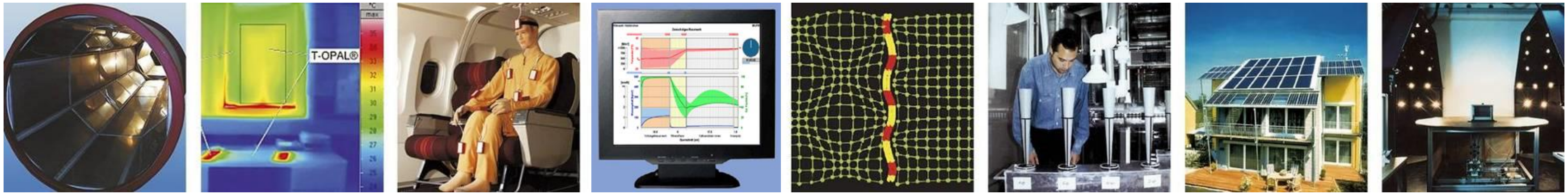

WUFI®

Guideline for Assessing the Risk of Corrosion with WUFI® Corr

Date: January 2024

Fraunhofer
IBP

Content

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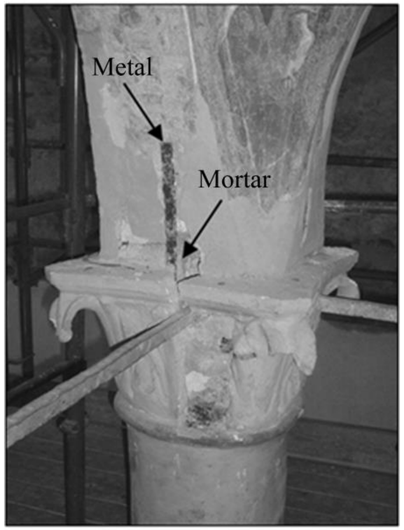
Basics: Cause of Corrosion

Corrosion of metallic fixings:

- Common cause of damage to old buildings
- **Corrosion** can occur when the **steel surface comes into contact with moisture** (e.g. condensate, rainwater, rising moisture).
  Exception: steel is protected by the alkalinity of the environment (e.g. in concrete).
- Corrosion can **weaken metal** and **create oxides** that expand and lead to detachment of the top layer

→ **Disadvantageous** for the **durability** of the construction

→ Challenge for refurbishment!
Possibilities: Limiting the rate of corrosion by controlling the temperature and humidity conditions in the component or in the indoor air



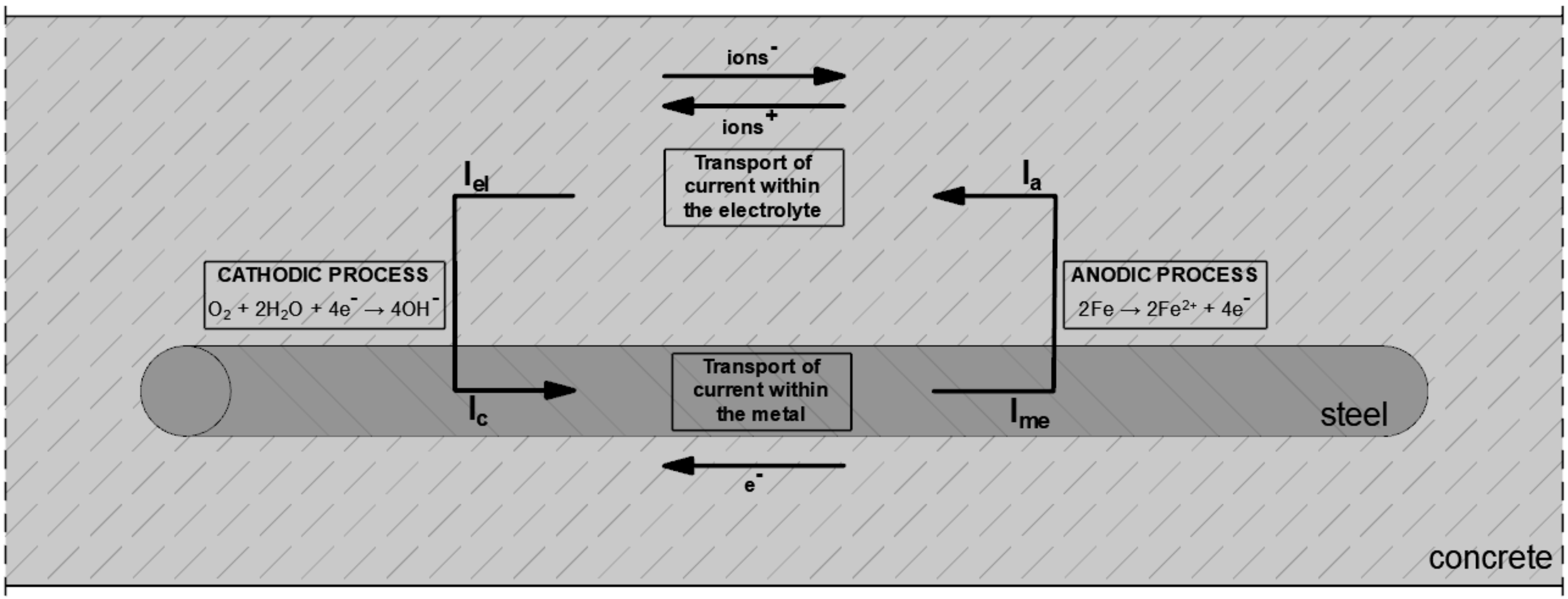
Corrosion behaviour of embedded metals:

- Depends on the steel itself, on the embedded material and on the moisture conditions.
- Is **influenced by** the **microstructure of the embedded material** and the **chemical composition of solution contained in their pores**.
- Corrosion rate depends on the availability of **water and oxygen** in the pores of the embedding material near the steel surface.
- **Temperature and relative humidity** of the environment **influence** the **electrical resistivity** of the building materials and thus also the **corrosion rate**.

In general: the lower the moisture content, the higher the electrical resistivity of these materials and the lower the corrosion rate of steel.

Basics: Mechanism of Corrosion

- **Circuit of the corrosion process**, where four complementary partial processes occur simultaneously, which means they occur at the same time and rate. → The **corrosion rate** will be **controlled by the slowest of the four partial processes**.
- The transport of current within the steel is always very fast and thus never has a limiting effect. The other three processes can occur very slowly and thus become the limiting ones.



Basics: Mechanism of Corrosion

The **corrosion rate becomes negligible** when one of the **following conditions exist**:

- The **anodic process is slow**, because the reinforcement is passive e.g. the steel is in contact with alkaline or non-carbonated mortars / concrete (unusual in historic constructions).
- The **cathodic process is slow**, because the rate at which oxygen reaches the surface of the reinforcement is low
  e.g. embedding material is permanently saturated by water (rare in buildings).
- The **electrical resistance** of the embedded material **is high**,
  e.g. if structure is exposed to dry environment with low relative humidity.

Three Stage Evaluation Procedure

For the evaluation of the corrosion risk of reinforcement in mortar / concrete, lime mortar and gypsum, the temperature and humidity conditions in the structure at the position of the embedded steel are determined using hygrothermal simulations and then evaluated according to following stages:

Stage I:

Evaluation of the limit moisture below which no corrosion is to be expected.

Stage II:

Evaluation using a temperature and moisture dependent limit curve

Stage III:

Evaluation of the corrosion behavior over time depending on the corrosion conditions and binder types

Three Stage Evaluation Procedure

Stage I:

Moisture at steel level

< 80 % RH for carbonated concrete
< 60 % RH for non-cementitious embedding materials

Here the lower moisture limit below which no corrosion is to be expected is used. For carbonated concrete, this is 80 % RH (NAVE report 2023). For other, non-cementitious embedding materials, the limit value is 60 % RH (ISO 13788:2013).

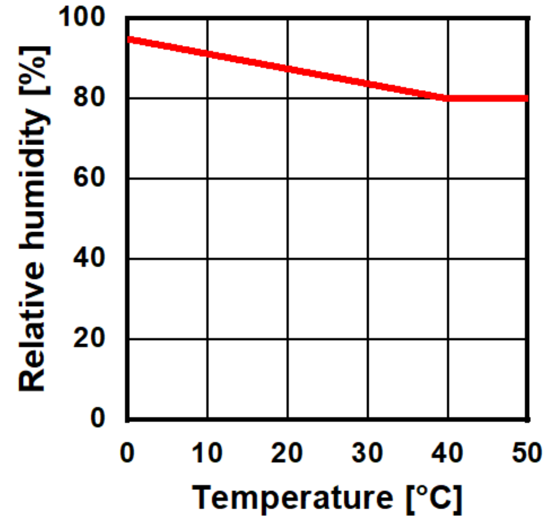
These criteria are clearly on the safe side. If the limits are not met, a more detailed design can be made for gypsum, lime and carbonated concrete/mortar, according to Stage II or Stage III. For other embedding materials, currently no specific information on corrosion of steel as a function of temperature and humidity conditions are available.

Three Stage Evaluation Procedure

Stage II:

The hourly values must remain below the temperature and moisture dependent limit curve

$$f(\vartheta) = \begin{cases} -0{,}375\vartheta + 95, & 0°C < \vartheta < 40°C \\ 80 & \vartheta \geq 40°C \end{cases} \quad [\%]$$

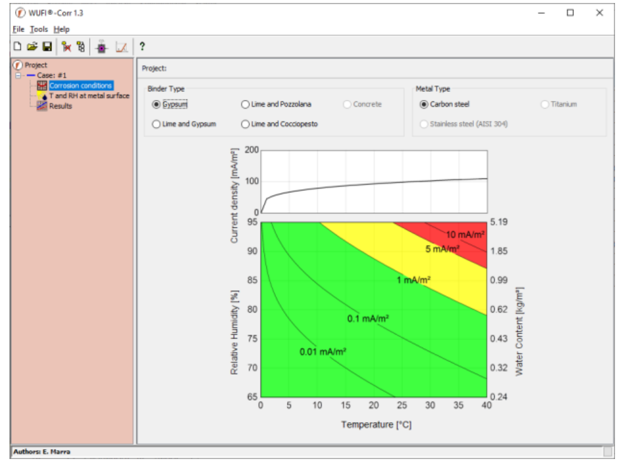


In evaluation stage II, the evaluation of the corrosion risk in carbonated mortar / concrete, lime mortar and gypsum in the reinforcement level is carried out via a temperature and moisture dependent limit curve according to the equation above. This limit curve represents a safe-side simplification of the transition to the critical (yellow) region of the corrosion maps for concrete in stage III. If the hourly values are below the limit curve, no corrosion is expected; for values above the limit curve, corrosion conditions are present, and it is recommended to perform a more detailed evaluation using stage III.

Three Stage Evaluation Procedure

Stage III:

Determination of the time depending corrosion behavior using corrosion maps.



In stage III, the evaluation of the corrosion risk in carbonated mortar / concrete, lime mortar and gypsum in the reinforcement level is carried out depending on the corrosion conditions and binder types (using corrosion maps) and thus the temporal corrosion behavior of the steel is determined. This can be done via the postprocessor WUFI® Corr, which is described on the following slides.

traffic light evaluation scheme

	I_{corr} [mA/m²]	Loss [µm/25years]
	≤ 1	≤ 30 µm
	≤ 5	≤ 150 µm
	> 5	> 150 µm

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WUFI® Corr: Description of the Model

- The corrosion model describes the **effect of the environmental and material factors affecting corrosion of steel inserts** embedded in building components.
- It allows the **prediction of the corrosion rate** of steel inserts in porous building materials **over time** depending on temperature and relative humidity at the steel surface.
- The model allows:
    - Preventive conservation / restoration (of cultural heritage buildings)
    - Safe design (of new building components)
    - State-of-preservation assessment (if material sampling is not possible)
    - Design of measures to reduce / prevent corrosion of steel inserts

Download-Link: WUFI® Add-ons | WUFI (en)

WUFI® Corr: Experimental Data

- The model is based on **laboratory tests**, mainly **focused on heritage buildings and materials**.
- Prediction of the corrosion in mortar and bricks is possible.
- Following **four different kinds of mortars** were considered:
  - Two aerial mortars:
    gypsum and a mixture of lime and gypsum
  - Two hydraulic mortars:
    blending lime with two different types of hydraulic additions: Pozzolana (powdered volcanic minerals) and Cocciopesto (crushed clay bricks)
- The experimental studies are divided into **two different humidity ranges**:
  - The first one considered a humidity range up to the sorption equilibrium at 95 % RH (hygroscopic region).
  - The second one takes place at saturation.

WUFI® Corr: Research Results

- In the corrosion behaviour of steel inserts in masonry, **temperature, relative humidity and water content play a key role**.
- **Clear correlation between** the **corrosion rate** of steel **and** the **electrical resistivity** of each embedding material.
  → the lower the resistivity of the embedding material, the higher the corrosion rate of the inserts.
- The resistivity can be related to both the temperature and the relative humidity of the environment
  → correlation between the corrosion rate and the hygrothermal conditions of the environment.
- The corrosion rate is negligible in samples exposed to 65 % and 80 % RH (even at 40 °C).
- The corrosion rate reaches high values in wet environments or during the presence of liquid water.

WUFI® Corr: Calculation Model

- Hygroscopic region (up to 95 % RH):
  - Exponential relationship between corrosion rate, temperature and relative humidity.

$$i_{corr,1} = d_1 \vartheta \cdot e^{(a_1 \cdot \vartheta + b_1 \cdot RH + c_1)} \quad (1)$$

- Saturation (with partial submersion):
  - Power relationship between corrosion rate and temperature

$$i_{corr,sat} = a_{sat} \cdot \vartheta^{b_{sat}} \quad (2)$$

In case of 0 °C, corrosion rate is set to zero!

