Complex glass façade modelling for Model Predictive Control of thermal loads: impact of the solar load identification on the state-space model accuracy

F. Veynandt, C. Heschl, P. Klanatsky, H. Plank
Fachhochschule Burgenland GmbH, Pinkafeld, Austria

ABSTRACT: Above and beyond improving the efficiency of the building envelope and the energy supply system, the demand-side flexibility in terms of load shifting and peak reduction are vital factors in further increasing the share of volatile renewable energy sources. The thermal activation of building components, like floors and ceilings, enables the cost-effective potential for short-term energy storage to fulfil these requirements. In order to exploit the storage capabilities of active building systems, a reliable model predicted control (MPC) approach is required. However, primarily if a large glass façade element is utilised, the appropriate modelling of solar loads is critical for an effective MPC operation. Hence, based on a dynamic building simulation tool, a characteristic map for the solar load prediction of a glass façade system in combination of external venetian blinds was generated to enhance the state-space model approach for the MPC algorithm. The comparison with a conventional state-space model approach shows the integration of a detailed characteristic map can only marginally improve the prediction accuracy. The additional information required from the glass façade manufacturer and the associated simulation effort is not of substantial value. In contrast, the conventional grey box model enables an entirely data-driven parameter identification, without the manufacturers' data. Furthermore, the MPC optimisation procedure, searching for the best control strategy, can be more efficient (solver-based optimisation), with shorter computing turnaround times.

1. INTRODUCTION

Due to the increasing solar and wind energy production, new control and sector coupling strategies are required to align the load profiles with the volatile energy yields. Given this, Model Predictive Control (MPC) can enhance buildings' efficiency (Serale et al. 2018). A promising solution is to use an MPC approach together with Thermally Activated Building System (TABS) (Arteconi et al. 2014). Such system solutions offer high energy efficiency and demand-side flexibility for heating and cooling. However, applying MPC requires an accurate state-space model and the successful operation of TABS needs slowly load disturbances. Especially in the case of large glass façade elements, the thermal balance is strongly affected, and stable operation is still a challenge (Wang et al. 2019). Hence, within the PVadapt project, an adaptive MPC algorithm for space heating and cooling is developed, focusing on the solar load identification. The adaptive MPC uses a grey-box model that represents the building zone with a simplified resistances and capacities network. This is a state-space model, with data-driven calibration, regularly updated with up to date historical data –therefore "adaptive". The details on the state-space model development are to be revealed in a separate publication.

In this paper, the focus is on the glass façade model. In the conventional state-space model, the glass façade is modelled with two parameters: a constant Solar Heat Gain Coefficient and the fraction of the shaded area (shutters height). In constructions with complex glass façades, the solar gains are especially time dependant, from the sun position as well as glass properties and shading settings. These dynamics are questionably well represented in the *simple glass façade model* using only two parameters.

The development of a *detailed glass façade model* is presented in this article. A characteristic map is generated by extracting information from a white-box model –detailed, dynamic model. This characteristic map gives for any possible configuration of the façade –a multi-dimensional combination of parameters– the solar transmittance of the façade. By integrating this map in the state-space model, the solar gains can be evaluated precisely, according to essentially the solar irradiance and the shading settings. This "characteristic map-based" method is applied to a thermal zone in a reference building: the living laboratory ENERGETIKUM. Section 2 covers the white-box model development in software IDA ICE, and section 3 shows the characteristic map generation. The conclusion brings the results in the perspective of their further application in MPC algorithms.

2. WHITE-BOX MODEL

2.1 SIMULATION TOOL IDA ICE

IDA ICE is a high-quality software for dynamic multi-zone simulation of buildings' energy and comfort. It uses a powerful equation-based modelling, with the NMF language, similar to Modelica (EQUA).

2.2 BUILDING MODEL

2.2.1 Selected zone in the living-laboratory ENERGETIKUM

The living-lab ENERGETIKUM is an office building equipped with comprehensive measurement technology to monitor the building's behaviour in detail. Several technologies are also integrated into the building's: heating, cooling, ventilation, shading, as well as energy production and storage. This offers numerous opportunities for investigating and learning the technologies and the building operation itself.

One thermal zone is modelled in details in IDA ICE: the corner office in the upper floor (room 12), as illustrated in Fig. 1. The model parameters (from plans and documentation) and input variables (from measurements) are detailed in the following.

