Coupling of Dynamic Thermal Bridge and Whole-Building Simulation

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ABSTRACT

The effect of thermal bridges on the overall energy performance of buildings is not fully taken into account in standard compliance methods. Steady-state methods are predominately deployed for thermal bridge analysis. One important issue that is often underestimated is the dynamic performance of thermal bridges under different exterior climate conditions.

This paper shows the coupling of a hygrothermal whole-building simulation software with a three-dimensional dynamic thermal bridge simulation. The basics of the hygrothermal whole-building model and the thermal bridge model are explained. The coupling of both models allows the validation of the software for standard conform computations.

The steady-state validation of the thermal bridge model was successful and allows the discussion of application areas in a dynamic simulation.

INTRODUCTION

With higher requirements on energetic envelope design and on airtightness, the ratio of thermal bridge losses compared to the overall losses under heating conditions increases. But the effect of thermal bridges on the overall energy performance of buildings is often not fully taken into account in standard compliance methods. In such methods, steady-state methods are predominately deployed for thermal bridge analysis. Dynamic interaction of the thermal bridge with the building zones is not adequately accounted for.

This was the basis for the coupling of a dynamic thermal bridge simulation with a hygrothermal whole-building simulation. In this combination, the dynamic effects on the thermal bridge can interact with the dynamics of overall building envelope and space. Besides the energy effects, the potential risk for harmful humidity conditions, e.g., on the coldest spots in a zone, can be assessed.

A critical review of existing literature is required to determine documented effects of thermal bridge simulation in combination with dynamic building simulation. In the next step, a model for three-dimensional objects is developed that needs to be implemented and validated in a whole-building simulation environment in order to produce reliable results. The implemented and validated model can then be used to demonstrate the effect of thermal bridges on the energy demand of buildings.

DYNAMIC SIMULATION OF THERMAL BRIDGES

In literature, the necessity of taking thermal bridges into account for both compliance methods and dynamic simulation is discussed controversially. Standard methods to compute the building energy demand are usually monthly-balance-based methods and take thermal bridges with their linear loss coefficient into account. This could be a simple approach to account for the thermal bridge effect in dynamic building simulation. But the dynamic behavior of the thermal bridge is not taken into account.

Martin et al. (2012a) describe two ways to account for thermal bridges in dynamic building simulation. The first is to solve the two-dimensional (2-D) and three-dimensional (3-D) heat transfer and the second is to use an equivalent building assembly that performs just as the dynamic thermal bridge.

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For the direct implementation the authors see further demand in solving time and simplification of the problem specification. By using equivalent assemblies the results are no longer that accurate (Martin et al. 2011, 2012b).

Kosny and Kossecka had already concluded in 2002 in a comparison of the equivalence method with detailed calculations and hot-box measurements that serious deviations in the demand calculations with dynamic simulations can be a result if only one-dimensional (1-D) components are taken into account.

Ascione et al. (2012) compare results of conventional approaches with detailed 2-D and 3-D simulation model results. It is described that different modeling approaches can lead to 20% divergence in the results for the energy demand of a typical office building in Italy. The authors recommend the development of dynamic building simulation software that provides modules to take into account thermal bridges according to the standard DIN EN ISO 10211 (DIN 2008).

Besides the assessment of the effect of a thermal bridge on the energy demand of a building, a detailed thermal bridge simulation also allows determination of surface temperatures and therefore the analysis of potential mold growth risk. To simulate realistic hygrothermal conditions inside a building, a hygrothermal whole-building model is required. With this background a new module to dynamically compute 2-D and 3-D thermal bridges was implemented into the existing hygrothermal whole-building simulation software WUFI® Plus (Fraunhofer IBP 2013). In the following the basics of both simulation methods and their coupling are explained.

HYGROTHERMAL WHOLE-BUILDING SIMULATION SOFTWARE WITH 3-D THERMAL BRIDGE SIMULATION

This section describes in short the used software model WUFI Plus. It furthermore shows how the 3-D elements are implemented in the whole-building simulation model.

The WUFI Plus software

WUFI Plus is a dynamic whole-building simulation model based on the hygrothermal envelope calculation model developed by Künzel (1994). The 1D coupled heat and moisture transfer in opaque building components is simulated. Moisture sources or sinks inside a component, capillary action, diffusion, and vapor absorption and desorption as a response to the exterior and interior climate boundary condition as well as thermal parameters are taken into account. The conductive heat and enthalpy flow by vapor diffusion with phase changes depends strongly on the moisture field. The vapor flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapor pressure with temperature. Resulting differential equations are discretized by means of an implicit finite volume method. The model was validated by comparing its simulation results with the measured data of extensive field experiments (Künzel 1994) and corresponds to the specifications of DIN EN 15026 (DIN 2007).

