

Wall-ACE

Deliverable

D4.1: Characterisation and development of models to assess the heat loss reductions, indoor surface temperature improvement, and moisture buffering behavior of the different Wall-ACE products at system level

WP	4	Demonstration: building validation and tool development
Task	4.1	System characterisation using numerical tools-detailed and characterisation tool at system level (public domain freely available)

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¹ Dissemination level: **PU** = Public, **PP** = Restricted to other programme participants (including the Commission services), **RE** = Restricted to a group specified by the consortium (including the Commission services), **CO** = Confidential, only for members of the consortium (including the Commission services)

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Deliverable abstract

The objective of the Task 4.1 for the thermal zone modelling is to deliver a free, publicly available dynamic simulation model for one zone which allows to simulate the thermal behavior of the type of walls developed under the Wall-ACE project.

1.1 Background: Practice and normative situation for hygrothermal calculations

In European countries, the predominant hygrothermal assessment to prevent excess moisture is based on the EN ISO 13788 as well as the recent edition of the DIN 4108-3:October 2018. Both of these norms present calculation methods for the interstitial condensation based on the Glaser method. Another European standard EN 15026 deals with hygrothermal performance of building components and building elements through assessment of moisture transfer by numerical simulation. This standard recommends the use of hygrothermal coupled dynamic simulations. Such “modern” tools are essentially used by academics and advanced specialists. Today, most projects are assessed with the “old” Glaser method, and the latter is still referred to in case of court legal disputes in many countries. The Glaser method tends to be pessimistic especially for complex walling systems with internal insulation solutions.

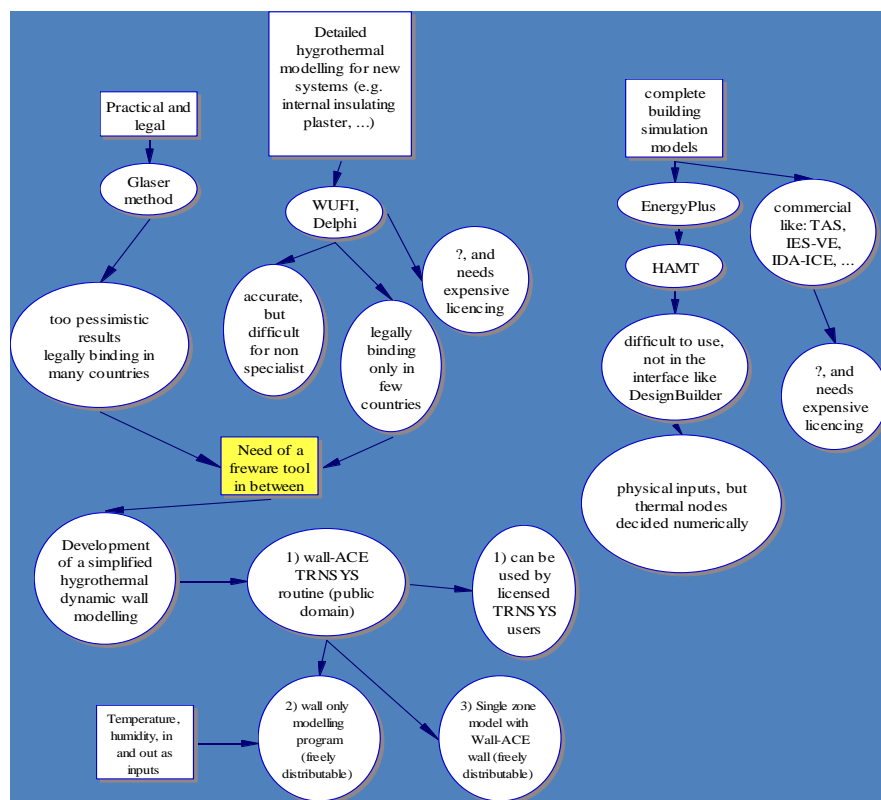


Figure 1: Illustration of the modelling issues for non-specialists and for retrofits, new walls with a mix of internal/external insulation techniques (gap of modelling solutions for non-specialists a no cost)

1.2 Objectives of the deliverable

This comprehensive dynamic simulation program will be distributed freely. It is based on the TRNSYS 17.02 environment. In the TRNSYS environment and many other building simulation programs, the wall models are based on transfer functions. It is therefore not possible to get the dynamic temperature profile inside the wall. In order to get the temperature profiles inside the wall layers, a specific finite-difference wall model has been developed. This specific wall model has been coupled with the TRNSYS environment (replacing one transfer function wall model by the developed finite difference model).

Deliverable Review

Reviewer #1: Timea Béjat - CEA			Reviewer #2: Tina Oertel – Quick-Mix		
Answer	Comments	Type*	Answer	Comments	Type*

Is the deliverable in accordance with

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Is the quality of the deliverable in a status

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* Type of comments: M = Major comment; m = minor comment; a = advice

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1 Introduction

The development of the software package was initiated because it became necessary to have a freely distributable tool to assess both the energy savings and the condensation risks for a wall corresponding to the Wall-ACE components. It has been specially developed to assess the issues related to the application of internal insulation during retrofits.

2 State of the Art

2.1 Background

Wall-ACE products have a great potential for application to buildings with listed façades under conservation like the historical centers in European cities. The addition of internal plasters particularly will reduce significantly the thermal losses of the wall where they are applied. But at the same time the temperature of the layers behind the plaster will be significantly reduced, which may lead to condensation.

The common practice is to analyse the condensation risk with the Glaser method. This method is quite conservative and may show that there is a risk of condensation, when this would not actually be the case. The method has been used over the last decades, is still in use, and is still the legal reference in many European countries. The new Heat And Moisture Transfer (HAMT) dynamic tools, like WUFI and Delphin, are generally used by building physics specialists and so their market tends to be limited. There are number of free tools to calculate the static energy saving by adding insulation. There are also number of tools to calculate the condensation risks with the Glaser method.

To our knowledge, there is no tool allowing to compare the conventional monthly, dynamic calculation using the Glaser method with a HAMT modelling approach.

The software developed allows to simulate dynamically the thermal behavior of a wall with a specially developed finite difference code. This code has been developed to assist non-specialists to assess energy savings and the condensation risks with the conventional Glaser method, while using results from a dynamic moisture transfer model.

3 Results and Analysis

The Wall-ACE dynamic wall has been developed, tested and finalised in the form of a wall simulation tool allowing to play with the different material layers. Up to 10 layers can be set in the model. The example below shows an application with 7 layers. The two first internal layers are replaced by air to avoid shifting the cells of the original wall composition. One can then add internal plaster in the layers previously inactivated by using air.

As an illustrative example, the typical case of the analysis of thermal energy saving by adding an insulation plaster on the internal side of a wall is presented with the thermal energy savings as well as the condensation risks and occurrence.

Layer	W/m ² -K	L(m)	Lambda (W/m-K)	R (m ² -K/W)	U (W/m ² -K)
SUM		0.357		2.558	0.39
Interior	8	-	-	0.125	
L1	-	0.050	0.034	1.47	
L2	-	0.001	0.034	0.029	
L3	-	0.120	1.2	0.10	
L4	-	0.050	0.08	0.625	
L5	-	0.120	1.12	0.11	
L6	-	0.015	0.7	0.021	
L7	-	0.001	0.034	0.03	
Exterior	20	-	-	0.050	

Figure 2: Wall characteristics for the example (obtained by the Excel workbook with a macros reading the wall.dat file after a single simulation run).

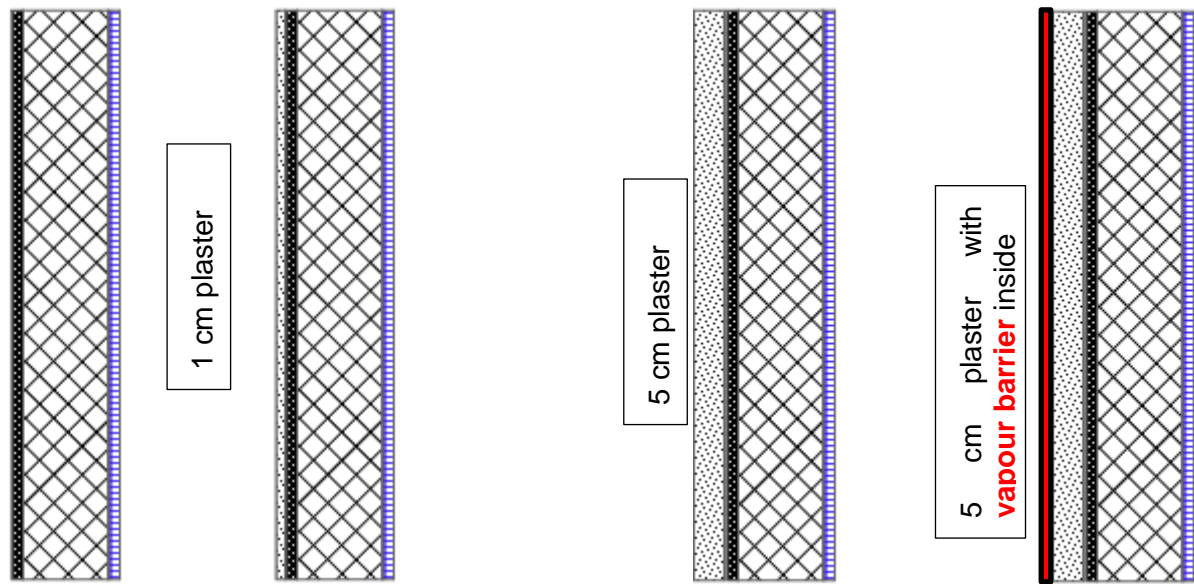


Figure 3: Scheme of the wall: non insulated, with 1 cm plaster inside thickness augmented gradually -----> up to 5 cm, then adding a vapour barrier to solve the condensation problem