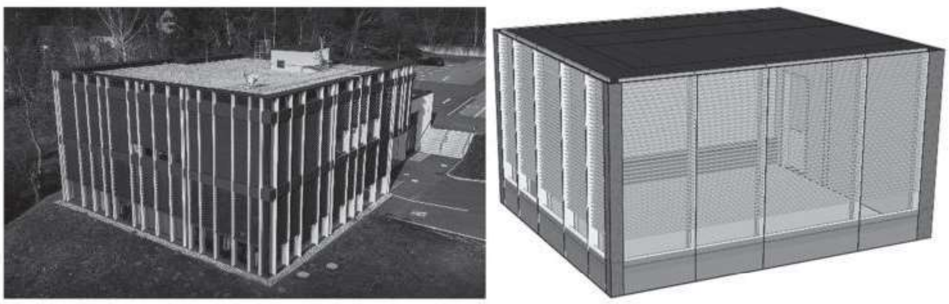

Fig. 1: Photo of the living-lab ENERGETIKUM (left) and 3D-view of the model of room 12 in IDA ICE simulation software (right).

2.2.2 Model parameters

The building is located at a latitude of N 47.3620° and a longitude of E 16.1279°. The South façade is oriented 17° to the East. Horizon height is negligible in the energy balance and ignored. An average ground reflection of 0.2 (albedo for vegetation and parking) is used.

The detailed constructions are defined in the model layer-by-layer with their thickness and material properties. The corresponding U-values are 0.133 W/(m²K) for the ceiling (external), 0.667 W/(m²K) for the floor (internal), 0.190 W/(m²K) for external walls and 0.315 W/(m²K) for internal walls. The frames of the glazed elements are modelled, including thermal properties, geometry, and optical properties to account for reflections.

The glass façade with triple glazing is critical to the model which is the primary motivation for developing the white-box model. From the overall properties of each pane, the optical properties of the glazing give a wrong overall Solar Heat Gain Coefficient (g-value) of 45.8 %. To correctly model the glazing with its actual g-value of 0.5, the spectral properties of each pane are required –and were kindly provided by the manufacturer *AGC Interpane*. The detailed and overall properties of the glazing (VSG Warmglas iplus neutral 3E) are presented in Table 1. Each pane is of float glass annealed, separated by a 14 mm wide gap filled with 90 % argon. The first and third panes have a low emittance coating on the inner side. The security glass includes a 0.76 mm polyvinyl butyral plastic layer between two 6 mm glass panes. With the selective coatings, the glazing achieves a relatively low g-value of 0.5 and U-value of 0.6 W/(m²K), compared to its 70 % visible transmittance.

External venetian blinds ensure the shading of the façade. The slats are defined in terms of geometry (80 mm slat width, 62 mm spacing between slats and 85 mm distance from the axis to the glass) and optical properties (using a similar material from the database: 3.7 % reflectance and 0.28 % transmittance). The position of the shading is measured (see next section).

Several parameters are not easily set from the building documentation and have an important influence on the thermal behaviour of the building. These parameters are tuned in the calibration procedure, within their expected range [given in square brackets]:

- three thermal bridges: ○ between external wall and internal slab, [0.15 0.23] W/(Km); ○ between roof and external wall, [0.15 0.23] W/(Km); ○ at external window perimeter, [0.15 0.23] W/(Km),
- internal mass equivalent to a surface of 5 cm thick wood plate, [30 70] m²
- air infiltration rate, [0.4 1.6] ACH (air change per hour),
- floor heating circuit: depth under the surface [0.02 0.1] m and heat transfer coefficient from the water in the pipe to the surrounding construction material [15 60] W/(m²K)
- ceiling cooling circuit: similarly depth [0.01 0.1] m and heat transfer coefficient [30 90] W/(m²K) and correction heat transfer from the supply line [5 25] Wm/K.