The hygrothermal behavior of the building envelope affects the overall performance of a building. Therefore, the components are coupled to a whole-building model (Holm et al. 2004). It can be discretized in different zones regarding one or more rooms with the same interior condition. Thus, the components define the zone boundaries and deliver the heat and moisture flow across the building envelope. The zones provide the boundary conditions for the components. Depending on all current heat and moisture flows across the zone boundaries and the previous states of the components and zones, the indoor climate is simulated iteratively. Heat and moisture balances within the zones are examined. As long as they are not satisfied, the indoor temperature and humidity are adapted for each iteration and time step (Lengsfeld and Holm 2007).

Additionally, there is one predefined zone, the outdoor zone, where the climate data is the input, e.g., obtained by measurements. This climate data mainly contains outdoor air temperature, relative humidity, wind speed and direction, normal rain, and solar radiation data, which influence the exterior building envelope. In the envelope, there can be transparent components, the fenestration. The solar radiation is not only absorbed by the exterior surfaces but a part of it passes through the transparent components and directly heats the indoor air and interior surfaces. Internal heat and moisture sources and sinks, due to people, lighting, and household and plant equipment, are considered too and are a part of the balance equations. Last but not least, the natural, mechanical, and interzonal ventilation influence the simulated indoor climate.

Ideal plant equipment systems provide space heating, cooling, humidification, dehumidification, and ventilation. Furthermore, minimum and maximum design conditions for the zones can be set. If the indoor climate exceeds those design conditions, the required demand to counteract the excess is calculated, as long as the plant equipment capability is sufficient.

Some results of the dynamic hygrothermal building simulation model are the mentioned indoor temperature and humidity for each calculated time step. Usually the time step size is one hour. Further results are the heating, cooling, humidification, dehumidification, and ventilation demands for each time step, summarized over the simulation period. Every heat and moisture profile across a component can be saved, including the surface conditions, which allows the assessment of moisture-related problems, e.g., wood rotting or mold growth. The predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) are calculated. Even if some of those simulated values exceed custom limits, one can make a statement about how long or how often they will be exceeded. The zone model was validated via cross-validation with other tools, experiments, and standards such as ANSI/ASHRAE Standard 140 (2007). The validation for both the energetic and the hygric parts of the zone model is described by Antretter et al. (2011).

Coupling of Dynamic Building Simulation with 3-D Element

The WUFI® Plus software was developed with the ambition to be a reliable and easy-to-operate calculation tool for architects and engineers. It enables thermal, energy, and moisture simulations of buildings exposed to transient real climate conditions. The coupled heat and moisture 1D transfer calculation algorithm through multilayer assembly has been extensively verified by experimental measurements (Antretter et al. 2011). The thermal building envelope, however, includes places where processes can only be analyzed in 2-D or 3-D states. To close this gap, the software was supplemented by so-called 3-D objects. These objects are applied for 2-D and 3-D thermal bridges and some special cases, such as transient heat exchange of rooms with the ground. In fact, ground thermal coupling can also be regarded as a large-scale thermal bridge with some special assumptions.

Every real building includes some geometrical or structural (or both) thermal bridges. Transmission heat loss through these elements in steady-state calculations is accounted for by linear or point thermal transmittance coefficients. In the most simplified case, some lump value is added to the overall heat loss coefficient. In DIN EN 12831 (DIN 2003), for calculation of the design heat load only linear thermal bridges are included. The gross variety of thermal bridges and complexity of their calculations compared to 1-D calculations are the reason that these essential parts of the thermal envelope are frequently omitted in transient calculations. Hence, great development effort was invested in the addition of thermal bridges to the WUFI Plus software to make the process as easy as possible on one hand, preserving appropriate calculation accuracy on the other.

For the calculation of 3-D objects the finite volume technique is used (Eymard et al. 2000). This method, based on the thermodynamic law of energy conservation, with clear physical interpretation of heat flow and accumulation, is ideal for the calculation of thermal bridges. In this method, heat-transferring space is divided into small control volumes and the evaluation of integrals and fluxes is conducted via numerical methods.

