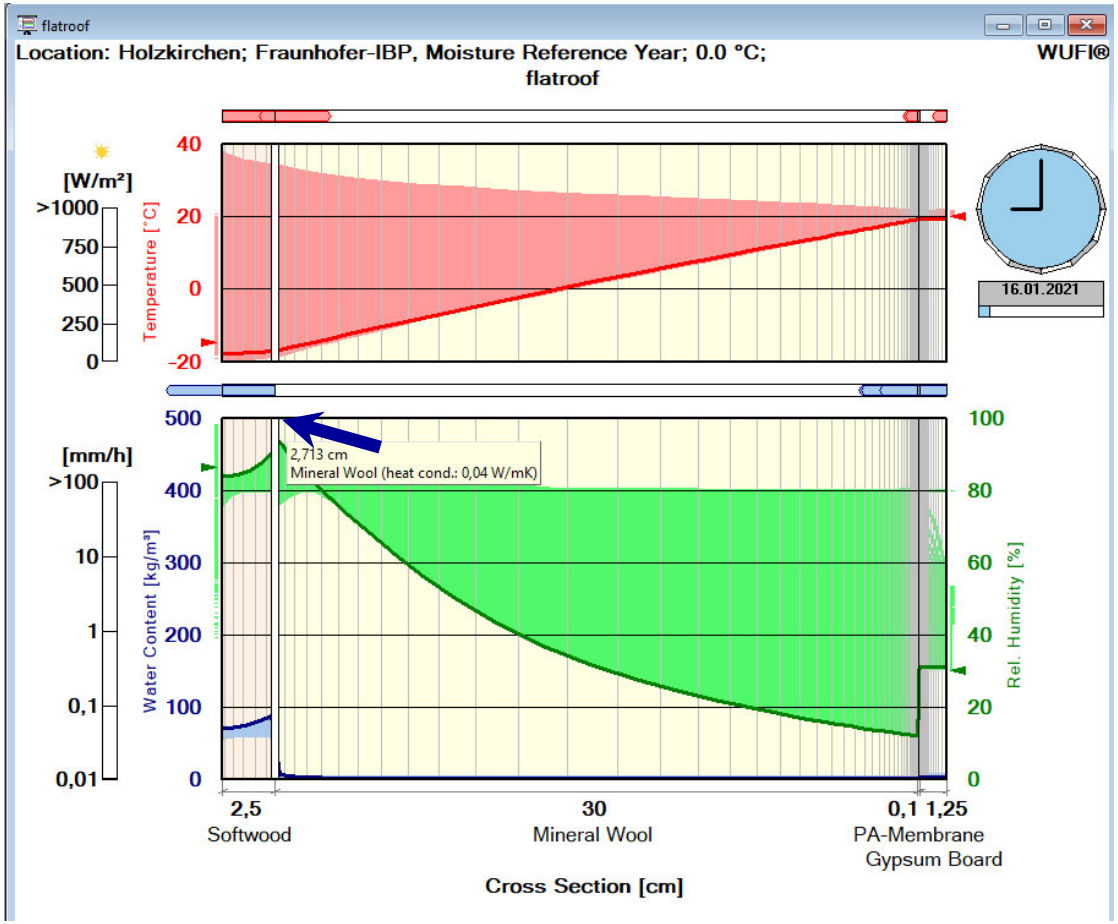
Additional extraction of a monitor position:

- Plotting of the course of temperature, relative humidity and water content for every grid element is possible.

- Procedure:
  1. Stop motion picture

  2. Right mouse click
     → „Create course“

  3. Select desired
     position / grid element



Note:
Does not work at the end of the movie picture – jump back a time step if necessary!

Tools for Result Evaluation – WUFI® Animation

Additional monitor position:

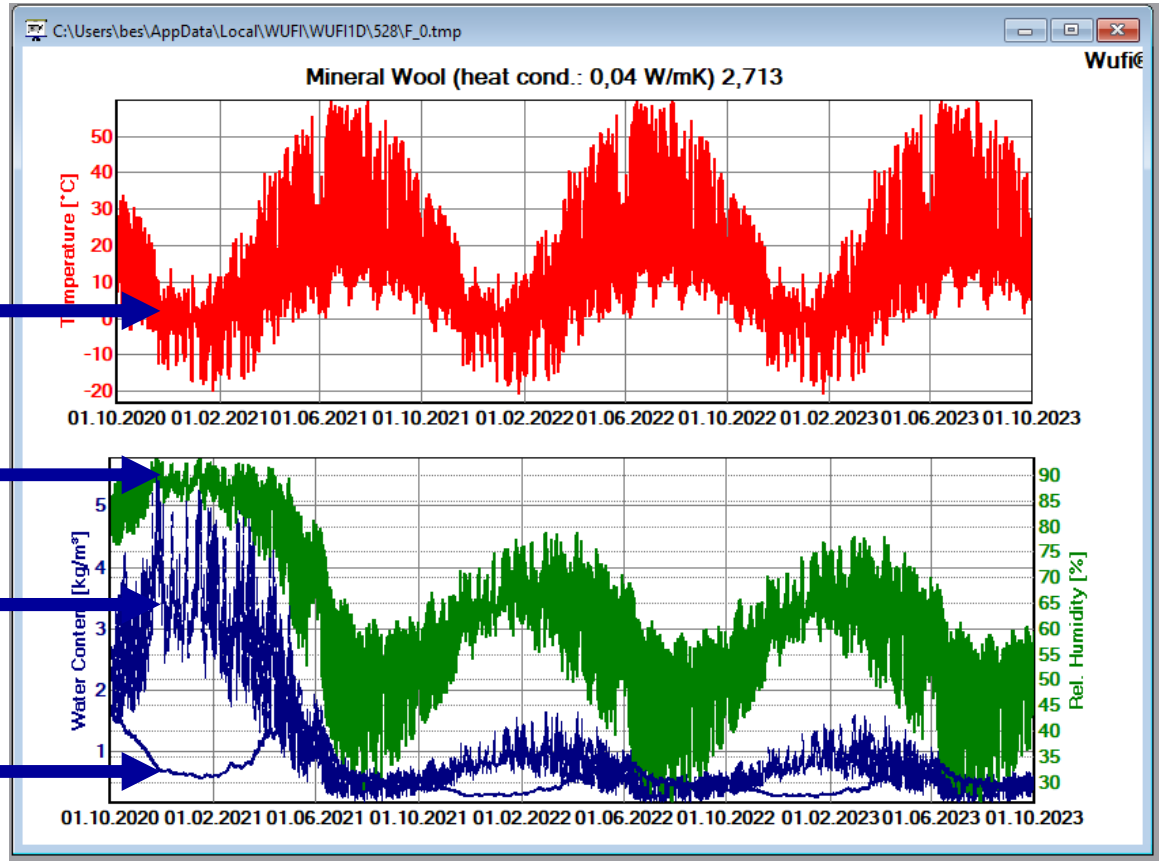
- Display of the course of temperature, relative humidity and water content in the grid element selected

temperature

relative humidity

water content in the grid element (dotted line)

Water content in the total layer

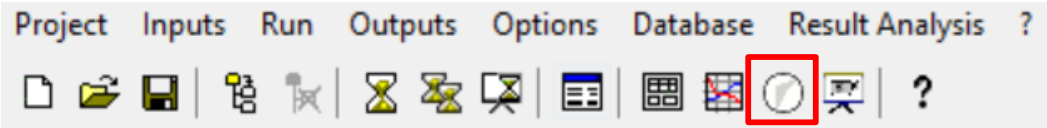


Tools for Result Evaluation – WUFI® Graph

Open WUFI® Graph:

- Evaluation tool available from version WUFI® Pro 6
- Prerequisite: WUFI® Pro project file has been saved including the film data (Menu: „Options“ → „Result data“)

- Menu: „Result analysis“ → „WUFI® Graph“



Opens the currently selected case in WUFI® Graph.

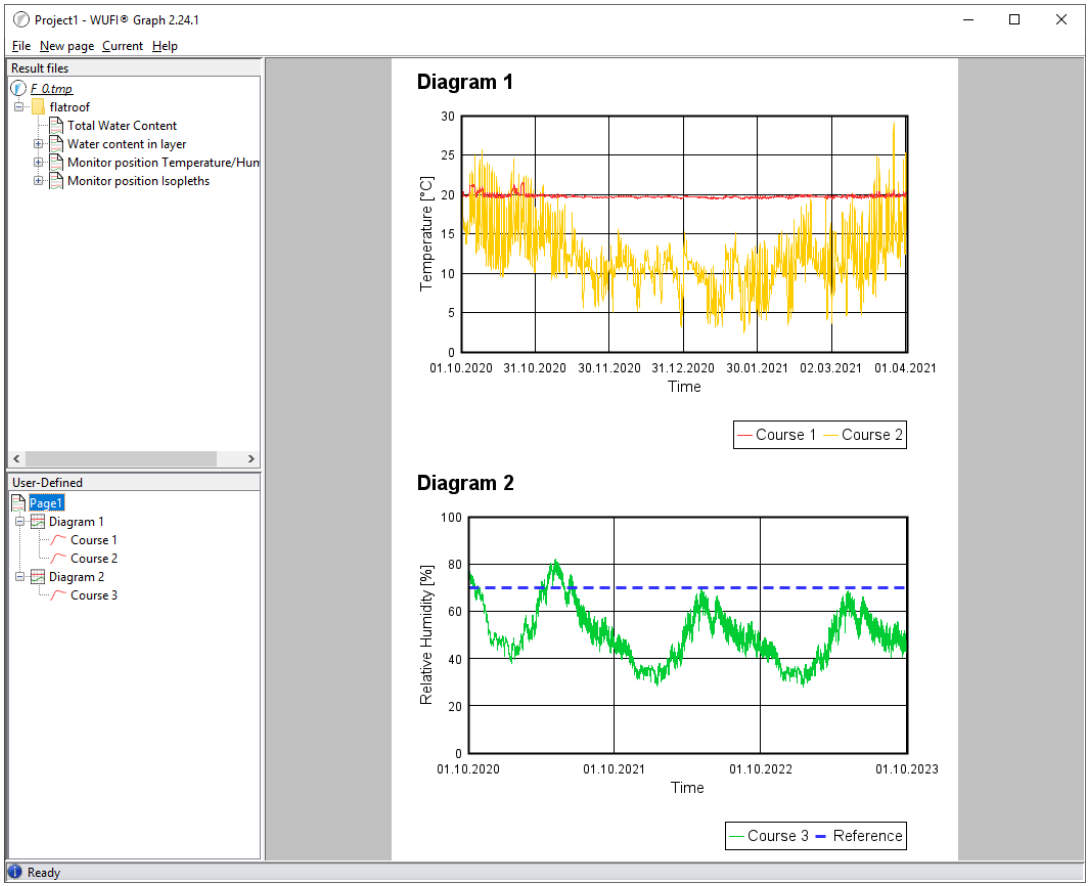
- Open WUFI® Graph: „File“ → „Open WUFI result file…“
  All cases saved and calculated in the project file are opened in WUFI® Graph.