Table 1: Detailed and overall optical properties of the security glass in ENERGETIKUM

Glazing pane	Thickness mm	τ_v %	ρ_v %	ρ'_v %	τ_e %	ρ_e %	ρ'_e %	ϵ_n %
iplus 1.1	8	88	5	6	62	26	20	3
Planibel clearlite	6	90	8	8	85	8	8	89
Stratobel iplus 1.1 66.2	12.76	87	5	6	56	26	16	3

Overall glazing	Thickness mm	U-value W/(m²K)	g %	τ_v %	τ_e %
AGC Interpane	54.76	0.6	50	70	38
IDA ICE no spectral data	54.76	0.614	45.8	69.6	32.4
IDA ICE with spectral data	51.3	0.631	51.3	69.5	37.7

Notation in the table: τ_v: transmittance of visible light; ρ_v: reflectance of visible light on the coated side; ρ'_v: reflectance of visible light on the other side; τ_e: transmittance of shortwave irradiance; ρ_e: reflectance of shortwave irradiance on the coated side; ρ'_e: reflectance of shortwave irradiance on the other side; ϵ_n: emittance of longwave irradiance on the coated side; U-value: heat transfer coefficient of glazing; g: total energy transmission factor of the glazing (also called Solar Heat Gain Coefficient)

2.2.3 Measurement data

The measurement data are collected with the UTC time zone as a time reference. The accuracy of the overall energy balance is ensured through a careful resampling from the minute server data to hourly data set for IDA ICE simulation. A year of data (366 days) is used, from 27th July 2018 to 27th July 2019. The measured variables are fed to the simulation model through input files (.prn format).

The climate is determined from measurement data of the weather station at ENERGETIKUM: outside air temperature, relative humidity, solar irradiance (direct normal and diffuse horizontal), wind speed (vector components towards East and South).

Internal gains come from lighting, equipment and occupancy. The measured lighting power and equipment power are considered to 100 % as heat contributions to the room. Occupancy is estimated to one occupant, whenever the measured CO_2 concentration in the room rises over 500 ppm. The influence of the neighbouring rooms is modelled by imposing the measured temperature in these rooms to the corresponding zones: room below, room East, room North and corridor.

The shading's impact to the solar load properties depend on many parameters, especially the sun position and the slat angle (Carli Inc. 2006). IDA ICE includes its own physical model to pre-compute these properties at each simulation start. The shutters position in height (%) and the slat angle (°) are converted from the measured variables (control system of the building) to the IDA ICE variables with precisely adjusted functions (no direct proportionality).

Heating and cooling are provided via hydraulic circuits: one in the floor for heating (45 W/m² design power with 5 °C temperature difference) and three in the ceiling for cooling (80 W/m² with 3 °C difference). Modelling the three cooling circuits separately, with their exact geometrical implementation improves the model fit. For each circuit, the measured supply temperature and mass flow are fed into the simulation. For the cooling circuits, a correction of the supply temperature has been included to account for the heat transfer between the sensor and the room (several meters away). The return temperature is then a result of the thermal balance in the zone, represented by the physical model. The fit with the measured return temperature is a quality indicator of the model calibration.

The ventilation of the room is set from the measured air mass flow and supply temperature. The return temperature is calculated through the model.

For the calibration process, three measured variables are involved: the room temperature –akin to the operative room temperature– and the return temperatures from the heating and cooling circuits.

Several additional variables can be inserted in the simulation, to compare in IDA ICE, the simulation output with measurements: inner glass surface temperatures, solar irradiance, as well as longwave radiations, outside and inside, on South and West facades.

2.3 CALIBRATION

2.3.1 Method

Initially, parametric runs help understand the dynamics of the model and identify relevant calibration parameters (as presented in section 2.2.2). Partial optimisations with one control variable have been carried out, before the final optimisation on three control variables (as mentioned in section 2.2.3). Out of these variables, the objective function combines four minimisation criteria of standard deviations: σ_{Top} on operative temperature, $\sigma_{\dot{Q}Hf}$ on heating load (from floor circuit), $\sigma_{\dot{Q}Cf}$ on cooling load (from floor circuit) and $\sigma_{\dot{Q}Cc}$ on cooling load (from ceiling circuits). The overall objective function blends these criteria as follow: $\sigma_{HCT} = 0.1\ \sigma_{\dot{Q}Hf} + 0.1\ \sigma_{\dot{Q}Cf} + 0.1\ \sigma_{\dot{Q}Cc} + 2\ \sigma_{Top}$

$\sigma_{\dot{Q}Hf}$, $\sigma_{\dot{Q}Cf}$ and $\sigma_{\dot{Q}Cc}$ are in the order of magnitude of 30-60 W, while σ_{Top} is in the range 0.4-0.7 °C. The weighing coefficients put the priority on fitting the heating and cooling loads while keeping consistent temperatures.