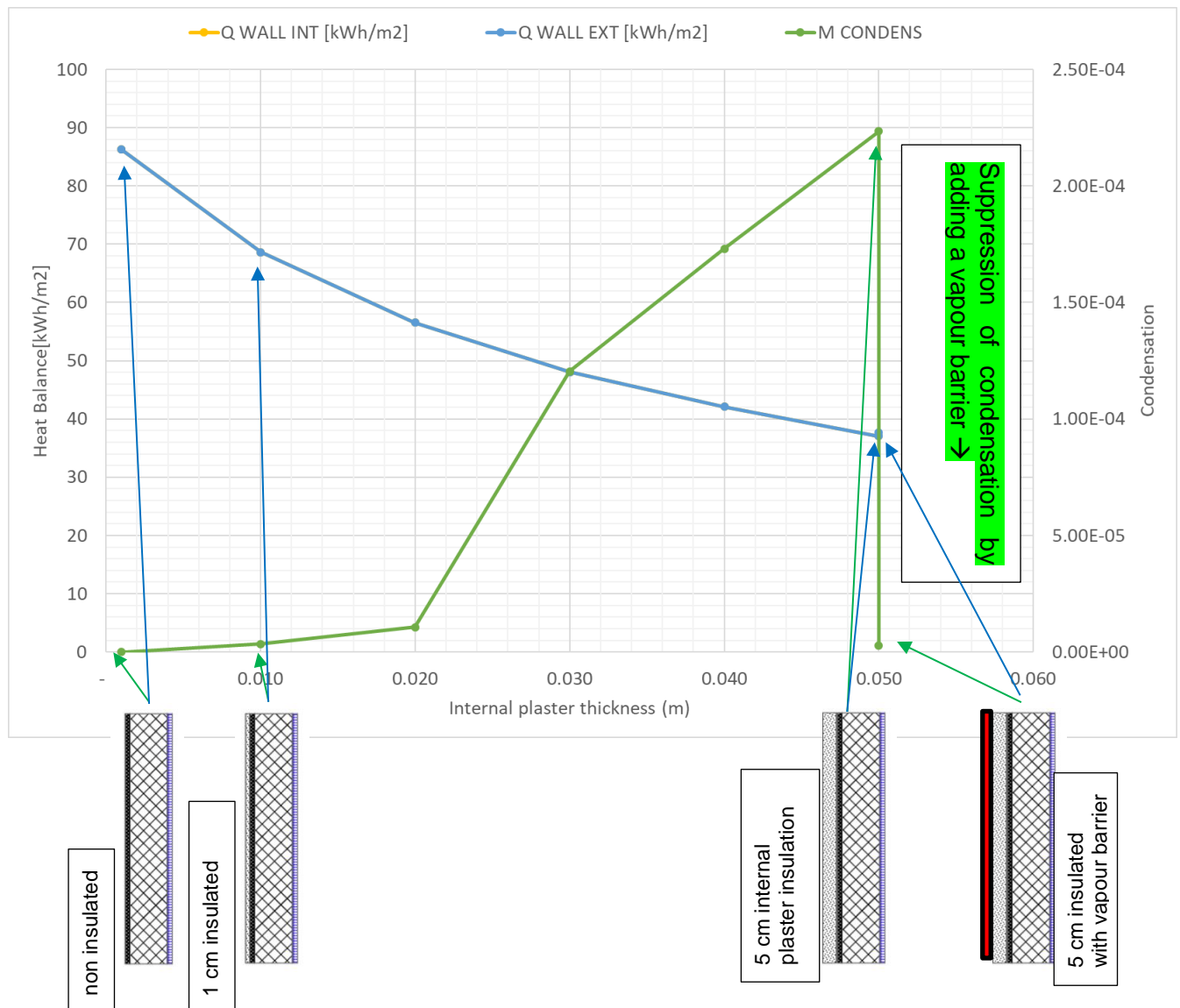


Figure 4: Thickness of the plaster from 0 to 5 cm and then adding a vapour barrier solving condensation

The addition of an internal high-performance plaster reduces the thermal losses of the wall, but there is a non-linear increase of condensation between 2 and 3 cm. This can be explained by the reduction of the temperature behind the plaster between 2 and 3 cm thickness. The figure below presents the increase of annual cumulative hours below the dew point temperature behind the plaster in relation to its thickness.

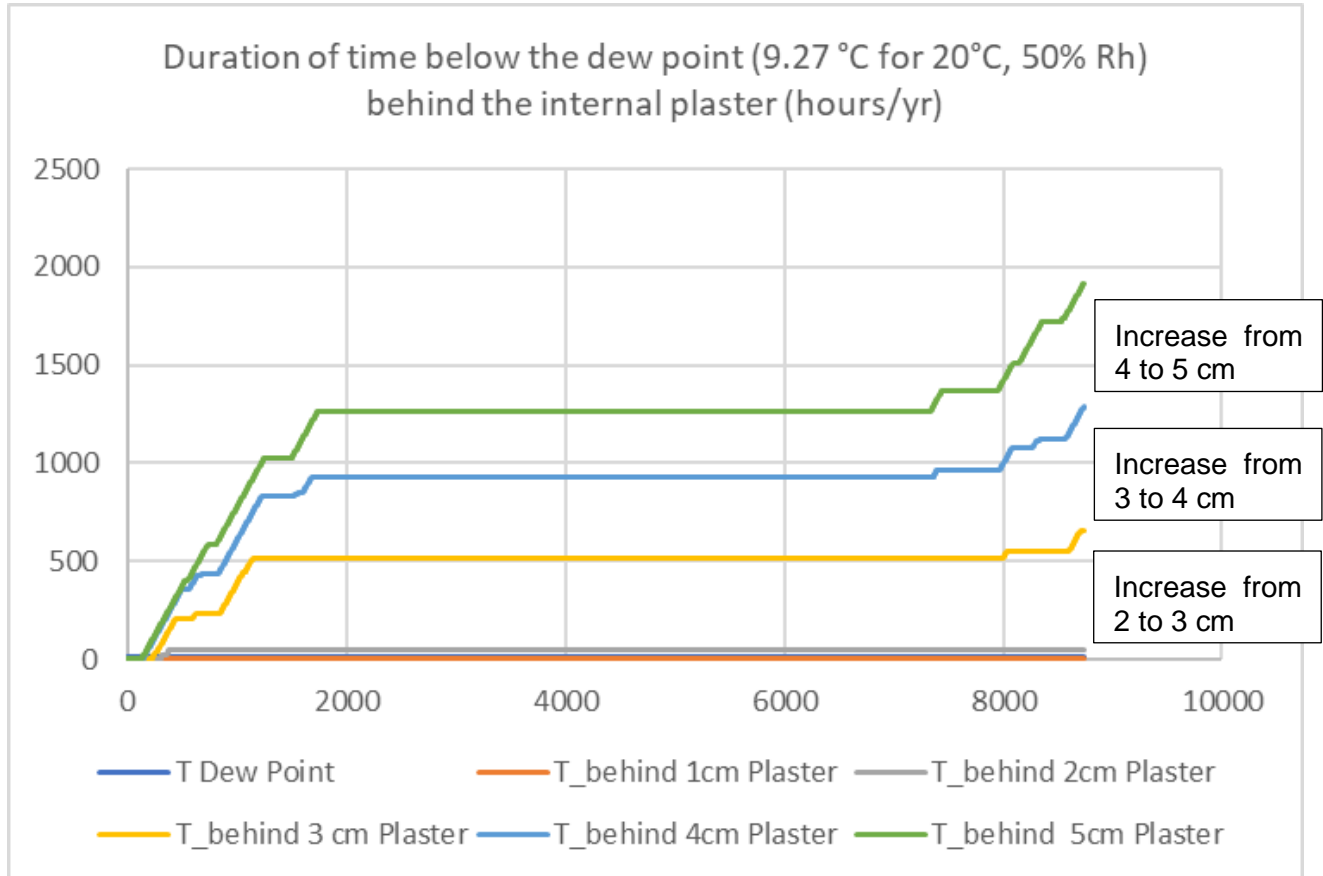


Figure 5: Explanation for the non-linearity in the sudden increase of condensation as shown in the Figure 3 above

The number of hours below the dew point behind the plaster increases from 44 hours per year for 2 cm to 660 hours per year, when the thickness is increased to 3 cm. This example shows how important it is to check the condensation behind the internal insulation and to apply solutions such as applying a vapour barrier (can be a film or special paints). The condensation is reduced by a factor 1000 by applying a vapour barrier adequately placed on the inside face of the plaster.

4 Conclusion

This software package has been developed with the aim of making a specific tool available, which uses different complementary methods to assess the condensation risk as well as the energy saving potential of Wall-ACE products.

This freely distributable software package allows users to assess thermal savings and condensation risks with different methods. To the best of our knowledge, no such tools are available today.

5 Annex

5.1 Theory and capabilities of the TRNSED-Wall-ACE-v1

5.1.1 Finite difference thermal model of the dynamic wall

5.1.1.1 Thermal wall model development and validation

The application of the Wall-ACE products will allow to significantly reduce the thermal losses, especially for renovation with inside insulating plasters.

5.1.1.2 Heat equations for the dynamic thermal modelling

The basis for the finite difference model are presented below.

5.1.1.3 Nodes within the same material

Energy balance for nodes in the control volume 2 located within the same material:

$$\rho_2 A C p_2 \Delta x_2 \frac{\partial T}{\partial t} = \frac{K_2 A (T_{i-1} - T_i)}{\Delta x_2} + \frac{K_2 A (T_{i+1} - T_i)}{\Delta x_2} \quad (1)$$

This can be expressed as:

$$\frac{\partial T}{\partial t} = \frac{K_2 A (T_{i-1} + T_{i+1} - 2T_i)}{\rho_2 C p_2 \Delta x_2} \quad (2)$$

5.1.1.4 Nodes at the interface between two materials

The energy balance at the interface between material regions 2 and 3 can be written as:

$$\rho_{avg} A C p_{avg} \Delta x_{avg} \frac{\partial T}{\partial t} = \frac{K_2 A (T_{i-1} - T_i)}{\Delta x_2} + \frac{K_3 A (T_{i+1} - T_i)}{\Delta x_3} \quad (3)$$

Rearranging this equation yields:

$$\frac{\partial T}{\partial t} = \left(\frac{K_2}{\rho_{avg} C p_{avg} \Delta x_{avg} \Delta x_2} \right) T_{i-1} + \left(\frac{K_3}{\rho_{avg} C p_{avg} \Delta x_{avg} \Delta x_3} \right) T_{i+1} - \left(\frac{K_2}{\rho_{avg} C p_{avg} \Delta x_{avg} \Delta x_2} + \frac{K_3}{\rho_{avg} C p_{avg} \Delta x_{avg} \Delta x_3} \right) T_i \quad (4)$$

5.1.1.5 Nodes at the extremities

For nodes located at the outer surface of the wall, the energy balance must account for convection-driven heat transfer:

$$\frac{\partial U}{\partial t} = \dot{q}_{cond} + \dot{q}_{conv} \quad (5)$$

For the last node N, this equation yields:

$$\rho A C p \frac{\Delta x}{2} \frac{\partial T_N}{\partial t} = \frac{K A (T_{N-1} - T_N)}{\Delta x} + \bar{h} A (T_\infty - T_N) \quad (6)$$

Solving for the time rate of temperature change:

$$\frac{\partial T_N}{\partial t} = \frac{2K(T_{N-1} - T_N)}{\rho C p \Delta x^2} + \frac{2\bar{h}}{\rho C p \Delta x} (T_\infty - T_N) \quad (7)$$

L(1)	L(2)	L(3)	L(4)	L(5)	L(6)	L(7)	L(8)	L(9)	L(10)
Mu(1)	Mu(2)	Mu(3)	Mu(4)	Mu(5)	Mu(6)	Mu(7)	Mu(8)	Mu(9)	Mu(10)
Ko(1)	Ko(2)	Ko(3)	Ko(4)	Ko(5)	Ko(6)	Ko(7)	Ko(8)	Ko(9)	Ko(10)
Rho(1)	Rho(2)	Rho(3)	Rho(4)	Rho(5)	Rho(6)	Rho(7)	Rho(8)	Rho(9)	Rho(10)
Cp(1)	Cp(2)	Cp(3)	Cp(4)	Cp(5)	Cp(6)	Cp(7)	Cp(8)	Cp(9)	Cp(10)

Figure 6: Description of the studied situation

5.1.1.6 Numerical solving

The equations above can be written for each node of a particular problem, and the resulting system of equations can be expressed in matricial form. The development of the matrix solution system is shown for a two-material element, with 7 nodes:

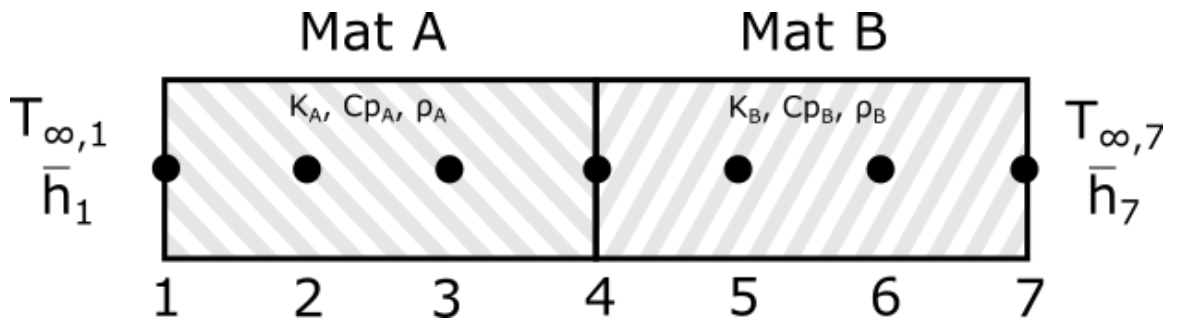


Figure 2 – Two material layer problem with 7 nodes as an example

With equal distance between the nodes, the following terms can be introduced:

$$\omega_A = \frac{K_A \Delta t}{\rho_A C p_A (\Delta x)^2} \quad (8)$$

$$\omega_B = \frac{K_B \Delta t}{\rho_B C p_B (\Delta x)^2} \quad (9)$$

$$x = \frac{K_A \Delta t}{\rho_{avg} C p_{avg} (\Delta x)^2} \quad (10)$$

$$z = \frac{(K_A + K_B) \Delta t}{\rho_{avg} C p_{avg} (\Delta x)^2} \quad (11)$$

$$z = \frac{(K_A + K_B) \Delta t}{\rho_{avg} C p_{avg} (\Delta x)^2} \quad (12)$$

Knowing the temperature at each node at time $t = n$, the equations for each node at time $t = n + 1$ are :

$$\begin{aligned}
 (1) \quad & T_1^{n+1} = T_{1-\delta x_1}^n \\
 (2) \quad & -\omega_A T_1^{n+1} + (1 + 2\omega_A) T_2^{n+1} - \omega_A T_3^{n+1} = T_2^n \\
 (3) \quad & -\omega_A T_2^{n+1} + (1 + 2\omega_A) T_3^{n+1} - \omega_A T_4^{n+1} = T_3^n \\
 (4) \quad & -x T_3^{n+1} + (1 + z) T_4^{n+1} - y T_5^{n+1} = T_4^n \\
 (5) \quad & -\omega_B T_4^{n+1} + (1 + 2\omega_B) T_5^{n+1} - \omega_B T_6^{n+1} = T_5^n \\
 (6) \quad & -\omega_B T_5^{n+1} + (1 + 2\omega_B) T_6^{n+1} - \omega_B T_7^{n+1} = T_6^n \\
 (7) \quad & T_7^{n+1} = T_{7-\delta x_7}^n
 \end{aligned}$$

Figure 7: equation for each node from previous equations

Where the boundary condition temperatures are:

$$T_{1-\delta x_1}^n = T_1^n + \frac{2\bar{h}_1 \Delta t}{\Delta x \rho_A C p_A} T_{\infty,1} \quad (13)$$

$$T_{7-\delta x_7}^n = T_7^n + \frac{2\bar{h}_7 \Delta t}{\Delta x \rho_B C p_B} T_{\infty,7} \quad (14)$$

The equations can be written in a matrix form as $AT^{n+1} = b$ where A is the coefficient matrix, AT^{n+1} is the unknown values vector to be calculated, and b the known values vector:

$$\begin{bmatrix}
 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
 -\omega_A & 1 + 2\omega_A & -\omega_A & 0 & 0 & 0 & 0 \\
 0 & -\omega_A & 1 + 2\omega_A & -\omega_A & 0 & 0 & 0 \\
 0 & 0 & -x & 1 + z & -y & 0 & 0 \\
 0 & 0 & 0 & -\omega_B & 1 + 2\omega_B & -\omega_B & 0 \\
 0 & 0 & 0 & 0 & -\omega_B & 1 + 2\omega_B & -\omega_B \\
 0 & 0 & 0 & 0 & 0 & 0 & 1
 \end{bmatrix}
 \begin{bmatrix}
 T_1^{n+1} \\
 T_2^{n+1} \\
 T_3^{n+1} \\
 T_4^{n+1} \\
 T_5^{n+1} \\
 T_6^{n+1} \\
 T_7^{n+1}
 \end{bmatrix}
 =
 \begin{bmatrix}
 T_{1-\delta x_1}^n \\
 T_2^n \\
 T_3^n \\
 T_4^n \\
 T_5^n \\
 T_6^n \\
 T_{7-\delta x_7}^n
 \end{bmatrix}$$

Figure 8: Coefficient matrix

Unknown Known values

5.1.1.7 Numerical solution

The scheme presented above (based on the backward implicit Euler finite difference method) has been developed to allow to calculate numerically with 1 to 10 layers of different materials which can be chosen by the user.

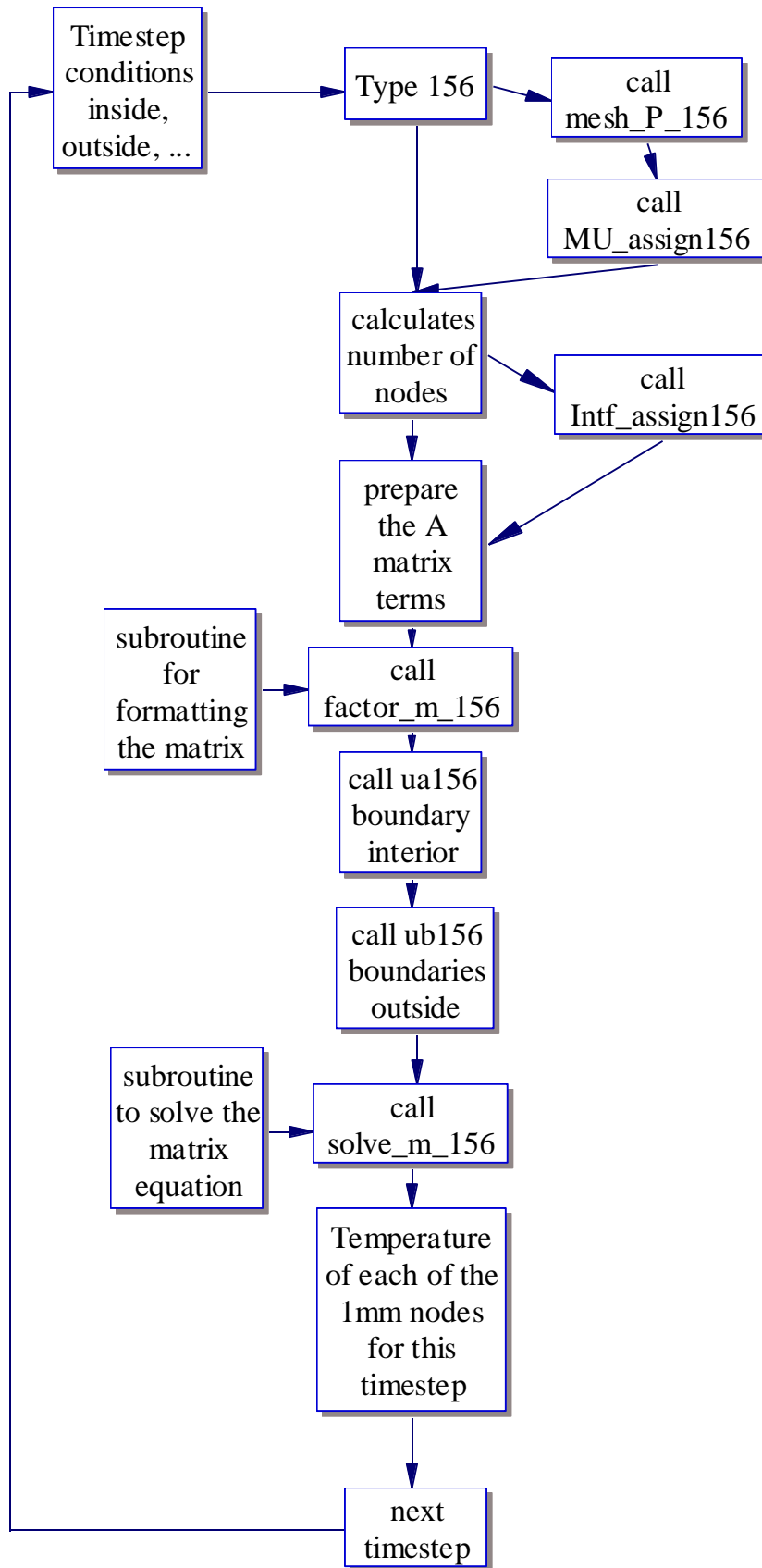


Figure 9: Schematic description of the finite difference type 156 routine and subroutines (thermal part)

a) Subroutine mesh_P_156 (x_num1, K_layers, L, X_mesh)

Mesh generator based on the number of material layers (K_layers), mm layers (x_num1) their thickness (L) giving back the X_mesh array with the position of the x_num1 numerical on mm nodes.

b) Subroutine MU_assign156(MU_layer, L, X_mesh, K, x_num1, MU_nodes)

Assigns the MU values from the different material layers to the one mm nodes.

c) Subroutine Intf_assign156 (K, x_num, MU_nodes, x_int)

Locates the interfaces points between two layers in the one mm node numerical model of the wall and assigns the physical characteristics to each.

d) Subroutine _factor_156 (x_num1, a, info)

Checks the tridiagonal matrix for singularity with x_num1 (the number of nodes of mm), the tridiagonal matrix prepared in the type156 code before, it may give a singularity check flag output.

e) Subroutine solve_m_156 (x_num1,a,b,job)

Subroutine to solve the formatted A matrix equation $A \cdot X = B$, with the matrix A, b the B vector, X the unknown temperatures.

f) Subroutine ua156 (x_min, x_max, t_min, tm(j), b(1),u(1,j-1),Tint_term)

Setting interior temperature boundary conditions.

g) Subroutine ub156 (x_min,x_max,t_min,tm(j),b(x_num1),u(x_num1,j-1),Text_term)

Setting interior temperature boundary conditions.

5.1.1.8 Number of possible layers in the wall model

	L(1)	L(2)	L(3)	L(4)	L(5)	L(6)	L(7)	L(8)	L(9)	L(10)	
	Mu(1)	Mu(2)	Mu(3)	Mu(4)	Mu(5)	Mu(6)	Mu(7)	Mu(8)	Mu(9)	Mu(10)	
T_int	Ko(1)	Ko(2)	Ko(3)	Ko(4)	Ko(5)	Ko(6)	Ko(7)	Ko(8)	Ko(9)	Ko(10)	T_ext
h_int	Rho(1)	Rho(2)	Rho(3)	Rho(4)	Rho(5)	Rho(6)	Rho(7)	Rho(8)	Rho(9)	Rho(10)	h_ext
	Cp(1)	Cp(2)	Cp(3)	Cp(4)	Cp(5)	Cp(6)	Cp(7)	Cp(8)	Cp(9)	Cp(10)	

Figure 10: The wall can be divided into a maximum of ten layers ($i=1$ to 10) of different material, $L(i)$ layer thickness, $Mu(i)$ moisture dependent vapor diffusion resistance factor, $Ko(i)$ thermal conductivity, $Rho(i)$ material density, $Cp(i)$ specific heat capacity of the material

Once the layers are entered, the actual numerical layers used in the algorithm of the finite difference model are of one mm thickness to get an accurate definition of the temperatures at the interface with a one mm resolution. The maximum thickness of the wall is set at 1000 millimeter.

The developed finite difference model is under the form of a TRNSYS component Subroutine, which can be used by licensed TRNSYS users.