Tools for Result Evaluation – WUFI® Graph

Possibilities of evaluation in WUFI® Graph:

- In the “Result Files“ area the quick graphs from WUFI® Pro are displayed as predefined diagrams.

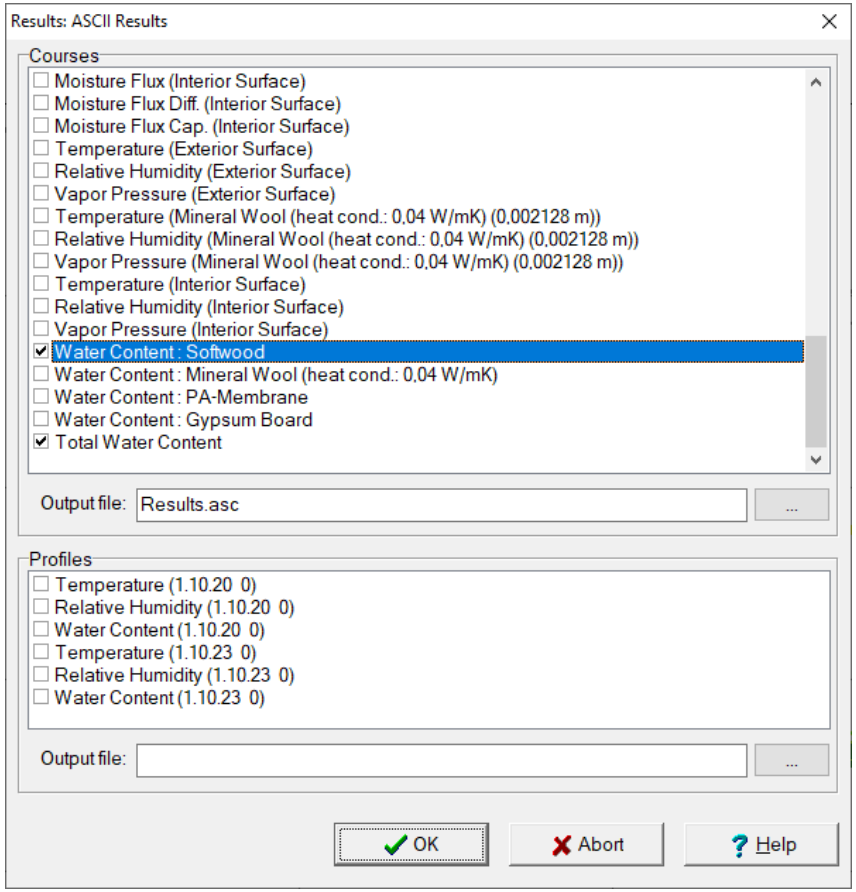
- In the “User-Defined“ area, you can create your own pages with result diagrams:
  - Temperature
  - Relative Humidity
  - Water Content
  - Isopleths
  - Averaged Flux Density
  - Flow
  - WTA 6-8
    (Evaluation of wood moisture)



Tools for Result Evaluation – ASCII-Export

Output of the calculation results:

- Menu: „Outputs“ → „ASCII-Export“
- Output of the calculation results as ASCII file for further evaluation e.g. in Excel…
- Select the result elements (courses / profiles) to be output
- ASCII file with several columns:
  - First column:
    Time in hours (courses)
    or coordinates on the X-axis
    in meters (profiles)
  - Other columns:
    selected calculation results in the order given by the selection list

