All-in-One Design Tool Solution for Passive Houses and Buildings—Monthly Energy Balance and Hygrothermal Simulation

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ABSTRACT

The U.S. Department of Energy (DOE) outlined a path to advance high-performance and zero-energy homes in its Building America research program (DOE 2008). *That program—and other efforts in the Unites States over the last few years to tighten energy codes—follow closely the evolution of energy standard developments in Europe. That is, developments moved from conventional buildings to low-energy buildings, then to passive buildings, net zero, and recently even plus energy. The common denominator is low-load homes that require less energy from the start. Designing these homes requires specialized design tools to achieve targeted performance and quality assurance. The tools must enable the designer to meet the energy performance of the envelope and the minimized mechanical system and—critically—to achieve proper hygrothermal design of building skins before the detailed construction documents phase. The hygrothermal component reduces the risk of potentially catastrophic design flaws, thereby reducing risk for designers, builders, and homeowners.*

The passive design approach offers a solid baseline for all low-load homes. The simplified static balance-based method has provided early adopters a useful tool. But it lacks the capacity to assess certain dynamic factors of the energy balance, such as transient effects that occur under real conditions—for example, thermal lag time and related overheating in summer or the hygrothermal performance of the building envelope.

This paper outlines the incorporation of the balance-based method currently employed to design passive buildings into hygrothermal whole-building simulation software. A case study illustrates both methods as they are applied to an actual building. Additional results and insights from the dynamic building simulation are highlighted. The comparison of the balance-based method with the dynamic simulation, both performed within one tool based on the exact same building data and inputs, demonstrates benefits and drawbacks as well as improvement potential for tools and methods moving forward. While the static monthly balance method simplifies the required steps and the time required to design a passive house, it might not be fine-grained enough for all climate zones and building types. The results from the dynamic simulation are more granular and offer a more realistic depiction of the actual behavior of the building and its interaction with mechanical equipment in terms of comfort.

INTRODUCTION

Households account for a significant part of global energy consumption. In the USA, the domestic consumption in 2011 accounted for 22% of the total energy use (EIA 2012). Energy-efficient building standards can reduce this consumption. While in the USA on average all existing buildings (with the exception of strip malls) consume approximately 220 kWh/m^2/yr (69.7 kBtu/ft^2/yr) for heating, residential energy consumption for heating is on average significantly lower. Households in the state of New York, which has a cold climate, consume on average 95 kWh/m^2/yr (30.1 kBtu/ft^2/yr) (EIA 2005). For comparison, ENERGY STAR® (EPA 20123) and the *International Energy Conservation Code* (ICC 2012) have over the past three years put requirements in place that reduce this consumption further, by up to 30%. A house built to the most efficient choices to receive ENERGY STAR certification today

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requires approximately 70 kWh/m^2/yr (22.2 kBtu/ft^2/yr) for heating (EPA 2012) in the state of New York. The certification criteria for a passive house built to meet the current European standards is much lower, 15 kWh/m^2/yr (4.75 kBtu/ft^2/yr). This energy reduction corresponds to 85% savings over the current average in the state of New York in terms of heating energy and illustrates how the use of energy-efficient technologies and design can significantly improve the current performance standards of the leading U.S. energy codes and programs.

When designing energy-efficient buildings, a designer often uses different approaches to tweak the building in terms of energy efficiency, comfort, and the 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, such as the effects of thermal inertia. A comprehensive analysis of comfort conditions indoors is also not possible.

This causes the designer to switch to a 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, WUFI Passive (Fraunhofer IBP 2013), 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.

HISTORY OF THE PASSIVE HOUSE CONCEPT

Passive house is a quantitative, performance-based energy concept for buildings based on the understanding of the relationship between the influence of the thermal quality of the envelope and the resulting sizing of the mechanical system. The underlying principles were pioneered in the United States in the 1970s following the oil embargo crisis. The current *International Energy Conservation Code* (*IECC*) recognizes extremely-low-load homes, defining them as homes with a peak load smaller than 1 W/ft^2 for heating in section 101.5.2 (ICC 2012). According to the International Code Council (ICC), the *IECC* is the successor of the first 1975 *Model Energy Code* (*MEC*), from which this definition was originally adopted. William Shurcliff, a physicist at Harvard at the time, published many books on the passive solar and superinsulation concept in the late 1970s and early 1980s. Shurcliff first used the term *passive house* in his 1982 self-published book *The Saunders-Shrewsbury House*. In his later writings he defines the same set of physics principles and guiding energy metrics that characterize passive houses today. At the time the term *superinsulation* evolved as the most commonly used label for this set of principles in the sizable North American high-performance community. Shurcliff also noted in 1988 in his book *Superinsulated Houses and Air-To-Air Heat Exchangers* that this type of energy-efficient home construction was already a "mature technology" and that one might see further improvements in window technologies, vapor retarders, and compact minimized mechanical systems. In the early 1990s physicist Wolfgang Feist continued that research and development in Europe by further codifying the influence of highly improved envelope components (including triple-pane windows) on the minimization potential of the heat load in low-energy buildings for his research project Kranichstein (Feist 1992). His research facilitated those critical improvements predicted by Shurcliff to passive house components, components that soon became available on the European market at reasonable costs.

When Feist applied these principles and improved technologies in Germany in the 1990s, he also applied the same guiding energy metrics defined earlier in the USA. He found that designing a building in Central Europe to meet 1 W/ft^2 peak load (defined in the 1975 *MEC* and now in the *IECC*) resulted in an approximate annual heating demand of 15 kWh/m^2/yr. That figure became the defining energy metric for the standard. The metric quickly became successful in all of Europe and is now considered by many to be the world's leading standard in energy-efficient construction.

Shurcliff's original passive building definition outlined in a 1986 article mentioned one additional principle that was omitted in the later European definitions—that of the "prevention of moisture migration into cold regions within the wall, and other regions where much condensation could occur" (Shurcliff 1986). Shurcliff, working in the varied and often humidity-laden climates of the United States, was fully aware of the critical importance of good hygrothermal design of the envelope components when it comes to superinsulated and airtight walls and components.

In 2002 the first home using the European metrics and design tools for passive houses was built in the United States in Urbana, Illinois, by architect Katrin Klingenberg. Since then many projects have been completed in all U.S. climates except the southern Florida region. Collective experience has shown that the general principles hold true in all climates but that the standard would benefit from refinement. For example, in very cold climates (Fairbanks, Alaska, for example), home designs tend to require over-insulation with walls of 1 m (3.28 ft) thick, while in California comparatively very little insulation is required to meet the standard—leaving further, cost-effective efficiency untapped. This suggests it might be productive to propose relaxing the standard in the north and tightening it in the south for North America.