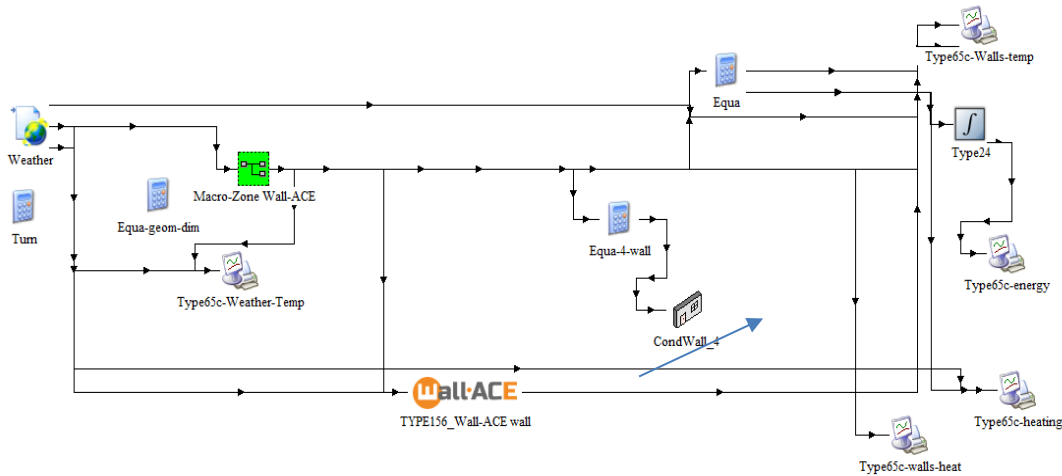


Figure 11: Simplified schematic view of the simulate model as developed in TRNSYS 17, the type 156 Wall-ACE specially developed and coupled with the detailed single zone model of TRNSYS Type 19

The objective of the software developed is to model at the zone level the energy and hygrothermal aspects and to propose a simulation model using the Glaser method and a hygrothermal decoupled method for a wall.

5.1.1.9 Comparison between the Type 156 Wall-ACE model and other validated dynamic thermal wall modelling

The following graphs present the comparison between the results obtained using Trnsys 17 and the finite difference model.

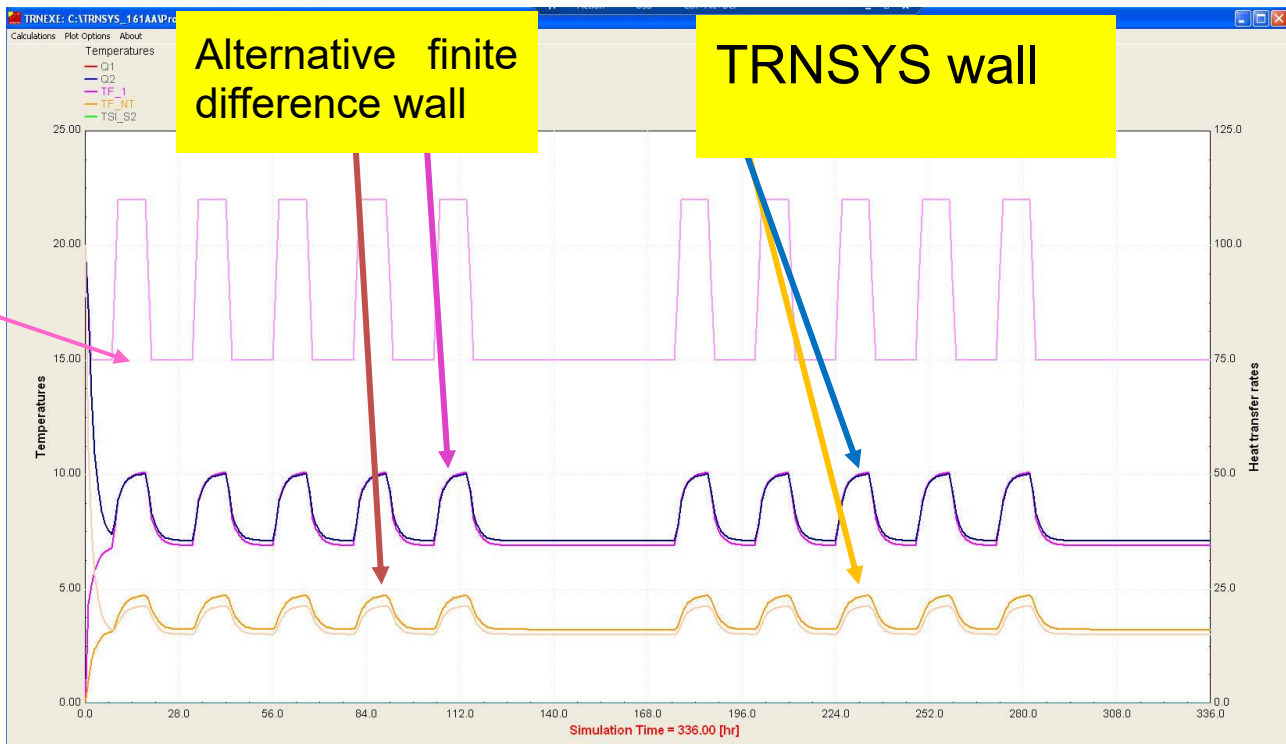


Figure 12: comparison between the surface temperatures inside and outside of the same wall modelled in the TRNSYS 17 multi-zone type 56 and with the type156 Wall-ACE dynamic finite difference model developed.

The picture below shows the balance of thermal cumulative losses on the internal and external surface of the finite difference wall.

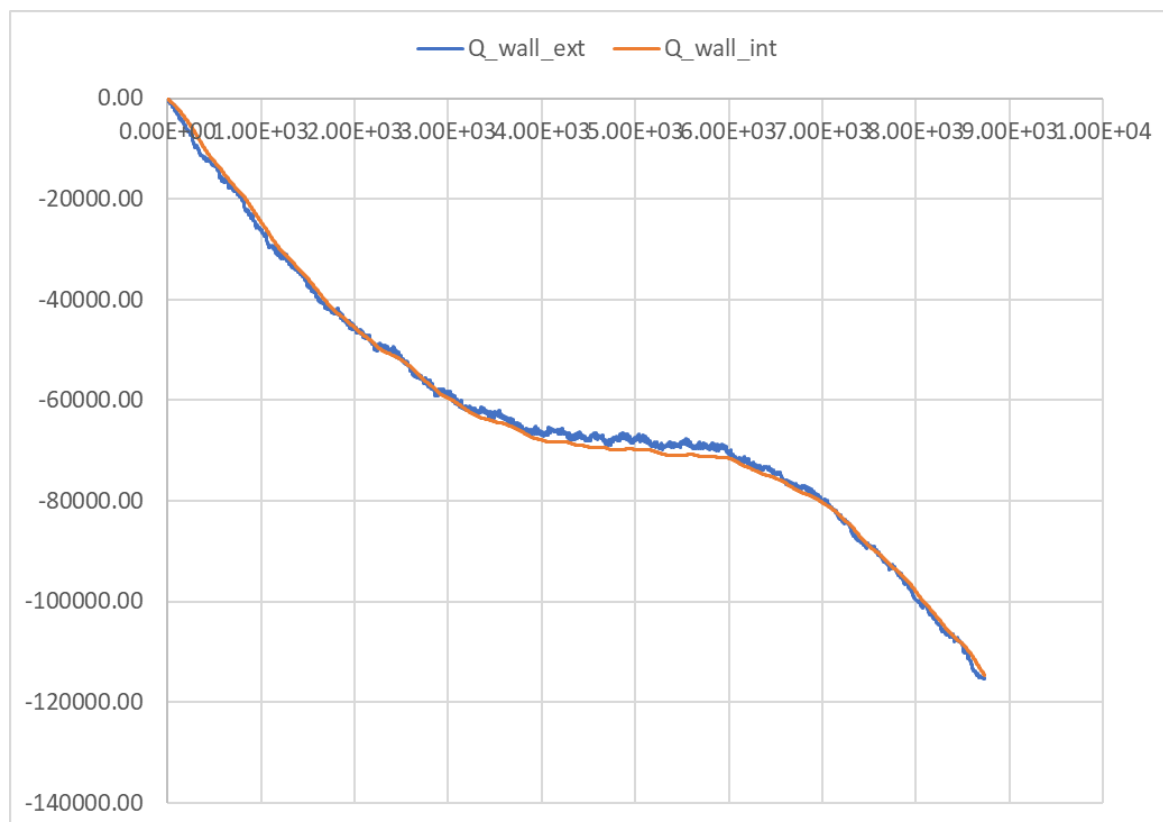


Figure 13: Comparison of the cumulative wall losses on the inside and outside for one year, the calculated thermal power across the wall is then used from the inside for the user and for the thermal calculations.

5.1.2 Humidity and Moisture Transfer Model

5.1.2.1 Glaser calculation method as programmed in the Wall-ACE wall model

h) Glaser monthly as per ISO 13788⁵

The case is: “Annex C, (informative), Examples of calculation of interstitial condensation, C.2 Example 1: Building component with condensation in one interface plane”

⁵INTERNATIONAL STANDARD ISO 13788, Second edition, 2012-12-15, Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods

C.1 Environmental conditions

[Table C.1](#) shows the external and internal environmental conditions used in the two examples in C.2 and C.3. The internal conditions are derived from the external conditions using the lines in [Figure A.1](#), assuming low and high occupancy.

Table C.1 — External and internal conditions used for analysis

Month	External		Internal Normal occupancy		Internal High occupancy	
	θ_e °C	φ_e	θ_i °C	φ_i	θ_i °C	φ_i
January	-1	0,85	20,0	0,39	20,0	0,49
February	0	0,84	20,0	0,40	20,0	0,50
March	4	0,78	20,0	0,44	20,0	0,54
April	9	0,72	20,0	0,49	20,0	0,59
May	14	0,68	22,0	0,54	22,0	0,64
June	18	0,69	24,0	0,58	24,0	0,68
July	19	0,73	24,5	0,59	24,5	0,69
August	19	0,75	24,5	0,59	24,5	0,69
September	15	0,79	22,5	0,55	22,5	0,65
October	10	0,83	20,0	0,50	20,0	0,60
November	5	0,88	20,0	0,45	20,0	0,55
December	1	0,88	20,0	0,41	20,0	0,51

C.2 Example 1: Building component with condensation in one interface plane

In this example, the flat roof with an impermeable weather proofing layer over the insulation, shown in [Figure C.1](#) is analysed using the internal and external climates shown in [Table C.1](#) and the material properties shown in [Table C.2](#).

Figure 14: Example and figures taken from the reference⁴.