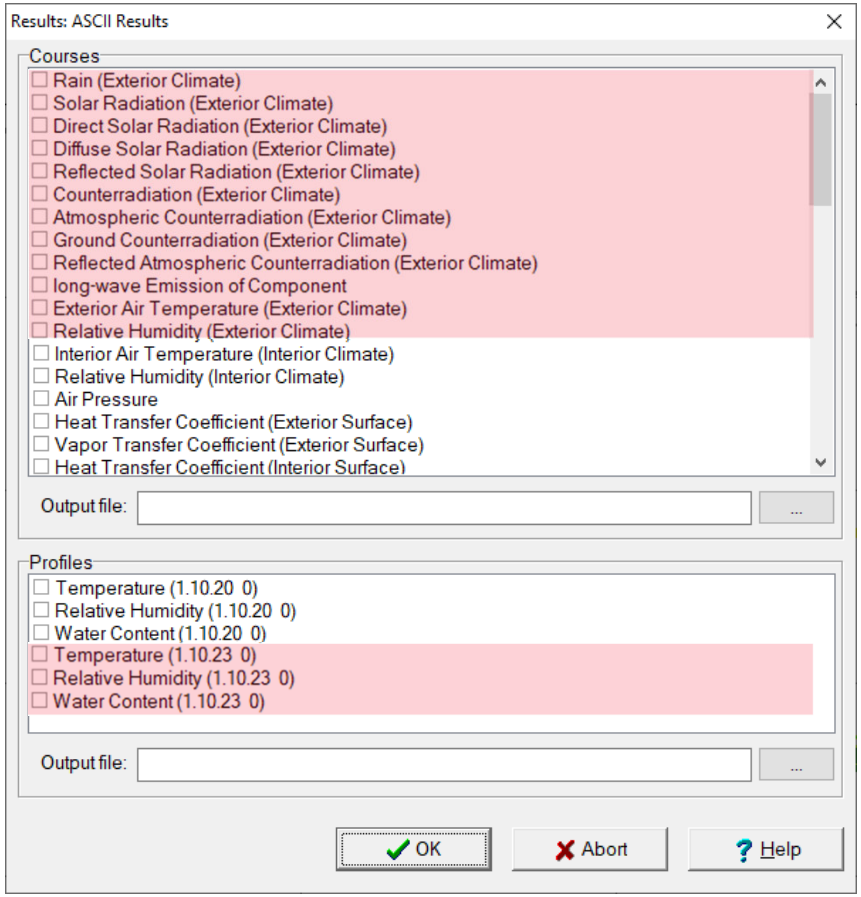


Tools for Result Evaluation – ASCII-Export

Output of boundary conditions and profiles:

- Output of ***boundary conditions***:
  - basically ***possible*** (e.g. solar radiation on the component surface, outside air temperature etc.)
  - ***blocked*** (elements are greyed out), if a climate file was used for the calculation which is only intended for use with WUFI® for license reasons

- ***Temperature-*** and/or ***water content profile*** of a calculation step can be used as the initial temperature- and/or initial water content profile for a further calculation.



Tools for Result Evaluation – Post Process Modules

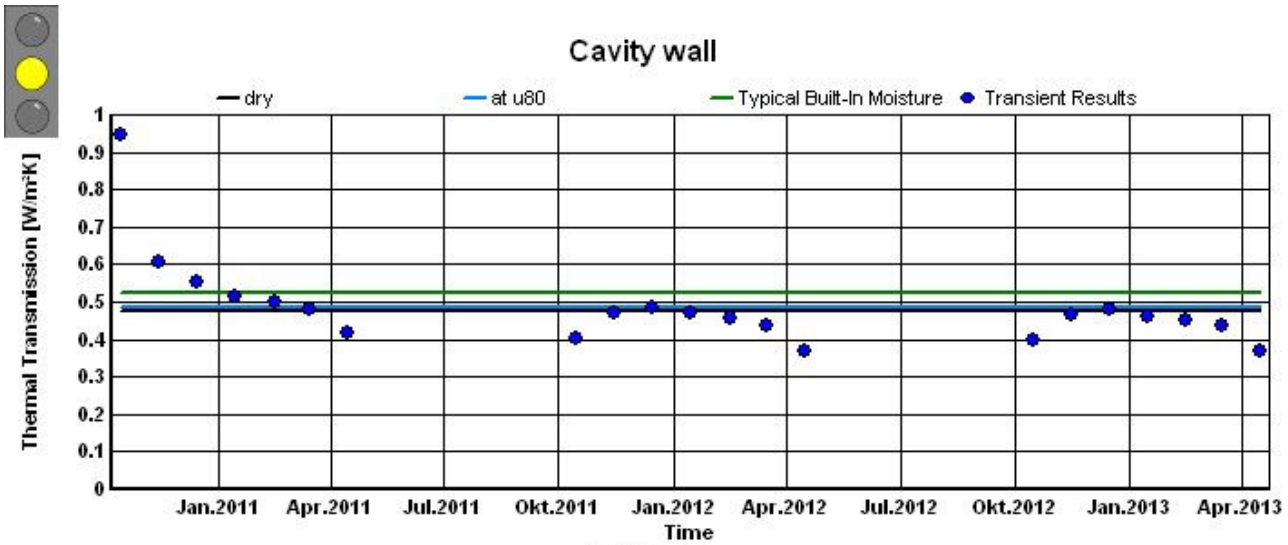
What are post process modules?