The most important lessons learned from the reawakening of passive house implementation in the United States over the past 11 years is that hygrothermal analysis is a critical necessity in North America's varied climate zones. Improper hygrothermal design can quickly lead to catastrophic failure in the structure. Designers and builders need a tool to manage this risk properly in conjunction with the energy optimization. With high solar radiation, the lack of comfort assessment is also a significant issue and has led to serious overheating problems in many projects. Nonetheless, efforts to rekindle the interest in the passive house concept in the U.S. are bearing fruit: the number of certified projects in the U.S. and Canada (PHIUS 2013) has been increasing steadily and is now reaching a point of exponential growth, as shown in Figure 1.

Passive House Basic Principles

The passive house concept is based on the following five main principles:

- Excellent continuous thermal insulation of the envelope components, including avoidance of thermal bridges
- Airtightness of the building envelope to minimize ventilation energy loads
- Avoidance of moisture migration into the envelope assembly, where condensation or other moisture problems could occur by means of airtightness, and accurate climate-specific placement of a vapor control layer
- High-performance windows and window areas specified and sized according to climate
- Constant fresh air supply, in most climates via a mechanical ventilation system with heat and/or moisture recovery

In addition, the space conditioning should be, but does not have to be, integrated into the balanced ventilation delivery system for optimal conditioning distribution. Eliminating a separate space-conditioning distribution system also optimizes the initial additional investment cost.

Passive building is a comprehensive approach to cost-effective, durable, comfortable, and sustainable construction. Under the current European protocol, buildings can use no more than 15kWh/m^2/yr (4.75 KBtu/ft^2/yr) for heating and cooling or have to have a peak load for heating and cooling not to exceed 10 W/m^2 (1 W/ft^2). These requirements for the envelope translate into about a 90% reduction in the energy needed to heat and cool a typical new U.S. house built to code while health and comfort in these homes are increased. In addition to the energy criteria, the European standard also defines a primary energy limit total for all space-conditioning and household energy consumed. This limit is 120 kWh/m^2/yr (38 kBtu/ft^{2}yr).

Passive house standards emphasize the importance of a high-performing building envelope that allows for the reduction or elimination of HVAC equipment first. Active photovoltaic production is only accounted for as savings after all energy criteria have been satisfied by envelope and efficient mechanical measures. The thus-optimized envelope and systems make for the most cost-effective baseline to reach net-zero energy or plus-energy home levels. Only a very small active system, typically a 2–3 kW (about 8.5 kBtu/h) size for a small 1000 ft^2 (92.9 m^2) residence, is required to attain zero site energy status.

In the first multifamily projects currently underway in the U.S., passive house construction appears to be almost cost-neutral (Cohen 2012). The single-family projects that have been built over the past five years in the U.S. are showing good initial results in terms of cost-effectiveness (Oram 2011) and should improve significantly with increased market availability of high-performance materials and equipment.

Figure 1 *PHIUS+ certified passive building projects over the past 10 years.*

The Energy Balancing Method for Passive Houses

The underlying method of a passive house design is an accurate energy balancing of the thermal losses or gains through the envelope with the internal gains or losses of that building. In the heating case, in a cold climate the losses need to be almost equal to the internal gains, and only a small difference is allowed to be made up for by a very small auxiliary heating system. As per *IECC* section 101.5.2 (ICC 2012), if after the balancing process the peak load can be shown to be less than 1 W/ft^2 the home is exempt from needing a separate heating system as it is assumed that the internal heat gains in a typical residence will make up for the extremely low peak loss. The balancing is performed similarly for the cooling case, except that in the cooling case all internal gains are added to the thermal peak cooling load and are not helpful to offset it.

For the past decade, only one guiding simplified modeling tool has been on the market that was specifically created to facilitate this balancing process for structures following passive house design principles: the Passive House Planning Package (PHPP) from the Passivhaus Institute (PHI) in Darmstadt, Germany (Feist et al. 2007). The PHPP tool employes Excel© as its base and calculates the annual heating demand by monthly heat balances. For an estimation of the total annual heating demand, the monthly method is adequate. It is assumed that the monthly method has been validated by performing a transient calibration simulation (Feist et al. 2007).

There are limitations of the PHPP tool for North American users:

- While well validated for moderately cool and cold climates, the PHPP is clearly limited in assessing cooling loads and demands and related dehumidification requirements accurately. In those cases, dynamic simulation more accurately assessing thermal lag time should improve the model.
- Energy balancing in areas with very high solar radiation potential (hence with a greater percentage of internal gains as part of the overall energy balance) is also wanting. Early projects have frequently led to comfort issues such as overheating in the shoulder seasons. Comfort assessments concerning interior relative humidity by individual zone are also not possible.
- As of now the PHPP provides no path of risk assessment for the designer in regards to a very important factor: the appropriate envelope design for many different climate zones from very cold to hot and humid—hygrothermal assessments of superinsulated components are critical to avoid moisture concerns in walls. Widely varying climate combinations have distinctly different moisture-control layer requirements. Moisture-related issues in the U.S. market—mold problems, for example—have been widespread and well documented. Designers, builders, and homeowners need confidence that an airtight home will not present problems.
- Multizone modeling of more complex buildings such as, for example, a mixed-use larger building with commercial spaces on the first floor and apartments above, is not possible.

In addition, the user-friendliness of the PHPP tool is rather poor. The PHPP operator may make many "what-if?" design changes but is left to keep track of various optimization steps and must manually record the results of each option in the energy balance; there is no way to log and manage changes in one comprehensive file. The architect/designer in charge of the project needs to be closely involved with the PHPP to understand and remember the optimization process and assumed boundary conditions. Creating representations of this process to communicate results to clients also becomes very time consuming. For small single-family projects this is manageable but inconvenient. For larger project management, where the tool technician is not also the project architect, the tool becomes rather clumsy and time-consuming if not altogether unworkable.

SIMULATION METHODOLOGY

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

Monthly-Balance-Based Method

The monthly-balance-based method depends strongly on overall heat transfer coefficients, temperature difference, and considered time period. It is in accordance with DIN EN ISO 13790 (2008), 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 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 the 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 (Equation 1) following Feist et al. (2007). Monthly heating degree-hours consider the hour count of a month. The period under consideration in the PHPP 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 (about 0.341 kBtu) the month will be considered in the calculation of the total annual heating demand. This means that the period under observation could vary 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.

$$G_t = (\vartheta_i - \vartheta_e) \cdot t / 1000 \qquad (1)$$

where

G_t	=	heating degree-hours, kK·h
ϑ_i	=	interior temperature, °C
ϑ_e	=	exterior temperature, °C
t	=	period under review, h

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 by Equation 2 following Feist et.al. (2007) and in accordance with EN ISO 13790 (2008).