- Capillary water region (95 to 100 % RH)
  - Mathematical approach, as it is difficult to precisely measure the moisture content in this high humidity levels.

$$i_{corr,2} = i_{corr,sat} \cdot \frac{(k-100) \cdot RH}{k - RH} \cdot \frac{1}{100} \quad (3)$$

$$k = a_2 \cdot \vartheta^{b_2} + c_2 \quad (4)$$

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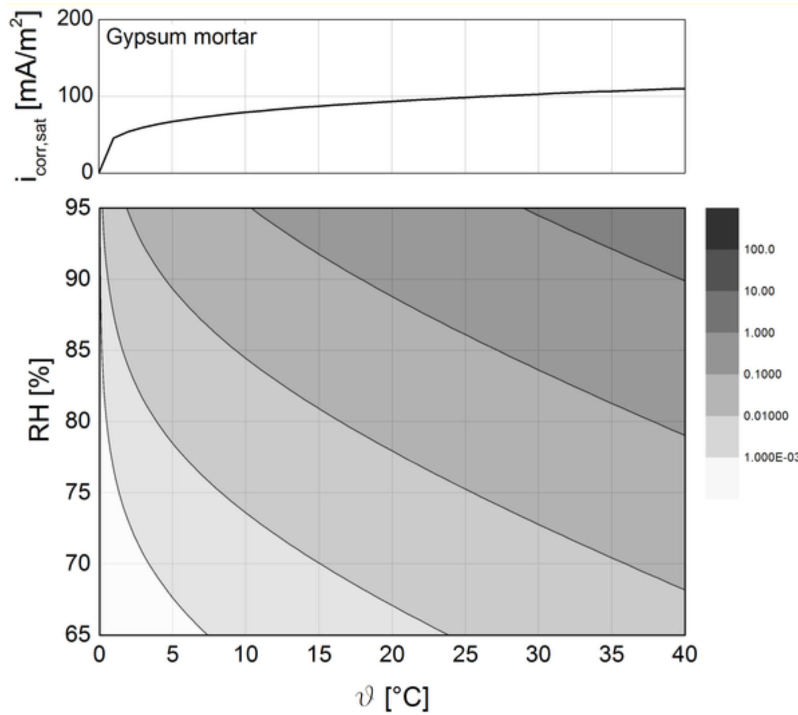
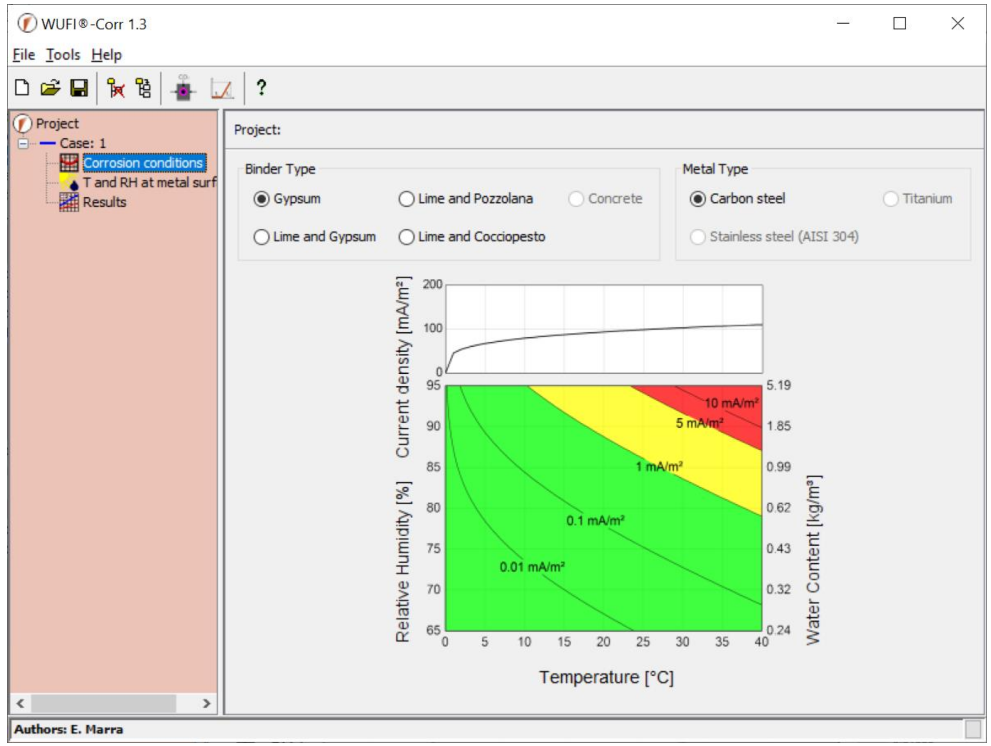
WUFI® Corr: Calculation Model

- Using equation (1) a corrosion map can be created for the specific material.
- On x- and y-axis temperature and relative humidity are plotted. The isolines represent the corrosion rate in a logarithmic scale and the different grey-scale gradations correspond to different rates of corrosion. The range of the graph is limited to the range of the laboratory tests (RH up to 95 %).
- In the upper part of the figure the corrosion rate as a function of temperature at saturation is represented, according to equation (2).



WUFI® Corr: Input Data

- Corrosion conditions are determined by the **selection of the binder / embedded material and the metal** (currently only carbon steel available).
- The type of embedding material influences the corrosion behaviour of the steel with its microstructure and the chemical composition of the pore solution. Included at the moment:
  - Gypsum
  - Lime and Gypsum
  - Lime and Pozzolana
  - Lime and Cocciopesto



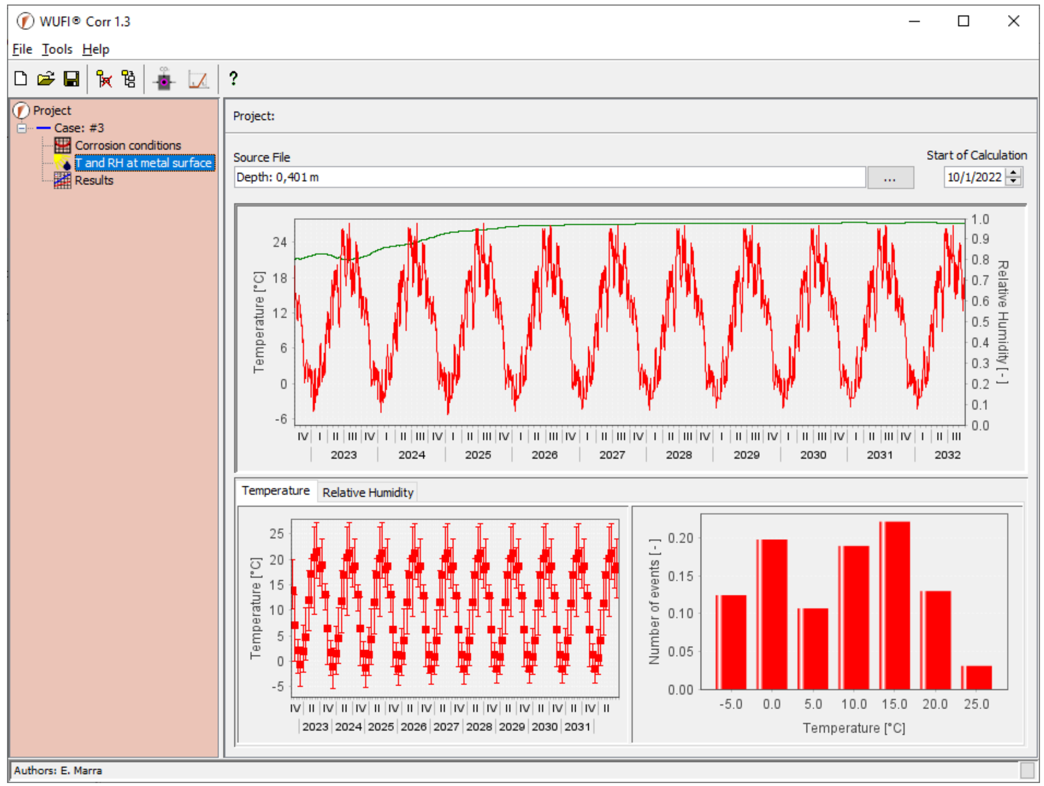
WUFI® Corr: Input Data

Notes:

- **Concrete** itself **as well as the traffic light scheme** (slide 10) have **not** yet been **implemented,** since investigations on the corresponding scales and limits are still going on.
- Simplified and on the safe side, **carbonated concrete** can be **considered** in the simulation **by a hydraulic mortar** (preferably lime-pozzolana), since this is most similar to concrete in its chemical composition of the pore solution.
- To account for a **more aggressive mineral environment**, one of the **gypsum mortars (pH about 4.5 – 6) can be used**.

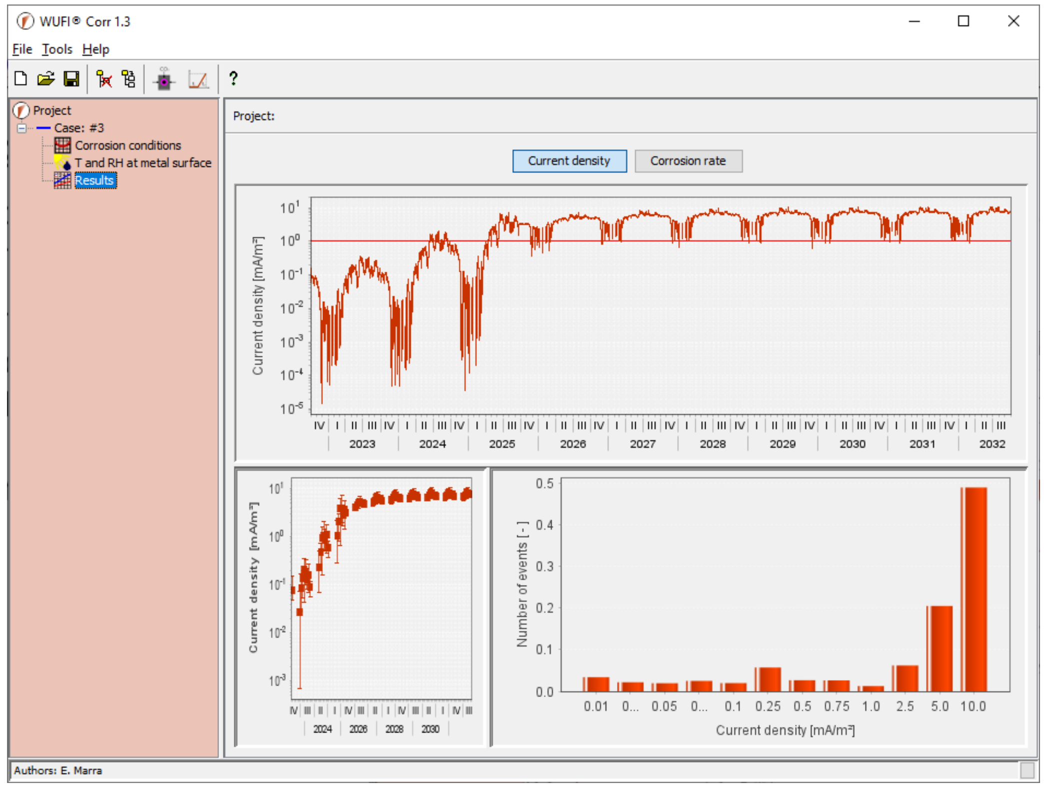
WUFI® Corr: Input Data

- The **transient local hygrothermal conditions** (hourly values for temperature and relative humidity) **at the contact surface** between the steel and its embedding material (measured or from a hygrothermal simulation).
- When opening WUFI® Corr from Animation1D, the climate conditions are automatically transferred to WUFI® Corr and displayed.
- Otherwise, temperature and relative humidity can be imported manually.



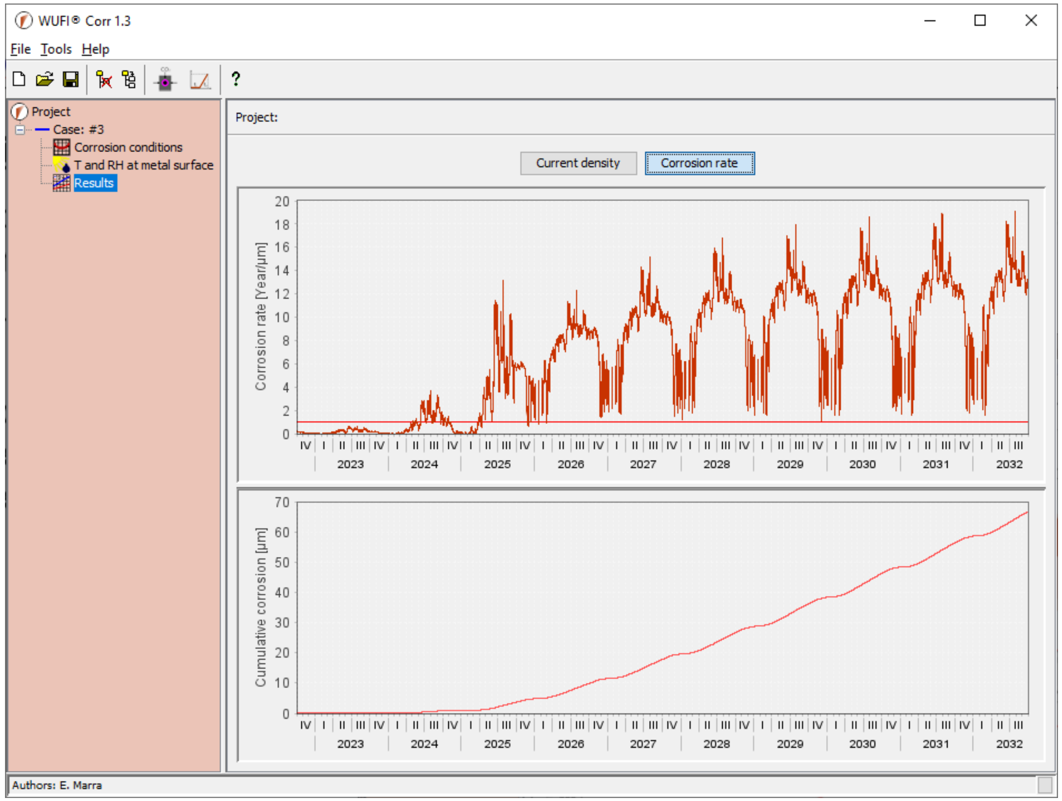
Current density [mA/m²]

- Top diagram: calculated corrosion rate of the metallic insert over time given as current density [mA/m²] and the critical threshold.
- Bottom diagrams: monthly mean values (left) and the frequency values of the current density (right).



Penetration rate [µm/year]

- Top diagram: calculated corrosion rate of the metallic insert over time given as penetration rate density [µm/year] and the critical threshold.
- Bottom diagram: Cumulative penetration of corrosion in the metallic insert during the whole period of calculation.

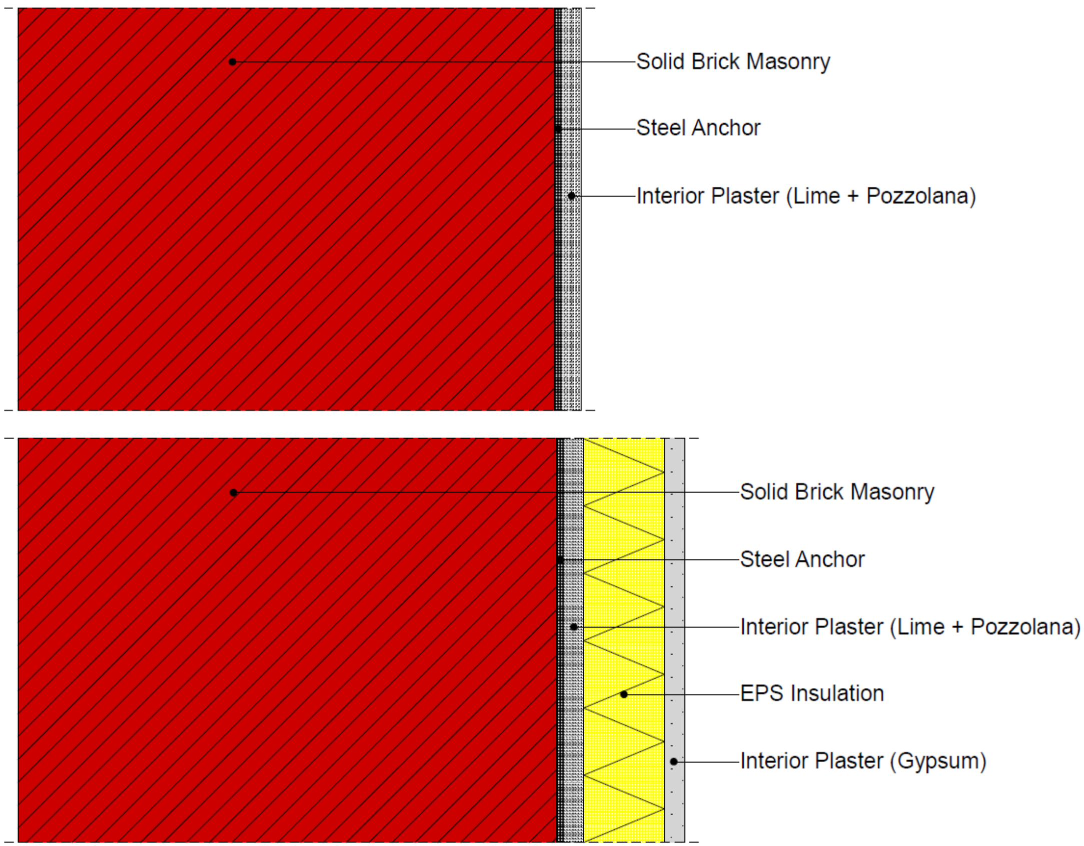


WUFI® Corr: Evaluation of the Results

- The **calculation result** is meant to provide a semi-quantitative **criterion for comparing and ranking different construction variants**.
- The traffic light scheme on slide 10 can be used as a first suggestion for corrosion in carbonated concrete.
- If the corrosion rate exceeds the critical threshold only by a small amount or for a short period, corrosion should not necessarily be expected in a real building component, since the model contains a few safety factors to make sure that the prediction “no corrosion” can be relied on.
- **Note:** Corrosion rate is generally assumed negligible if lower than 1 µm/year and severe if above 10 µm/year.

