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Building indoor model in PALM model system 6.0: Indoor climate, energy demand, and the interaction between buildings and the urban climate

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Abstract. There is a strong interaction between the urban and the building energy balance. The urban climate affects the heat transfer through exterior walls, the longwave heat transfer between the building surfaces and the surroundings, the shortwave solar heat gains and the heat transport by ventilation. Considering also the internal heat gains and the heat capacity of the building structure, the energy demand for heating and cooling and the indoor thermal environment can be calculated based on the urban climate. According to the building energy concept, the energy demand results in an (anthropogenic) waste heat, this is directly transferred to the urban environment. Furthermore, the indoor temperature is re-coupled via the building envelope to the urban environment and affects indirectly the urban climate with a time shifted and damped temperature fluctuation. We developed and implemented a holistic building model for the combined calculation of indoor climate and energy demand based on an analytic solution of Fourier's equation. The building model is integrated via an urban surface model into the urban climate model.

1 Building indoor model for urban climate simulation

Buildings strongly affect the urban climate. And the urban climate strongly affects the indoor climate and energy demand of buildings. A good review on experimental and numerical studies from the 1960s to today is given by Helbig et al. (2013). Hence, urban climate simulation models should contain a powerful building indoor model in order to evaluate the strong interaction between the building and the urban climate.

In a preliminary simulation study, Jacob and Pfafferott (2012) applied different test reference years (Deutscher Wetterdienst, 2014) on different building concepts and operation strategies. These test reference years consider both the climate change and the urban climate effect. The study clearly revealed that the urban heat island effect has a stronger effect on the building energy balance than the climate change. As expected, the building physical parameters of the building envelope (i.e. heat transfer coefficients, window area related to façade and floor area, fabric, solar shading) and the user behaviour (i.e. attendance, ventilation, use of shading device) strongly affects energy demand in summer and winter and indoor environment for both residential and office buildings. Results from monitoring campaigns confirm these findings, (Kalz et al., 2014) and (Pfafferott and Becker, 2008).

Favourably, those complex interactions between the built environment and the urban climate can be evaluated based on a sophisticated simulation model (Bueno et al., 2012). Within the MOSAIK project (Maronga et al., 2020), we developed a holistic building model for the coupled calculation of indoor climate (i.e. operative room temperature) and energy demand for heating, cooling, lighting and ventilation. The building indoor model is based on an analytic solution of Fourier's equation and is directly integrated into the PALM model system 6.0 (Knoop et al., 2018). Furthermore, the building indoor model has an interface with the urban surface model (Resler et al., 2017):

- The façade near temperature from the urban climate model is the input variable for the calculation of heat transport by (free or mechanical) ventilation.
- The building indoor model gets the locally allocated wall, window, and roof temperature, respectively, as an input from the urban surface model for the simulation of indoor climate and energy demand.
- The urban surface model gets the specific heat flux through the exterior walls as an input from the building indoor model for the simulation of façade temperatures.

2 Building indoor model for urban climate simulation

The building indoor model is based on an analytical solution of Fourier's law considering a resistance model with five resistances R [K/W] and one heat capacity C [J/K]. The solution is based on a Crank-Nicolson scheme for a one-hour time step. Since the whole programming is based on heat transfer coefficients, all figures and equations are based on heat transfer coefficients H [W/K]. This is the reciprocal value of R and takes short wave, long wave, convective and conductive heat transfer and heat transport (by air) into account.

The model considers four driving heat fluxes:

- Φ_{hc} heating and cooling energy,
- Φ_{conv} convective internal heat gains,
- $\Phi_{rad,s}$ radiative internal and solar heat gains to the room-enclosing surfaces, and
- $\Phi_{rad,m}$ radiative internal and solar heat gains to the room-enclosing building structure.

All heat sources and sinks are coupled with

- ϑ_i indoor air,
- ϑ_s interior surface temperature, or
- ϑ_m temperature of the room-enclosing building structure, respectively.

These interior temperatures are coupled with three exterior temperatures:

- ϑ_n façade near temperature for the incoming air,
- ϑ_e ambient air temperature for the calculation of the heat transfer through the window, and

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– ϑ_w wall temperature from the urban surface model.

Figure 1 shows all temperatures and heat fluxes in this R5C1 network.