The optimisation procedure uses GenOpt as a genetic algorithm to calibrate the model.

2.3.2 Results

Fig. 2 shows the error distribution on the three control variables obtained after calibration. The deviation from the measurements is below 1 °C in 96 % of the hours on room operative temperature; below 14 % in 80 % of the hours on the heating load and below 22 % in 80 % of the hours on the cooling load. The calibration remains valid for other periods (tested in the entirety of the year 2019).

The model represents the detailed thermal balance of the building zone. This enables a detailed analysis of different aspects of the buildings. In particular, the focus is set on the glass façade with movable shutters. The results show, the irradiance inside is mostly correctly estimated in terms of the order of magnitude, but with a systematic underestimation by around 20 %, independent of the shading settings. The inside glass surface temperature is also underestimated by 0.5 °C to 1 °C on average. These slight deviations could be linked to local effects on the sensors, in comparison to the average on the façade, calculated from the model. The white-box model development enabled to identify the most significant influencing factors, including especially the use of spectral data for the triple glazing facade. The performance of this white-box model is therefore acceptable for enhancing the grey-box model, as exposed in the following.

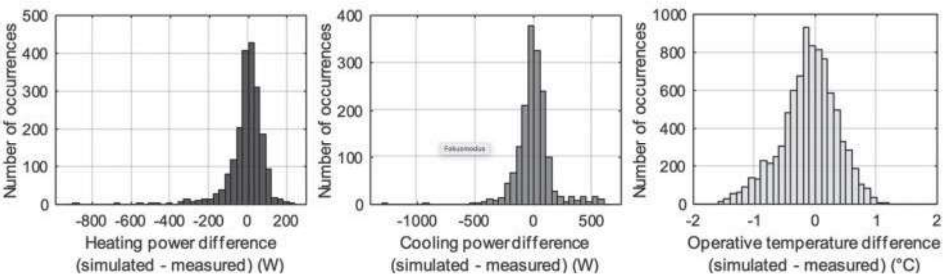

Fig. 2: Absolute error distribution in yearly frequency (number of occurrences on an hourly basis), between simulation and measurement of (left) heating load, (centre) cooling load and (right) operative temperature from measured room temperature.

3. CHARACTERISTIC MAP

3.1 APPROACH

3.1.1 Characteristic map definition

Out of the white-box model, it is possible to know the heat balance of the glass façade for any configuration of sun position and shading settings. The solar transmittance of the façade tells on the direct contribution of solar irradiance to the thermal balance. For a complete thermal balance of the façade, conduction, convection and longwave radiative heat transfer have to be considered. These contributions on the heat balance are already well represented, in the grey-box model, by a thermal resistance between the zone (inside) and the ambient (outside). Therefore, for the solar gains modelling according to the shading system, the solar transmittance is a relevant representative parameter. As simple equations cannot a priori describe the complexity of the façade with the shading system, a database is used to have information on all possible configurations. This gives a multi-dimensional characteristic diagram or characteristic map of the solar transmittance of the complex glass façade. The grey-box model can then use the data from this characteristic map via an interpolation function or machine learning algorithms.

3.1.2 Input and output variables

Five variables influence the transmission of the façade. The sun position is characterised by the azimuth angle Φ (°), relative to the façade, and the elevation angle α (°). The shading settings are the slat orientation angle λ (°) and the relative shutters height h as shaded share in % of glazing surface. The transmittance has two components: direct and diffuse transmittance. Therefore, the share of direct and diffuse irradiance is also an essential factor. The fraction of direct irradiance outside f_{Bo} in % of global irradiance is introduced, as an additional parameter.

For a straightforward use in the grey-box model, the characteristic map is split into two matrices with one output variable each: the global transmittance τ_{Gs} of the glazing with shading and the global transmittance τ_G of the glazing alone (without shading).

The transmittance with shading is applied to the shaded part h, while the transmittance without shading is applied to the rest of the glazing surface (1-*h*). This reduces the number of parameters in the matrix to four input variables for the case with shading $(\Phi,\alpha,\lambda,f_{Bo})$ and three for the case without shading (Φ,α,f_{Bo}) and one output variable each (τ_{Gs} or τ_G).