Examples – Description of the Problem

The procedure for assessing the corrosion risk is explained using the example of an uninsulated exterior wall (Example A) and an exterior wall with interior insulation (Example B) with a steel anchor.



Example A: Component Assembly and Boundary Conditions

Assembly:

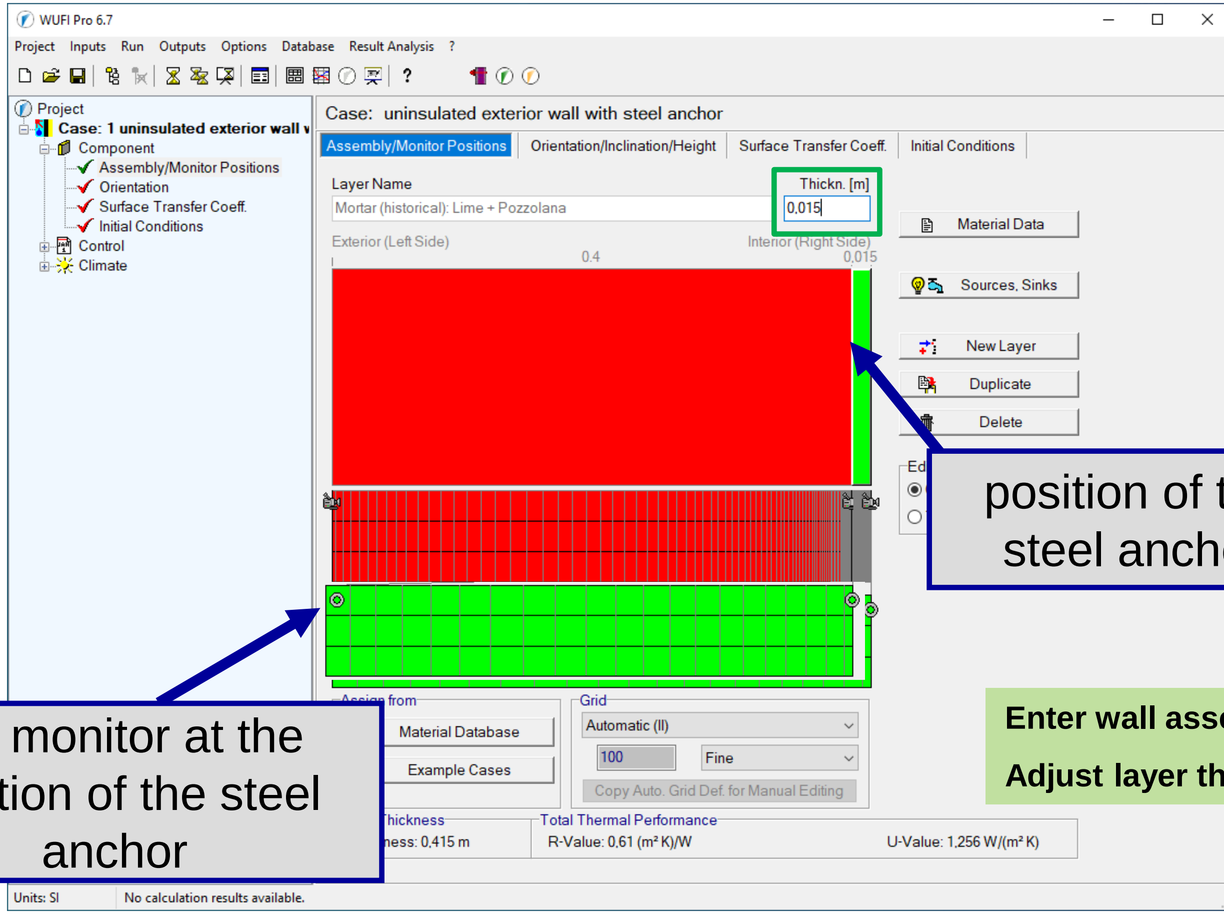
• Solid Brick Masonry	0.4	m
• Interior Plaster (Lime + Pozzolana)	0.015	m

Boundary Conditions:

- Exterior wall, orientated to the West
- Red Brick (a = 0.68)
- Outdoor climate: Holzkirchen
- Indoor climate: Medium moisture load +5%
- Calculation period: 25 years
  (for easier application to the traffic light scheme)

Example A: Component Assembly

Input: Component - Assembly / Monitor Positions



position of the steel anchor

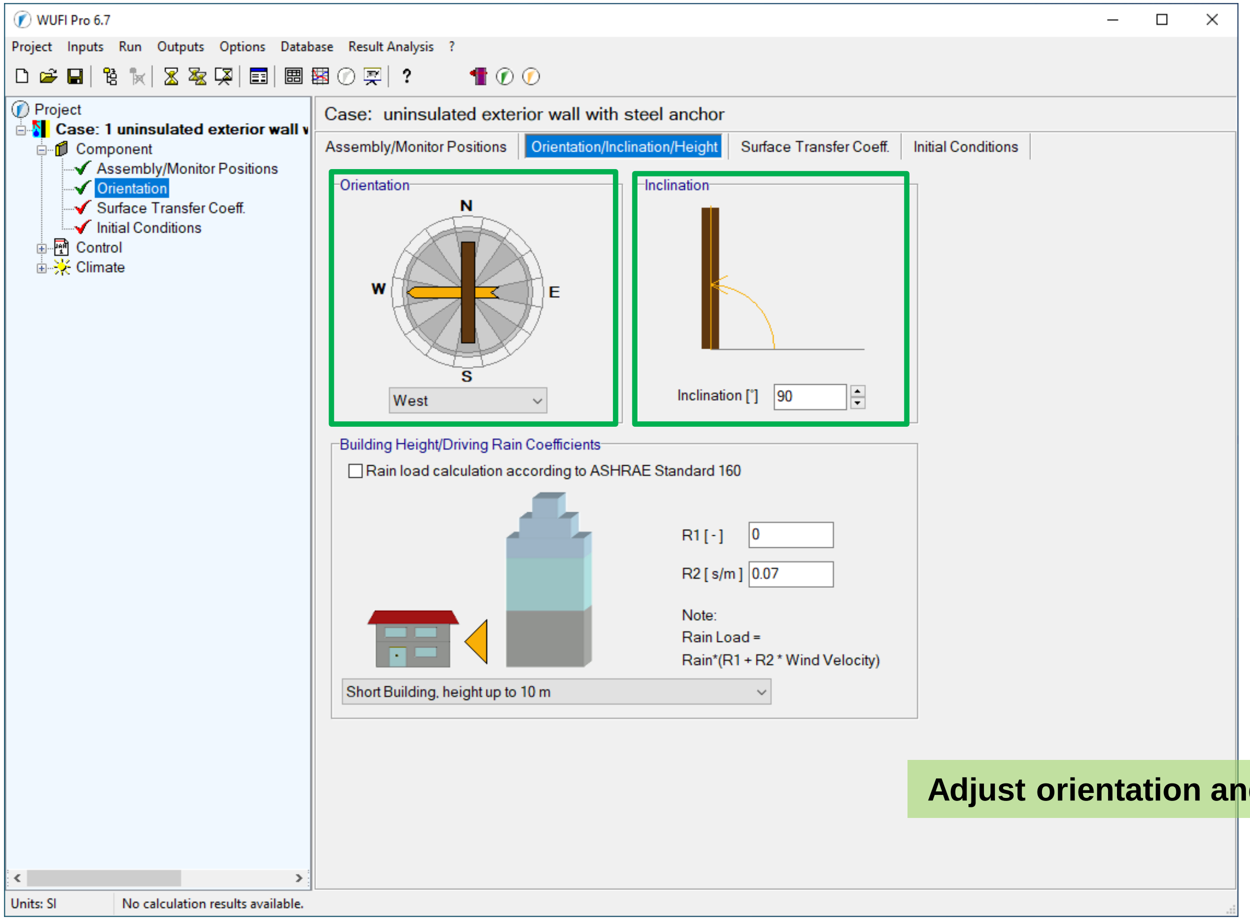
Set monitor at the position of the steel anchor

Enter wall assembly

Adjust layer thicknesses if necessary

Example A: Orientation and Inclination of the Component

<u>Input:</u> Component - Orientation



Adjust orientation and inclination

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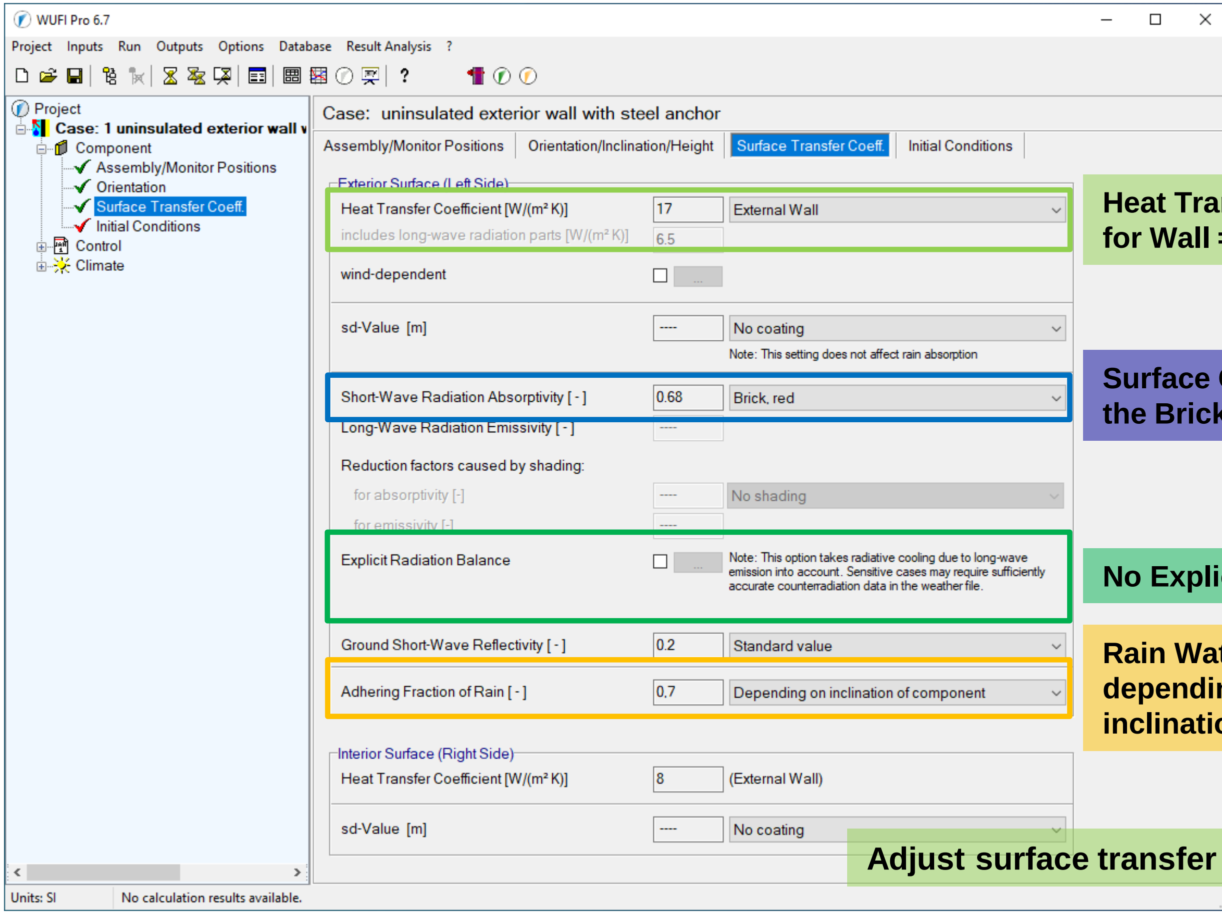
Example A: Surface Transfer Coefficients

Input: Component – Surface Transfer Coefficients



Heat Transfer Coefficient for Wall = 17 W/m²K

Surface Color of the Brick Masonry (a = 0.68)

No Explicite Radiation Balance

Rain Water Absorption depending on inclination of component

Adjust surface transfer coefficients!

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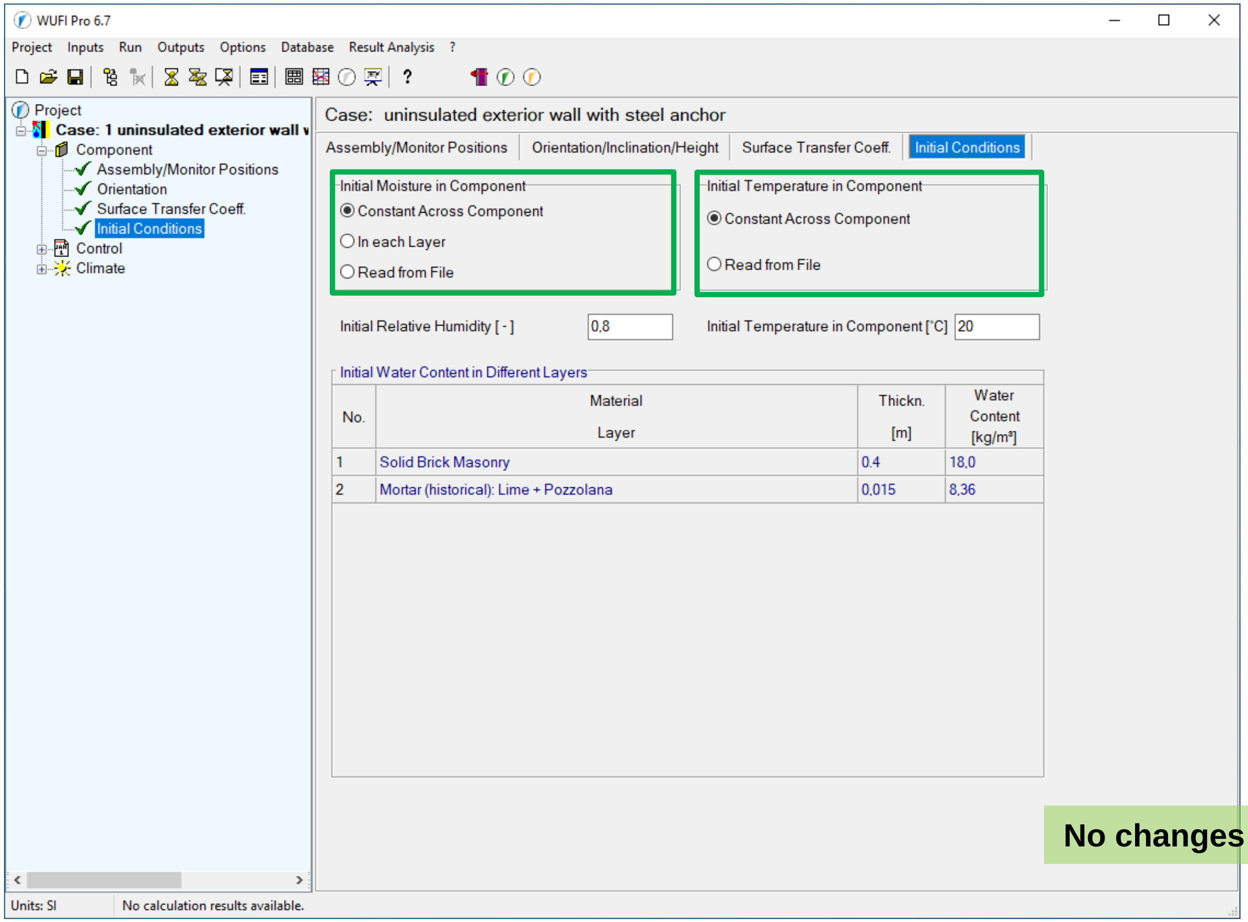
Example A: Initial Conditions