The addition of a 3-D object starts with dividing the space into X, Y, and Z directions to prepare the geometry that reflects the location of materials and boundary conditions (Figure 1). Based on the WUFI database (Fraunhofer IBP 2013) or user input, relevant materials are stored in the upper list box. In the second list box all kinds of boundary conditions defined in the project—e.g., outer climate, inner zone air, file-based climate, optional climate—are already included. Materials and boundary conditions are assigned in a graphical way with the mouse after choosing the appropriate element from the list box. Any 2-D plane (X, Y, Z slice) can be accessed for assigning materials and boundary conditions. Simultaneously, the 3-D picture

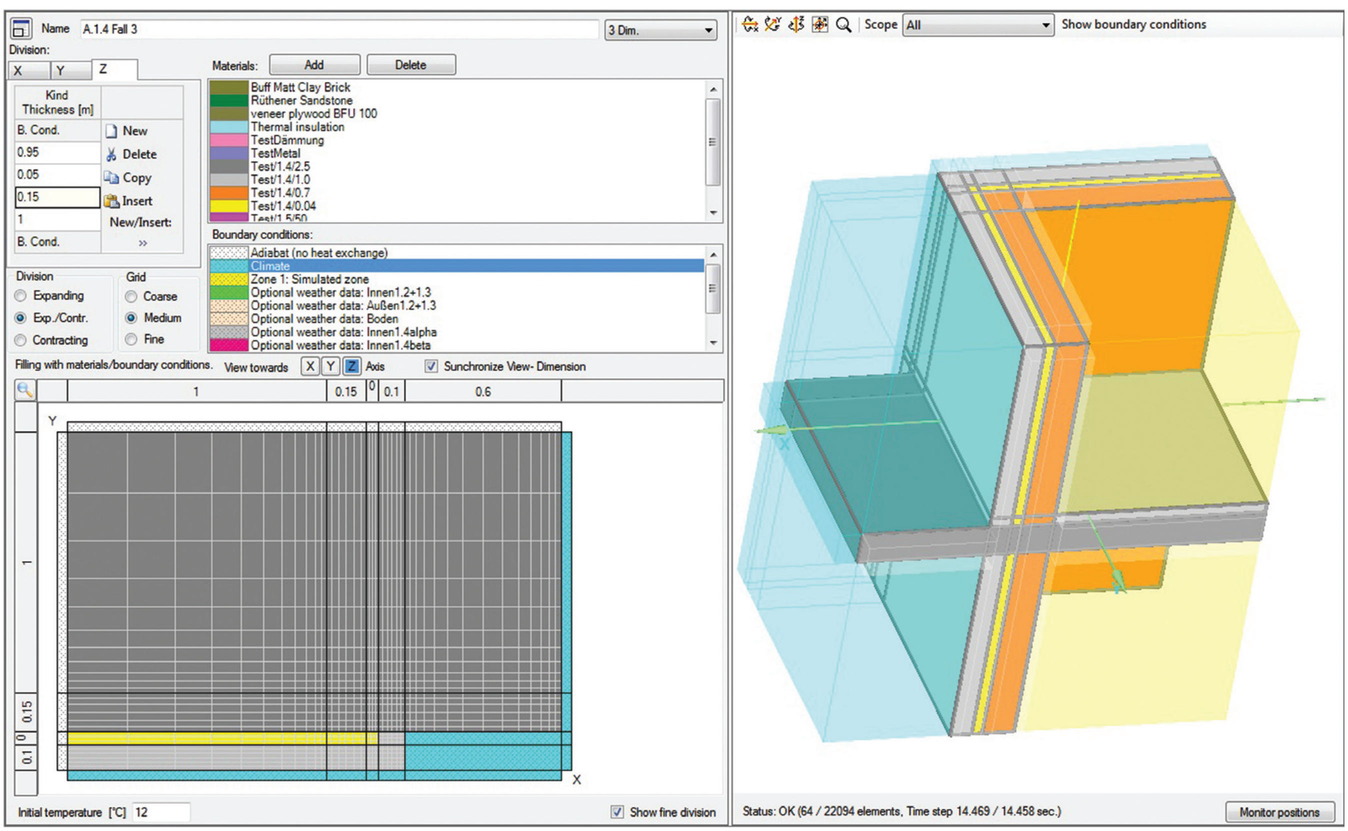

Figure 1 *Addition of a 3-D object in WUFI Plus software—in this case a mesh generated for a concrete ceiling and balcony.*

of the edited object is generated and updated in the window on the right. Boundary conditions are depicted transparent (such as air) but with different colors to allow identification.

The fine division into control volumes is done automatically by the program. The user can choose coarse, medium, or fine division to get more or less elements. The overall section is divided according to geometrical series with expanding, expanding/contracting, or contracting elements. This enables better adjustment of the mesh to the object and some kind of optimization. The initial series segment, scale factor, and number of terms are adapted depending on the division type. Figure 1 shows the adapted mesh by an example of a balcony.