- WUFI® calculates the hygrothermal conditions in the component, but does not evaluate them.
- Post process modules are programs to which WUFI® can transfer the results of the hygrothermal calculation for further analysis.
- The modules are installed additionally or can also be programmed and made available by third parties.
- Available post process modules:
  - Thermal Transmission (transient U-value)
  - WUFI® Bio
  - WUFI® Corr
  - WUFI® VTT

  https://wufi.de/en/software/wufi-add-ons/

Tools for Result Evaluation – Post Process Modules

Thermal Transmission – Options for evaluation

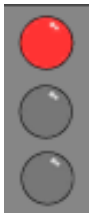


- Allows the ***transient evaluation of thermal transmission*** taking into account the influence of humidity, radiation, latent heat, etc.
- In the case of high radiation gains, the transient U-value may also become negative under certain circumstances, if the outside surface becomes warmer than the room air temperature despite a low outside air temperature.
- The ***evaluation*** is only useful ***during the heating period.***

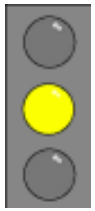
Thermal Transmission – Evaluation with traffic light system

- The traffic light limit values for U_1 and U_2 are based on the current and old minimum thermal insulation for hygienic reasons regulated in the German Standard DIN 4108-2
  - $U_1 \leq 0{,}73$ W/m²K or $R_1 \geq 1{,}2$ m²K/W → for mould-free conditions (Version 2003)
  - $U_2 \leq 1{,}39$ W/m²K or $R_2 \geq 0{,}55$ m²K/W → for condensation-free conditions (Version 1981)

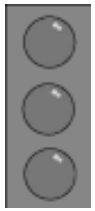
All evaluated months have a thermal transmission below U_1.



At least one of the evaluated months has a thermal transmission exceeding U_2.



All evaluated months have a thermal transmission below U_2, but at least one is above U_1.



Evaluation period is less than one year.

WUFI® Bio

- For the evaluation of mould growth under transient hygrothermal conditions.
- The moisture balance of the mould spores is modeled and compared with the critical water content where spore germination occurs.
- If germination occurs, the subsequent level of the mould infestation can also be estimated by comparison with growth curves.

More detailed information can be found in the **WUFI® Bio program help**

Tools for Result Evaluation – Post Process Modules

WUFI® Corr

- Allows the prediction of the corrosion risk of metal components in mineral building materials.
- The temperature and moisture conditions at the metal surface as well as the chemical milieu of the surrounding materials are taken into account.
- It allows the evaluation of preventive restoration measures, the refurbishment of listed buildings and a safe and durable design of new building components.

More detailed information can be found in the **WUFI® Corr program help**!

Evaluation Criteria

General:

- The results of a hygrothermal simulation are the courses over time of temperature, humidity and water content in the different material layers.
- The results can be evaluated individually and has to be assessed depending on the materials used.
- ***Evaluation criteria***:
  1. Moisture balance based on the total water content
  2. Moisture limit values (layers, positions)
     - Wood moisture
     - Increase in thermal conductivity
     - Condensation in fiber insulation
     - Mould growth
     - Risk of frost
     - Risk of corrosion

Evaluation Criteria – Moisture Balance based on Total Water Content

Hygrothermal behavior of a construction:

- ***No excessive amount of moisture should accumulate in the structure over the long term.***

- Initial increases or decreases in water content are normal if the specified initial water content is above or below the water content of the resulting steady state.