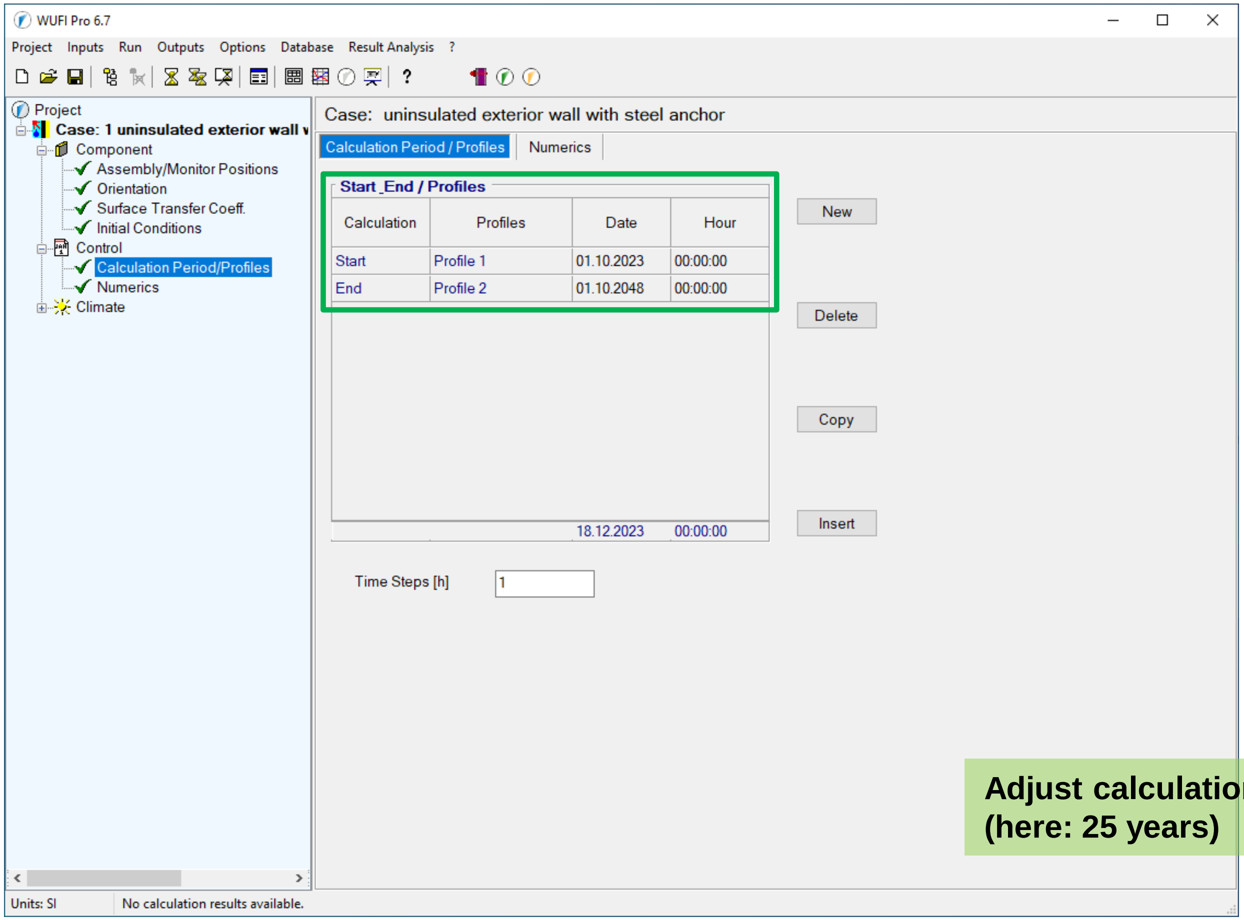
<u>Input:</u> Component – Initial Conditions



No changes required

Example A: Calculation Period

Input: Control – Calculation Period / Profiles



Adjust calculation period (here: 25 years)

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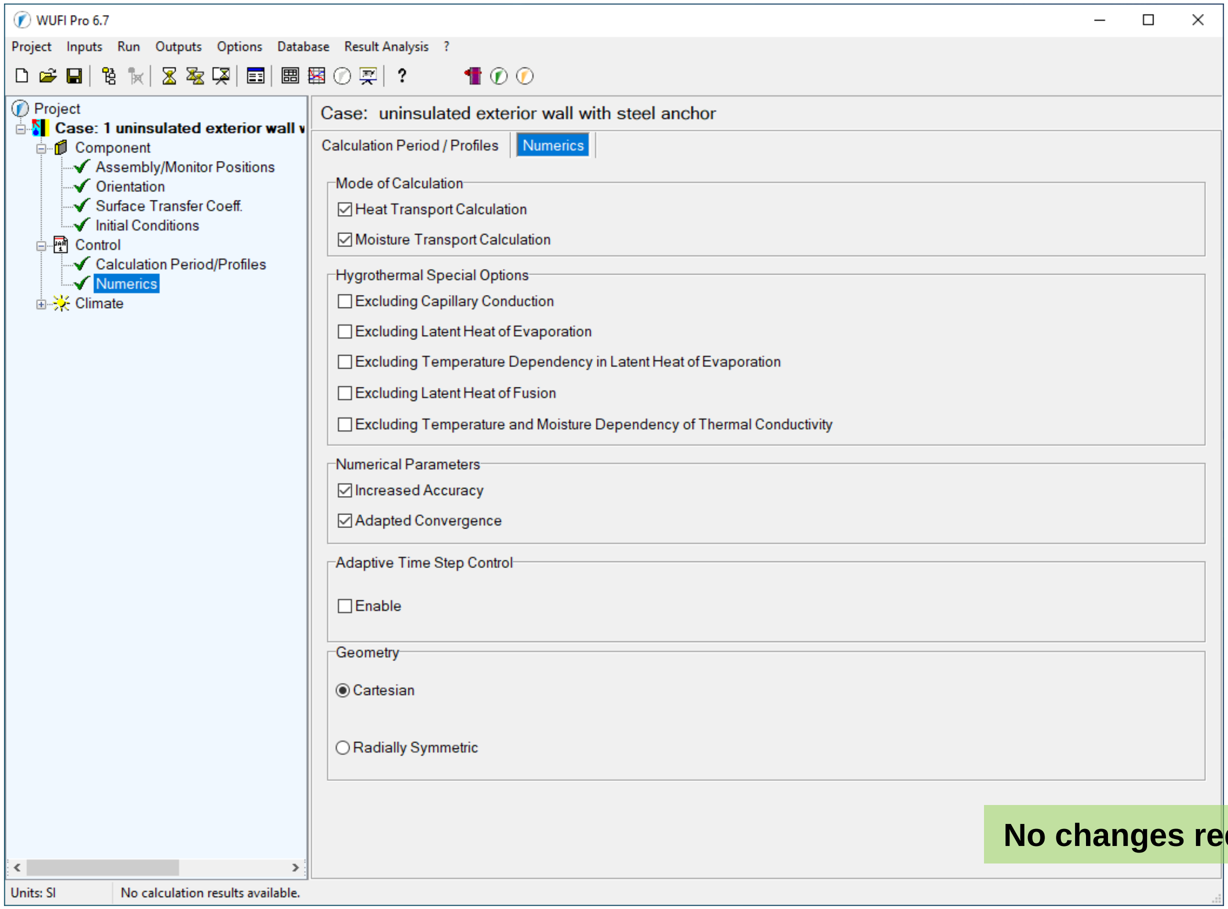
Example A: Numerics

Input: Control – Numerics



No changes required

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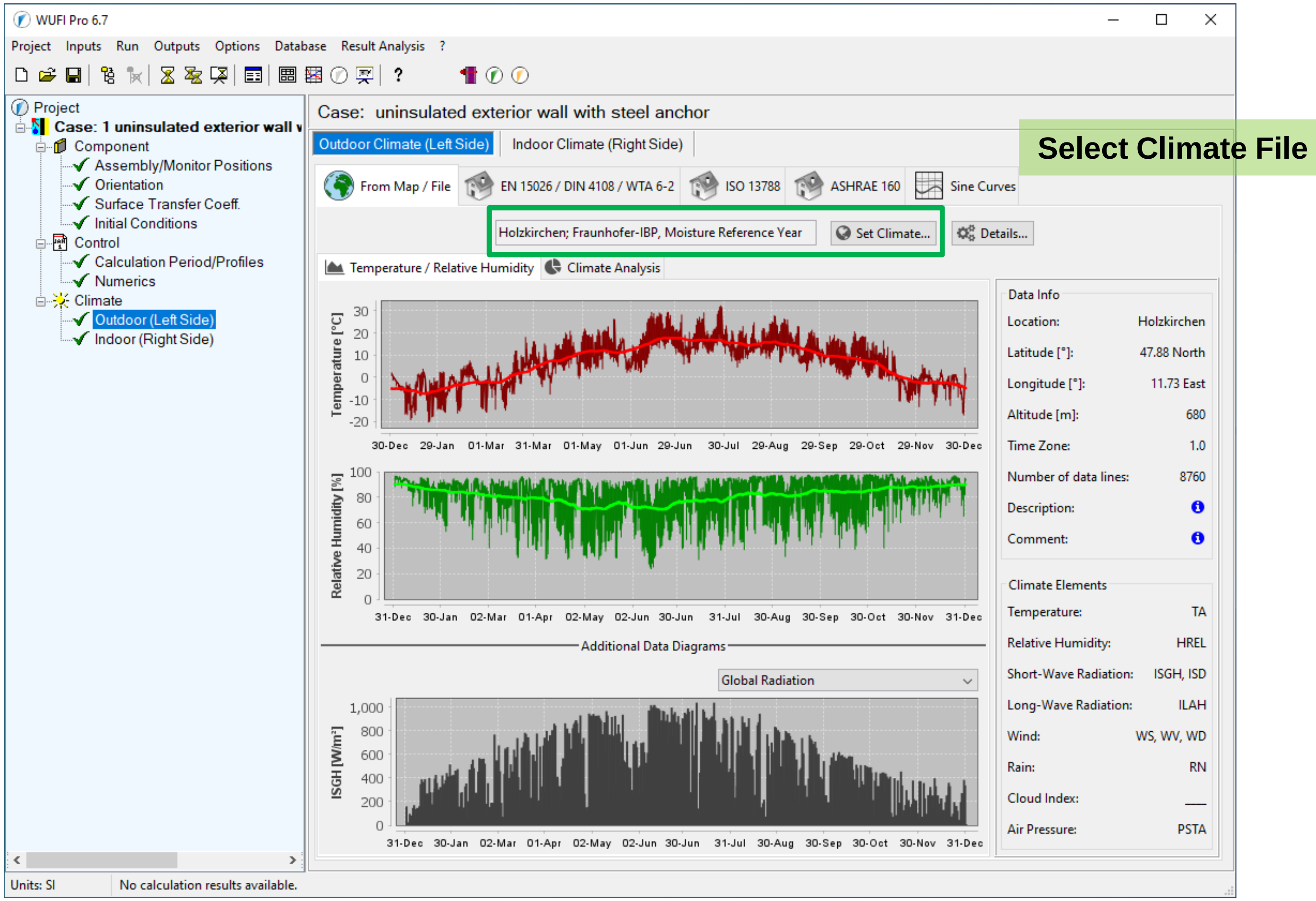
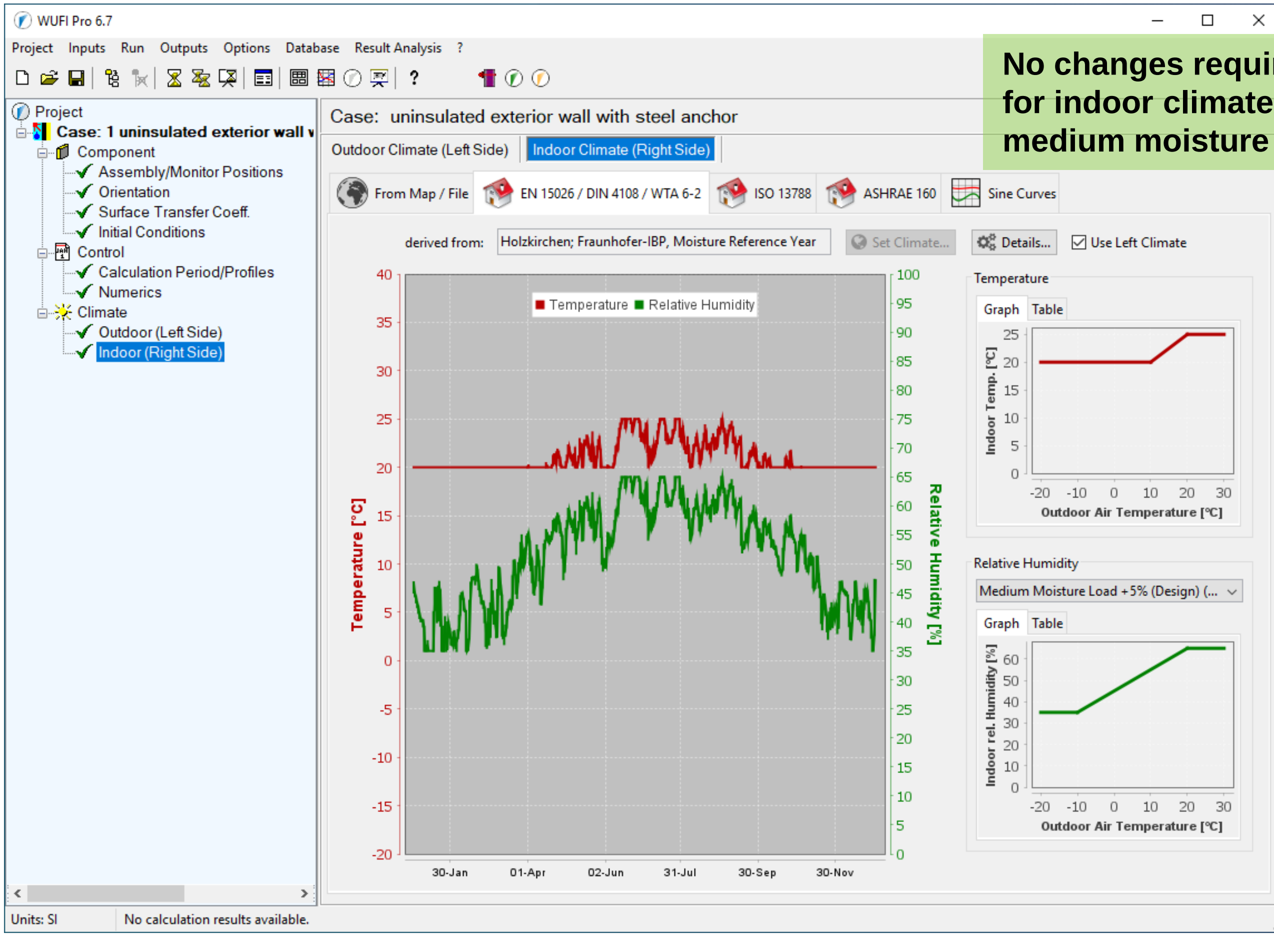
Example A: Outdoor Climate

