

A new Passive House Design Tool and its Application in Cold Climates

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SUMMARY:

Due to an increasing demand for sustainable low energy buildings, the application of the passive house design methodology spreads worldwide. The methodology applied to balance monthly heat gains and losses is developed for fast energy demand investigations in moderate climates; issues can occur in other climate zones. Furthermore, the hygrothermal effects within the building and the building components are neglected. The monthly method is not suitable for moisture relevant risk management, nor is it for transient effects that influence the building energy performance. This leads to the requirement of a dynamic simulation.

A new user friendly software tool is available that couples the established passive house design methodology, for quite instant energy demand simulation results, with an sophisticated hygrothermal dynamic simulation. The dynamic whole building simulation is based on a detailed building component model simulating the coupled heat and moisture transfer and a multi-zone building model, calculating hourly indoor climate and energy demand.

An advantage of the new tool is the opportunity to work with only one building model while conducting a monthly balance based energy assessment or a dynamic hygrothermal whole building simulation. The graphical user interface exchanges a small amount of parameters which are required by the respective setting. Additionally some results of the monthly method may be used automatically as approach for the dynamic simulation.

This paper includes the description of the coupling of both methodologies and an application example, explaining the usage of the tool for a building in cold climates. Furthermore the possible additional and in-depth analysis options and results by the application of the new tool are shown as well as some recommendations for the design process in cold climates.

1. Introduction

While designing energy-efficient buildings, a designer often uses different approaches to tweak the building in terms of energy efficiency, comfort and hygrothermal performance of the components. Common approaches for the assessment - and also for the certification - of the energy demand rely on steady state methods, using monthly balances, to compute the values used for the estimation of energy demand and for comparing different building designs under predefined boundary conditions. Those methods exclude all transient effects in buildings like the effects of thermal inertia. A comprehensive analysis of comfort conditions indoors is also not possible.

This causes the designer to switch to a dynamic whole-building model using hourly data to evaluate the dynamic behavior of the building. Often, very new and innovative building component

configurations are employed to meet the stringent energy criteria. Therefore, a third step is critical to performance and quality assurance: assessing the hygrothermal performance of envelope components. This third step evaluates the most critical components by employing a hygrothermal component simulation model.

This paper shows the development of a single tool that integrates all three steps. A steady-state approach for assessing the energy performance is combined with the dynamic modeling features of a whole-building simulation model including a full-scale hygrothermal component analysis.

2. Simulation Methodology

This section describes in short the basic equations for the calculation of the steady-state and dynamic model. Furthermore, it describes how integration into one tool for energy, comfort and hygrothermal component performance was implemented in the new WUFI Passive software.

2.1 Methodology for passive house assessment

The monthly balance based method depends strongly on overall heat transfer coefficients, temperature difference and considered time period. It is in accordance with the DIN EN ISO 13790, in particular the simplified approach. The heat transfer coefficient, the reciprocal of the thermal resistance, is an important input value for opaque components. It is calculated from the thermal conductivity and layer thickness of the building envelope materials. For transparent components, the heat transfer coefficient is input data. The monthly heat losses across the building envelope are calculated by determining the heat transfer coefficients, areas of the components and the appropriate temperature differences according to component location. The external boundary condition of exterior walls can be the ambient air temperature, it can also be the ground temperature in case of a basement wall or an increased or decreased derivative of the ambient air temperature in cases of attached spaces exterior of the thermal envelope, such as garages. With the temperature difference and a considered time period, the heating degree hours are calculated following [Feist 1992, Feist et.al. 2007]. Monthly heating degree hours consider the hour count of a month. The period under consideration for the annual demand depends on the monthly difference between the heat losses and the heat gains. If this difference is greater than 0.1 kWh the month will be considered in the calculation of the total annual heating demand. This means that the period under observation could be varying between the different cases. Ventilation heat losses are calculated considering the effective air change rate, building volume, effective heat recovery efficiency and annual heating degree hours as well.

Climate data contains information on the solar radiation for north, east, south, west and horizontal. Each component is associated with a cardinal or horizontal direction. For transparent components, the solar heat gain is calculated considering heat transmittance, shading reduction factors due to obstructions, overhangs and reveals. The solar heat gain of opaque components is computed considering the exterior absorptivity and emissivity. The required heating demand, over a specified time period, is calculated following [Feist et.al. 2007] and in accordance with [EN ISO 13790].

The monthly utilization factors indicate how much of the available heat gains can be used to counteract the heating demand during the heating period. It is calculated from the heat gain and loss ratio and a so-called time constant, depending on the internal heat capacity and the total heat loss coefficient of the building. For the time constant equation a continuously heated building (more than

12 hours per day) is considered.