$$Q_H = (Q_{T,H} + Q_{V,H}) - (Q_{S,H} + Q_{I,H}) \cdot \eta_H \qquad (2)$$

where

Q_H = heating demand
$Q_{T,H}$ = transmission heat loss
$Q_{V,H}$ = ventilation heat loss
$Q_{S,H}$ = solar heat gain
$Q_{I,H}$ = internal heat gain
η_H = heat gain utilization factor

The monthly utilization factors (Equation 3) 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 4), a continuously heated building (heated more than 12 hours per day) is considered and the coefficients $a_0 = 1$ and $\tau_0 = 16$ are used.

$$\eta_H = \frac{1 - \gamma_H^{a_H}}{1 + \gamma_H^{a_H}} \tag{3}$$

where

γ_H = heat gain and loss ratio for heating demand $\left(\gamma_H = \frac{Q_T + Q_V}{Q_S + Q_I}\right)$, dimensionless
a_H = time constant for heating demand, h

$$a_H = a_0 + \frac{C / H_{L,H}}{\tau_0} \tag{4}$$

where

C = internal building heat capacity, Wh/K
$H_{L,H}$ = total heat loss coefficient of the building for heating demand, W/K
a_0, τ_0 = defined coefficients

The monthly losses are calculated using monthly heating degree-hours, the annual losses using annual heating degree-hours. The total heating demand, including the transmission heat losses (Equation 5) for all components and thermal bridges and the ventilation heat loss (Equation 6), is decreased by the total heat gain comprised of the solar (Equation 7) and internal heat gains, multiplied by an utilization factor. Monthly heating degree-hours are determined by multiplying the hour count of the month with a temperature difference. The difference between the interior setpoint and the ambient air temperature is used for components adjacent to ambient. The ground heating degree-hours are calculated using the interior setpoint difference to the ground temperature. If the difference between monthly heat loss and monthly heat gain is greater than 0.1 kWh (about 0.341 kBtu), then the heating degree-hours of that month are added to the annual heating degree-hours. To make projects comparable or verify specific limitations, all losses and gains and especially the total heat demand are specific to the treated floor area of the building.

$$Q_T = \Sigma_j(A_j \cdot U_j \cdot f_{T,j} \cdot G_{t,j}) + \Sigma_k(L_k \cdot \psi_k \cdot f_{T,k} \cdot G_{t,k}) \tag{5}$$

where

A_j = component area, m^2
U_j = thermal transmittance, $W/m^2 \cdot K$
$f_{T,j}$ = reduction factor for decreased temperature difference, dimensionless
$G_{t,j}$ = heating degree-hours, kK·h
L_k = thermal bridge length, m
ψ_k = linear thermal transmittance, W/m·K

$$Q_V = V_{RAX} \cdot [n_{V,Sys} \cdot (1 - \eta_{SHX}) \cdot (1 - \eta_{HR}) + n_{V,Res}] \cdot c \cdot G_{t,e} + V_{RAX} \cdot [n_{V,Sys} \cdot \eta_{SHX} \cdot (1 - \eta_{HR})] \cdot c \cdot G_{t,g} \tag{6}$$

where

$G_{t,e}$ = heating degree-hours against ambient air, kK·h
$G_{t,g}$ = heating degree-hours against ground, kK·h
V_{RAX} = effective air volume, m^3
$n_{V,Sys}$ = mean system air change rate, 1/h
$n_{V,Res}$ = mean natural air change rate, 1/h
n_{HR} = effective ventilation heat recovery efficiency, dimensionless
n_{SHX} = effective recovery efficiency soil heat exchanger, dimensionless
c = specific heat capacity of air, J/kg·K

$$Q_s = \Sigma_\theta(r_\theta \cdot g_\theta \cdot A_{F,\theta} \cdot J_\theta) \tag{7}$$

where

θ = associated direction (north, east, south, west, horizontal), dimensionless
r_θ = radiation reduction factor (averaged per orientation), dimensionless
g_θ = g-value (used in Europe, averaged per orientation), dimensionless
$A_{F,\theta}$ = window rough opening area (averaged per orientation), m^2
J_θ = global radiation, W/m^2

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 nonelectrical 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. Here the factor indicates the usability of the heat losses as shown in Equation 8. Another difference is the calculation of the heating degree-hours. The interior temperature is set to the overheating limit temperature or summer interior temperature (slightly higher). Furthermore, the month July is divided into 1-, 4-, and 12-day peaks with increased ambient temperatures, and the rest of July results mostly in negative heating degree-hours (heat gains across the building envelope). The time constant for the cooling demand is, in contrast to the time constant for the heating demand, computed using the total heat loss coefficient for the cooling demand.

$$Q_C = (Q_{S,C} + Q_{I,C}) - (Q_{T,C} + Q_{V,C}) \cdot \eta_C \tag{8}$$

where

Q_C	=	cooling demand
$Q_{T,C}$	=	transmission heat losses
$Q_{V,C}$	=	ventilation heat losses
$Q_{S,C}$	=	solar heat gains
$Q_{I,C}$	=	internal heat gains
η_C	=	heat loss utilization factor

$$\eta_C = \frac{1 - \gamma_C^{a_C}}{1 + \gamma_C^{a_C + 1}} \tag{9}$$

where

γ_C	=	heat loss and gain ratio for cooling demand $\left(\gamma_C = \dfrac{Q_S + Q_I}{Q_T + Q_V}\right)$, dimensionless
a_C	=	time constant for cooling demand, h

A frequency of overheating is calculated for the entire year using the length of time period of when the maximum allowed summer temperature is exceeded. If this frequency is too high then additional shading measures are necessary to decrease summer overheating. Natural ventilation strategies can be employed to increase ventilation losses if the climate permits. If shading measures or natural ventilation strategies alone are not sufficient to decrease overheating then active cooling will become necessary.

For sizing of the mechanical system, peak heating and cooling loads are determined using the worst-case scenario climate conditions for summer and winter. The values used are different from ASHRAE's (2010) worst-case design temperatures. Here the worst case is determined using a 24-hour average to account for the delayed response time of well-insulated buildings to short-term extreme temperature swings. The conditions are provided as part of the climate data set. It contains two weather conditions to determine the peak heat load (one very cold day and one with very low solar radiation but with milder temperatures) and one weather condition to determine the peak cooling load. The transmission heat losses across the building envelope are calculated for this peak condition similarly to the annual demand calculations—so are the peak ventilation heat losses and the solar and internal peak heat gains. A utilization factor is not required.