From a numerical perspective, this network consists of five reciprocal heat-transfer resistances H and one heat storage capacity C:

– H_v [W/K] for heat transport by ventilation between surface-near exterior air ϑ_n and indoor air ϑ_i
– $H_{t,is}$ [W/K] for convective heat transfer between indoor air ϑ_i and interior surfaces ϑ_s with specific heat transfer coefficient h_{is}=3.45 W/(m² K) considering all room-enclosing surfaces
– $H_{t,es}$ [W/K] for heat transfer through windows between exterior air ϑ_e and interior surfaces ϑ_s
– $H_{t,ms}$ [W/K] for conductive heat transfer between interior surfaces ϑ_s and interior mass node ϑ_m with specific heat transfer coefficient h_{ms}=9.1 W/(m² K) considering room-enclosing surfaces
– $H_{t,wm}$ [W/K] for conductive heat transfer between wall ϑ_w and interior mass node ϑ_m
– C [J/K] heat storage capacity of all the whole room-enclosing building structure

The heat transfer through the façade consists of the heat transfer through windows (transparent façade component without heat storage capacity) and the heat transfer through walls (opaque façade component with heat storage capacity). The heat transfer coefficient $H_{t,es}$ through the window is reversely calculated from $H_{t,window}$ which takes the window U-value [W/(m² K)] and the window area A_{window} [m²] into account. The heat transfer through the outside wall is calculated by the urban surface model (Resler et al., 2017) in which the temperature ϑ_w and the heat flux Φ_w [W] in the inside node of the wall construction is the interface between both models. The heat transfer coefficient $H_{t,ws}$ between the exterior wall and the room-enclosing surfaces is divided into a heat transfer coefficient between the wall and the room-enclosing building structure $H_{t,wm}$ and a heat transfer coefficient between the room-enclosing building structure and the room-enclosing surfaces $H_{t,ms}$. The heat transfer coefficient $H_{t,ws}$ is calculated from the wall U-value [W/(m² K)] and the wall area A_{wall} [m²] considering the three wall layers and their heat conductivity, see below.

Fourier's equation is mathematically solved for a time-step of 1 hour or 3,600 seconds, respectively. The temperature of the room-enclosing building structure ϑm is calculated from its value at the previous time step $\vartheta_{m,prev}$ and the overall heat flux into the room-enclosing building structure $\Phi_{m,tot}$ which is calculated from Φ_{hc}, Φ_{conv}, $\Phi_{rad,s}$, and $\Phi_{rad,m}$.

$$\vartheta_m = \frac{\vartheta_{m,prev} \cdot \left(\frac{C}{3600} - 0.5 \cdot (H_{t,m} + H_{t,wm})\right) + \Phi_{m,tot}}{\frac{C}{3600} + 0.5 \cdot (H_{t,m} + H_{t,wm})} \quad (1)$$

with $H_{t,m} = \frac{1}{\frac{1}{H_{t,s} + H_{t,es}} + \frac{1}{H_{t,ms}}}$ and $H_{t,s} = \frac{1}{\frac{1}{H_v} + \frac{1}{H_{t,is}}}$

The surface temperature ϑ_s is a function of the convective and radiative heat fluxes to the surface (Φ_{hc}, Φ_{conv}, and $\Phi_{rad,s}$) and is connected with the temperature of the room-enclosing building structure ϑ_m, the façade near temperature ϑ_n, and the ambient air temperature ϑ_e.

$$\vartheta_s = \frac{H_{t,ms} \cdot \vartheta_m + \Phi_{rad,s} + H_{t,es} \cdot \vartheta_e + H_{t,s} \cdot \left(\vartheta_n + \frac{\Phi_{conv} + \Phi_{hc}}{H_v}\right)}{H_{t,ms} + H_{t,es} + H_{t,s}} \quad (2)$$

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The indoor air temperature ϑi is a function of convective heat fluxes Φ_{hc} and Φ_{conv} and is coupled to the surface temperature ϑ_s and the ϑ_n façade near temperature.

$$\vartheta_i = \frac{H_{t,is} \cdot \vartheta_s + H_v \cdot \vartheta_n + \Phi_{conv} + \Phi_{hc}}{H_{t,is} + H_v} \quad (3)$$