Spatial division and number of control volumes have a crucial impact on both accuracy and calculation time. A more dense mesh should be applied in places where higher temperature gradients and rapid changes of boundary conditions are expected, and a less dense mesh should be applied towards adiabatic planes to reduce computation time.

High numbers of control volume elements and 3-D objects in one building lead to problems with random access memory (RAM) space when a personal computer is used for calculation. An implicit solving method would require the construction of a linear equation matrix with N × N numbers (N = number of control volumes). N grows exponentially with rank. If the space is divided into 50 elements in each direction, 2500 elements are used for a 2-D object and 125000 for a 3-D object. Using standard double numbers (8 bytes each), an appropriate matrix would take, accordingly, 47.7 MB of RAM for the 2-D object and 116.5 GB of RAM for the 3-D object. To avoid memory problems, the explicit method (forward Euler method, where the results of a current time step depend only on the results of the last time step and no iterations have been done) is used to solve for the temperature distribution. Numerical stability of this method requires a limitation of the time step width. This can be very "painful" when objects include materials with high thermal conductivity (e.g., metal). In such a case, at least for 2-D objects, the implicit method would be a better solution.

Once 3-D objects and remaining building data are ready the calculation can be started. Coupling with simulated zones is accomplished by boundary conditions. For every 3-D object any boundary condition can be applied (from a simulated and/or attached zone, outer air, or any optional climate). Boundary conditions vary from time step to time step. Temperature and relative humidity parameters of the air in the simulated zones are calculated iteratively. First, time step initial values, mostly design conditions, are assumed. Then the coupled heat and moisture flows in assemblies and 3-D objects are calculated. After that the heat and moisture balance is checked and, if necessary, the temperature and relative humidity are corrected. The process is repeated as long as calculated parameters comply with the defined accuracy for the given time step. The maximal viable time step for thermal bridges is usually much lower than the overall time step (mostly 1 hour). Thermal bridges are repeatedly calculated with small sub time steps starting with the initial temperature distribution obtained by the previous time step. After the iteration process is finished, the actual temperature distribution is used as the initial condition for the next time step. The heat exchange with 3-D objects is accounted for in the heat balance of simulated zones and has direct impact on the inner temperature, heating demand, cooling demand, etc. The temperature distribution in 3-D objects can be visualized for every cross-section during the calculation (see Figure 2).

VALIDATION OF THE 3-D THERMAL BRIDGE SIMULATION

The newly developed model for the calculation of 3-D elements is validated with the standard DIN EN ISO 10211 (DIN 2008), which provides information and validation examples for the detailed calculation of heat flows and surface temperatures of thermal bridges in building construction. Specified are geometrical 2-D and 3-D models of thermal bridges to compute the heat flows for assessing the energy losses of a building and the lowest surface temperatures to compute the risk for condensate. The standard also contains modeling rules.

Appendix A of the standard provides reference cases for the validation of simulation models—two 2-D cases and two 3-D cases. According to the standard, a model is an accurate model if the simulated results are within a defined accuracy of the given solutions.

The validation examples present steady-state results. Therefore, fixed boundary conditions as provided in the standard were used on the elements. The simulations were conducted until steady-state conditions in the elements were achieved.

Figure 3 shows case 1 of the standard, half of a quadratic stud with known surface temperatures, for which an analytical solution is possible, as well as its implementation in the software. Table 1 shows that all results are in the required accuracy range of less than 0.1 K deviations (listed in Table 2) from the given solution.

Figure 4 shows case 2 of the standard, a 2-D insulated aluminum profile covered with concrete and wood, as well as its implementation in the software. Table 3 shows that all results are in the required accuracy range of less than 0.1 K for temperature or 0.1 W/m for the heat flow deviations from the given solution (Table 4).

Figure 5 shows case 3 of the standard, a 3-D edge, and its implementation in the software. Table 5 shows that all results are in the required accuracy range of less than 0.1 K for temperature from the given solution. The heat flow calculation given in the standard has two flaws: first there are two wrong algebraic signs in Equations A.8 and A.9 (DIN 2008). The temperature boundary condition within room Alpha, below the ceiling (Figure 5), is higher than the temperature in the room Beta, above the ceiling. Following a heat flow from room Alpha to room Beta is expected and not, as given in the standard, a heat flow from room Beta to room Alpha. The second is a simple numerical mistake in Equation A.7, where 24.36 +