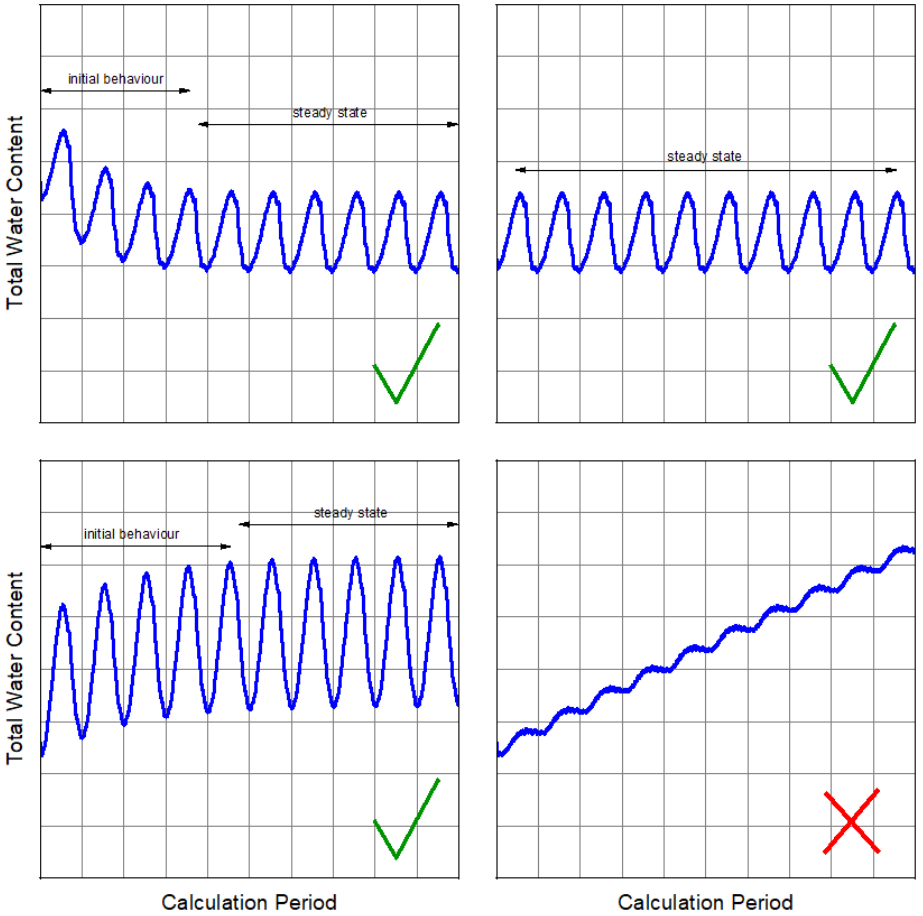
- ***Seasonal variations*** in total water content are also ***normal*** to a limited extent.

- Seasonal differences in the water content in the individual layers can be caused by the variations in the total water content or by periodical redistributions within the component.

Evaluation Criteria – Moisture Balance based on Total Water Content

Evaluation of the total water content

- ***Decreasing***: Component dries out
- ***No change over annual cycle***: steady state is reached (dynamic equilibrium)
- ***Short-term increase***: moisture level in steady state higher than the initial moisture level set; often unproblematic
- ***Long-term increase***: permanent moisture accumulation in the construction (higher wetting than drying – may be acceptable at low levels if no critical moisture conditions are reached during lifetime)



Evaluation of the moisture balance is only the first step,
the analysis must always include the water contents in the layers!!!

Evaluation Criteria – Moisture Limit Values: Wood Moisture

Established limit values:

- ***Limit values according to DIN 68800*** to prevent wood decay and strength loss:
  - 20 M.-% for wood
  - 18 M.-% for wood-based materials

  The limit values contain certain margins – only from a fiber saturation above about 25 to 30 M.-% can the fungi extract enough moisture from the wood to allow degradation of the material.

- ***WTA-Guideline 6-8***:
  Includes a model for a more precise assessment of the wood rot risk as a function of relative humidity and the simultaneously occurring temperature.

Evaluation Criteria – Moisture Limit Values: Wood Moisture

Evaluation according to WTA-Guideline 6-8:

- According to the WTA-Guideline 6-8, the evaluation is based on two criteria:

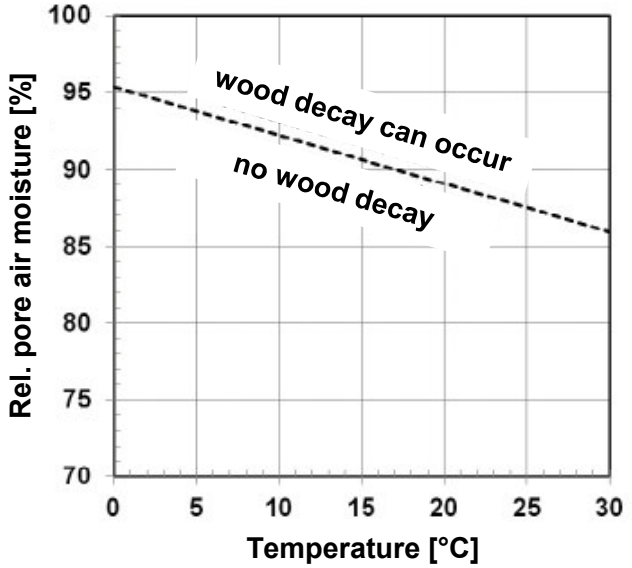
1. The ***evaluation with regard to wood-destroying fungi*** is carried out for wood on the basis of the average pore air moisture content of the relevant critical 10 mm layer.

2. For the ***evaluation of the constructive aspects*** the average wood moisture content of the entire material layer is used.