Dynamic 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 Künzel (1994). It considers capillary action, diffusion, and vapor absorption 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. The differential equation for heat and enthalpy flow is Equation 10 and the one for vapor flow in a component is Equation 11.

$$\frac{\partial H}{\partial \vartheta} \cdot \frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \vartheta}{\partial x}\right) + h_V \frac{\partial}{\partial x}\left(\frac{\delta}{\mu} \cdot \frac{\partial p_{sat}}{\partial x}\right) \tag{10}$$

$$\rho_w \frac{\partial u}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w D_\varphi \cdot \frac{\partial u}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu} \cdot \frac{\partial p_{sat}}{\partial x}\right) \tag{11}$$

where

D_φ	=	liquid conduction coefficient, m^2/s
H	=	enthalpy of the moist building material, J/m^3
h_V	=	evaporation enthalpy of the water, J/kg
p_{sat}	=	water vapor saturation pressure, Pa
u	=	water content, m^3/m^3
ϑ	=	temperature, °C
λ	=	thermal conductivity of the moist building material, W/m·K
μ	=	water vapor diffusion resistance factor of a dry building material, dimensionless
ρ_w	=	density of water, kg/m^3

φ = relative humidity, dimensionless

t = time, s

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. If there are two zones attached to each other then the respective indoor climates of the neighboring zones become the exterior boundary conditions of the other. 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 (Equations 12 and 13) (Lengsfeld and 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 can occur not only 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, such as 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. The solar heat gain that results from global radiation is dependent on the sun radiation incidence angle. Therefore, the solar heat gain coefficient is a varying input for different incidence angles. The solar heat gain—due to diffuse radiation—is calculated using the hemispherical solar heat gain coefficient. 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 shortwave solar irradiation, the longwave balance is also considered for the opaque building components. Therefore, not only the solar heat gains but also the longwave irradiation losses can be calculated.

$$\rho \cdot c \cdot V \cdot \frac{d\vartheta_i}{dt} = \Sigma_j A_j \cdot a_j(\vartheta_j - \vartheta_i) + \dot{Q}_{Sol} + \dot{Q}_{IHG} + n \cdot V \cdot \rho \cdot c \cdot (\vartheta_a - \vartheta_i) + \dot{Q}_{VAC} \tag{12}$$

where

ρ = air density, kg/m^3

α_j = heat transfer coefficient, W/m^2·K

ϑ_a = ambient air temperature, °C

ϑ_j = component indoor surface temperatures, °C

ϑ_i = indoor air temperature, °C

t = time, s

A_j = component areas, m^2

c = specific heat capacity of air, J/kg·K

n = air change rate, h^{-1}

$\dot{Q}_{Sol}$ = short wave solar irradiance, directly to indoor air, W

$\dot{Q}_{IHG}$ = internal heat sources due to people, lighting, equipment, W

$\dot{Q}_{VAC}$ = heat flow due to mechanical ventilation, W

V = zone volume, m^3

$$V \cdot \frac{dc_i}{dt} = \Sigma_j A_j \cdot \dot{g}_{wj} + n \cdot V(c_a - c_i) + \dot{W}_{IMS} + \dot{W}_{VAC} \tag{13}$$

where

c_a = absolute humidity of ambient air, kg/m^3

c_i = absolute humidity of indoor air, kg/m^3

$\dot{g}_{wi}$ = moisture flow from indoor surface to indoor air, kg/s·m^2

$\dot{W}_{IMS}$ = internal moisture source, kg/h

$\dot{W}_{VAC}$ = moisture flow due to mechanical ventilation, kg/h

The zone model was validated via cross-validation with other tools, experiments, and standards such as ANSI/ASHRAE Standard 140 (2007). The validation of both—the energetic and the hygric parts of the zone model—is described by 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 such as 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 are iteratively adapted.

Combining both Models into WUFI Passive

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

The predefined 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. For example, the moisture storage function provides the information of the water content depending on the relative humidity of a material. However, the building geometry, room and component dimensions, widths and heights, and roof inclination are the same. Fenestration parameters such as 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 are required. Additionally needed is information on wind velocity and the quantity of rainfall to calculate the driving rain on the external surfaces. Aside from predefined input data, some results of the steady-state method can be used for the dynamic simulation, such as, for example, the mechanical ventilation volume flow rates for summer and winter ventilation, the simplified effective heat recovery efficiency, and the space heating and cooling capacities of the mechanical equipment. Internal heat sources due to people, lighting, and 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 between the models is the level of detail. A much more detailed simulation needs more time to compute. The monthly method is fast. An ordinary personal computer can compute all results within less than a second. The dynamic results may need some minutes up to some hours, depending on the complexity of the building model. In the dynamic simulation not just the indoor air temperature is simulated but also the 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 within WUFI Passive 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 components, and of course interior comfort conditions.

To simulate a building, different inputs for the desired results are necessary, as shown in Figure 2. Typically a user starts with the passive house calculation. The first thing to do is to input the building geometry, including structure, material,

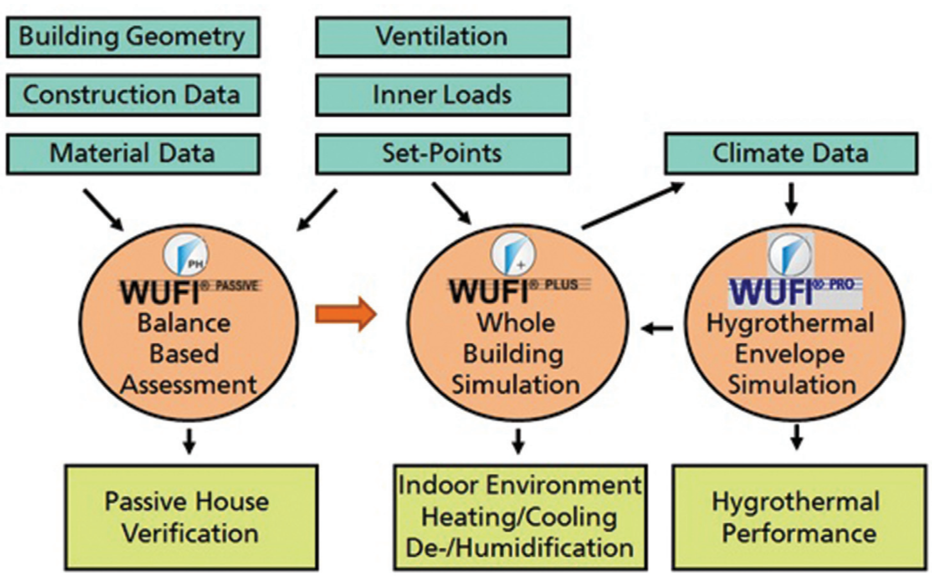

Figure 2 *Inputs, interaction of the different parts of the simulation engine, and outputs.*

location, and all essential passive house verification data. An import function allows importing a three-dimensional (3-D) building model from SketchUp, a free drawing program (Trimble 2013) (other commercial drawing programs can typically save files as a SketchUp file, which then can be imported as well). Another way is to use the integrated building wizard for more typical and simpler building geometries. It is important to designate inner and outer sides of each component correctly to ensure that boundary conditions get assigned accurately. The input using component lists and databases only is also possible; the model cannot be visualized in 3-D if this path is used. 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 nonresidential) as the 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 their distribution. The software gives feedback at all times during the entry process to inform the user about still-missing inputs. 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 WUFI Plus mode. Some input screens change to the dynamic relevant input data. Some boundary conditions are not applied automatically because more detailed information may be required (like the indoor setpoint 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 starts. During the simulation a user can monitor movies for the heat and moisture profiles of each component or the hourly heating demand. Once the simulation is finished, detailed reports and graphs illustrate the simulation results.