<u>Input:</u> Climate – Outdoor (Left Side)



Example A: Indoor Climate

Input: Climate – Indoor (Right Side)



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

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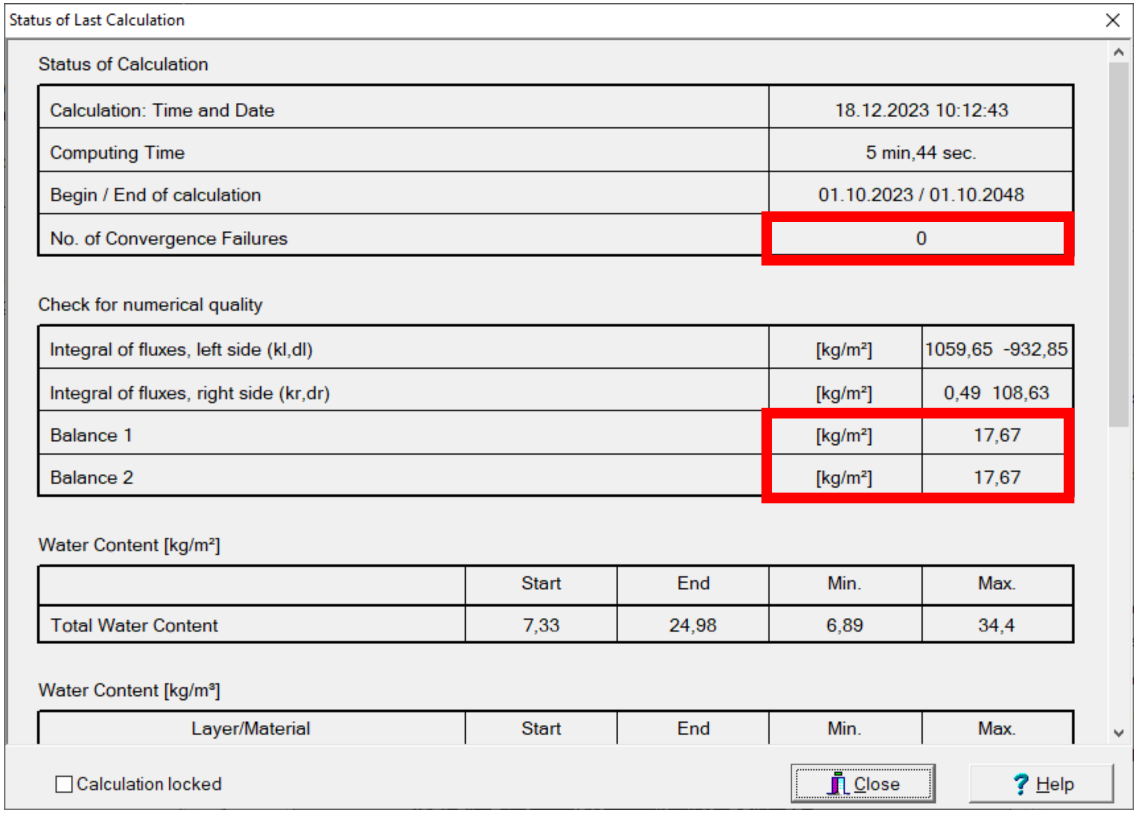
Example A: Evaluation - Numerics

<u>Evaluation:</u> Numerics



Status of Last Calculation

Status of Calculation

Calculation: Time and Date	18.12.2023 10:12:43
Computing Time	5 min,44 sec.
Begin / End of calculation	01.10.2023 / 01.10.2048
No. of Convergence Failures	0

Check for numerical quality

Integral of fluxes, left side (kl,dl)	[kg/m²]	1059,65 -932,85
Integral of fluxes, right side (kr,dr)	[kg/m²]	0,49 108,63
Balance 1	[kg/m²]	17,67
Balance 2	[kg/m²]	17,67

Water Content [kg/m²]

	Start	End	Min.	Max.
Total Water Content	7,33	24,98	6,89	34,4

Water Content [kg/m³]

Layer/Material	Start	End	Min.	Max.

Calculation locked

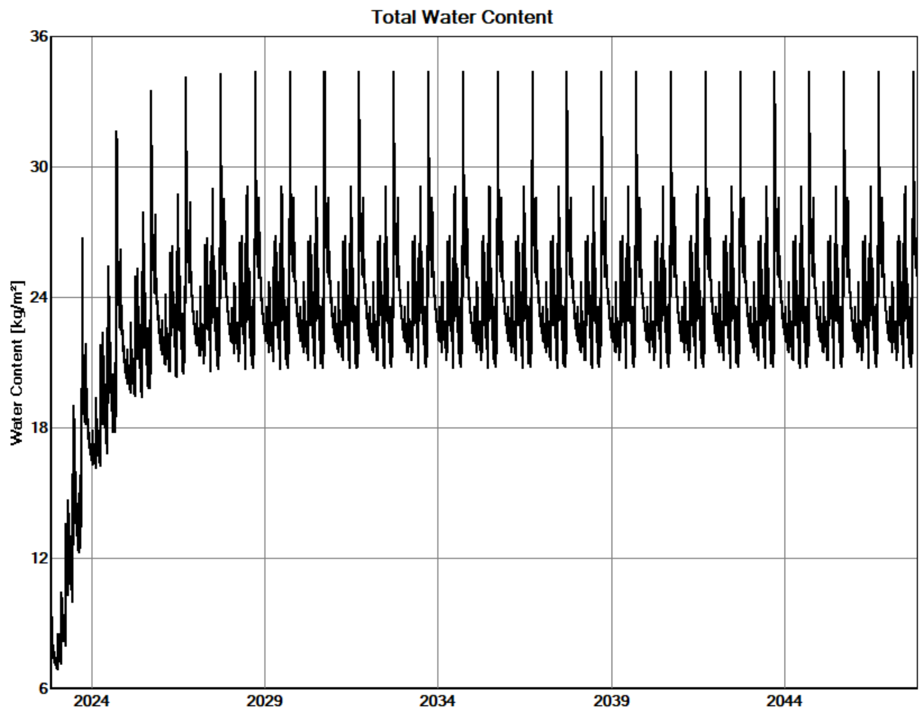
Close

Help

No convergence failures and no balance differences!

Example A: Evaluation Total Water Content

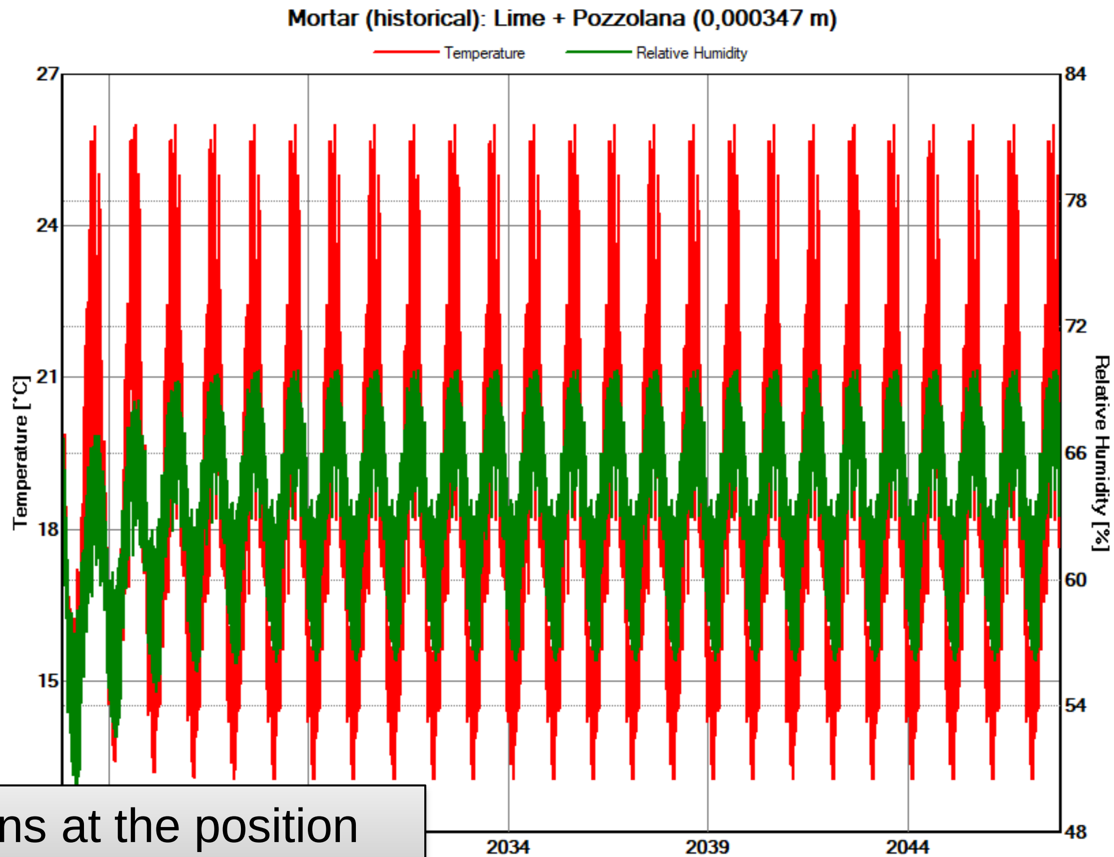
Evaluation: Total Water Content



Steady state conditions after 5 years.

Example A: Evaluation Moisture Conditions at Steel Anchor

Evaluation: Monitor at the position of the steel anchor

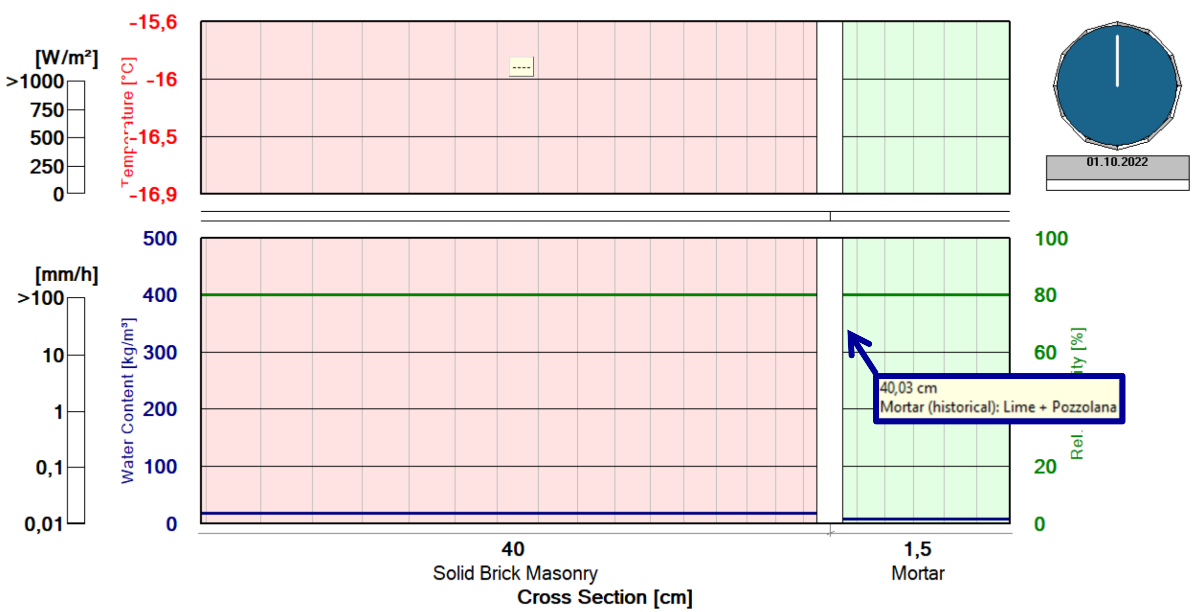


Local conditions at the position of the steel anchor

Example A: Evaluation Moisture Conditions at Steel Anchor

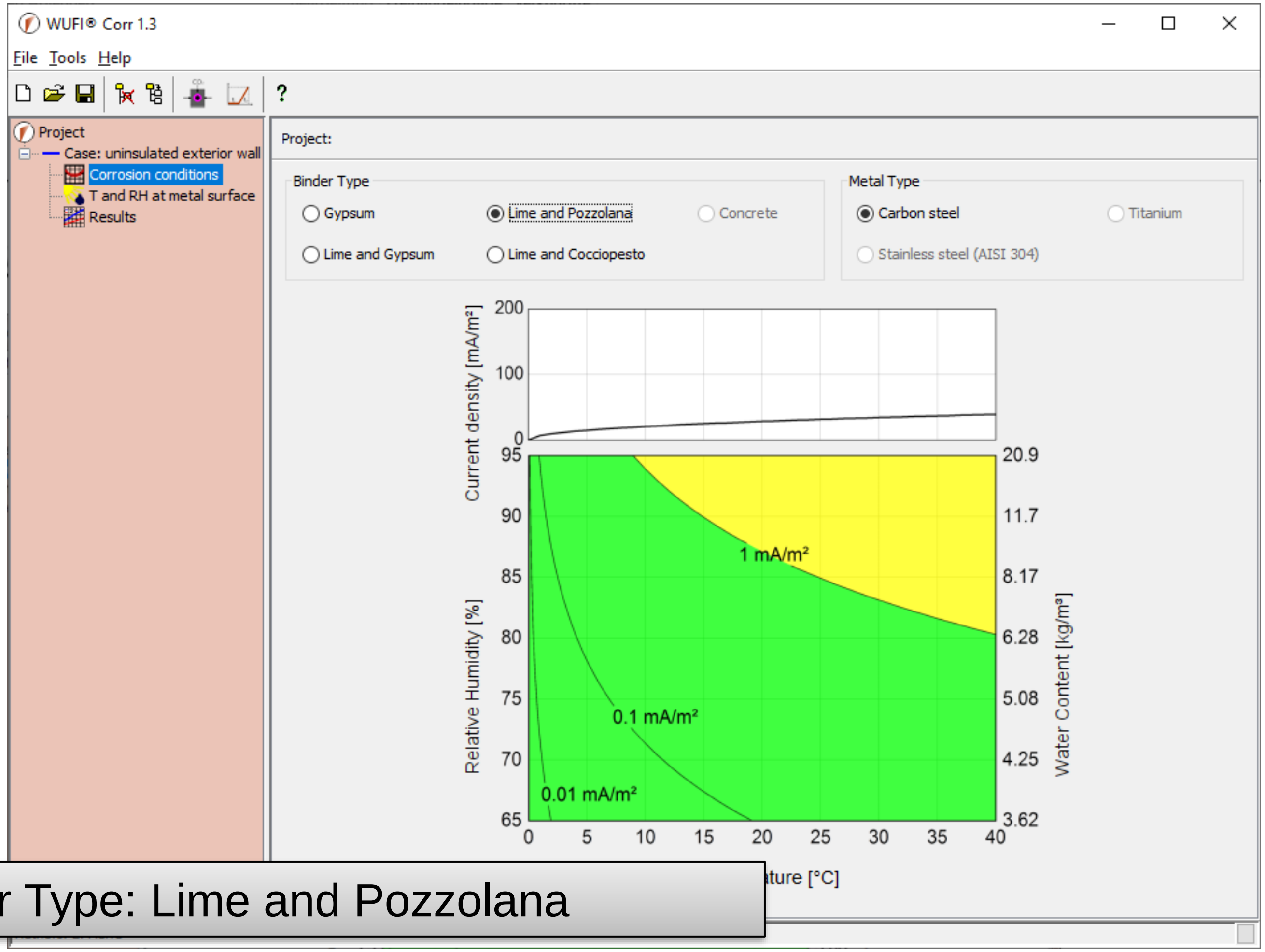
Evaluation: Corrosion risk at the position of the steel anchor

- Open WUFI® Animation
- Zoom in on the boundary layer of solid brick masonry / interior plaster (while holding down the left mouse button: drag the box from top left to bottom right)
- Press the WUFI® Corr icon  in the task bar and select the outermost element of the interior plaster.