The monthly losses are calculated using monthly heating degree hours and the annual losses using annual heating degree hours. The total heating demand, including the transmission heat losses for all components and thermal bridges and the ventilation heat loss is decreased by the total heat gain comprised of the solar and internal heat gain, multiplied by a utilization factor. Monthly heating degree hours are determined multiplying the hour count of the month with a temperature difference.

One of the passive house certification criteria is the total annual primary energy demand. To calculate the primary energy demand of a building the electrical and non-electrical demand of the mechanical system, including auxiliary energy, plug loads, appliances and lighting are summed up. The heating demand of the domestic hot water production and distribution is taken into account and if solar hot water generation is used, it is reduced by an estimated solar fraction. It is assumed that the energy use by any device or service is not necessarily continuous. The uses are either reduced by different usage or utilization factors stemming from predetermined utilization patterns or a certain frequency is assumed for each usage. If such energy use takes place within the thermal envelope it is added to the internal heat gains. Heat gains from people are already included in the heat gains. Then an annual specific internal heat gain is estimated. The total is then multiplied by the treated floor area and hours of the month resulting in the total monthly internal heat gains.

In addition to the heating demand the cooling demand is calculated using a very similar algorithm. One difference is that the heat gains are not weighted by the utilization factor as the heat losses are.

2.2 Hygrothermal whole building simulation

The dynamic hygrothermal simulation combines single building components such as walls, floors, and roofs to be modeled as a whole building. Coupled heat and moisture transport is simulated for each opaque component composed of different layers of materials such as wood, insulation, membranes or even air layers. This model was developed by Künzle [Künzel, 1994]. It considers capillary action, diffusion and vapor ab- and desorption. The conductive heat and enthalpy flow by vapor diffusion with phase changes strongly depends 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 component model was validated by comparing its simulation results with measured data of extensive field experiments [Künzel, 1994]. The temperature and moisture field within the component is simulated as a result of the model.

Coupling all the envelope components leads to the multi-zone building model. A zone constitutes one or more rooms with the same indoor climate. The zone boundaries are the components. There is also an outdoor zone. The outdoor climate is specified by location in the climate files assuming that the building itself does not influence the climate. However, the indoor climate is influenced by the simulation results of the component and vice versa - the component simulation is influenced by the indoor climate. Considering this interaction the indoor climate can be simulated. With every time step the zone temperature and humidity values are generated by solving heat- and moisture balance equations [Lengsfeld, Holm, 2007]. Besides the heat and moisture flow across the building the envelope internal heat and moisture sources and sinks are taken into account. They are caused by

people, lighting, mechanical equipment, infiltration and solar radiation. Such sources or sinks cannot only occur in the zones of the building itself but can also occur in the building envelope component with a direct influence on the heat- and moisture field of the component. Additionally transparent components, like windows, can be modeled more accurately. The solar transmission that passes through a transparent component is calculated taking into account the sun elevation and azimuth angle and the orientation and inclination of the component. Solar heat gain contributions that pass through the transparent components are apportioned out directly to the indoor air and to the inner-surfaces of opaque components according to a defined percentage (user defined, or estimated according to surface area). Besides the short wave solar irradiation also the long wave balance is considered for the opaque building components. Therefore not only the solar heat gains but also the long wave irradiation losses can be calculated.

The zone model was validated via cross-validation with other tools, experiments and standards like [ASHRAE 140, 2007]. The validation of both - the energetic and the hygric part of the zone model - is described in [Antretter et.al. 2011]. Currently the ideal mechanical system has the capacity to supply all minimized heating, cooling, humidification, dehumidification and mechanical ventilation loads. As long as the system's capacity is sufficient the indoor temperature and moisture can be maintained between defined design conditions and thus the hourly demand can be calculated. If the capacity is not sufficient then the temperature or moisture will rise above or fall below the specified design conditions. If there is no ideal mechanical equipment defined, a "free floating" indoor climate is simulated.

Every time step depends strongly on the previous steps because of the water content and thermal energy storage within the envelope and the air in the zones. A time step is characterized by these dynamic previous variables. New boundary conditions are created with each time step and varying input data like the outdoor climate. Using these initialization values the coupled heat and moisture transport is calculated and consequently the zone heat and moisture balance equations are created. Should these balances not be within an expected defined accuracy of the simulation then the indoor temperature and relative humidity is iteratively adapted.

2.3 Coupling of both methods

Both models, the monthly passive house calculation and the dynamic whole building simulation, rely on user inputs and assumptions. Some inputs are pre-defined, such as specific building materials, their dimensions, location and orientation. Some have to be estimated by measurements or experience.

The pre-defined input is fundamentally the same for both models, though quite more detailed for the dynamic simulation - not only because of the additional consideration of moisture. However, the building geometry, room and component dimensions, widths and heights, roof inclination are the same. Fenestration parameters like solar heat gain coefficients, frame geometries, shading reduction factors and many other boundary conditions such as the design indoor temperature, the overheating limit temperature and the natural air change rate are the same as well.