APPLICATION EXAMPLE

The above-described design and certification tool is used in this section to reassess an already certified passive house. The results for the steady-state method match the results of the previously used tool to certify passive houses. It is also shown that the combination of the steady-state methodology with a dynamic building simulation allows a more thorough analysis of the thermal and hygric performance of the building and its components.

Building Model and Boundary Conditions

A passive house designed for the Northern Central climate of the United States is used as a case study to demonstrate how to use the new tool and how to showcase the range of possible results. The building is located in Urbana, Illinois. Cold winters and relatively warm summers have to be taken into account while designing an energy-efficient building. The weather file for Chicago, Illinois, was used for the dynamic simulation. The hourly temperature and relative humidity conditions as well as mean, minimum, and maximum conditions are shown in Figure 3. Those conditions were the basis

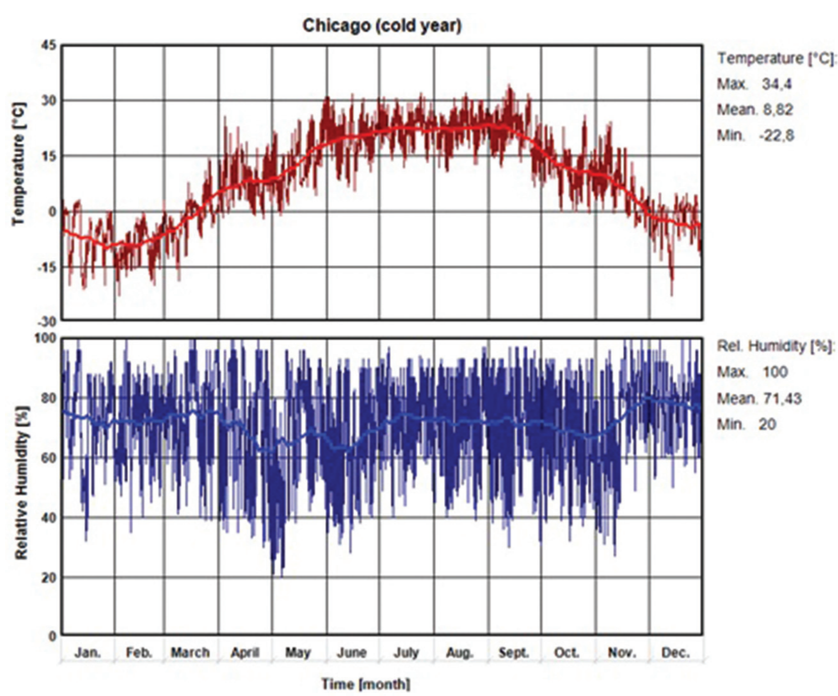

Figure 3 *Hourly weather data in Chicago, IL, representing the used weather file.*

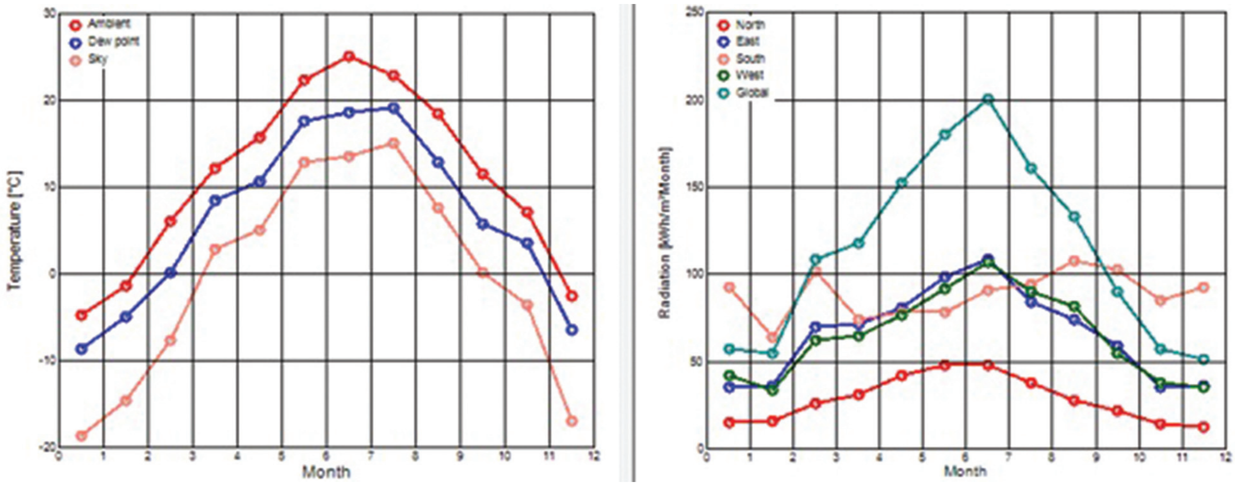

Figure 4 *Screenshot of the monthly mean weather data used for the balance-based assessment.*

for the dynamic simulation. The monthly method uses monthly conditions as described previously. Figure 4 shows the used monthly values.

The building is a two-story residential building with a relatively open floor plan. The first and second floors are connected by an open staircase. The home has three bedrooms and two bath and a discounted interior conditioned floor area (treated floor area, TFA) of approximately 1000 ft^2. The construction type is light frame insulated with high-density blown-in fiberglass and cellulose blown into the vented attic. The foundation is a fully insulated float foundation frost protected system—exposed finished concrete floors insulated to the ground with expanded polystyrene. The envelope is thermal-bridge free other than the installation thermal bridges from windows and doors and bridges due to mechanically necessary penetrations. Construction cost was \$128/ft^2 of TFA. A screenshot of the 3-D building representation in the software is shown in Figure 5.

The standard boundary conditions for passive house verification are used for the balance method.

The dynamic simulation uses the same assumptions for ventilation (0.05 ach for infiltration and a mechanical ventilation with 83% heat recovery of 0.32 ach), setpoints (temperature between 73°F and 77°F), and inner loads (4.2 kWh/d).

This is suitable for comparison purposes. To get more detailed information on the building performance under transient boundary conditions it is possible to apply schedules for day profiles on different days (e.g., weekday vs. weekend) or periods (e.g., holidays).

The building geometry was kept exactly the same, i.e., the same building model is used. Also, all component information is used for both models—the monthly balance and the dynamic assessment.