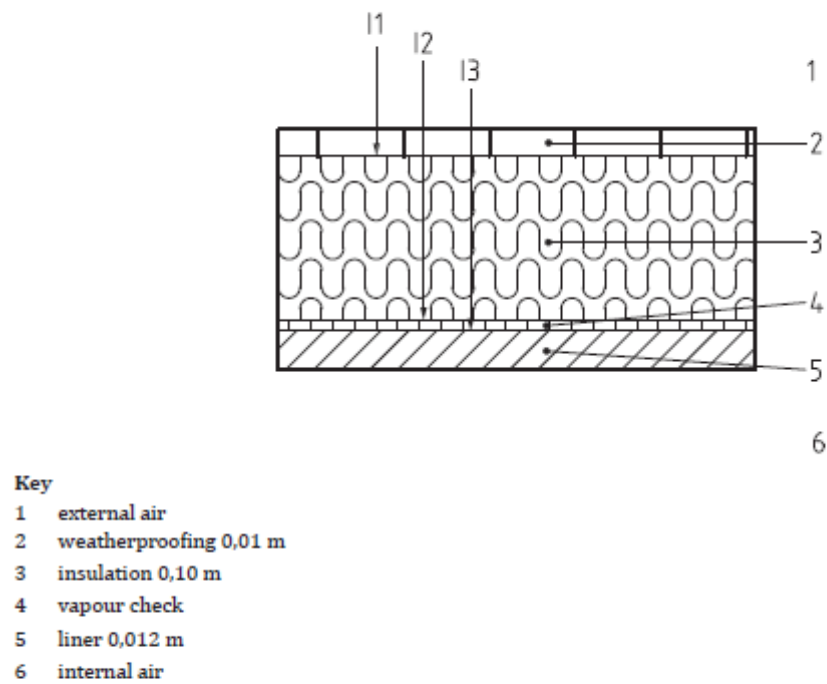


Figure C.1 — Materials for flat roof in example 1

Table C.2 — Material properties for flat roof

	<i>d</i> m	<i>R</i> m ² ·K/W	<i>μ</i>	<i>s_d</i> m
External resistance	–	0,04	–	–
Weatherproofing	0,010	0,05	500 000	5 000
Insulation	0,100	3	150	15
Vapour check	–	–	–	1 000
Liner	0,012	0,075	10	0,12
Internal resistance	–	0,10	–	–

NOTE The material properties shown in the examples refer to generic material types, not specific materials.

Figure 15: Example and figures taken from the reference⁴.

ISO 13788:2012(E)

Table C.3 — Monthly condensation rate and accumulation at interface 1

Month	Normal occupancy		High occupancy	
	g_c kg/m ²	M_a kg/m ²	g_c kg/m ²	M_a kg/m ²
October	0	0	0,00005	0,00005
November	0,00006	0,00006	0,00018	0,00023
December	0,00013	0,00019	0,00026	0,00049
January	0,00015	0,00035	0,00028	0,00077
February	0,00013	0,00048	0,00024	0,00101
March	0,00008	0,00055	0,00020	0,00120
April	-0,00005	0,00050	0,00007	0,00127
May	-0,00016	0,00034	-0,00002	0,00125
June	-0,00025	0,00009	-0,00010	0,00115
July	-0,00028	0	-0,00012	0,00103
August	0	0	-0,00011	0,00092
September	0	0	-0,00002	0,00090

From April onwards, the rate of condensation becomes negative, i.e. evaporation is occurring as specified in 6.4.6, and the accumulated moisture falls until it is close to zero in June. During July, the accumulated moisture dries out, and is set to zero.

If high occupancy is assumed, condensation starts in October and the rate again rises to a peak in January. Evaporation starts in May, but all the condensate has not evaporated by September.

C.3 Example 2: Building component with condensation in two interfaces

In this example a flat roof with an extra 100 mm of insulation added below the vapour control layer shown in Figure C.2 is analysed using the material properties shown in Table C.4 and the high occupancy internal and external climates shown in Table C.1.

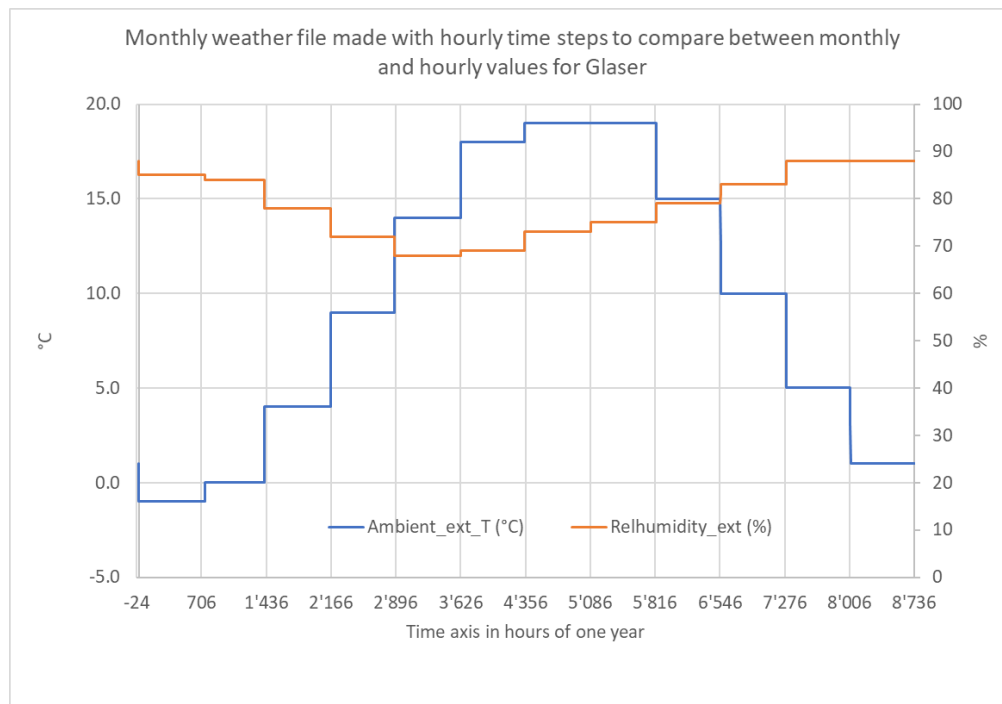
Figure 16: Example and figures taken from the reference⁴.

Figure 17: Hourly temperature and relative humidity profile based on monthly values

The results of the comparison between the ISO 13788 example case and the monthly and hourly Glaser calculation are presented below.

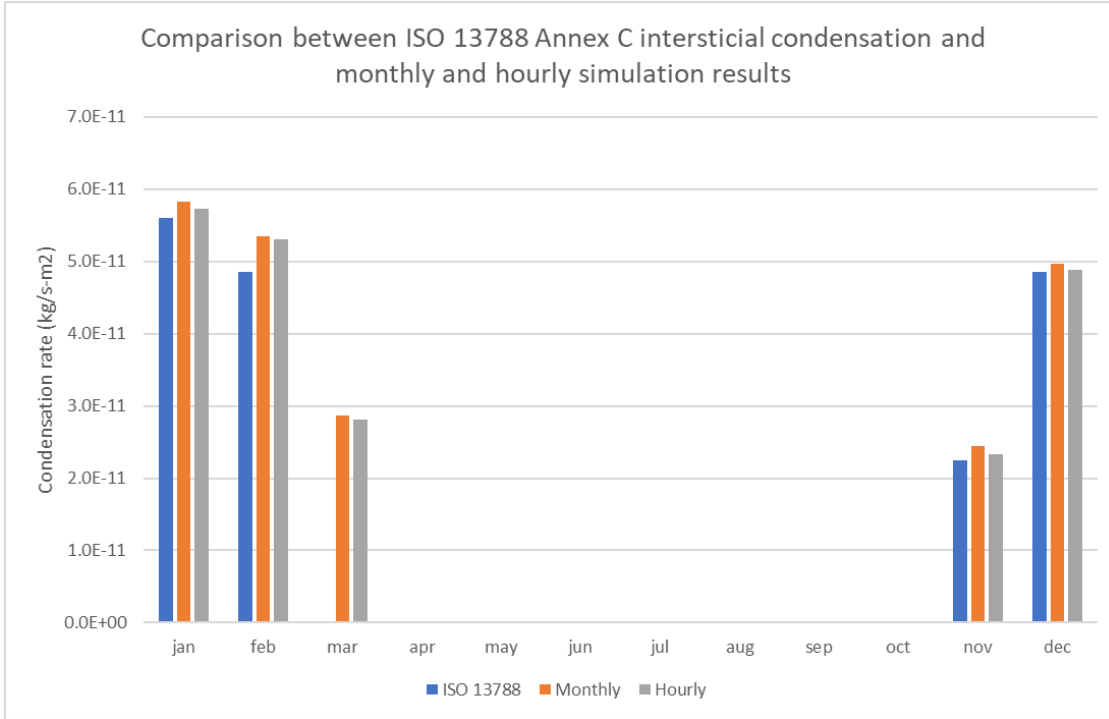


Figure 18: Results for a monthly calculation, hourly simulation compared with the official example of the ISO 13788 international standard

The results are quite consistent, showing that both the monthly and hourly calculated values match well with the example of the standard.

5.1.2.2 Humidity And Moisture Transfer Model (HAMT)

In order to complement the Glaser winter condensation analysis, a Humidity And Moisture Transfer Model (HAMT) has been added to the simulation program.

The model is based on the model concept developed by Hartwig Künzels⁶. The code has used some part of the EnergyPlus HAMT model⁷. The authors of the Wall-ACE software acknowledge the contribution by using part of the EnergyPlus (HAMT, HeatBalanceHAMTManager.f90) Source Code following the recognition as per the EnergyPlus Open Source License Version 1.0.

The temperatures are imposed by the Wall-ACE finite difference dynamic model for each node of the HAMT model.

$$\frac{dw}{d\phi_i} \Delta V_i \frac{\phi_i^{p+1} - \phi_i^p}{\Delta \tau} = \sum_j k_{ij} A_{ij} \frac{\phi_j^{p+1} - \phi_i^{p+1}}{x_{ij}} + \sum_j \frac{\delta_{ij}}{\mu_{ij}} A_{ij} \frac{p_j^{p+1} - p_i^{p+1}}{x_{ij}} \quad (1)$$

$$\phi_i^{p+1} = \frac{\sum_j \frac{\phi_j^{p+1}}{R_{ij}^w} + \sum_j \frac{p_j^{p+1}}{R_{ij}^v} + C_i^w \frac{\phi_i^p}{\Delta \tau}}{\frac{C_i^w}{\Delta \tau} + \sum_j \frac{1}{R_{ij}^w} + \sum_j \frac{p_i^{sat}}{R_{ij}^v}} \quad (2)$$

⁶ Künzels H. M., 1995. Simultaneous heat and moisture transport in building components. PhD Thesis: IRB-Verlag, Stuttgart, Germany

⁷ Combined Heat and Moisture Transfer (HAMT) Model, EnergyPlus Documentation, Engineering Reference

The model divides in nodes based on the interfaces between the material layers

The temperature profile is imposed by the thermal model. The moisture model solves only the moisture transfer part.

The outputs are of two kinds:

- a. The results values of the cells of the HAMT model are written for each simulation for each time step in the following files:
 - i. The temperatures of the cells (file: **cells_temp.csv**)
 - ii. The relative humidity of the cells (file: **cells_temp.csv**)
 - iii. The saturation pressure of the cells (file: **cells_vpsat.csv**)
 - iv. The partial pressure of the cells (file: **cells_vp.csv**)
 - v. The water content of the cells (file: **cells_water.csv**)
- b. The averaged water content of the layers (as per the defined material layers) (file: **layers_water.csv**)

5.1.2.3 HAMT comparison

The picture below presents the state as calculated by the HAMT model integrated in the Wall-ACE finite difference dynamic wall model for a typical wall at a given hour.