More different is the climate data. For the monthly method only monthly mean values for temperatures and solar radiation are necessary. For the dynamic hourly simulation, hourly input data for the outdoor climate must be provided. For the more detailed radiation calculation hourly diffuse and direct global solar radiation data is required. The static calculation method estimates ground

temperatures according to the given location and boundary conditions; those values can be used for the climate of the ground for the simulation by converting the data into a useable ground climate format. Additionally needed is information on wind velocity and the quantity of rainfall to calculate the driving rain on the external surfaces as well as the relative humidity of the outdoor climate to calculate the moisture balance. Aside from pre-defined input data some results of the steady-state method can be used for the dynamic simulation, as for example the mechanical ventilation volume flow rates for summer and winter ventilation, the simplified effective heat recovery efficiency, the space heating and cooling capacities of the mechanical equipment. Internal heat sources due to people, lighting, household and mechanical equipment are the same, but also have to be supplemented with moisture characteristics. For the monthly method it is possible to calculate these sources using a utilization factor depending on the average usage. For the dynamic hourly simulation this is a good first assumption, but it might be more realistic to create specific time schedules.

Basically, the main difference of both models is the level of detail. A much more detailed simulation needs more time to compute. The monthly method is fast. An ordinary PC can compute all results in real-time. The dynamic results may need some minutes up to some hours, depending on the complexity of the building model. Within the dynamic simulation not only the indoor air temperature is simulated. In addition the surface temperature of the surroundings of a room, e.g. to calculate the operative temperature, is computed and, once more, also the humidity. Assessments of comfort conditions become possible once those values have been generated. The predicted mean vote (PMV) or the predicted percentage of dissatisfied (PPD) is calculated hourly. Even if generally accepted boundary conditions are exceeded one can assess how long they will be exceeded.

The combination of both models using many of the same initial inputs, results in numerous positive synergy effects. On one hand it is possible to obtain very fast results using only the monthly method, including heating, cooling, electricity and primary energy demand and on the other, with some more calculation time, it is possible to get detailed information on risk of mould growth, rotting of components and of course detailed information on interior comfort conditions.

2.4 Basic application process

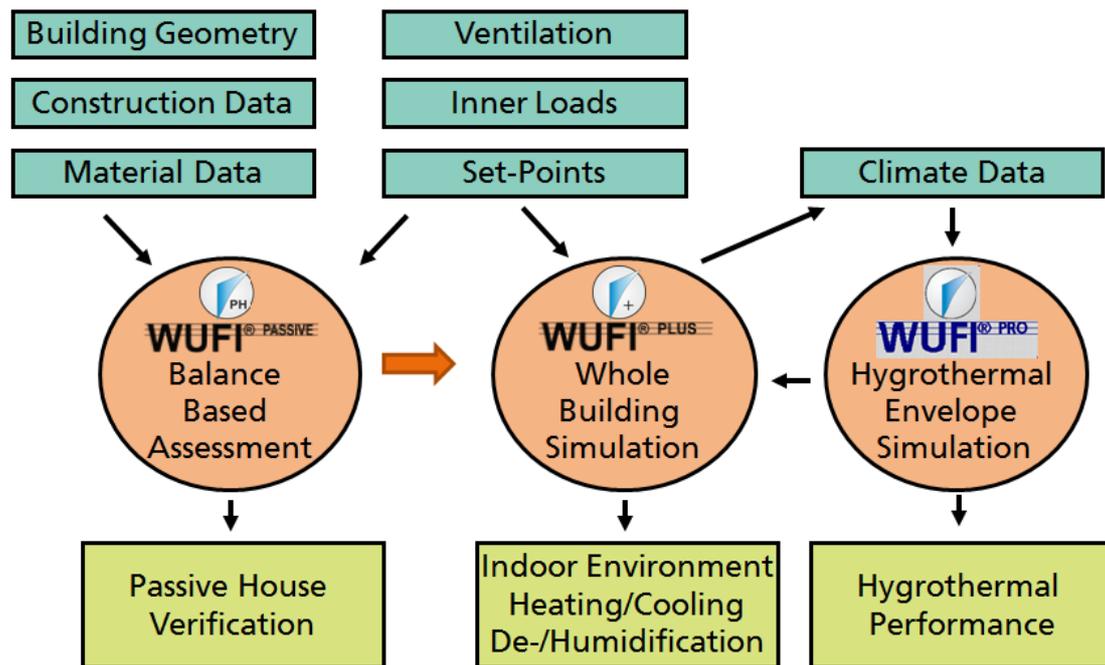


Figure 1: Inputs, interaction and outputs of the different parts of the simulation engine