From these equations, the specific heating / cooling energy demand $\varphi_{hc,nd}$ [W/m²] can be calculated for a specified set temperature for the indoor air $\vartheta_{i,set}$. This calculation is based on a linear approach based on the indoor air temperature without heating / cooling $\vartheta_{i,0}$ and the indoor air temperature $\vartheta_{i,10}$ with a specific heat flux $\varphi_{hc,10}$ of 10 W/m² net floor area.

$$\varphi_{hc,nd} = \varphi_{hc,10} \cdot \frac{\vartheta_{i,set} - \vartheta_{i,0}}{\vartheta_{i,10} - \vartheta_{i,0}} \quad (4)$$

If the indoor air temperature is higher than the set temperature for heating (e.g. $\vartheta_{i,set,h}$ = 20 °C) and lower than the set temperature for cooling (e.g. $\vartheta_{i,set,c}$ = 26 °C) the heat flux $\phi_{hc,nd}$ is 0. If the heating and cooling capacity is limited due to the technical facility, the heating and cooling heat flux might be limited to $\phi_{h,max}$ or $\phi_{c,min}$, respectively. Hence, the actual heating or cooling energy Φ_{hc} is recalculated with the net floor area for one of these five cases:

- $\phi_{hc} = 0$ W/m² if $\vartheta_{i,set,h} < \vartheta i < \vartheta_{i,set,c}$
- $\phi_{hc} = \phi_{hc,nd}$ if $\phi_{hc,nd} < \phi_{h,max}$ in heating mode, or $\phi_{hc,nd} < \phi_{c,max}$ in cooling mode, respectively.
- $\phi_{hc} = \phi_{h,max}$ if $\phi_{hc,nd} > \phi_{h,max}$ in heating mode, or $\phi_{hc} = \phi_{c,max}$ if $\phi_{hc,nd} > \phi_{c,max}$ in cooling mode, respectively.

With the heating or cooling energy Φ_{hc} [W] the actual temperatures ϑ_m, ϑ_s and ϑ_i are calculated from Eq. (1) to (3).

From these simulation results we calculate the operative room temperature, the final energy demand for heating and cooling, the anthropogenic waste heat and the heat flux from the room to the façade: The operative room temperature ϑ_o is used for the evaluation of the indoor climate and is calculated from the indoor air temperature ϑ_i and the surface temperature ϑ_s.

$$\vartheta_o = 0.3 \cdot \vartheta_i + 0.7 \cdot \vartheta_s \quad (5)$$

The final energy demand for heating and cooling $\Phi_{hc,f}$ is given in electrical and / or fuel energy and depends on the energy efficiency of the technical facility $e_{f,hc}$, e.g. from DIN V 18599 (2011):

$$\Phi_{hc,f} = \Phi_{hc} \cdot e_{f,hc} \quad (6)$$

The anthropogenic waste heat $\Phi_{hc,w}$ strongly depends on the energy supply system (e.g. district heating / cooling, heat pump, thermally driven or compression chiller, boiler) and is calculated from a coefficient q_{hc} waste heat from DIN V 18599 (2011), which is zero for district heating / cooling, positive for boilers or chillers and negative for heat pump systems.

$$\Phi_{hc,w} = \Phi_{hc} \cdot q_{hc} \quad (7)$$

The interface between the façade and the indoor model is given by the wall temperature ϑ_w and the heat flux into the wall Φ_w.

$$\Phi_w = H_{t,ms} \cdot (\vartheta_s - \vartheta_m) \quad (8)$$

The façade model is based on three wall layers and, hence, is numerically based on a 3R3C-model with four temperatures (the outside surface temperature of the wall and three wall node temperatures), three serial heat transfer resistances H [W/K] between these temperatures and three heat storage capacities C [J/K] for each wall layer. The energy balance at the outside

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surface is calculated from the heat flux between the surface ϑ_s and the first wall temperature ϑ_{n1} and the heat fluxes from short $\Phi_{rad,sw}$ [W] and long-wave radiation $\Phi_{rad,lw}$ [W] and the convective heat transfer to the exterior air Φ_{conv} [W]. The energy balance at the inside wall layer calculated from the heat flux from the building model Φ_w [W] and the heat flux between the third ϑ_{n3} and the second wall temperature ϑ_{n2}.