Example A: Settings WUFI® Corr

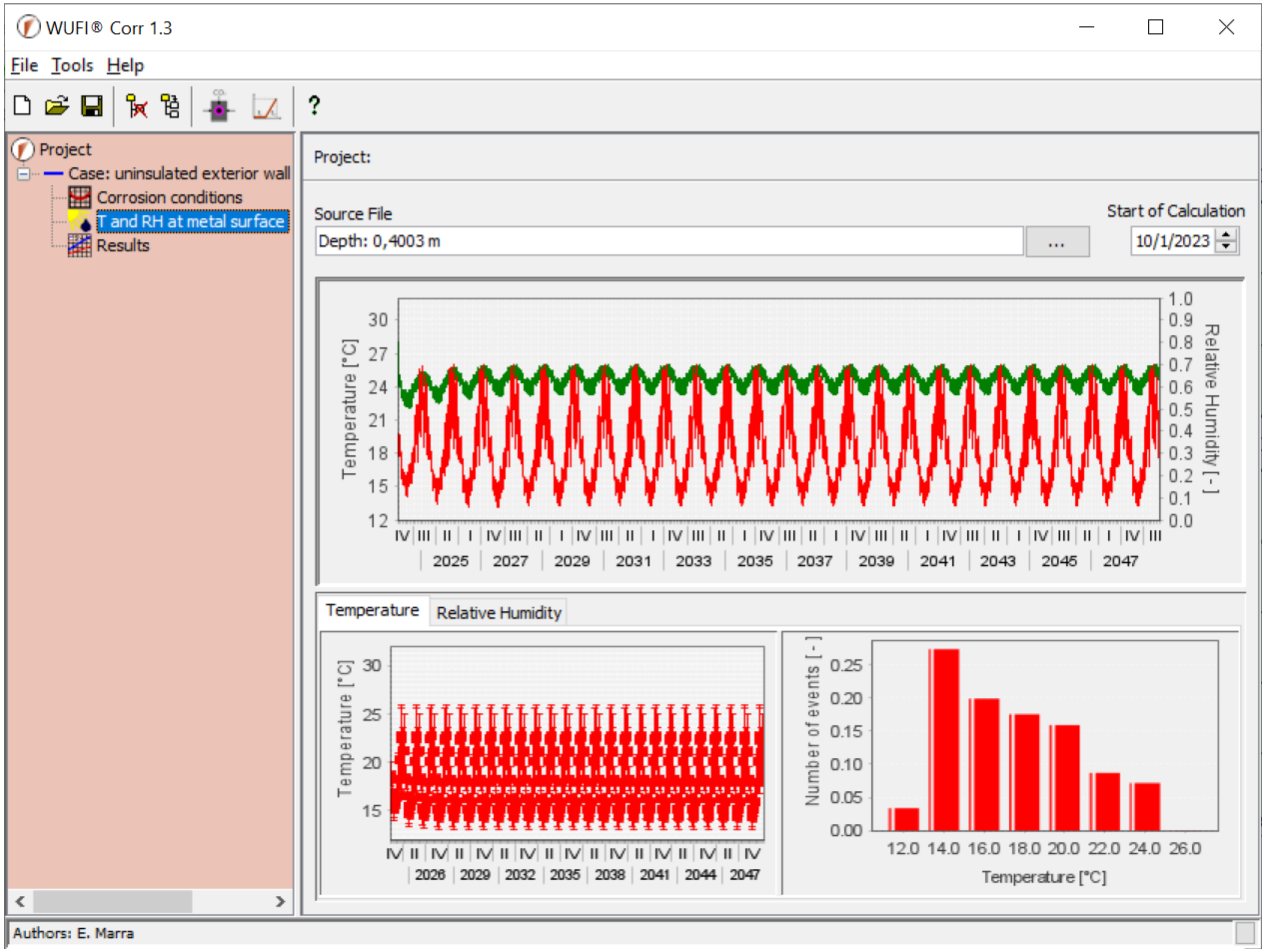
Evaluation: Corrosion risk at the position of the steel anchor



Binder Type: Lime and Pozzolana

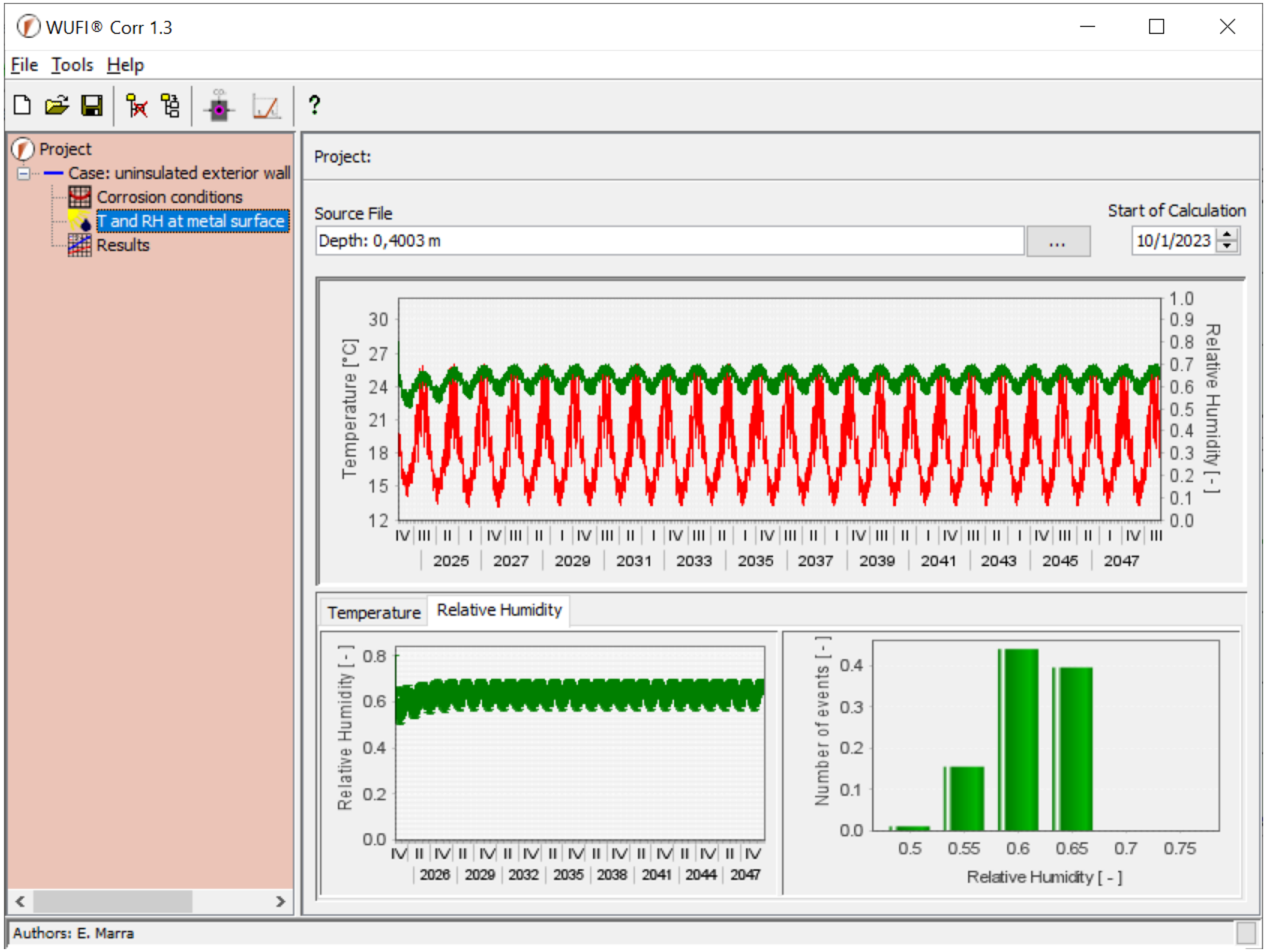
Example A: Settings WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



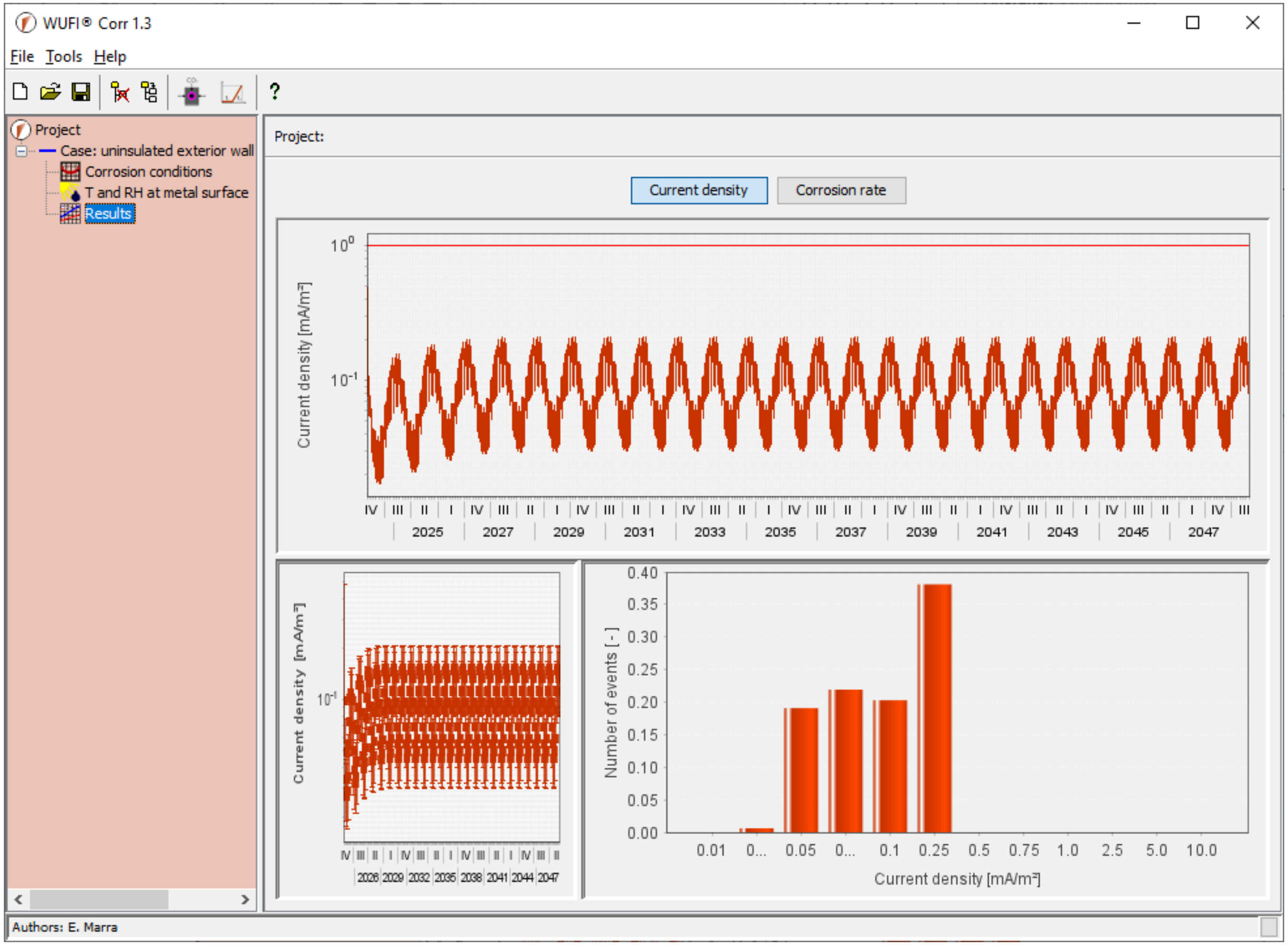
Example A: Settings WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



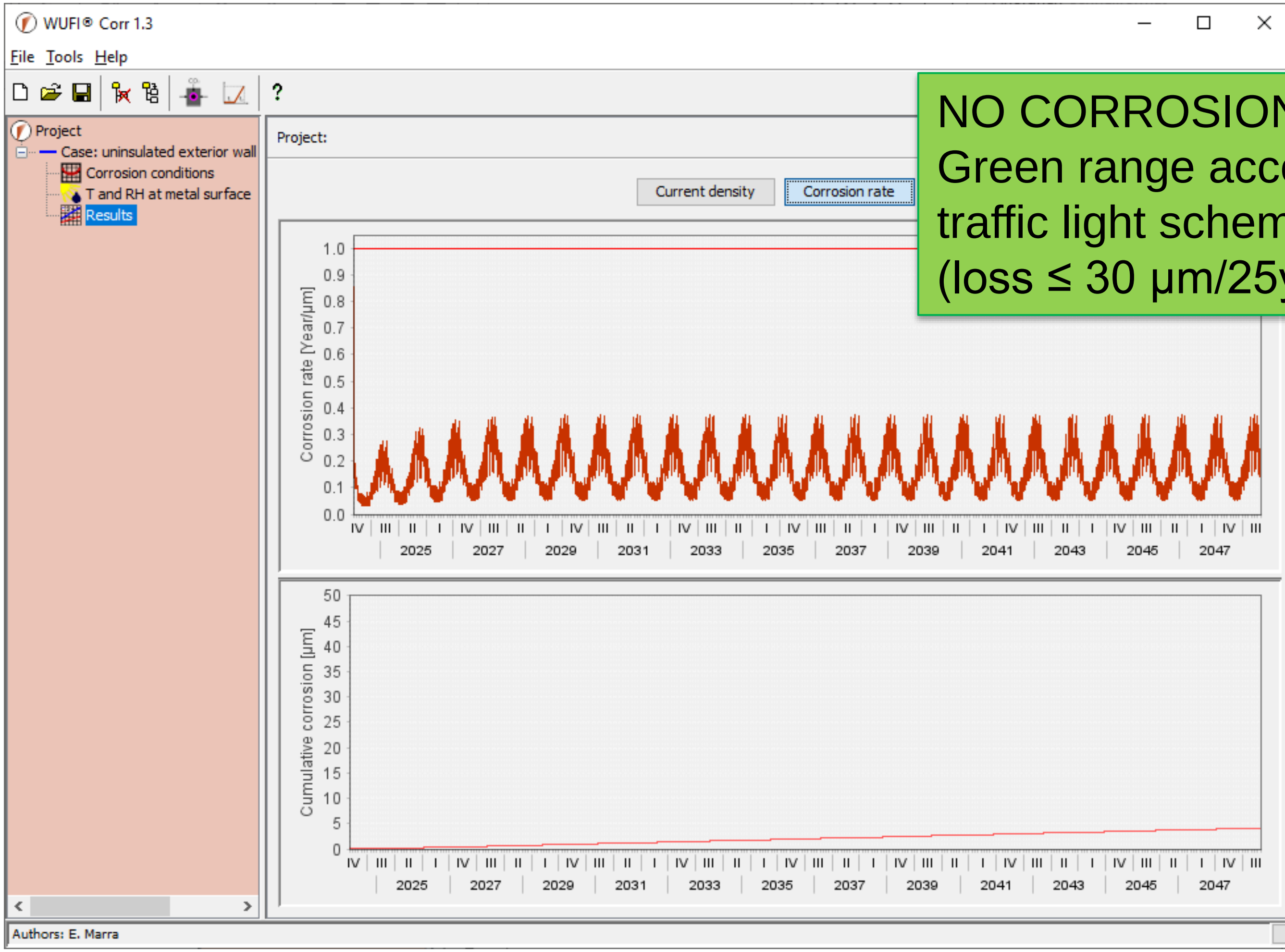
Example A: Evaluation WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



Example A: Evaluation WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



NO CORROSION!
Green range according to the traffic light scheme on slide 10 (loss ≤ 30 µm/25years).