To simulate a building different inputs for the desired results are necessary, as shown Figure 1. Typically a user starts with the passive house calculation. The first thing to do is to input the building geometry including structure, material, location and all essential passive house verification data. Once the geometry is set, thermal bridges and windows can be defined. The next step is to define the usage of the building (residential or non-residential) as the next input for inner loads is different for each type. Last but not least the user has to define the mechanical equipment. Therefore different systems for e.g. heating, domestic hot water production and ventilation can be defined as well as information about the distribution system. The software gives feedback at all times during the entry process to inform the user about still missing inputs and provides reasonable input values as well as explanations regarding the current input parameter. Once all inputs are complete, the heating demand and all other passive house verification results are calculated instantly.

For the dynamic hygrothermal simulation a user can switch to the “WUFI Plus” mode once the main passive house criteria are met to a degree. Some input screens change to the dynamic relevant input data. Certain boundary conditions are not applied automatically because more detailed information may be required (like the indoor set point temperature, which can be defined via time schedule), but there is an option to choose them with one click. If a user has used building materials or assemblies provided within the database, no additional information is needed but some additional parameters such as indoor moisture loads should be defined. The software will check all inputs for completeness and prompt the user for missing information before the simulation can start. During the simulation a user can monitor movies for the heat and moisture profiles of each component or the hourly heating demand. If the simulation is finished, detailed reports and graphs illustrate the

simulation results.

3. Application Example

In this example, a residential building in Göteborg, Sweden, is analyzed using WUFI® Plus simulation and the static passive house calculation approach. Results for heating demand are compared and further investigations of possible moisture risks are conducted.

3.1 Simulation Model and Boundary Conditions

3.1.1 Climate

Hourly values of the outdoor climate are required for the dynamic simulation which are available in the WUFI® Plus database (Figure 2, Figure 3). In contrast, the passive-house calculation method is based on monthly mean values. The climate of Göteborg has an amplitude of 48°C with 29.4°C as maximum and -18.6°C as minimum. There is also a significant amount of driving rain from the south.

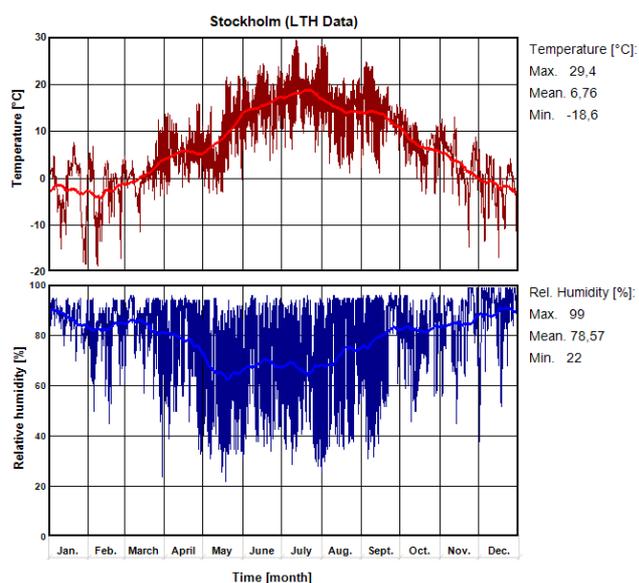


Figure 2: Outdoor climate - temperature and rel. humidity

3.1.2 Building and HVAC System

Within the framework of this paper a typical residential building model (Figure 4) has been used for both – the dynamic simulation as well as the static passive-house calculation method. The type of the residential building is a free-standing, two-story house with average wind exposure. In general, the assemblies of the building represent a typical Swedish construction type and are taken from (<http://www.scanhome.ie/passive.php>, also see 3.1.3). For detailed analysis, the building is subdivided into ten zones with individual internal loads and boundary conditions.



Figure 4: Reference Building 3D view

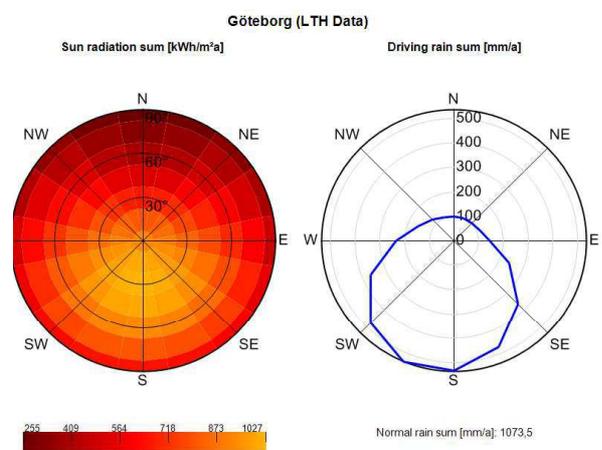


Figure 3: Outdoor climate - sun radiation and driving rain

A heat pump with a capacity to ensure the indoor design conditions are met at any time for most of the zones (e.g. not for storage room) is used. Furthermore, a ventilation system with heat recovery efficiency of 85% is

installed. The use of photovoltaic or solar modules is not included in this case.