Based on the building energy concepts and the input parameters from the model database, the electrical energy demand (e.g. for lighting, ventilation and office / residential equipment), the heating energy demand (e.g. heat pump systems, boilers, cogeneration or solar thermal energy) and the cooling energy demand (e.g. compression or thermally driven chillers, adiabatic cooling, cooling towers, ground cooling) are calculated. Considering this electrical or thermal energy demand, the anthropogenic heat production is calculated and is passed back to the urban climate model.

The model according to DIN EN ISO 13790 (2008) was validated with monitoring data (simulation-measurement validation) and other simulation programs (cross-model validation). The accuracy of the advanced analytical model has been compared repeatedly with numerical simulation models with special respect to uncertain input parameters, different building technologies, and stochastic user behaviour (Burhenne et al., 2010).

3 Model database

A model database is used for the parametrization of the building indoor model and the urban surface model. The database provides building physical parameters of the building envelope, geometry data and operational data (incl. user behaviour, control strategies and technical building services). The only available building information is often the age of the building, its construction material of façade and coating, the façade and window area, and the cubature. Hence, the model database defines all building physical parameters and operational data based on those basic parameters according to a building typology (IWU, 2018). The model database contains four areas:

- The building description is based on geometry, fabric, window fraction and ventilation models.
- The user description is based on (stochastic) user models regarding window opening and use of solar control, and user profiles regarding attendance and internal heat gains.
- The person description is based on the metabolic rate and the clothing value.
- The HVAC energy supply system is simulated with simplified models based on characteristic line models (considering the applicable standards) for different air-conditioning concepts. The model database contains also operation strategies for the energy supply system.

The input information on building physical parameters from a regional survey or an urban planning tool is often uncertain and inconsistent. The model database is well-structured and includes sub-models which process information on different levels of accuracy and precision. Hence, the database is built up on a standardized building topology and can manually be adapted in order to evaluate measures with regard to the façade or to the building energy supply.

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The standard database contains six building types according to the German building topology (IWU, 2018), i.e. building age from the 1920s, 1970s and the 1990s for residential and non-residential buildings. The summer heat protection corresponds to the minimum requirements with regard to DIN 4108-2 (2013). Typical attendance and internal heat gains are taken from DIN V 18599 (2011) and empirical values (Voss et al., 2006).

4 Integration into the urban climate model

The building indoor model has been implemented into the PALM model system 6.0 platform. The building geometry and the resolution given by the urban simulation model define both the volume of the building $V_{building}$ and the number of façade elements n_{facade}. Each building indoor model contains as many indoor volumes V_{indoor} as façade elements. Thus, all global parameters (i.e. air change per hour, internal heat gain per net floor area and heat capacity) are referred to this virtual room volume:

$$V_{indoor} = \frac{V_{building}}{n_{facade}} \quad (9)$$

While the PALM model system 6.0 runs with an adaptable timestep resolution (which differs from 3,600 seconds), the building indoor model is run for each hour of the day. The results (i.e. indoor environment, surface temperatures, and anthropogenic waste heat from building operation) are fixed for the next hour.

Figure 3 shows simulation results for a summer and a winter simulation run. Both graphs show the (local) temperature distribution in the building and around the building and the anthropogenic waste heat from heating and cooling at 11 a.m. in a typical urban situation with street canyons, block development and high-rise buildings, parks and water: Ernst-Reuter-Platz, Berlin (Germany). All simulation results are shown at 10 m above ground and clearly show that the combined simulation of urban climate, energy balance at the wall surface, and the indoor energy balance yield detail information on indoor and outdoor temperatures, surface temperatures and energy demand (not shown in the graph) and heat fluxes from the building's energy system to the urban environment:

- The outdoor temperature ϑ_e is around +24 °C in the summer scenario (above) and -10 °C in the winter scenario (below) and is locally calculated by the urban canopy model that represents the fluid dynamic and thermodynamic effects of the urbanized area around Ernst-Reuter-Platz in Berlin on the atmosphere.
- The operative room temperature ϑ_i is around 26 °C in the summer scenario (in buildings with active cooling) and around 20 °C in winter due to active heating. There is a remarkable temperature range in buildings with no active cooling: In this summer scenario, the operative room temperature in some buildings rise to 33 °C due to high solar and internal heat gains while other buildings stay at 22 °C due to their high thermal inertia and passive cooling strategies.
- The (use) energy demand for heating and cooling of each volume element depends strongly on the temperature difference between inside and outside, the wind speed at the façade, the building construction and window-to-