Example B: Component Assembly and Boundary Conditions

Assembly:

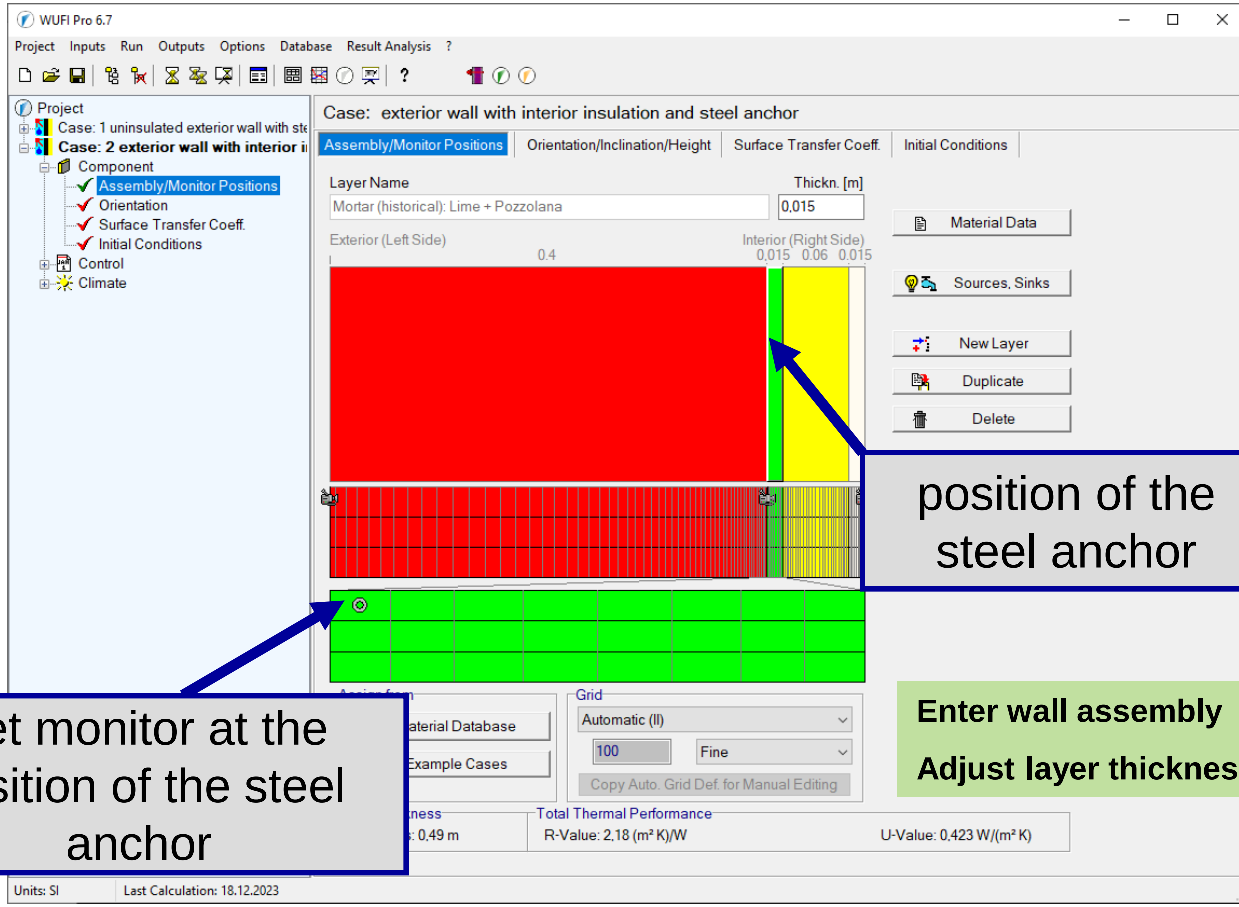
• Solid Brick Masonry	0.4	m
• Interior Plaster (Lime + Pozzolana)	0.015	m
• EPS (heat cond.: 0.04 W/mK – density: 15 kg/m^3)	0.06	m
• Interior Plaster (Gypsum)	0.015	m

Boundary Conditions:

- Exterior wall, orientated to the West
- Red Brick (a = 0.68)
- Outdoor climate: Holzkirchen
- Indoor climate: Medium moisture load +5%

Example B: Component Assembly

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



position of the steel anchor

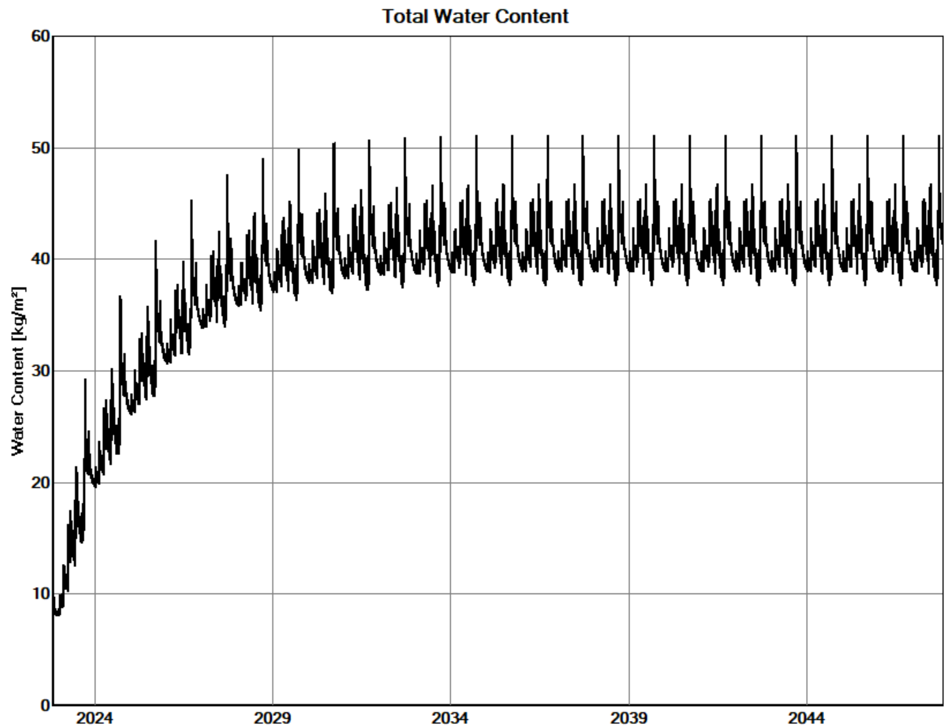
Set monitor at the position of the steel anchor

Enter wall assembly

Adjust layer thicknesses if necessary

Example B: Evaluation Total Water Content

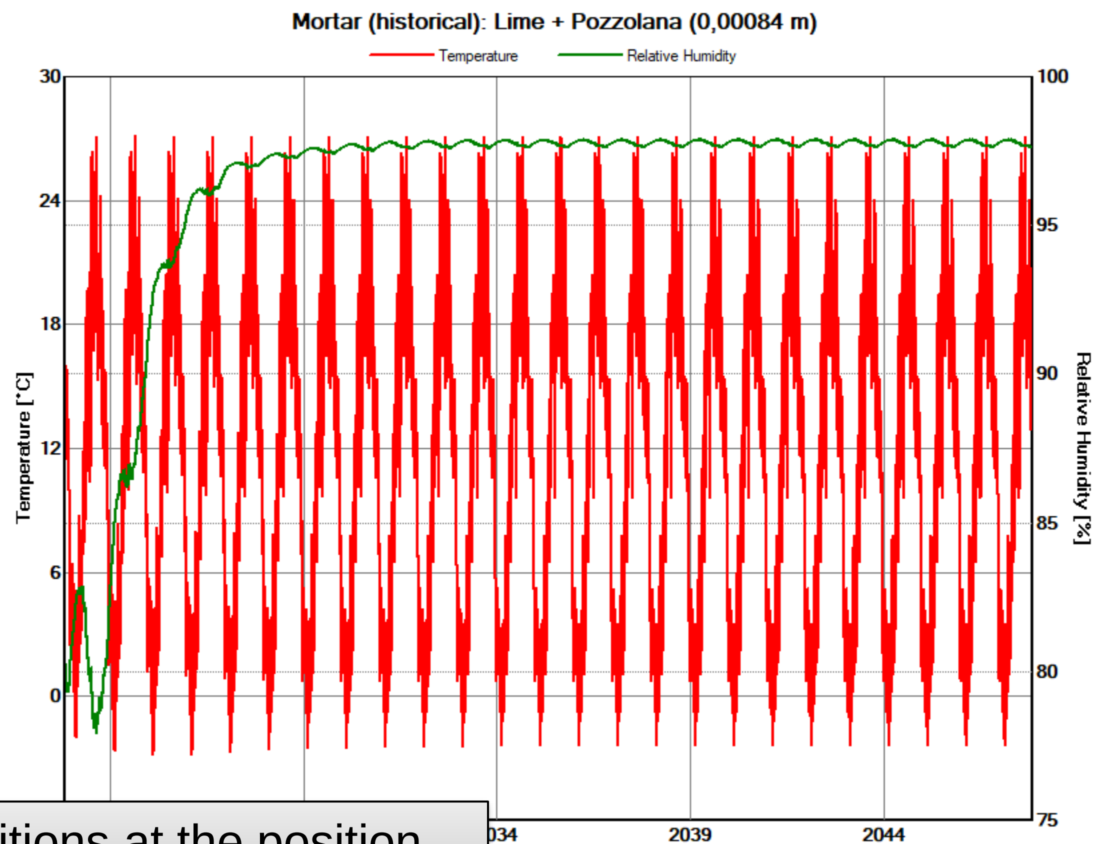
Evaluation: Total Water Content



Steady state conditions after 9 years.

Example B: Evaluation Moisture Conditions at Steel Anchor

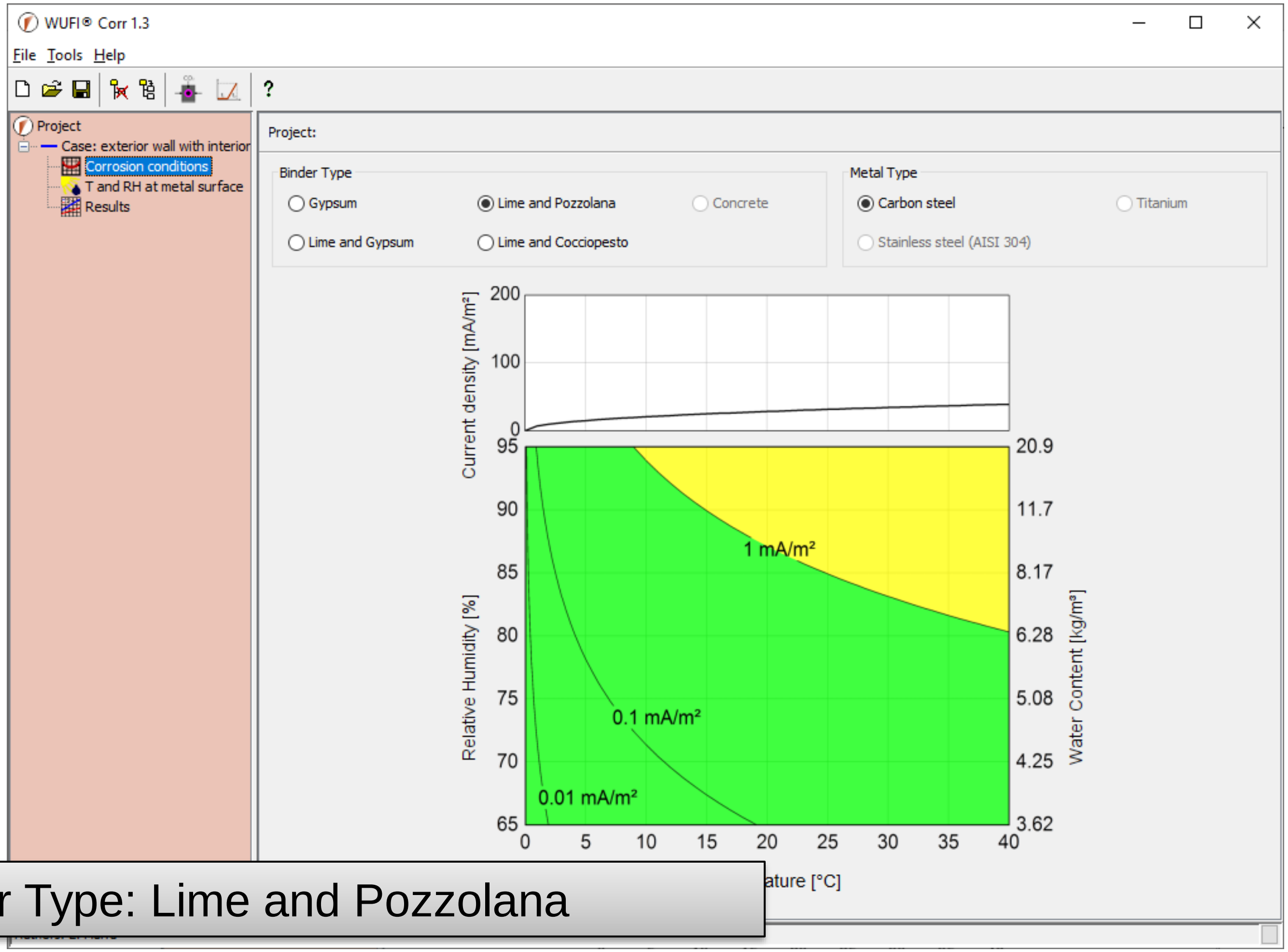
__Evaluation:__ Monitor at the position of the steel anchor