3.1.3 Components

The building envelope is specified that it fulfills the passive-house standard requirements of ≤ 15 kWh/m²a. For simplification, the construction is assumed to be without thermal bridges. For more information regarding the U-Values of the components see Table 1. As an example the exterior wall assembly is displayed in Figure 5.

Table 1: U-Values of components

Component	U-Value in [W/m ² K]
Exterior Wall	0.14 [W/m ² K]
Interior Wall *	1.93 [W/m ² K]
Roof	0.13 [W/m ² K]
Ceiling *	1.10 [W/m ² K]
Floor Slab	0.14 [W/m ² K]
Exterior Door	0.23 [W/m ² K]
Interior Door *	1.76 [W/m ² K]
Windows	0.80 [W/m ² K], SHGC = 0.55

* (only relevant for heat storage)

Nr.	Material/Layer (from outside to inside)	ρ [kg/m ³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Hardwood	650	1500	0,13	0,022	Orange
2	Air Layer 20 mm	1,3	1000	0,13	0,022	Cyan
3	Fibreboard with Paper Sheathing (one Surface)	284,4	1880	0,048	0,009	Grey
4	Cellulose Fibre Insulation New (yellow)	30	1880	0,036	0,2	Yellow
5	vapour retarder (sd=100m)	130	2300	2,3	0,001	Blue
6	Cellulose Fibre Insulation New (yellow)	30	1880	0,036	0,07	Yellow
7	Interior Plaster (Gypsum Plaster)	850	850	0,2	0,013	White

Figure 5: Exterior wall assembly

3.1.4 Inner Loads and Design Conditions

The internal loads are set to the passive-house defaults for residential buildings ($=2.1$ W/m² treated floor area, in this case a total of 166.2 m²). For better comparison of the results between simulation and static calculation method, the internal loads are kept constant the whole day. The heat distribution to the room is 2/3 convective and 1/3 radiant.

The design minimum indoor temperature is set to 20°C for each zone apart from the stairway and storage room and the maximum temperature for overheating is defined to 25°C. If the set-point of 20°C is not reached, ideal heating is provided to the space up to the maximum heating power. Cooling devices are not available.

3.1.5 Ventilation

The building is constructed in such way, that a blower door test would result to $n_{50} = 0.5$ 1/h which is below the passive-house requirements of 0.6 1/h. Empirical values suggest that a blower door test of 0.5 1/h corresponds to an infiltration rate of 0.03 1/h for this building. For sufficient fresh air supply a mechanical system is installed which runs at an air change rate of 0.35 1/h. The heat recovery efficiency is set to 85%. Manual window opening is not considered in this study.

3.1.6 Shading

For the simulation, a general shading factor (which is active at all-time) due to trees or neighboring buildings is specified to 0.9 (meaning reduction of incoming solar radiation of 10%). Furthermore, for the windows of the living room, there are overhangs of 50cm attached. To reduce overheating in the summer, a temporary sun protection (of 75% solar reduction) gets triggered whenever the design

temperature of 25°C is about to be exceeded. The shading for the static calculation method is estimated by the general factor, overhangs, reveal depth and shading objects.

3.2 Passive House Results

3.2.1 Passive House criteria

Apart from the heating load, all passive house criteria are met. Figure 5 shows a summary of all relevant values.

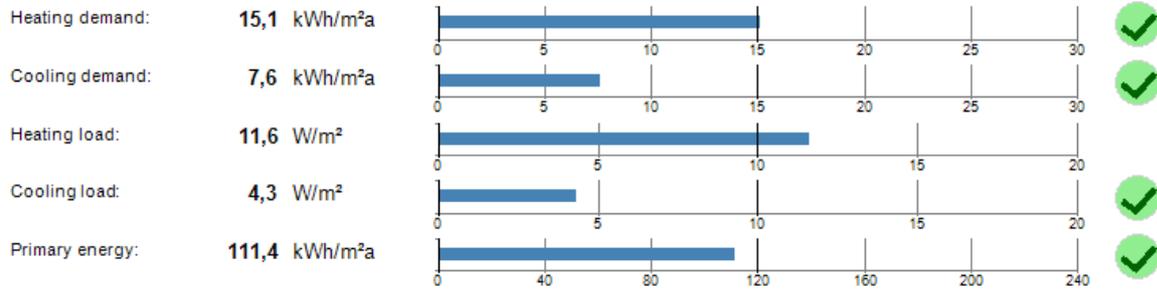


Figure 6: Passive-House criteria

3.2.2 Energy balance

The energy balances for the heating and cooling period are summarized in two graphs (Figure 7). In this case, the heat losses via windows are substantial to the overall heat losses during the winter months. For each section there are more detailed information provided for further analysis.