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façade ratio, and the solar radiation and the orientation of the building. The (final) energy demand considers the building's energy supply system. Based on the energy conversion factors for each heating or cooling system, the anthropogenic waste heat from the building $\Phi_{hc,w}$ is calculated for each façade element separately and is transferred to the urban area via the outside surface. Façade elements with no anthropogenic waste heat (i.e. buildings with district heating in winter or passive cooling in summer, respectively) are shown in black. The anthropogenic waste heat from the building $\Phi_{hc,w}$ due to energy losses of the heating supply system ranges between 2 and 7 W/m^2_{facade} in winter and due to the recooling systems of the cooling supply system between 20 and 60 W/m^2_{facade}.

5 Summary

An analytical solution of Fouriers equation is used to simulate the transient energy balance of a building. This building model is separated into virtual control volumes which are geometrically connected with the urban climate simulation. Thus, each simulated building consists of as many control volumes as the number of façade elements connected to the exterior environment. Since the energy balance is numerically solved together with the urban surface model (i.e. façade temperature and energy balance of convective, long and short wave radiation, transmission, and energy storage) and the urban climate simulation (i.e. air temperature of the first node connected to the respective façade element and surface near air temperature) the coupled energy flow to and from the building to the urban climate can be analysed.
From an application perspective, the indoor environment and the energy need of the building can be calculated as a function of urban climate. On the one hand, the heat transmission due to the temperature difference between indoor and outdoor environment, the heat transport due to ventilation and the radiative heat transfer between the building structure and the urban climate results in a strong interaction between the built environment and the urban climate. On the other hand, the energy supply of each building results in an anthropogenic waste heat, which heats up or cools down the urban climate.
First simulation results from a simulation study for the Berlin city centre show the impact of buildings defined by different building physical parameters and with different technical facilities for ventilation, heating and cooling on the urban climate.

Code and data availability. The PALM model system 6.0, including the building indoor model, can be freely download from https://palm.muk.uni-hannover.de/trac (last access: 19 June 2020). The distribution is under the terms of the GNU General Public License (v3). More about the revision control, code management and versioning of the PALM model system 6.0 can be found in Maronga et al. (2015). The input dataset is at https://doi.org/10.5281/zenodo.3906170 (Rissmann, 2020) (last access: 24.June 2020).

Author contribution. JP developed the building indoor model code with support from SR, MS, FK-S, and BM. SR performed the simulation with support from FK-S and MS. JP prepared the manuscript with contributions from all co-authors. SR submitted the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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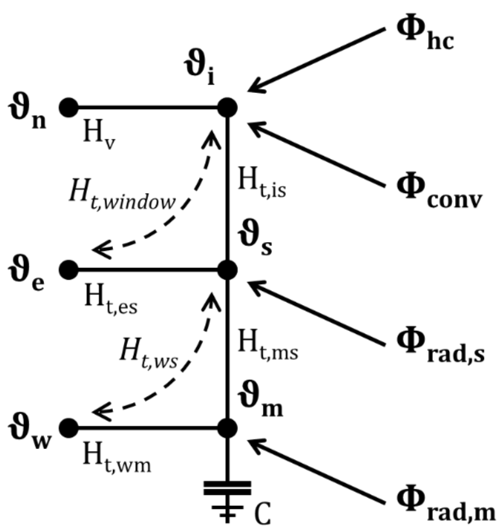

Figure 1: Building indoor model: Heat flux and temperature in the R5C1 network. The heat flux Φw between ϑm and ϑw is calculated additionally as input value for the urban surface model, not shown in this diagram. Furthermore, the anthropogenic waste heat $\Phi_{hc,w}$ from the heating and cooling system is calculated additionally as output value to the urban climate simulation, not shown in this diagram. (The dashed lines are for information only.)