Evaluation Criteria – Moisture Limit Values: Wood Moisture

Wood rot risk according to WTA 6-8

- The evaluation of the wood rot risk according to WTA 6-8 applies to solid wood products (e.g. solid construction wood, glued or dowelled solid wood products, solid wood formwork, three-layer panels, glued laminated timber, solid wood panels).
- For wood-based materials and wood fiber insulation, the general limit of 18 M.-% from DIN 68800 can be used. Alternatively, the manufacturer can guarantee up to which wood moisture content his product may be used.
- The relative pore air moisture must not exceed 95 % at 0 °C and 86 % at 30 °C in on a daily average in the most critical 10 mm layer.



This evaluation is possible with WUFI® Graph.

Evaluation Criteria – Moisture Limit Values: Wood Moisture

Load-bearing capacity (strength of materials)

- Wood and wood-based materials are classified in service classes according to EN 1995-1-1. The usability according to these classes must be ensured.

- In general, the following limit values must not be exceeded for load-bearing components to ensure the declared properties:

	Solid wood	Wood-based materials
Permissible humidity (permanent)	20 M.-%	18 M.-%
Permissible humidity (during dry-out in the 1st year)	22 M.-%	20 M.-%

Daily mean value of the wood moisture of the entire material layer!

Evaluation Criteria – Moisture Limit Values: Wood Moisture

Usability

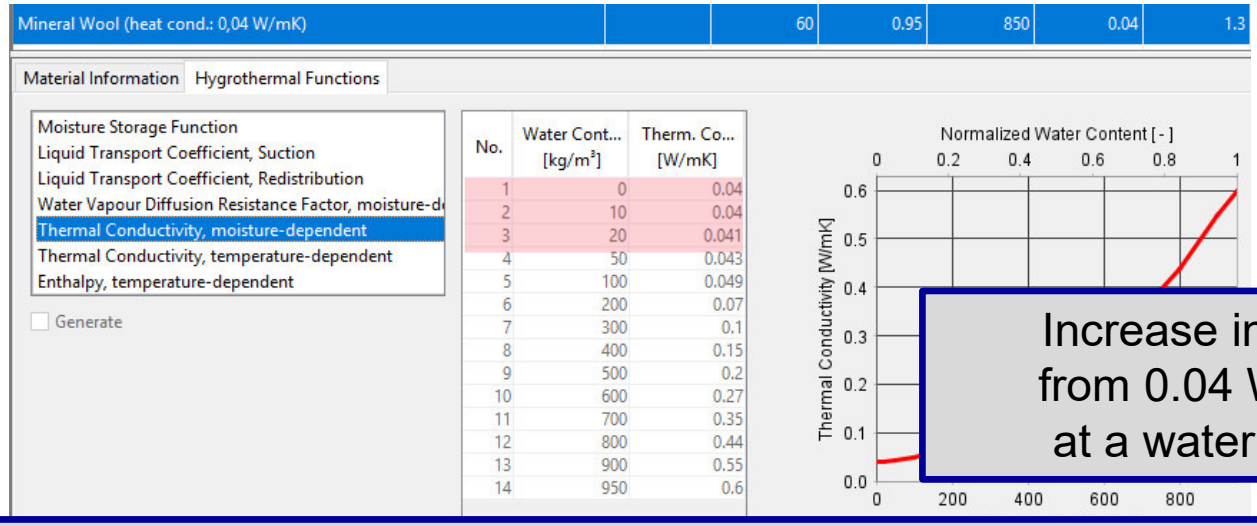
- Deformations of the overall construction e.g. due to seasonal moisture changes or an uneven moisture distribution in components.

- Deformations must remain within reasonable limits. Reference to limit values can be found in various standards such as e.g. EN 1995-1-1.

Evaluation Criteria – Moisture Limit Values: Increase Thermal Cond.

Increase of thermal conductivity in moisture-resistant insulation materials:

- Moisture absorbed via diffusion can lead to an increase in the thermal conductivity of moisture-insensitive insulation materials (rigid foam insulation or mineral fiber).
- This dependency is usually stored in the material data so that reasonable maximum values can be derived from it.



Increase in thermal conductivity from 0.04 W/mK to 0.041 W/mK at a water content of 20 kg/m³.

Unavoidable moisture inputs possibly can be compensated by greater insulation thicknesses if the moisture has no other negative effects.

Evaluation Criteria – Moisture Limit Values: Condensation in Fiber Insul.

Condensation on the cold side of fiber insulation:

- Rock wool and glass fiber insulation has low moisture storage.
  → Condensation on the cold side of the insulation is possible if moisture is introduced through diffusion!

- The amount of condensation should be limited so that no run-off of condensate can occur.

- DIN EN ISO 13788 recommends limiting the amount of condensation to 200 g/m² if the materials in the condensation area cannot absorb moisture.

Evaluation of the condensation amount according to
Guideline for assessing condensation problems in hydrophobic mineral fiber

Evaluation Criteria – Moisture Limit Values: Mould Growth

Mould risk assessment:

- Mould growth on the interior surface and in cavities at material boundaries is possible with higher humidity conditions.