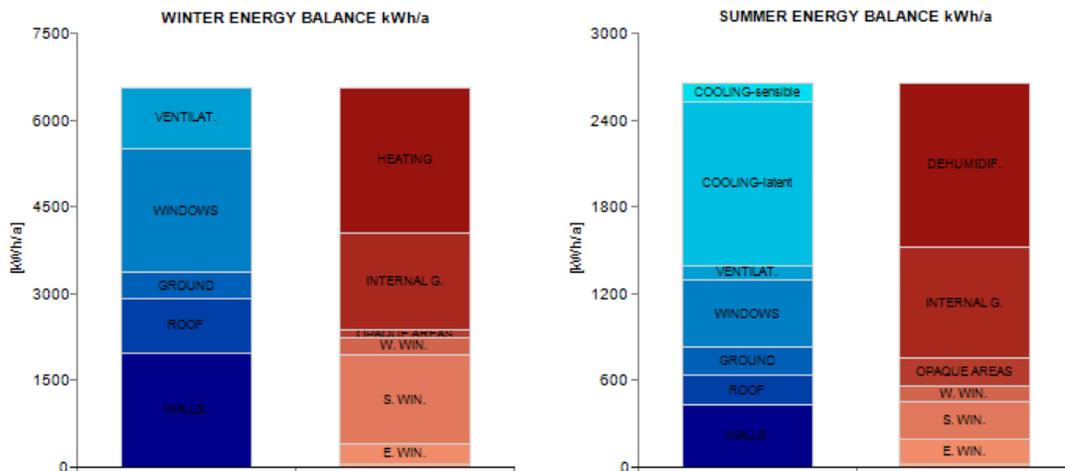


Figure 7: Passive-House result - energy balance

In case of windows for example there is an overview available (Figure 8), which can be used to quickly see the weak spots as well as detailed calculation for each window.

Windows

Average SHGC:	0,55
Average solar reduction factor heating:	0,5
Average solar reduction factor cooling:	0,12
Average U-Value:	0,818 W/m²K
Total glazing area:	20,3 m²

Heat gain/loss heating period:

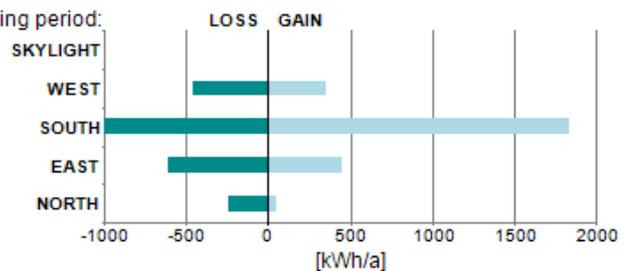


Figure 8: Passive-House result - window overview

A comprehensive output report is created, that shows all energy fluxes on building envelope, zone and systems level. All information required for certification is also included.

3.3 Dynamic Building Simulation Results

3.3.1 Main results

After completing the simulation, the main simulation results are listed in WUFI® Plus/Passive in a table displaying heating and cooling demand as well as computed indoor conditions. The total heating demand sums up to 2742,42 kWh which equals 15.5 kWh/m² (166m² treated floor area).

3.3.2 Energy balance

The energy balance for the heating period illustrates that the main fraction of the heat loss can be assigned to windows (for zone 1 = living room and south oriented, see Figure 9). It has to be pointed out, that the direct solar radiation on surfaces of surrounding components and radiant internal heating loads, are not considered in the energy balance graph, as is it only regards the zone balance (indoor air). Hence, the bars for heat gains and losses are slightly out of balance. Figure 10 shows the hourly heat fluxes for zone 1.

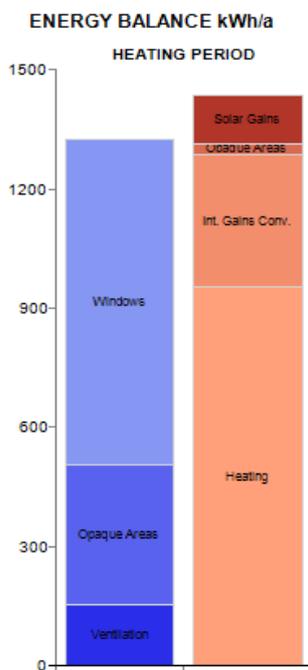


Figure 9: Simulation result - energy balance zone 1.