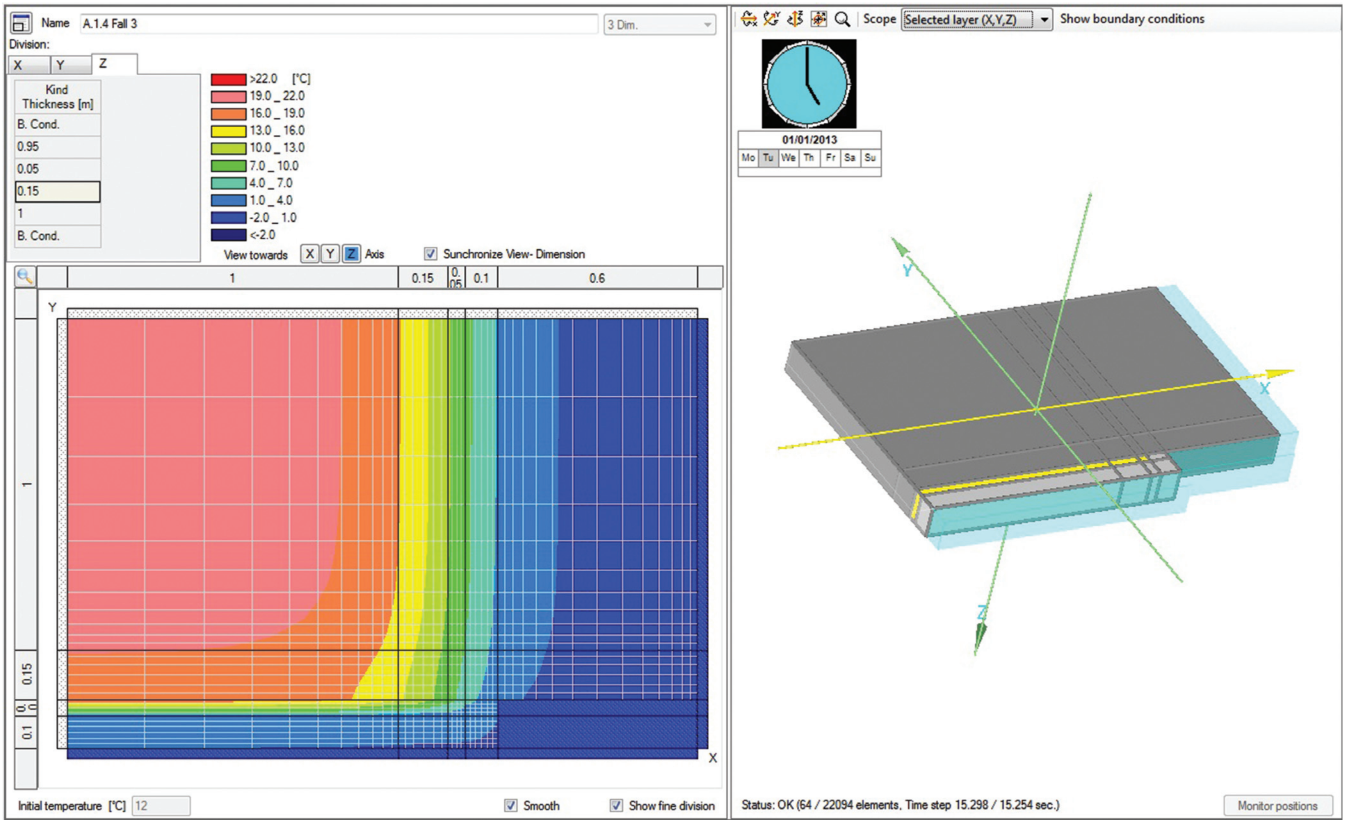

Figure 2 *Visualization of temperature distribution in 3-D objects during calculation in WUFI Plus software.*

35.62 should result in 59.98, not 58.98 as given in the standard (DIN 2008). The results and the corrected standard numbers are shown in Table 6. They are all within the 1% difference.

Figure 6 shows case 4 of the standard, a 3-D thermal bridge representing a steel bar penetrating an insulation layer, and its implementation in the software. Table 7 shows that the results are in the required accuracy range of less than 0.005 K for temperature, and Table 8 shows that the results are in the required accuracy range of less than 1% of the listed heat flow from the given solution.

It is shown that the implemented model can be validated against all four validation cases given in the standard. The validation was successful and the model can be regarded an accurate model conforming to the standard (DIN 2008).

DISCUSSION AND CONCLUSIONS

The use of energetic building simulation for the design of buildings increases. To achieve net-zero or plus-energy buildings, it is important to match the time-dependent energy production and demand. In this case, dynamic simulation software is essential for proper design. If the building simulation model uses in addition a component model that is able to compute the coupled heat and moisture transfer conclusions, not only energy demand but also comfort conditions and the hygrothermal performance of the components are possible.