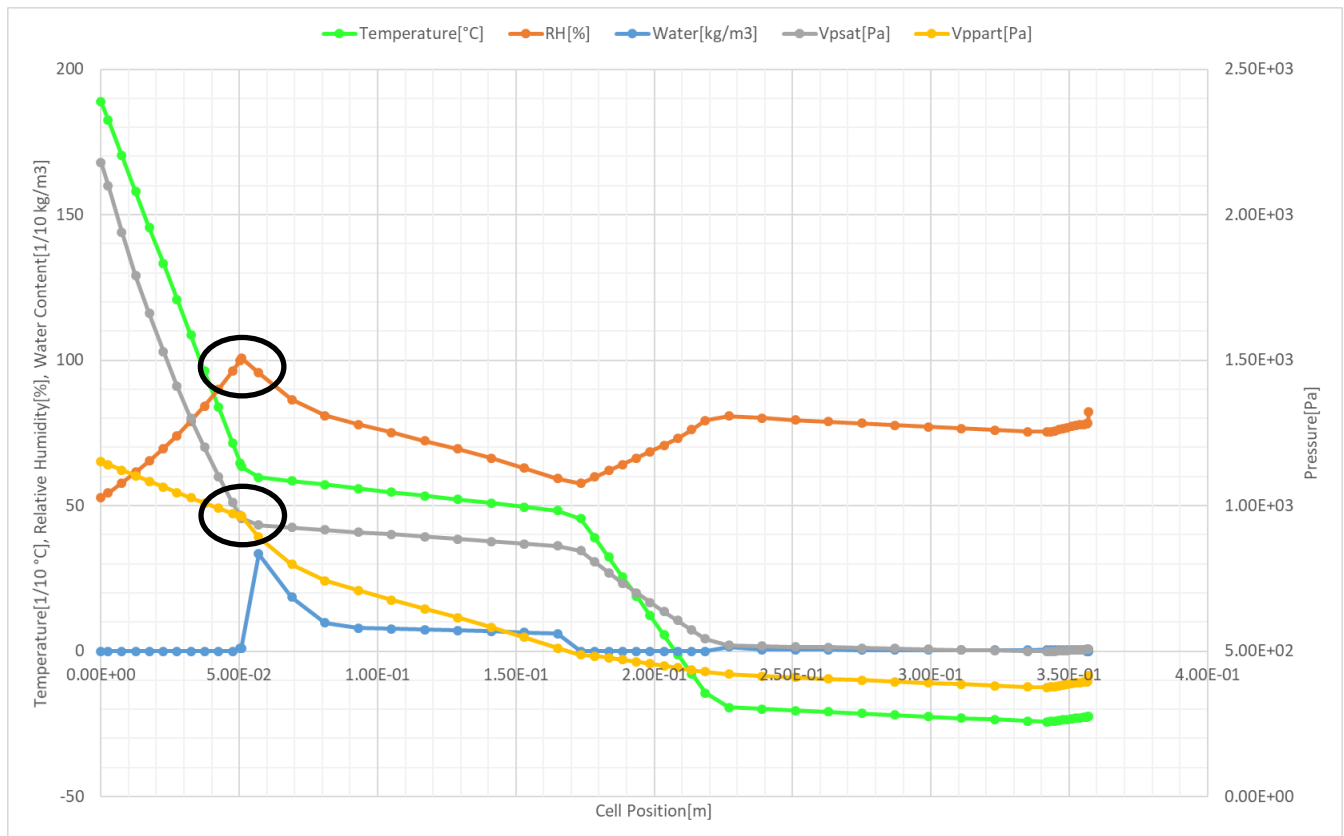



Figure 19: Profiles of saturated pressure, partial pressure, relative humidity, and water content for a specific hour of a simulation, on can see that while the Glaser method shows high condensation, the dynamic HAMT model shows that condensation occurs at this moment of time at only one point where the relative humidity reaches 100 % (see ) and the saturation pressure touching the partial pressure.

6 Manual for software use

6.1 Starting the TRNSED environment

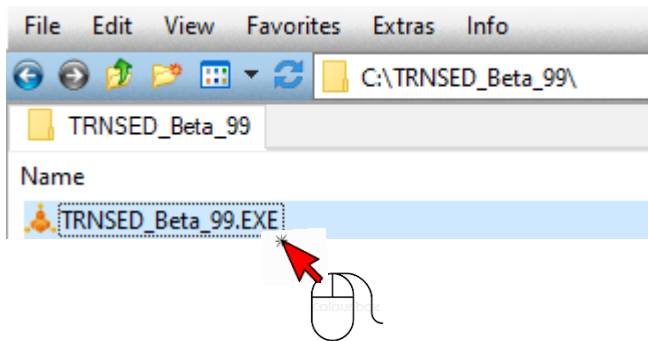


Figure 20: Launching the TRNSED environment by left double-clicking on the TRNSED_Beta_99.exe

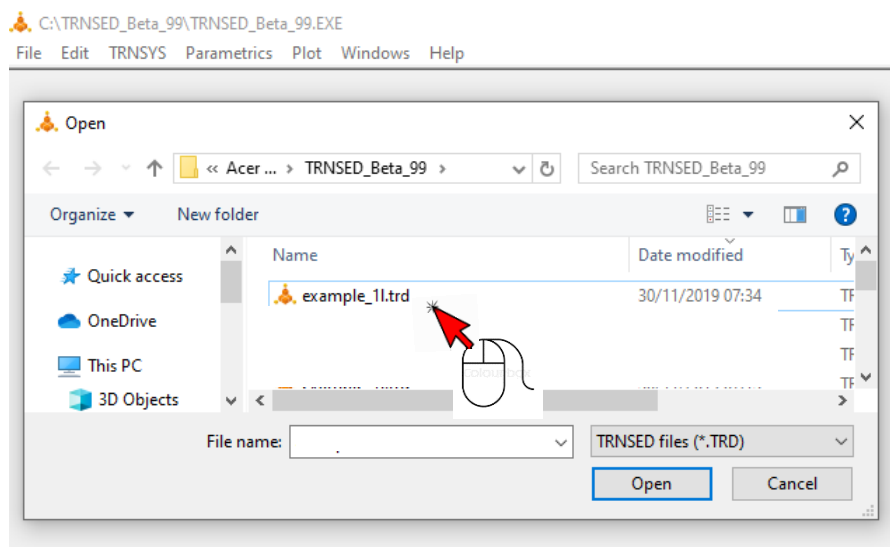


Figure 21: Select the example file example_1.trd and click Open

6.1.1.1 Running through the different tabs for preparing the inputs

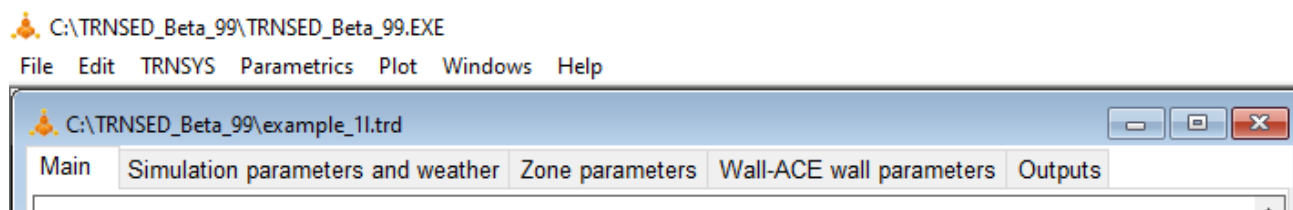


Figure 22: the example file is loaded and the different tabs are shown

- Main (opening page)
- Simulation parameters and weather
- Zone parameters
- Wall-ACE wall parameters
- Outputs

6.1.1.2 Simulation parameters and weather

Main	Simulation parameters and weather	Zone parameters	Wall-ACE wall parameters	Outputs
------	-----------------------------------	-----------------	--------------------------	---------

Weather related inputs

Which file contains the TMY-2 weather data (to see the files do select *)?

Select Europe subdirectroy and under Open choose the option "all files" *.*

Figure 23: The simulation default has been set for a 8736 hours year (365 days with exactly 7 days per week for graphical output of one week each)

6.1.1.3 Zone parameters

Main	Simulation parameters and weather	Zone parameters	Wall-ACE wall parameters	Outputs
Model Zone (Type 19)				
PARAMETERS			VALUES	
Volume of air			150.00000	m3
Infiltration constant 1			0.00010	-
Infiltration constant 2			0.00001	-
Infiltration constant 3			0.00001	-
Capacitance			180.00000	kJ/kg-K
Initial room temperature			20.00000	C
Initial room humidity ratio			0.007	kg/kg
INPUTS			v	
Ventilation stream temperature			0.00000	C
Ventilation flow rate			30.00000	kg/hr
Ventilation humidity ratio			0.005	kg/kg
Rate of moisture gain			0.00000	kg/hr
Number of people in zone			0.00000	-
Activity level of people			0.000	-
Radiative gains			0.00000	kJ/hr
Other internal gains			0.00000	kJ/hr
Cooling_setpoint			50.00000	C
Humidifif_setpoint			0.00100	kg/kg
Dehumidif_setpoint			0.02000	kg/kg
Heating_setpoint			20.00000	C
Height of the zone			3.00000	m
Width of the zone			3.00000	m
Length of the zone			3.00000	m
Table number			2	-
Table entry number			37.000	-

Figure 24: Zone model input parameters

6.1.1.4 Wall-ACE wall model parameters

a) Entering the thermal and vapour diffusion resistance parameters for the thermal and Glaser calculations

L(i) layer thickness (m), Mu(i) moisture dependent vapour diffusion resistance factor (-), Ko(i) thermal conductivity (W/m-K), Rho(i) material density (kg/m³), Cp(i) specific heat capacity of the material (Joule/kg-K)

Theses inputs are to be provided for each layer until the number of layers choose, between 3 and 10. The examples have been prepared with 7 layers, see the examples below.

Etc. for the layers 3 to K (max 10)

Wall-ACE Wall Dynamic Model TYPE156

PARAMETERS

VALUES

K number of material layers

7.00000	-
---------	---

Initial Wall temperature

20.00000	C
----------	---

Simulation Time Step

1.00000	hr
---------	----

L1

0.00100	m
---------	---

MU1

5.00000	-
---------	---

Ko1

0.03400	W/m-K
---------	-------

Rho1

1.20000	kg/m ³
---------	-------------------

Cp1

1000.00000	J/kg-K
------------	--------

L2

0.00100	m
---------	---

MU2

5.00000	-
---------	---

Ko2

0.03400	W/m-K
---------	-------

Rho2

1.20000	kg/m ³
---------	-------------------

Cp2

1000.00000	J/kg-K
------------	--------

L3

0.12000	m
---------	---

MU3

150.00000	-
-----------	---

Ko3

1.20000	W/m-K
---------	-------

Rho3

1600.00000	kg/m ³
------------	-------------------

Cp3

1000.00000	J/kg-K
------------	--------

L4

0.05000	m
---------	---

.....

Figure 25: Inputs for the thermal part of the wall model

Etc. up to 10 layers

b) Entering additional parameters used for the HAMT dynamic model

The parameters of the isothermal sorption are to be provided following the simplified approach with 3 points. This is based on the approximation for the moisture storage function which is explained in the Wufi-Wiki documentation⁸.

The parameters to input for the HAMT model for each material layer. The necessary parameters and which are normally available are the iso_w0 (water content at 0% relative humidity (kg/m³)), iso_w80 (water content at 80% relative humidity (kg/m³)), and iso_wf. (water content at 100% relative humidity (kg/m³)).

1 iso_w0	0.00000	kg/m ³
1 iso_w80	0.00000	kg/m ³
1 isowf	0.00000	kg/m ³
1 redwater1	0.00000	kg/m ³
1 redwater2	0.00000	kg/m ³
1 redwater3	0.00000	kg/m ³
1 reddata1	0.00000	m ² /s
1 reddata2	0.00000	m ² /s
1 reddata3	0.00000	m ² /s
2 iso_w0	0.00000	kg/m ³
2 iso_w80	5.70000	kg/m ³
2 isowf	176.00000	kg/m ³
2 redwater1	0.00000	kg/m ³
2 redwater2	0.00000	kg/m ³
2 redwater3	0.00000	kg/m ³
2 reddata1	0.00000	m ² /s
2 reddata2	0.00000	m ² /s
2 reddata3	0.00000	m ² /s

Figure 26: Parameters to input for the HAMT model for each material layer.