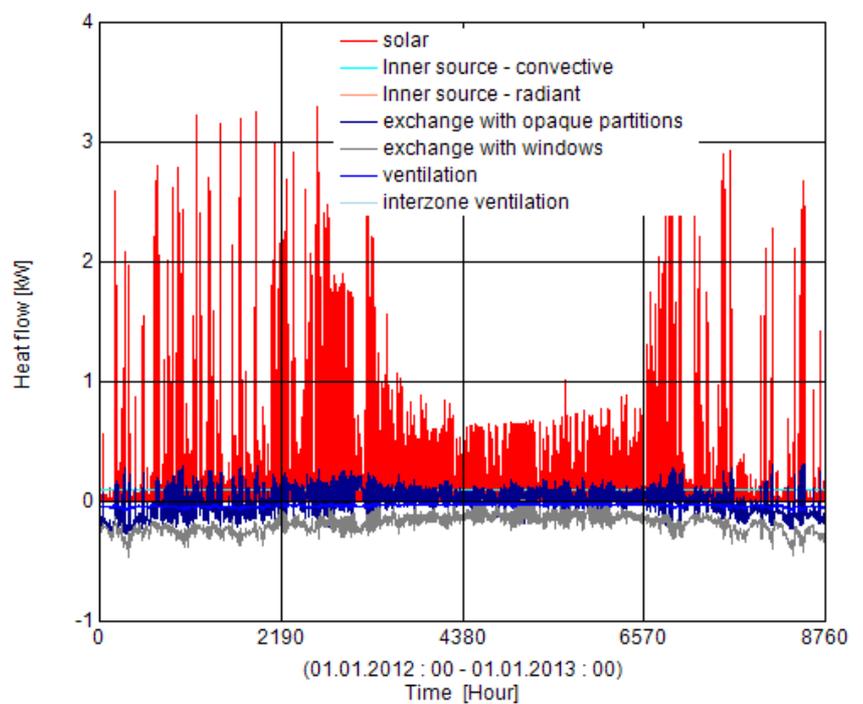


Figure 10: Simulation result - heat flow

3.3.3 Comfort, Moisture risks

The hourly output values allow assessment of comfort and potential moisture damages. Figure 11 shows a simple comfort diagram, plotting relative humidity over temperature in zone 1 in comparison to comfortable areas. Due to the high building standard and sufficient air supply, there are no moisture damages estimated by the simulation. The analysis of the comfort shows, that in most cases the optimum or at least good conditions are met. However, there is a noticeable risk of overheating in zone 1.

The hygrothermal behavior of the components cannot be assessed by the static calculation approach, but is essential to evaluate potential moisture risks. In this example the water content of the fibreboard of the exterior wall is assessed depending on its orientation and the percentage of driving rain hitting this layer. A safety assessment according to ASHRAE 160 [ASHRAE 160, 2009] shows that with the application of 1% driving rain critical conditions might occur in the south oriented components (Figure 12). If the detail conditions are worse and 2% driving rain arrive at the fibreboard a net accumulation of the total water content is found and the building assembly will fail (Figure 13).