Local conditions at the position of the steel anchor

Example B: Settings WUFI® Corr

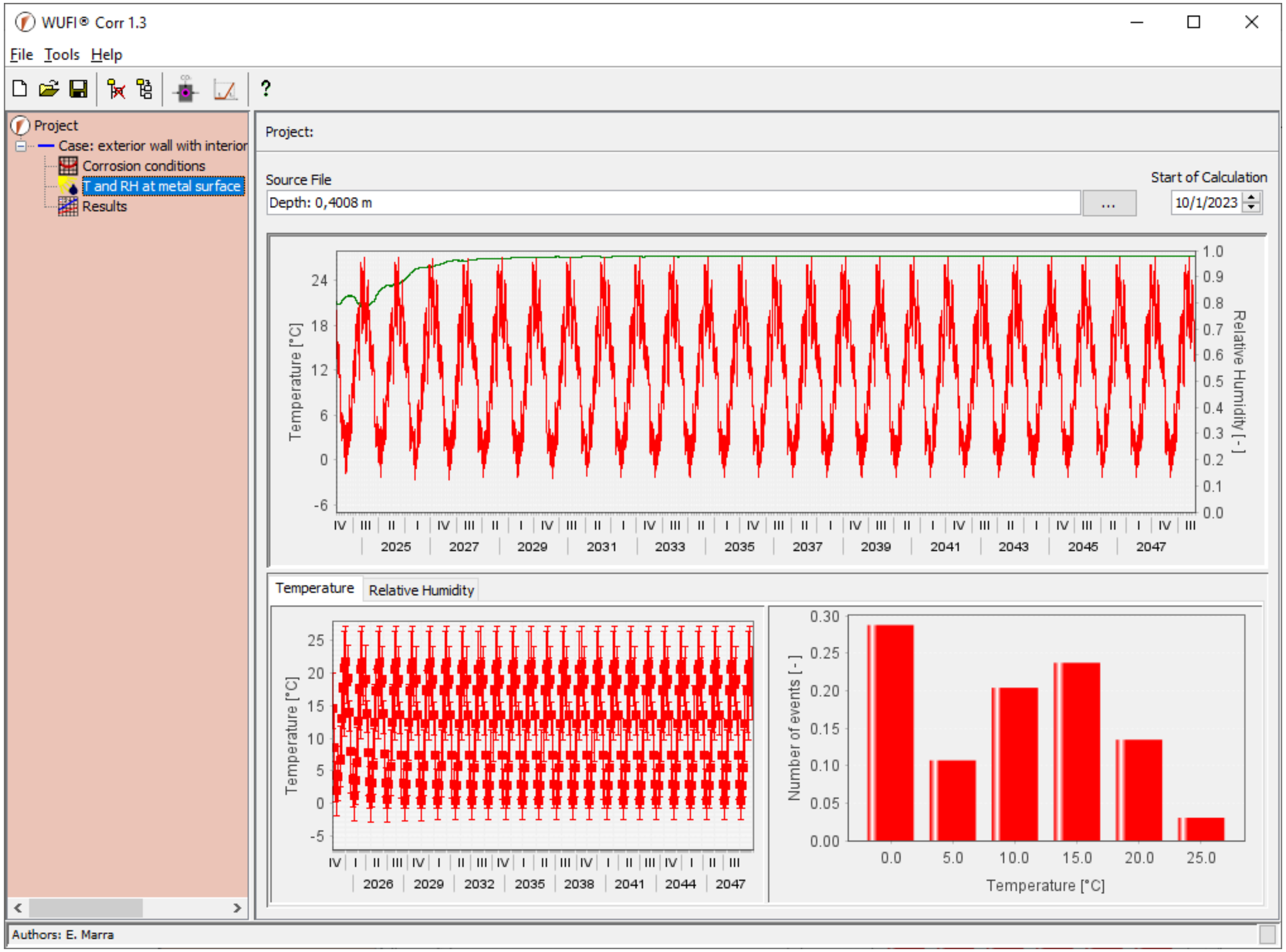
Evaluation: Corrosion risk at the position of the steel anchor



Binder Type: Lime and Pozzolana

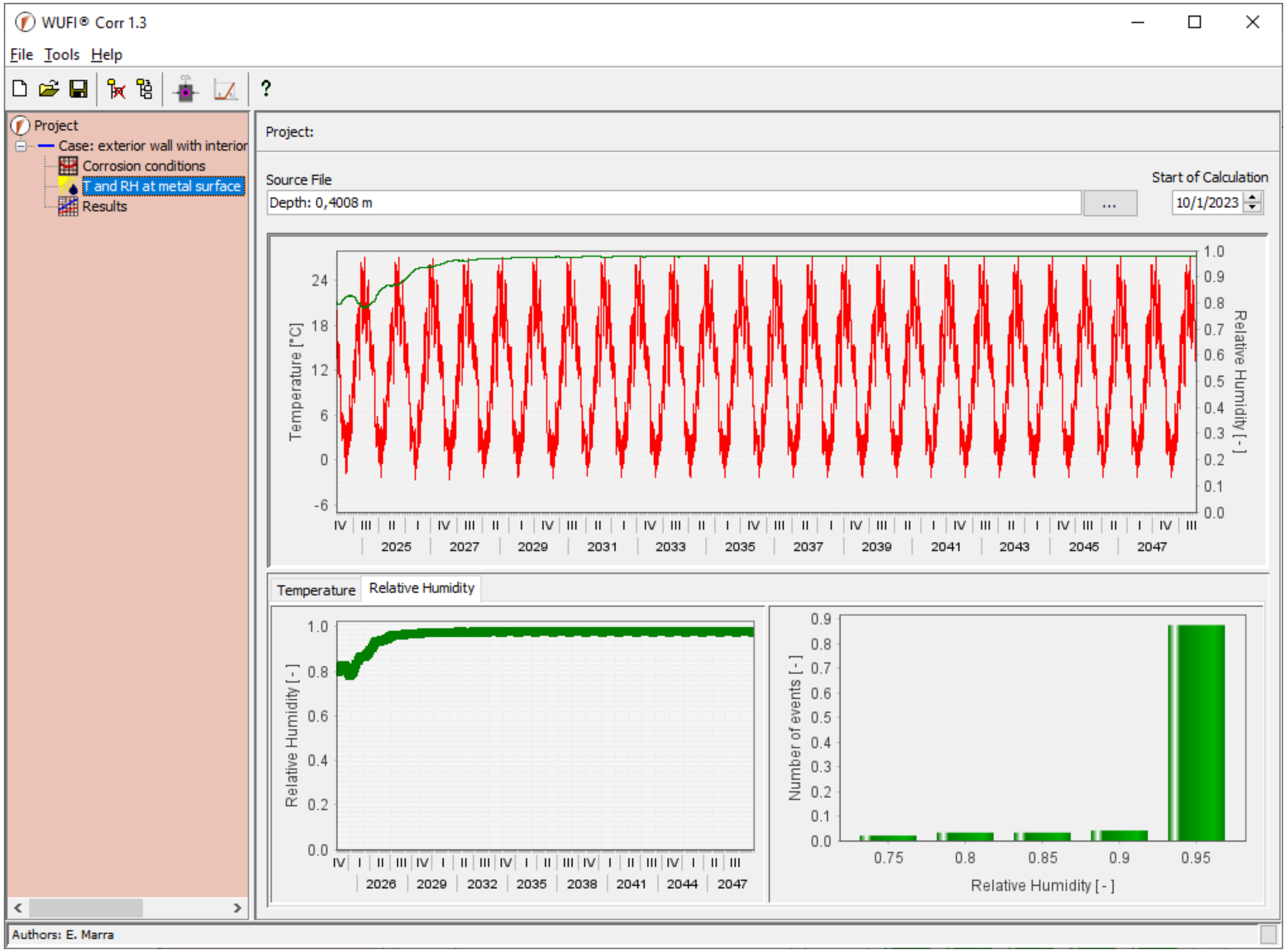
Example B: Settings WUFI® Corr

<u>Evaluation:</u> Corrosion risk at the position of the steel anchor



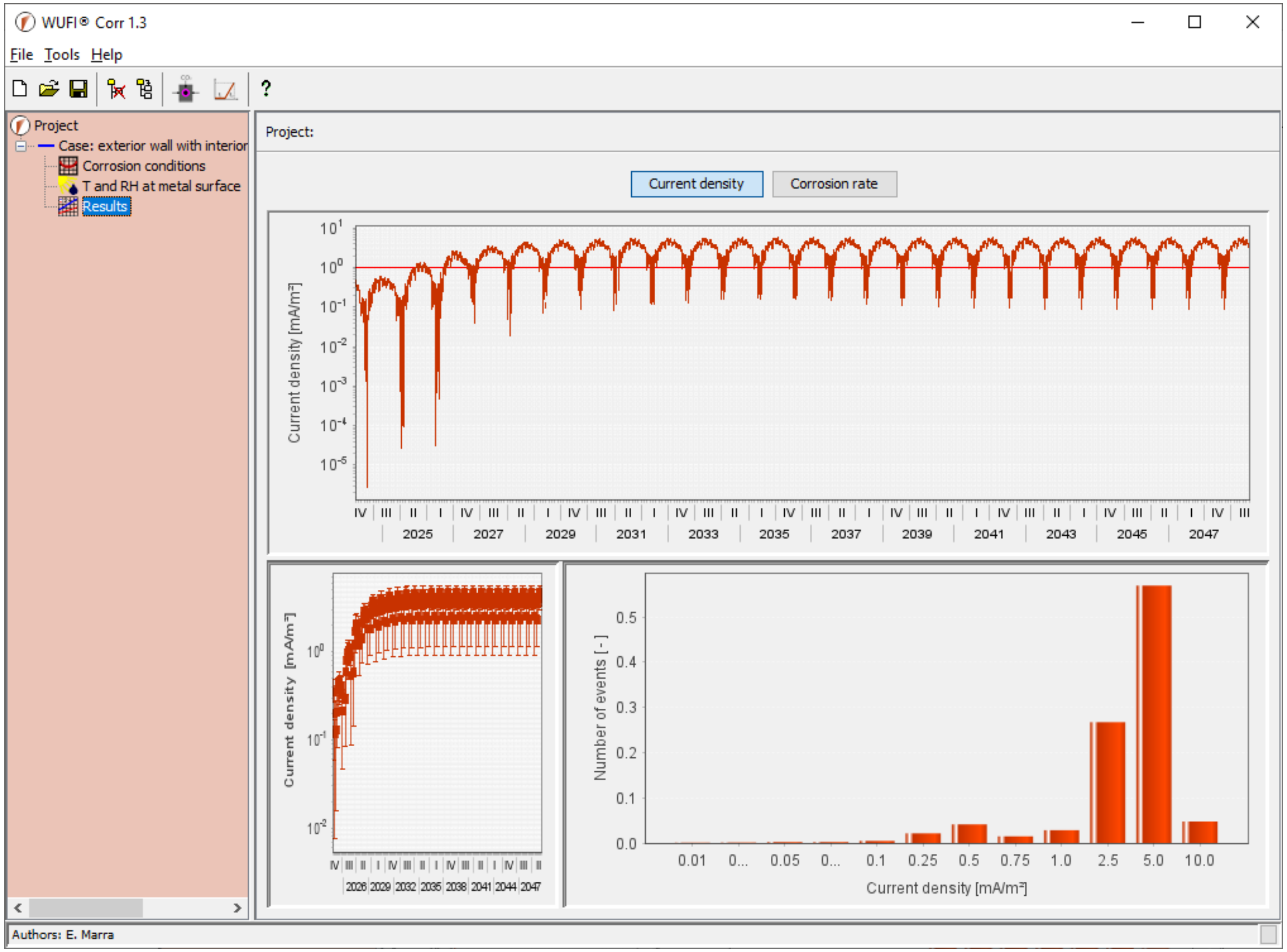
Example B: Settings WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



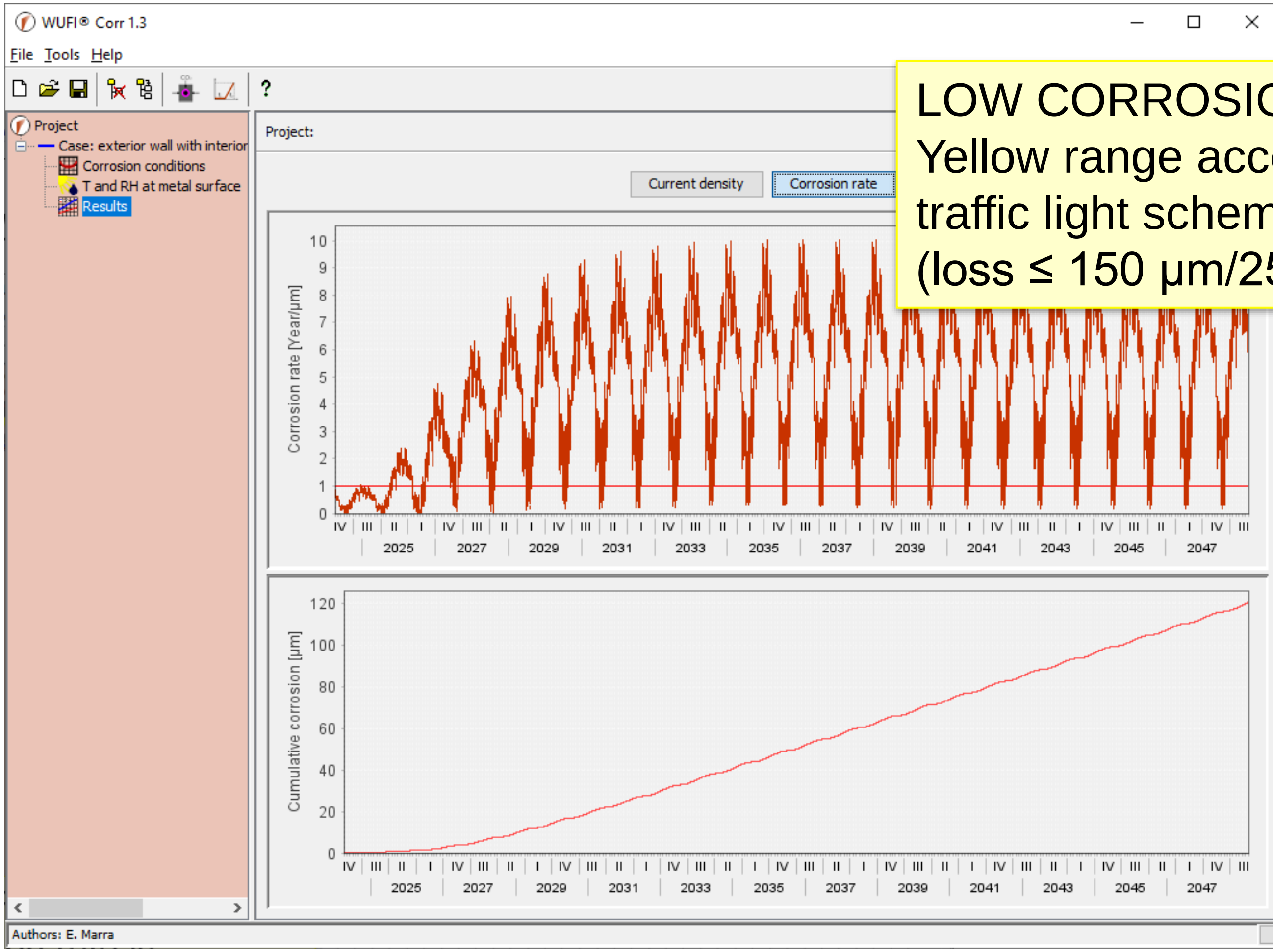
Example B: Evaluation WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



Example B: Evaluation WUFI® Corr

Evaluation: Corrosion risk at the position of the steel anchor



LOW CORROSION!
Yellow range according to the traffic light scheme on slide 10 (loss ≤ 150 µm/25years).