Up to 10 layers.

⁸ <https://www.wufi-wiki.com/mediawiki/index.php/Details:MoistureStorageFunction> under Approximation of the moisture storage function

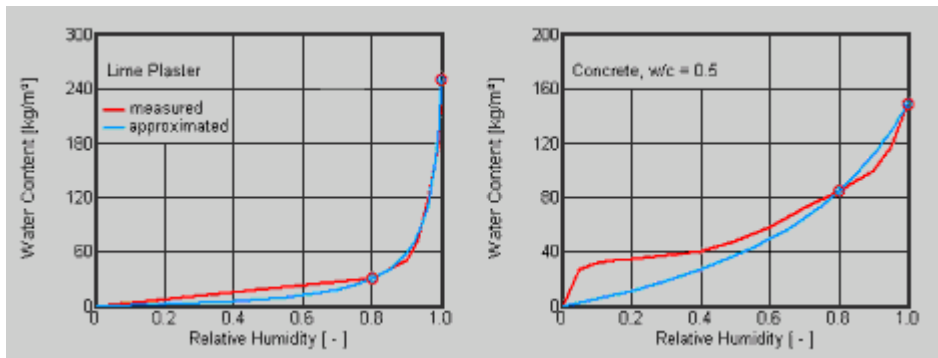


Figure 27: Example of three-points isothermal sorption modelling parameters, for most materials this approach is sufficient. See reference⁷.

The inputs to the type 156 dynamic Wall-ACE model are the total heat transfer coefficients h_{ext} (external) and h_{int} (internal) in $\text{W/m}^2\cdot\text{K}$. Temperature inside and outside are also input, and are linked to the Weather file (TMY2 files). The Relative humidity in % has also to be provided from the weather file for RelHumExt , and from the type 19 zone for the RelHumInt .

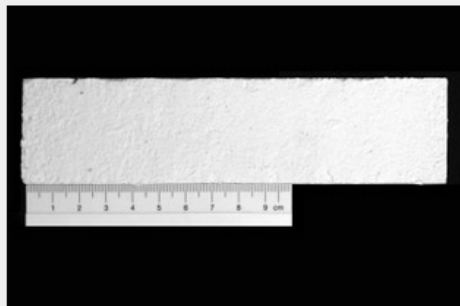
Many of needed parameters for studies for renovation can be found on the MASEA geprüfter Datenbank⁹. This data bank has hundreds of materials with measured characteristics.

Fachwerkmörtel

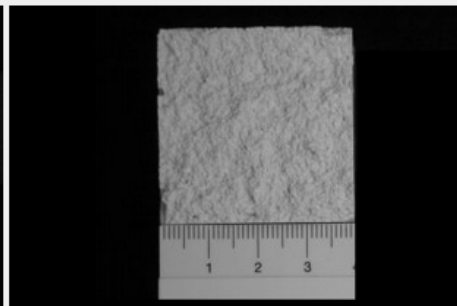
Kategorien: Putze, Mörtel und Ausfachungen

Bauphysikalische Kennwerte

Kennwert	Symbol	Einheit	Wert	Referenz
Rohdichte	ρ	$\left[\frac{\text{kg}}{\text{m}^3}\right]$	960	
Spezifische Wärmekapazität	\mathcal{P}	$\left[\frac{\text{J}}{\text{kg K}}\right]$	1000	
Wärmeleitfähigkeit	λ_r	$\left[\frac{\text{W}}{\text{m K}}\right]$	0.17	
Diffusionswiderstandszahl (dry) 23°C - 3/50%	μ	[—]	17.3	
Diffusionsäquivalente Luftschichtdicke (sd-Wert)	s_d	[m]	0.35	
Sorption	$u_{(80)}$	$\left[\frac{\text{kg}}{\text{m}^3}\right]$	10.4	
Freie Wassersättigung	$u_{(f)}$	$\left[\frac{\text{kg}}{\text{m}^3}\right]$	360	
Wasseraufnahmekoeffizient	W_w	$\left[\frac{\text{kg}}{\text{m}^2 \sqrt{\text{h}}}\right]$	1.92	
Offene Porosität	Φ	[Vol-%]	61.0	



Draufsicht



Bruch

⁹ <https://www.masea-ensan.de/>

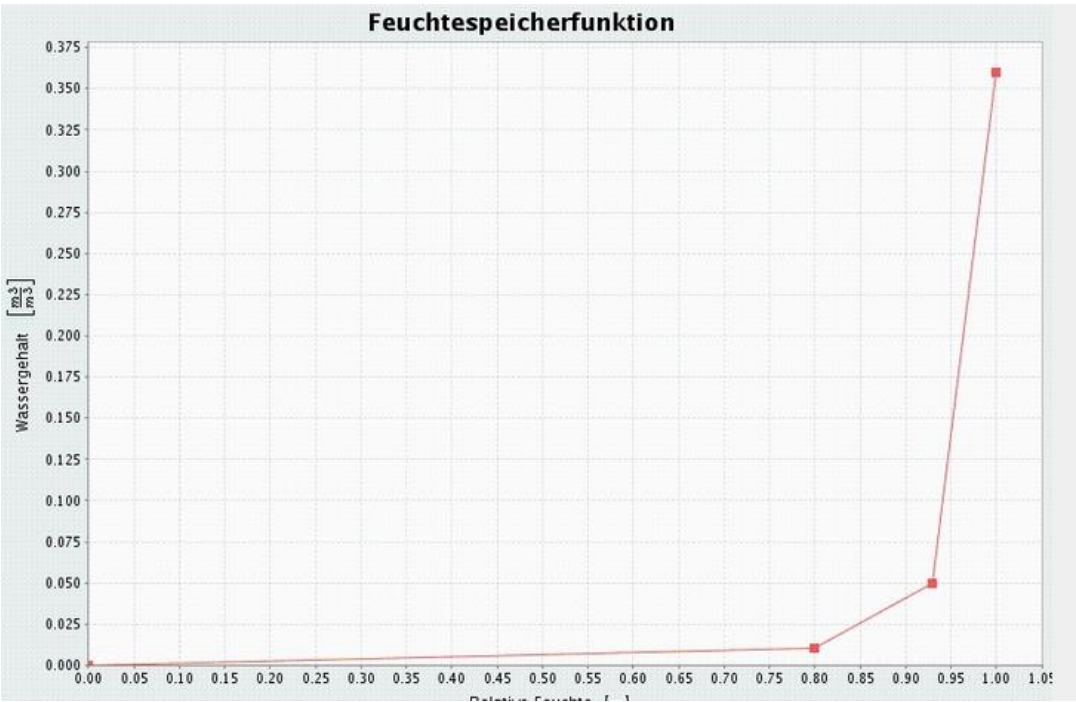


Figure 28: Example taken from the MASEA databank

This Data Bank is certainly one of the best data collection available for renovation.

INPUTS		
h_ext	20.00000	W/m2-K
T_ext	-10.00000	C
h_int	8.00000	W/m2-K
T_int	20.00000	C
Simulation Step in Hrs	1.00000	hr
RelHumExt	80.00000	C
RelHumInt	50.00000	%

Figure 29: Inputs to the Wall-ACE dynamic wall model in TRNSYS environment (they overridden during the simulation)

The monthly internal temperature are to be taken from the Glaser local data, or through the Type 19 return in case of coupling, otherwise the default value has been taken as 20 °C and 50% relative humidity inside for the monthly Glaser calculation.

Tint_01	20.00000	C
Tint_02	20.00000	C
Tint_03	20.00000	C
Tint_04	20.00000	C
Tint_05	20.00000	C
Tint_06	20.00000	C
Tint_07	20.00000	C
Tint_08	20.00000	C
Tint_09	20.00000	C
Tint_10	20.00000	C
Tint_11	20.00000	C
Tint_12	20.00000	C
Rhint_01	50.00000	%
Rhint_02	50.00000	%
Rhint_03	50.00000	%
Rhint_04	50.00000	%
Rhint_05	50.00000	%
Rhint_06	50.00000	%
Rhint_07	50.00000	%
Rhint_08	50.00000	%
Rhint_09	50.00000	%
Rhint_10	50.00000	%
Rhint_11	50.00000	%
Rhint_12	50.00000	%

Figure 30: input parameters for the internal conditions monthly (if coupling on, value from the zone model)

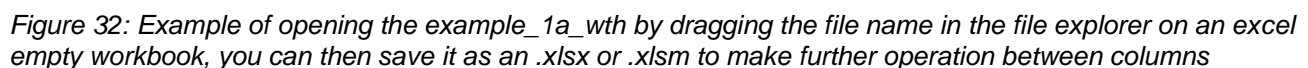
6.1.2 Outputs generated and stored with the name of the input file as beginning with parameters that can be changed if necessary

The outputs shown on the screen during the simulation are written in hourly files. The files are organised as per the simulation file name.trd

Each of the hourly output files generated has a format with the columns separated by tab characters, so they can be opened directly with excel or any other software separating columns with tab characters.

By default, the extension names allow to recognize the output files and select them for further analysis in software like Excel for example.

By simply dragging the file from the file explorer on an excel empty workbook, the file is opened with the columns directly in place in the excel files.



6.1.2.1 Table of the output in each file created by the TRNSED during each simulation

Page 29 of 36

a) *****.wth:**

Left axis minimum	-30.00000	-
Left axis maximum	30.00000	-
Right axis minimum	0.00000	-
Right axis maximum	5000.00000	-

*****.pwr :**

Left axis minimum	-50.00000	-
Left axis maximum	50.00000	-
Right axis minimum	-10.00000	-
Right axis maximum	40.00000	-

b) *****.enr**

Left axis minimum	-100000.000	-
Left axis maximum	100000.000	-
Right axis minimum	0.00000	-
Right axis maximum	1000.00000	-

c) *****.wal**

Left axis minimum	0.00000	-
Left axis maximum	50.00000	-
Right axis minimum	0.00000	-
Right axis maximum	50.00000	-

d) *****.htn**

Left axis minimum	-20.00000	-
Left axis maximum	30.00000	-
Right axis minimum	0.00000	-
Right axis maximum	10000.0000	-

e) *****.pre**

Left axis minimum	0.00000	-
Left axis maximum	4000.00000	-
Right axis minimum	0.00000	-
Right axis maximum	4000.00000	-

f) *****.plt**

Left axis minimum	-20.00000	-
Left axis maximum	30.00000	-
Right axis minimum	-20.00000	-
Right axis maximum	30.00000	-

g) *****.prt**

Left axis minimum	0.00000	-
Left axis maximum	2000.00000	-
Right axis minimum	0.00000	-
Right axis maximum	2000.00000	-

h) *****.par**

Left axis minimum	0.00000	-
Left axis maximum	1000.00000	-
Right axis minimum	-20.00000	-
Right axis maximum	30.00000	-

i) *****.pl1**

Left axis minimum	-20.00000	-
Left axis maximum	30.00000	-
Right axis minimum	0.00000	-
Right axis maximum	1 00000	-

6.2 Description of outputs Package

This section is listing and presenting the files and directories provided by the package, and how to use them. The first section presents the common workflow to follow in order to launch one of the provided examples.