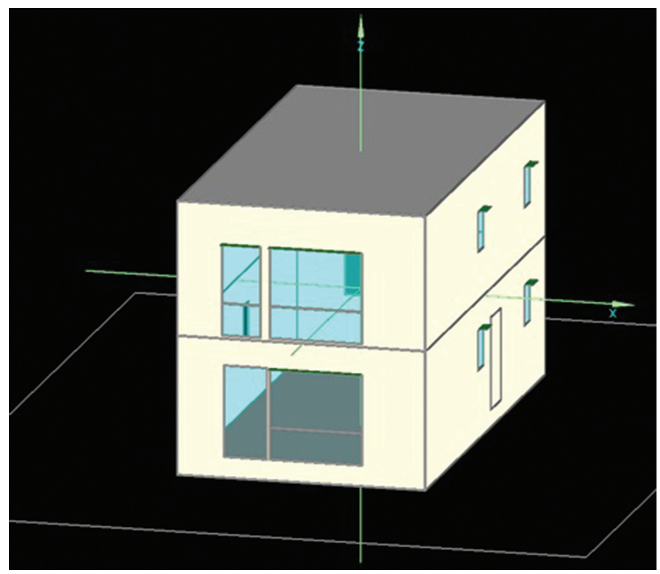

Figure 5 *Screenshot of the 3-D building representation in the software.*

Steady-State Results

In the steady-state mode, monthly balances are used to compute the heating and cooling energy demand. The heat flux for each component is simulated. This allows the identification of the highest contributors to heating and cooling loads and their improvement potential. Figure 6 shows the results for the contribution of different component types, ventilation, internal heat gains, solar gains, and heating or cooling to the overall energy balance.

All the information is available in graphical and numerical presentations. Figure 7 shows a screenshot of the actual results contributing to the heating and cooling energy balance.

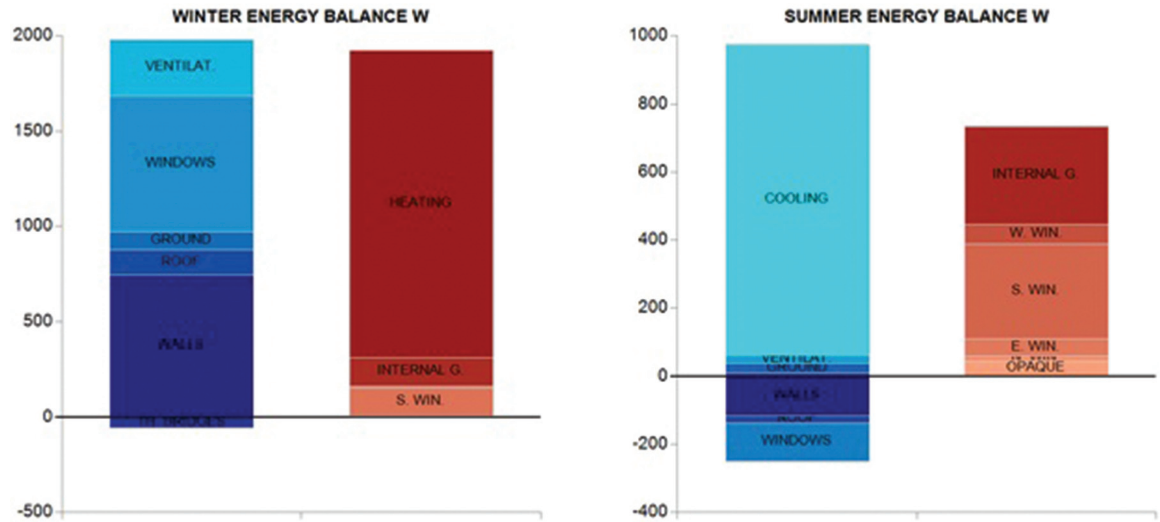

Figure 6 *Steady-state results for the winter and summer energy balance.*

ANNUAL HEAT DEMAND		
Transmission Losses :	3646,5	kWh/a
Ventilation Losses:	418,3	kWh/a
Total Heat Losses:	4064,8	kWh/a
Solar Heat Gains:	2156,9	kWh/a
Internal Heat Gains:	994,9	kWh/a
Total Heat Gains:	3151,8	kWh/a
Utilization Factor:	89,1	%
Useful Heat Gains:	2808,4	kWh/a
Annual Heat Demand:	1256,4	kWh/a
Specific Annual Heat Demand:	13,5	kWh/m²a

ANNUAL COOLING DEMAND		
Solar Heat Gains:	2355,7	kWh/a
Internal Heat Gains:	1290,5	kWh/a
Total Heat Gains:	3646,2	kWh/a
Transmission Losses :	2970,2	kWh/a
Ventilation Losses:	1986,9	kWh/a
Total Heat Losses:	4957	kWh/a
Utilization Factor:	62,3	%
Useful Heat Losses:	3088,7	kWh/a
Cooling Demand - sensible:	557,5	kWh/a
Cooling Demand - latent:	40,7	kWh/a
Annual Cooling Demand:	598,2	kWh/a
Specific Annual Cooling Demand:	6,4	kWh/m²a

Figure 7 *Screenshot of the annual heating and cooling demand contributions.*

Dynamic Results

A dynamic building simulation enables the user to assess the overall energy performance of a building and get a more detailed look at the transient interaction between building envelope and interior space. The implemented model also takes into account the coupled heat and moisture transport into the envelope components. Hence, the hygrothermal component performance can also be assessed.

Some example results from the dynamic simulation are shown in Figures 8–12. The energy performance can be assessed in more detail by looking at the hourly values. Thermal comfort values in the building can be computed according to common standards such as ANSI/ASHRAE Standard 55 (2010), and possible moisture-related problems can be identified by analyzing the time-dependent temperature and moisture distributions in each component layer.

Energy Demand

During the design phase of a building it is often necessary to divide the different contributions to the overall energy balance of a building. Figure 8 shows the monthly sum of all different heat fluxes. This example identifies that in the heating period the ventilation losses are small compared to the losses through opaque partitions and to the large losses through windows. The solar gains are high all year round. This leads to overheating/high cooling demand in the cooling period when gains through opaque wall assemblies and small inner gains are added to the balance. We find that a large first improvement for both heating and cooling demand can be achieved by using windows with a lower overall U-factor (reducing the losses in winter) and lower solar heat gain coefficient or/and better shading (reducing the gains in summer).

The dynamic model yields other important insights. A closer look at the hourly values in Figure 9 reveals some other shortcomings of the current design. Especially during the in-between seasons, the daily temperature swing reaches both the heating and the cooling setpoint temperatures. The graphs in Figure 9 illustrate clearly that on some sequential days heating and cooling is required on the same day. One design option would be to add some thermal inertia, to store the gained energy and release it later on. These effects can only be assessed with a dynamic simulation; a monthly balance gives no indication that this problem might occur.