- Assessment of the interior surface using the limit isopleths, which represent the minimum growth conditions.
  - Conditions remain below the limit curves:
    mould growth is not possible
  - Conditions exceed the limit curves:
    risk depends on the duration and degree of the exceedance
    → more precise evaluation possible with WUFI® Bio

More detailed information can be found in the
WUFI® Bio program help

Evaluation Criteria – Moisture Limit Values: Risk of Frost

Risk of frost in different materials:

- Due to the volume expansion of the freezing water, ***high water contents*** can weaken and ***damage a porous building material when a greater number of freeze-thaw cycles occur***.

- ***Frost-resistant materials*** such as plasters, masonry, concrete:
  - Water contents up to free water saturation usually acceptable
  - Please note: high moisture levels increase the risk of algae and mould on the outer surface.

- ***Non-frost-resistant materials***:
  - These must not exceed certain limit water contents during the frost period. However, no limit values for critical combinations of water content and temperature are known for most materials.

Evaluation Criteria – Moisture Limit Values: Risk of Frost

Assessment of the risk of frost according to WTA 6-5:

- Criterion according to WTA-Guideline 6-5 (for interior insulation):

  non-frost-resistant materials should not exceed a degree of moisture penetration of 30 % (i.e. 30 % of the maximum water content w_{max}). Higher levels of moisture penetration are permissible if the relative humidity of the pore air remains below 95 %.

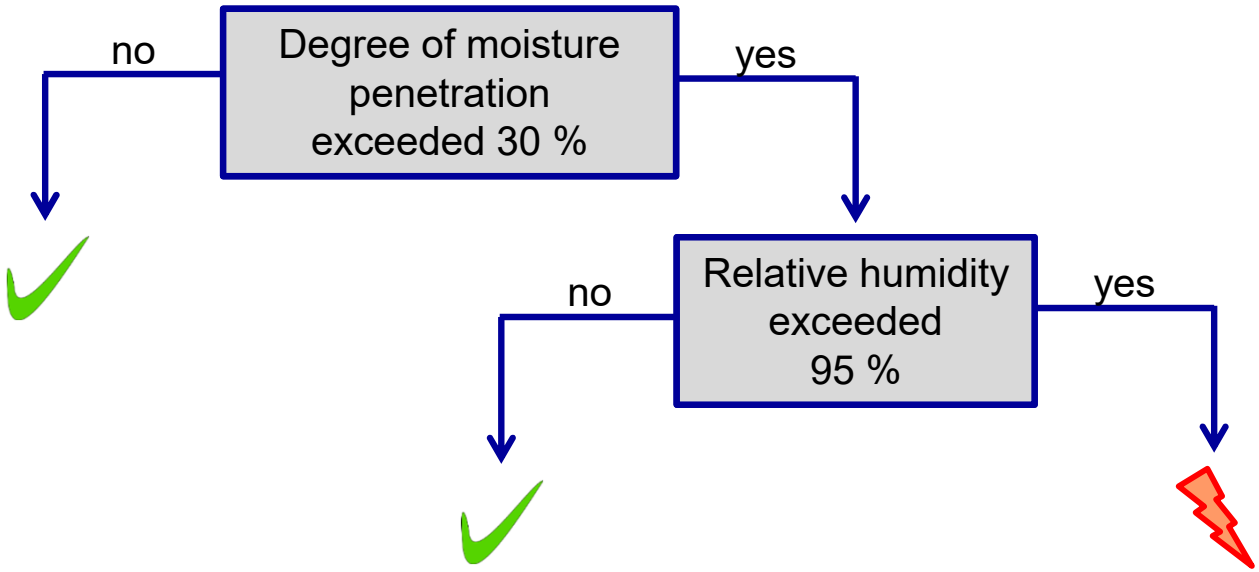
  → according to current information, this means that frost damage can be excluded for materials that are sensitive to frost.

- For ***materials with a high porosity*** (e.g. hollow bricks), the degree of moisture penetration of 30 % refers to the maximum water content in the brick shard itself – the voids must not be taken into account in the porosity.

Evaluation Criteria – Moisture Limit Values: Risk of Frost

Procedure for assessing the risk of frost:

- Evaluation of the water content at the most critical position of the frost-sensitive material.
- Find critical position / grid element using WUFI® film: position with high moisture content where the temperature is below 0 °C at the same time
- In the WUFI® film:
  right mouse button → Create Course
  then select the critical grid element



Evaluation Criteria – Moisture Limit Values: Risk of Corrosion

Corrosion risk assessment:

- Corrosion of metallic components, which are embedded in a mineral surrounding material, at high humidity (e.g. reinforcing steel in the concrete after its carbonation).

- Quantification of corrosion progress depending on temperature and relative air humidify in different mineral building materials.

More detailed information can be found in the **WUFI® Corr program help**!

Further Evaluation Criteria

Other possible evaluation criteria:

- Moisture-related softening
- Chemical behaviour
- Hygrothermal durability
- …

Since these are distinctly material-specific processes, an evaluation is only possible if the manufacturer can provide corresponding correlations or limit values.