6.2.1 Quick start

The entry point of the simulation software is *TRNSED_Beta_99.exe*. Double click on this executable to launch the software. A window containing some information on the software opens, click Ok to continue. It is now possible to open a TRD file. A TRD file provides all the information needed by TRNSED to setup and start a simulation. Several example files are provided, select one of these files, for example **example_1g.trd**. The selected file is then loaded and all the information and properties it contains are displayed in six tabs. It is possible to change some properties if wanted or start the simulation as it is. All the changes made can be saved through the file menu (Ctrl+S). To start the simulation, press F8 or click on the TRNSYS menu button, then on Calculate.

6.2.2 Files organisation

- **The executables:** This package contains the main executable files: **TRNSED_Wall-ACE-V1_0.EXE**. It is the entry point of our simulation tool and provides the most up-to-date version of our software.
- **TRD files:** The **.trd** files contain the configuration properties to start a simulation run. They can be opened and edited by the *TRNSED_Beta_99* executable.
- **The DLLs:** These are the compiled versions of every module used by the software.
- **Log files:** The log files contain some basic information and events for each run.
- **Descrips.dat, Formats.dat, Length.dat, Month1.dat, VarUnits.dat:** These files contain various parameters used by TRNSED and should not be modified.
- **SUM files:** The files having the **.SUM** extension are written during each run and also during parametric runs and contains the heat balance of each run. An Excel macro is provided in order to extract and format them.

6.2.3 Running and observing a simulation during execution

The run starts and a new window opens to display the computed properties at each timestep. It is possible to pause the simulation at any time by right clicking on the graph. This allows to review the computed values during the run.

At the end of the run, a prompt asks the user whether to close the window or not. Click yes to close the window or no in order to review the graphs.

6.2.4 Looking at results, outputs

The software creates several files to store the results computed during a run. These files are located in the subdirectories **out_data**, **out_hamt**, **out_monthly_reports**, which are presented in the following sections.

6.2.4.1 Directories

These are the directories under the **C:\TRNSED_Wall-ACE-V1** main directory

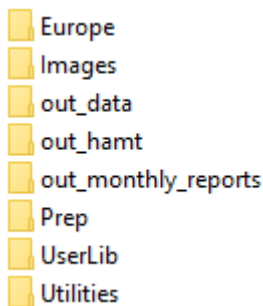


Figure 33: Directories under the main **C:\TRNSED_Wall-ACE-V1** main directory

a) Europe: This folder contains a sample of meteorological files for several European locations

They can be used in the simulation. Users can add new meteorological files to this folder. The files can be in any format supported by TRNSYS' Type 15.

b) Images

Pictures for the application are stored here (do not change)

c) out_data: This folder contains the data files created by TRNSYS' Type 156 hourly Glaser process to summarize the computed properties of the wall, for each iteration.

The naming convention is as follow: "[hr]_[cond]_diagram_glaser.dat". Where [hr] is replaced by the simulation iteration number (i.e. the hour) and [cond] is replaced by respectively "wcond" or "nocond", whether there has been condensation happening during the corresponding iteration or not.

Each file contains an array that summarises the main properties computed for each interface between two layers of the simulated wall. Each row of this array is thus an interface, ranging from the interior towards the exterior interface, with the exception of the first and last rows which represent the interior and exterior areas.

For each interface the following properties are recorded:

1. Sd_tot: The vapour diffusion thickness of the wall, measured from the interior surface, in millimeters. (Sd is defined as $d \cdot \mu$ and is used to represent the equivalent distance taking into account the thickness of each layer multiplied by the μ coefficient).

2. $T_{\text{interface}}$: The temperature at the interface in degrees Celsius.
3. P_{sat} : The saturation pressure in Pascal.
4. P_{part} : The partial pressure in Pascal.
5. $P_{\text{part_glaser}}$: The partial pressure corrected by the Glaser method in case of condensation, in Pascal.
6. X_{layer} : The interface position in the wall, measured from the interior surface, in millimeters.
7. S_d : The vapour diffusion thickness of a layer, in millimeters.

The time of simulation, as well as the interior and exterior relative humidity are also written at the end of each data file.

d) **out_hamt**: This folder contains the output files created by the Heat and Moisture Transfer module (HAMT) of Type 156

Each file records a single property for every cell that forms the simulated wall for every time step. The format for these files is as follows: Each column is a cell of the simulated wall ordered from the interior surface to the exterior. The first line contains the name of the cells. The second line is the position in meters of each cell in the wall, measured from the interior surface. The following lines are the values computed during each iteration.

The files created are always the same and are named in function of the property they record:

1. **cells_rh.csv**: The relative humidity computed for each cell at every iteration.
2. **cells_temp.csv**: The temperatures in degrees Celsius.
3. **cells_vp.csv**: The vapour partial pressure in Pascal.
4. **cells_vpsat.csv**: The vapour saturation pressure in Pascal.
5. **cells_water.csv**: The water content in kg.
6. **cells_water.csv**: The fraction of the cell containing water.

The last file created by the HAMT module is **layers_water.csv** and contains the average water content for each layer of the wall.

e) **out_monthly_reports**: This folder regroups the monthly summary files created by the Type 156

For each month, three files are created. The first one is named **[mth]_hamt_monthly_report.csv**, with [mth] being replaced by the month number and contains the monthly average of the properties computed by the HAMT module. The second file is named **[mth]_hourly_glaser_report.csv** and contains the monthly average of the properties computed by the hourly Glaser method of Type 156. The last type of file is named **[mth]_monthly_glaser_report.csv** and contains the result of the classical monthly Glaser algorithm.

These three types of files have the same structure as the Glaser diagram data files located in the *out_data* folder described above, added to which are found the average interior and exterior temperatures written at the end.

f) **Utilities**: This folder contains utilitarian scripts and excel macros

They can be used by the user to automatically extract and format the files resulting from a run.

The files with the extension .bat can be directly executed by

1. **del_hr_files.bat**: Deletes files that are generated during each run, located in the main **C:\TRNSED_Wall-ACE-V1** and that can be cleaned when their analysis and use is over. In order to clean the repository.

2. ***del_glaser.bat***: Deletes all the **glaser.dat* files that are generated by the Type 156 during a run and are located in the ***out_data*** subdirectory.
3. ***extract_monthly_reports.xlsm***: Assembles in the same excel file the three reports for a chosen month and creates their graph in order to allow an easy comparison between the HAMT algorithm and both hourly and monthly Glaser methods.
4. ***extract_q_sum.xlsm***: Extracts the **.sum* files created during parametric runs and assembles them in an array. Also creates a graph of the evolution of each exported property in relation to the parameter that was varying.

g) Prep:

This folder contains the Prep routine that can be used to compute transfer coefficients for custom wall compositions. These coefficients can then be used as inputs in the Type 19.

To compute the coefficient for a new wall composition, launch the prep executable. A command line window opens providing detailed instructions to setup a wall. The Type 19 Manual Supplement provides codes that allow to quickly setup walls with commonly used materials. The generated coefficients are written in *fortype19.dat*.

h) UserLib: (Empty)

6.2.4.2 Outputs from the HAMT model

In addition to the TRNSED generated files, specific files generated from the HAMT dynamic modelling are generated, see the applications mentioned above.

6.3 ***Example of a single simulation execution and results***

6.3.1 **Preparing the inputs**

Refer to the section above.

6.3.2 During the simulation

After launching the simulation, running and observing a simulation during execution.

The run starts and a new window opens to display the computed properties at each timestep. During the simulation weekly screens appear (52 of them for a simulation). Each screen shows a full 7 days divided by exactly 24 hours per day.

It is possible to pause the simulation at any time by right clicking on the graph. This allows to review the computed values during the run.

When pushing the SHIFT button and moving simultaneously the mouse to left or right, the values replace the legend of each variable.



At the end of the run, a prompt asks the user whether to close the window or not. Click yes to close the window or no in order to review the graphs.



6.3.3 Analyzing the results of a single simulation

During the simulation different files are written by the TRNSED environment:

6.3.3.1 Directly written hourly files with the defined extension *****.nnn** like a to j below

- a) wth
- b) pwr
- c) enr
- d) wal
- e) htn
- f) pre
- g) plt
- h) prt
- i) par
- j) pl1

For their definition see 6.1.2 Outputs generated and stored with the name of the input file as beginning with parameters that can be changed if necessary.

Each of these files can be directly opened in Excel or any other application able to separate the columns based on tab character (tab is a horizontal tab (HT), which in ASCII has the decimal character code of 9) .

09 HT (Horizontal Tab)

6.4 Running an example of a parametric analysis

See the example results in Results and Analysis

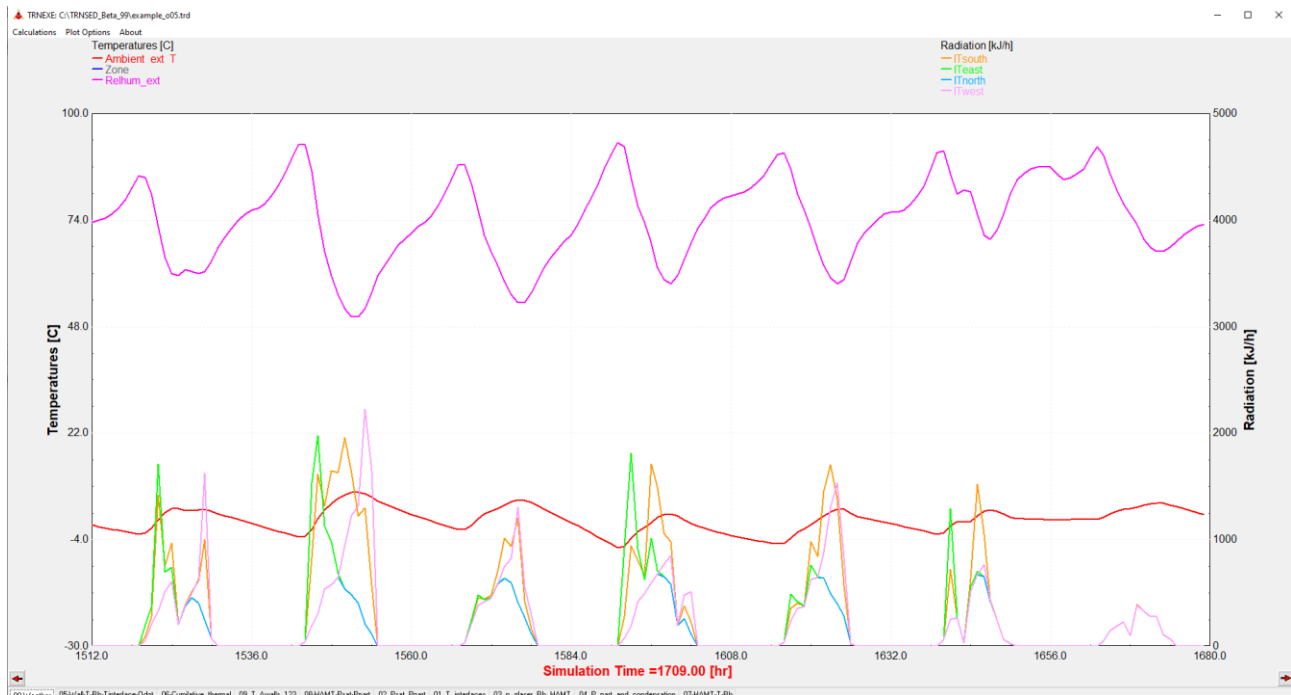


Figure 34: Screenshot, one per week during the simulation