Indoor Environment

Indoor environment, especially thermal comfort, can be assessed with different standards such as the North American standard ASHRAE Standard 55 (2010) or the international standard DIN EN ISO 15251 (2007). Both allow the assessment of the overall thermal comfort and localized thermal discomfort. The overall thermal comfort is in general assessed by the predicted mean vote (PMV) according to Fanger (1982), which describes the mean vote of people exposed to the climate conditions on a –3 to +3 scale with 0 being a neutral vote expressing the feeling that it is neither too warm nor too cold. The calculation of the PMV takes the air and the radiant temperature, the relative humidity of the air (all of which are a result of the simulation), the air velocity (which can be guessed in a regularly conditioned building), and some individual parameters such as clothing insulation and metabolic rate into account. Figure 10 shows the calculated PMV and the predicted percentage of dissatisfied (PPD) for the example building with the assumption of a 0.1 m/s (about 3.94 in./s) air speed, a clothing insulation of 0.9 clo, and a metabolic rate of 1 met. It shows that the conditions fluctuate between the two temperature setpoints, causing slightly cool conditions in winter with a PMV close to –1 for the assumed clothing level. During summer the mean vote is that it is slightly warm, but overall the conditions are in an acceptable range, coming in most of the time between –0.5 and +0.5.

Hygrothermal Component Assessment

The hygrothermal component assessment usually contains two parts. First, the total water content and the water content of different layers is assessed. Simply put, the total water content should not continuously increase over time and its annual fluctuations should remain within a certain limit. Figure 11 shows the total water content of the south-oriented exterior wall. Regular annual fluctuations are reached and the total water content does not increase over time.

Furthermore, the water content of different layers should remain below a certain limit. For example, one could analyze the mass percentage of the fiberboard sheathing to make sure that there is no long-term risk of wood rot. The drying capacity regarding built-in moisture can also be assessed.

Second, the hygrothermal conditions for critical locations can be assessed. This can be applied, for example, to assess the risk for mold growth on the interior surface of the exterior envelope using realistic interior conditions resulting from the zone simulation. A very helpful tool to assess the performance

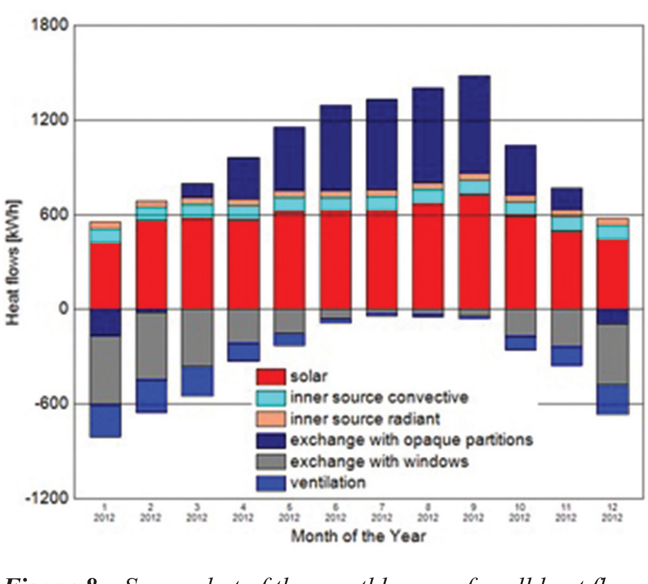

Figure 8 *Screenshot of the monthly sums for all heat flows in the dynamic simulation.*

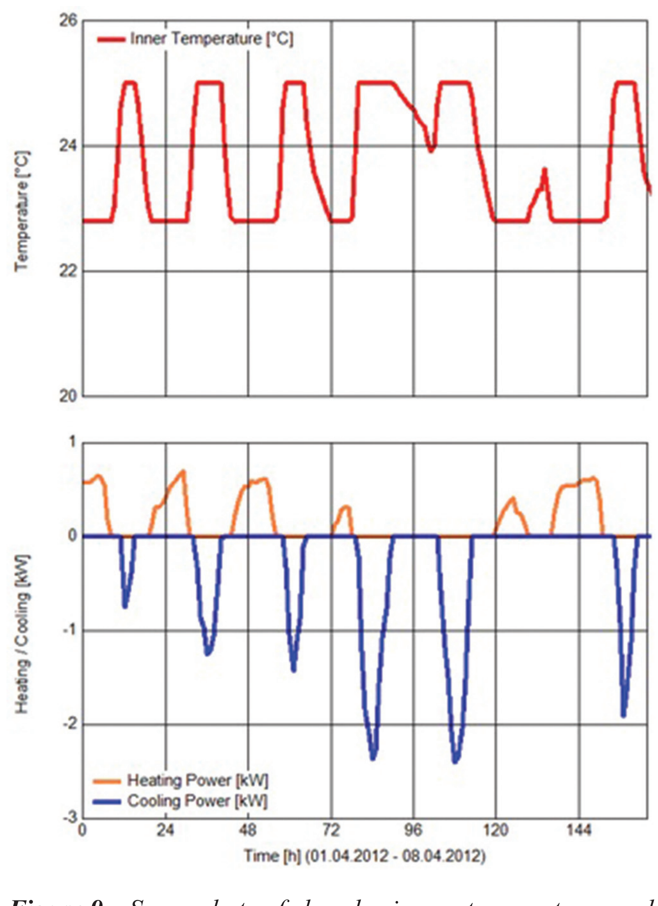

Figure 9 *Screenshot of hourly inner temperature and heating/cooling for the first week in April.*

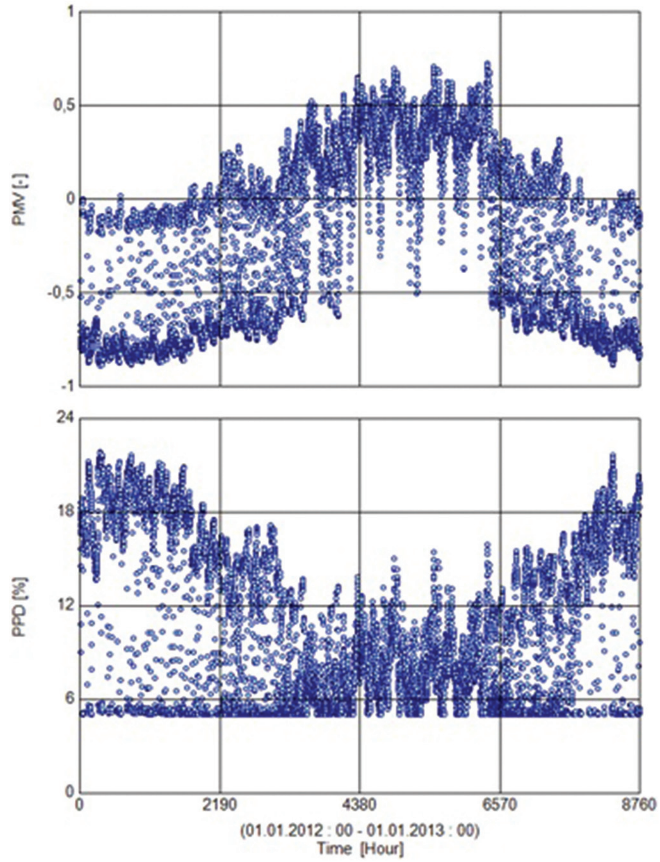

Figure 10 *Screenshot of the calculated PMV and PPD values for the example building.*

and the processes inside the components is the visualization of the temperature and humidity distribution across the building layers in the form of a movie. Figure 12 shows as an example a screenshot of the temperature and humidity in the different layers of the exterior wall assembly at a certain point in time.