Such a component model is usually 1-D. The literature, however, shows the necessity for a more detailed analysis that allows a detailed representation of 2-D and 3-D effects.

The coupling of a hygrothermal whole-building model with a transient 3-D thermal bridge calculation was described in this paper. The validation of the thermal bridge model under steady-state conditions according to DIN EN ISO 10211 (DIN 2008) was successful. One verification case in the standard needed adaption, as an application error was found in the standard and described in this paper.

The new combined software tool allows a broad range of applications. The effect of the dynamic thermal bridge performance on the overall energy demand of a building can be assessed. Furthermore, moisture-related problems on the thermal bridges can be assessed.

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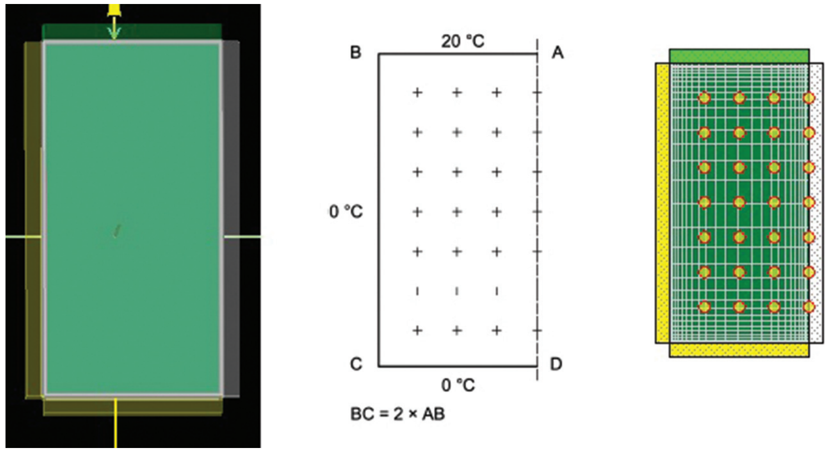

Figure 3 *Validation case 1 of DIN EN ISO 10211 (DIN 2008) and its implementation as a 3-D element in WUFI Plus.*

Table 1. Results of Case 1 of DIN EN ISO 10211 (DIN 2008)

WUFI | ISO 10211	WUFI | ISO 10211	WUFI | ISO 10211	WUFI | ISO 10211	Confirm
9.67 | 9.70	13.37 | 13.40	14.73 | 14.70	15.08 | 15.10	y | y | y | y
5.27 | 5.30	8.64 | 8.60	10.31 | 10.30	10.81 | 10.80	y | y | y | y
3.19 | 3.20	5.60 | 5.60	7.00 | 7.00	7.45 | 7.50	y | y | y | y
2.03 | 2.00	3.66 | 3.60	4.67 | 4.70	5.00 | 5.00	y | y | y | y
1.26 | 1.30	2.31 | 2.30	2.98 | 3.00	3.21 | 3.20	y | y | y | y
0.74 | 0.80	1.36 | 1.40	1.77 | 1.80	1.91 | 1.90	y | y | y | y
0.34 | 0.30	0.63 | 0.60	0.82 | 0.80	0.89 | 0.90	y | y | y | y

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Table 2. Differences between WUFI Plus (Fraunhofer IBP 2013) and Case 1 of DIN EN ISO 10211 (DIN 2008)

Difference	Difference	Difference	Difference
0.03	0.03	0.03	0.02
0.03	0.04	0.01	0.01
0.01	0.00	0.00	0.05
0.03	0.06	0.03	0.00
0.04	0.01	0.02	0.01
0.04	0.04	0.03	0.01
0.04	0.03	0.02	0.01

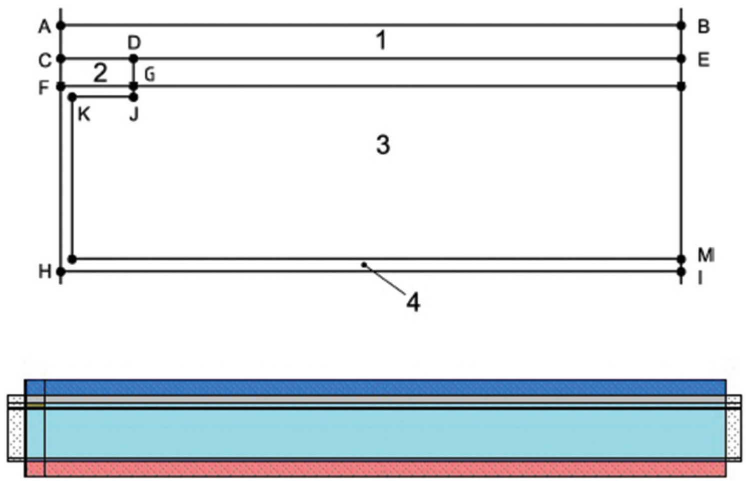


Figure 4 *Validation case 2 of DIN EN ISO 10211 (DIN 2008) and its implementation as a 3-D element in WUFI Plus.*