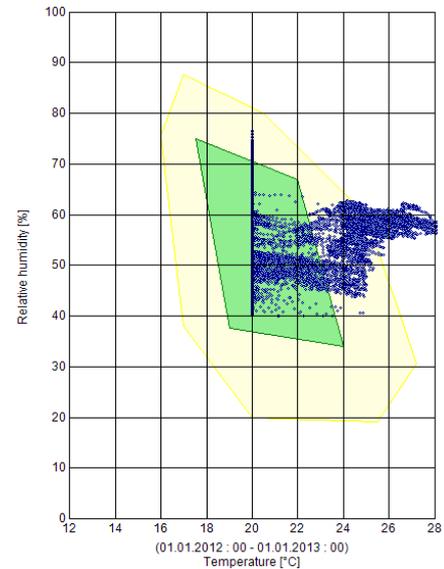


Figure 11: Simulation Comfort Assessment

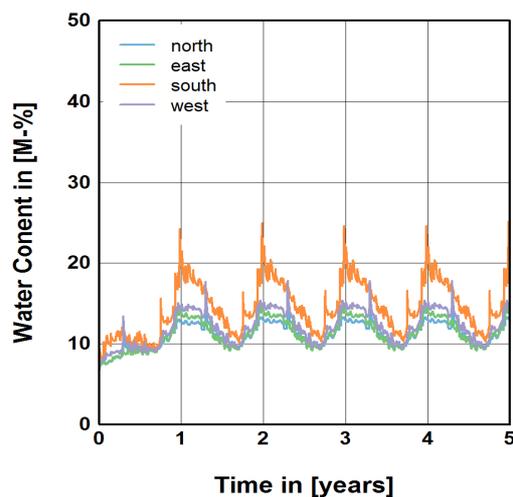


Figure 12: Water Content Fibreboard - Orientations

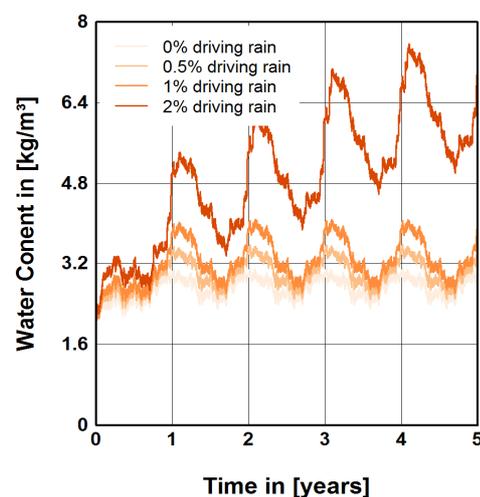


Figure 13: Total Water Content of the Ext. Wall – Percentage of Driving Rain behind cladding

3.4 Comparison and Summary

The static calculations method and the simulation show similar results in several aspects, while the simulation estimates rather higher overheating (see Table 2).

Table 2: Result comparison

	static calculation	simulation
Heating Demand	15.1 kWh/m ²	16.5 kWh/m ²
Heating Period	212 days	180.5 days *
Heating Load	11.6 W/m ²	10.9 W/m ²
Overheating Frequency (>25°C)	10.6%	18.6 % (critical zone 1)

* Sum of heating hours

Figure 14 shows the mean daily heating demand for the whole building and each zone over the whole simulation period computed with the selected climate file. A high heating demand can be found for only a very short period of time. Zone 1, the living room, is the main contributor to the overall building heating demand.

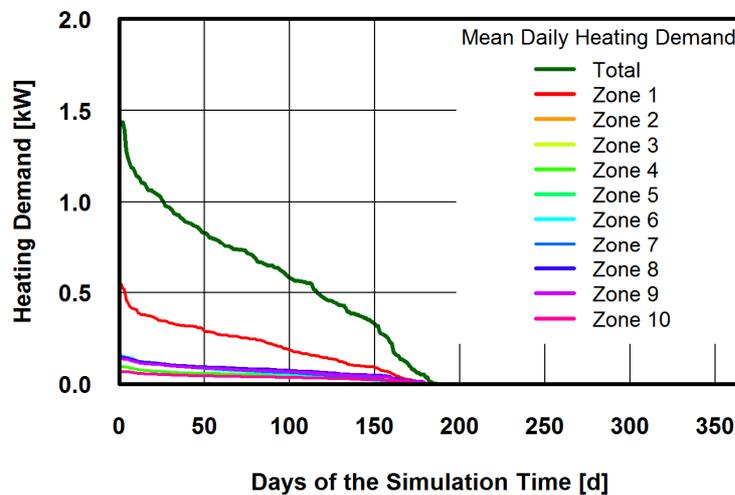


Figure 14: Annual load duration curve for mean daily heating demand of the whole building and single zones

Overall both approaches are viable as they complement each other. The static calculation method provides fast results and additional information regarding e.g. primary energy, electricity demand. WUFI® Plus on the other hand gives further information regarding hygrothermal behavior of the indoor climate and components including comfort assessment and potential moisture risks.

4. Summary, Conclusions and Outlook

The combination of both models – a monthly balanced and a dynamic simulation - into one tool has real potential to transform the passive building design process by making very complex processes accessible to more design professionals. Improvements start from a simple work flow perspective; it organizes the input process along a clearly guided path of the familiar tree structure of the WUFI software family while providing constant feedback on missing data entries. In addition, it supports the user by providing recommended and reasonable input values and explanation of the current parameter. Management help to optimize the design process in passive verification mode by allowing the modeler to store side by side an essentially infinite number of different cases is offered. The static calculation is fast and efficient and outputs include both numerical and illustrative graphical representations of the results, which are very helpful in discussions with clients.

Even more significant are the improvements in regards to the design process. Many designers have been forced to master and use separate hygrothermal tools and secondary dynamic energy models to assess wall component appropriateness by climate and thermal comfort by zone. All additional tools required some form of double entry of material properties, dimensions and mechanical specifications. In the design process many of those pieces of information are still in flux and lead to the need of updating three instead of one model when a design change is made. This is not only labor intensive but also increases the likelihood of error.

In conclusion, the most significant improvements aside from the more efficient and organized workflow is the all-in-one risk management capability. The next generation passive modeling needs to

include dynamic simulation and the ability to predict comfort issues such as overheating and high relative indoor humidity. And to conclude with a gaze into the future: as larger buildings with multiple zones also are being modeled to meet the passive building energy metrics it will become imperative to model and verify comfort in multiple zones in more complex buildings. WUFI Passive will meet those challenges on the horizon.

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