DISCUSSION AND CONCLUSIONS

A concern about the new tool is that it will not allow access to the underlying formulas and calculation paths. But because it provides an organized self-guiding user interface, the kind of tracing and navigation that was necessary for a very large Excel calculator will likely no longer be necessary. Furthermore, the Excel output and export function of the new tool allows integration of all data into other spreadsheet calculators or custom optimizers.

Overall the benefits of a user-friendly interface and modeling synergies significantly outweigh any drawbacks. If passive buildings go mainstream, the majority of users will be architects who appreciate a simple interface and being guided through the tool. So far the percentage of architects taking up passive building design has been limited to those who already have a physics interest or strong mathematical inclination. Most architects like more guidance. Thus, the combination of

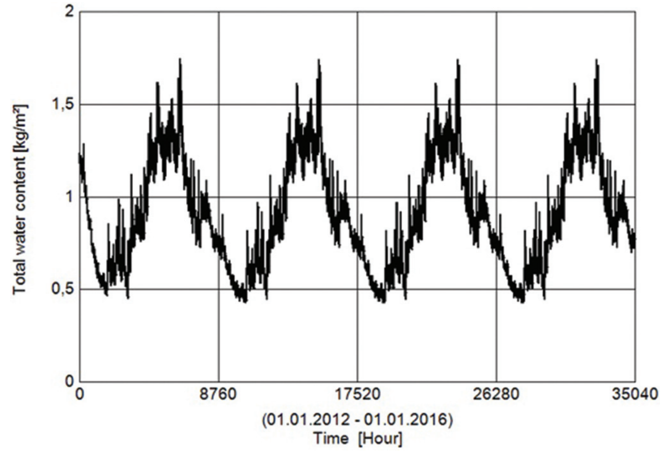

Figure 11 *Screenshot of the total water content of the south-oriented exterior wall.*

both models into one tool has real potential to transform the passive building design process in North America 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. It offers 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. It organizes all required project and systems data for certification into one file and has the promise to simplify the certification process itself by eliminating opportunities for mistakes, essentially making critical quality assurance during the planning process much easier. 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. Previously the designer did not have enough information to dial in the correct window value combinations for greatly varying climates in the United States. The general recommendation of installed window U-factors of 0.85 $W/m^2/K$ (0.15 $Btu/ft^2{\cdot}hr{\cdot}°F$) and a g-value/solar heat gain coefficient higher than 50% might lead to overheating and in some cases produces the need for heating and cooling during the same day during the in-between seasons. The designer had no feedback that would help to identify the most effective climate-specific combination of those values while ensuring thermal comfort as demonstrated in the previous application example (where the designer was forced to come up with a best guess).

Many designers in North America hence have been forced to master and use separate hygrothermal tools and secondary dynamic energy models to assess wall component appropri-

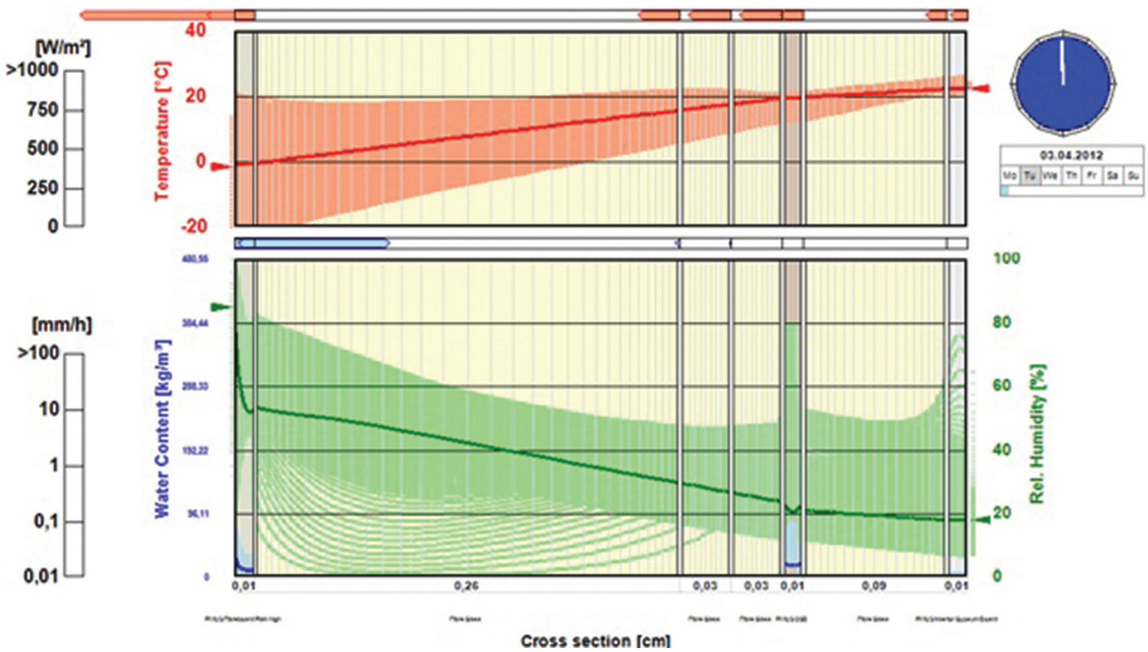

Figure 12 *Exemplary screenshot of the temperature and humidity visualization of a component.*

ateness 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 models instead of one when a design change is made. This is not only labor intensive but also increases the likelihood of error.

In conclusion, the most significant improvement of WUFI Passive, aside from the more efficient and organized workflow, is the all-in-one risk management capability. The next-generation passive modeling for varying climates needs to include dynamic simulation to improve models in regards to cooling and dehumidification load accuracy as well as to improve the ability to predict comfort issues such as overheating and high relative indoor humidity. The few optimization conclusions highlighted over the course of this paper based on the dynamic model outputs of the built example in Urbana are excellent examples of how the dynamic results are informing the design process to ensure passive building designs in North America are the most efficient and comfortable.

And to conclude with a gaze into the future: as larger buildings with multiple zones 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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