Table 3. Results of Case 2 of DIN EN ISO 10211 (DIN 2008)

WUFI Result	DIN EN ISO 10211 (DIN 2008)	Difference	Confirm
7.05	7.10	0.05	y
0.76	0.80	0.04	y
7.88	7.80	0.02	y
6.26	6.30	0.04	y
0.83	0.80	0.03	y
16.42	16.40	0.02	y
16.35	16.30	0.05	y
16.78	16.80	0.02	y
18.34	18.30	0.04	y

Table 4. Heat Exchange of Case 2 of DIN EN ISO 10211 (DIN 2008)

WUFI Result	DIN EN ISO 10211 (DIN 2008)	Difference
9.461	9.500	0.039

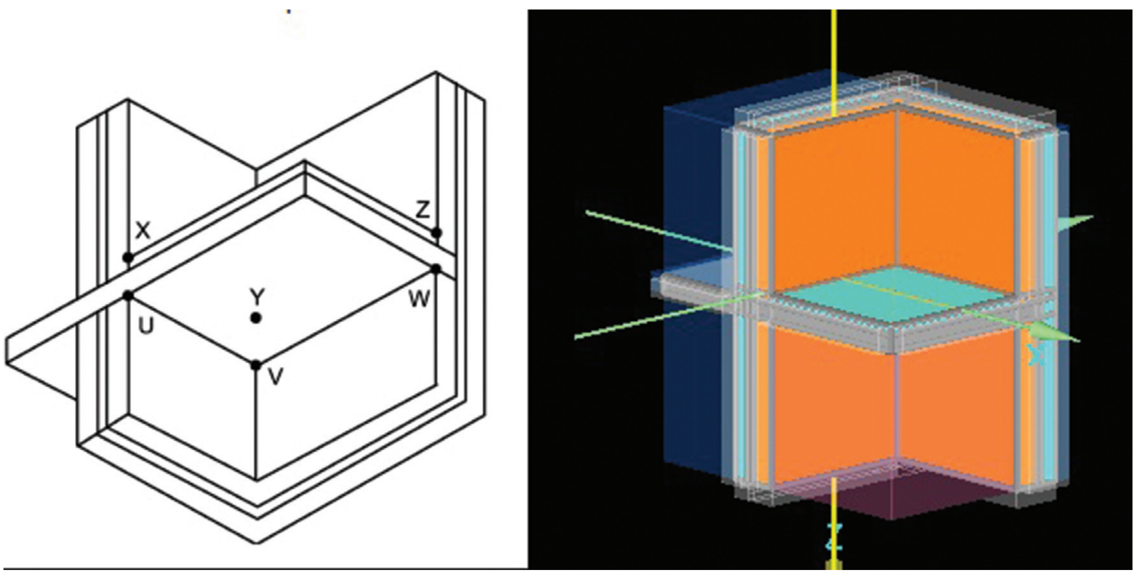


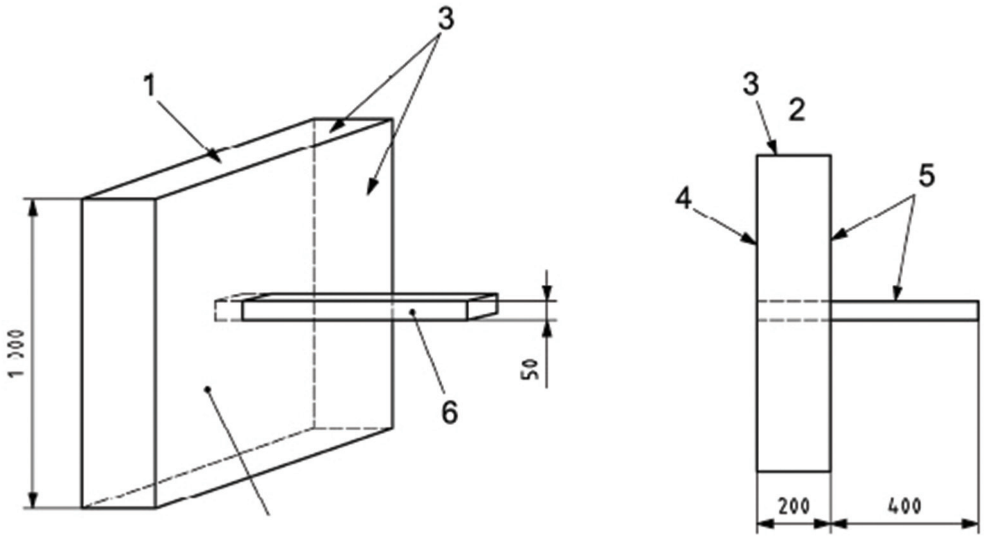
Figure 5 *Validation case 3 of DIN EN ISO 10211 (DIN 2008) and its implementation as a 3-D element in WUFI Plus.*