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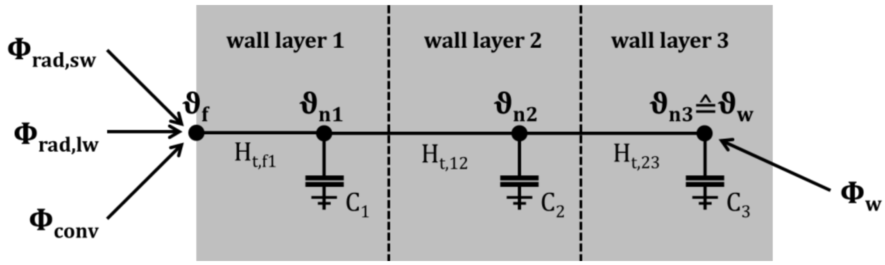

Figure 2: Urban surface model: Heat flux and temperature in the R3C3 network with three wall layers. The wall temperature ϑ_w is the model output to the building indoor model and the heat flux into the wall Φ_w is the input from the building indoor model, see Figure 1.

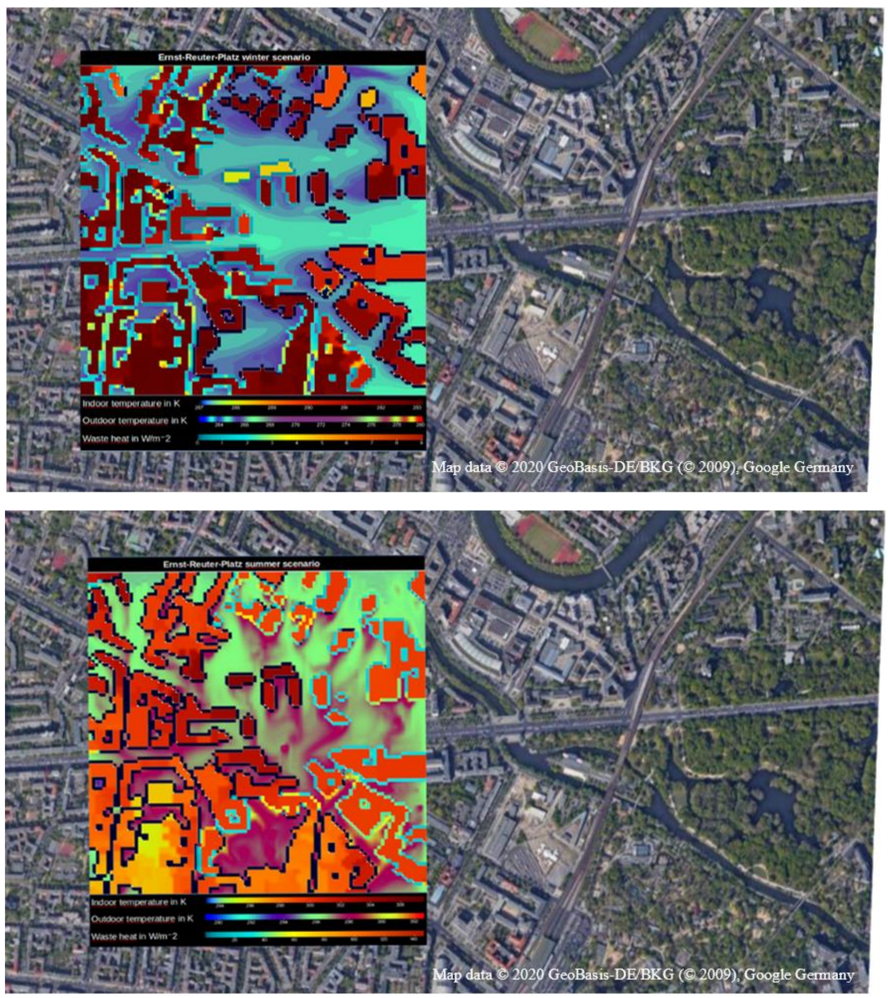

Figure 3: Urban surface and building indoor model in a test setup: The Ernst-Reuter-Platz connects five urban street canyons and is surrounded by high-rise buildings. The simulation runs with a resolution of 1 m x 1 m x 1m. The graphs show the operative room temperature ϑ_i, the ambient air temperature ϑ_e and the anthropogenic waste heat $\Phi_{hc,w}$ at the outside surface. The outdoor temperature is around +24 °C in the summer scenario (above) and -10 °C in the winter scenario (below). Façade elements with no

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anthropogenic waste heat (i.e. buildings with district heating in winter or passive cooling in summer, respectively) are shown in black.