Table 5. Results of Case 3 of DIN EN ISO 10211 (DIN 2008)

WUFI Result	DIN EN ISO 10211 (DIN 2008)	Difference	Confirm
11.39	11.32	0.07	y
11.02	11.11	0.09	y

Table 6. Heat Exchange of Case 3 of DIN EN ISO 10211 (DIN 2008)

Watt	Outside	Room Alpha	Room Beta
WUFI	59.80713	45.97178	13.83534
DIN EN ISO	59.98000	46.09000	13.89000
1% of DIN	0.59980	0.46090	0.13890
Difference	0.17287	0.11822	0.05466



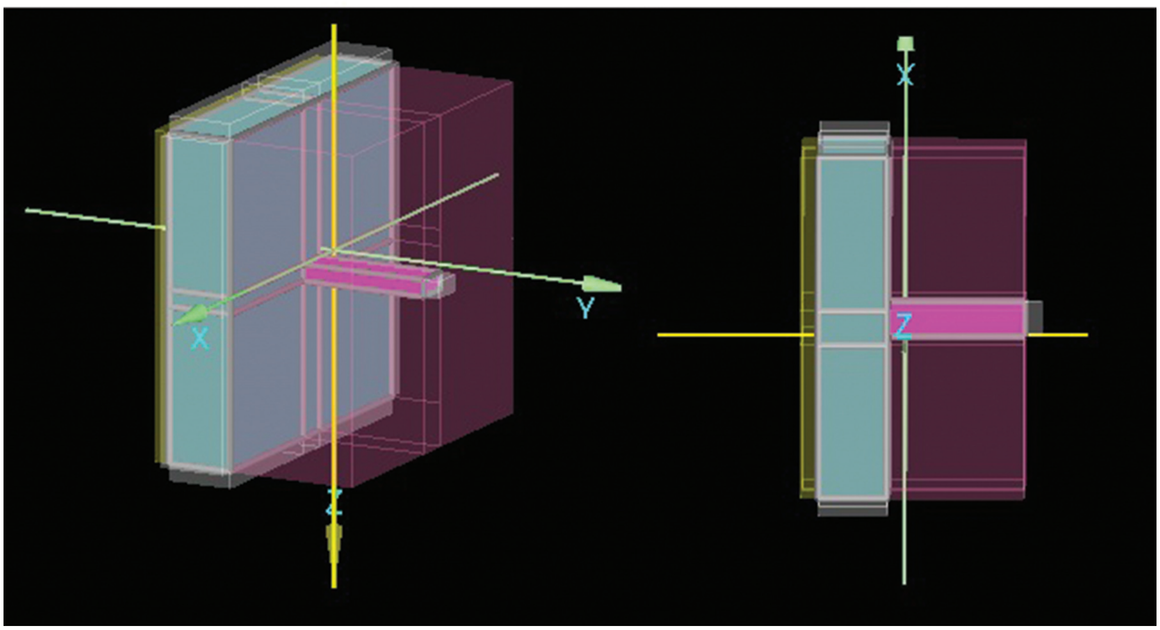


Figure 6 *Validation case 4 of DIN EN ISO 10211 (DIN 2008) and its implementation as a 3-D element in WUFI Plus.*

Table 7. Results of Case 4 of DIN EN ISO 10211 (DIN 2008)

WUFI Result	DIN EN ISO 10211 (DIN 2008)	Difference	Confirm
0.807169	0.805	0.002169	y

Table 8. Heat Exchange of Case 4 of DIN EN ISO 10211 (DIN 2008)

WUFI Result	DIN EN ISO 10211 (DIN 2008)	Difference	1% of ISO
0.5375	0.5400	0.0025	0.0054