3.2 GENERATION

The characteristic map is generated by using simulation from the white box model. Several approaches have been tested, using the entire model or a sub-model and using measurement data or virtual data. The entire model with measurement data has the disadvantage to cover only cases that have occurred in the past. Unusual shading events are not well represented. Virtual data, scanning all possible sun positions and shading settings, solves this issue, leaving no gap in the characteristic map. In the following, the focus is set on virtual data applied to the entire model and to a sub-model.

3.2.1 Simulation with the entire white-box model

With the entire model, the results are gathered over a yearly simulation, with a 10 minutes time step, to ensure a fine resolution over all possible sun positions. Input files are defined to vary daily the slat angle in 10° steps from 80° to -90° in a loop. So every 18 days, all sun positions from the current season are evaluated with all slat angles: this is less than 7° maximum variation of sun elevation. One simulation runs with shading fully drawn, one without shading.

Out of IDA ICE results, the transmittance can be calculated from the thermal balance, by logging four output variables: I_{Bo} and I_{Do} respectively direct and diffuse irradiance outside, I_{Bi} and I_{Di} resp. direct and diffuse irradiance inside. The irradiance inside is needed for both cases: with shading (I_{Bis} and I_{Dis}) and without shading (I_{Bi} and I_{Di}). The characteristic map can be defined precisely for each façade, with different orientations (South and West).

3.2.2 Simulation with a sub-model

The sub-model keeps only the model of one window, with its glazing and shading system, extracted from the entire model. With this sub-model, input files are defined to scan all combinations in sorted order. The characteristics of the glazing with shading and without shading are valid for any orientation.

As explained in the post-processing section (3.3), sorted parameter values in the input files and consequently in the output files simplify the access to information through interpolation. The drawback is the loss of specificities from the entire building zone (façade orientation with landscape and external shading objects, influence from furniture).

3.3 POST-PROCESSING

The obtained data is exported from IDA ICE output file (Excel format) and post-processed in MATLAB (into a matrix) to be used in the grey-box model.

The variables of the characteristic map are converted, if necessary, or calculated from the simulation results. The sun position (Φ,α) is kept as is. The shading settings (h,λ) are converted back to the corresponding variables in ENERGETIKUM control system. The direct irradiance share f_{Bo} is calculated as follows:

$$f_{Bo} = \frac{I_{Bo}}{I_{Bo} + I_{Do}}$$

The overall transmittance with shading and without shading (independent of the slat angle) and are:

$$\tau_{Gs}(\Phi, \alpha, \lambda, f_{Bo}) = \frac{I_{Bis} + I_{Dis}}{I_{Bo} + I_{Do}} \qquad \text{and} \qquad \tau_G(\Phi, \alpha, f_{Bo}) = \frac{I_{Gi}}{I_{Go}} = \frac{I_{Bi} + I_{Di}}{I_{Bo} + I_{Do}}$$

In the end, the characteristic map information is contained in two matrices:

- glazing with shading: $[\Phi, \alpha, \lambda, f_{Bo}, \tau_{Gs}]$
- glazing (no shading): $[\Phi, \alpha, f_{Bo}, \tau_G]$

From the sub-model approach, the data is sorted. In this case, an N-dimensional interpolation algorithm (e.g. MATLAB function interpn) gives fast access to the relevant transmittance information.

The data generated with the entire model and the yearly simulation is not sorted and requires an alternative method. Pre-defined interpolation functions are generated (e.g. MATLAB function scatteredInterpolant, limited to 3-dimensional interpolation). To solve the case with the shading (4-dimensional), a step by step interpolation is implemented. In the grey-box model, the relevant pre-defined interpolation functions (3 dimensions) are called, and a complementary interpolation (fourth dimension) is performed in a second step. This method provides an interesting and relatively efficient workaround for a characteristic map with non-sorted data (Zalewski 2020).

3.4 RESULTS

Fig. 3 and Fig. 4 illustrate the characteristic map from the sub-model with respectively the global transmittance without shading τ_G and with shading τ_{Gs} Relative azimuth of incident direct solar irradiance on façade Φ goes from -90° to +90° through 0° (perpendicular to façade) growing in the sun path direction. Elevation of incident direct solar irradiance α goes from 0° horizontal to 90° vertical. The slat angle λ is defined in 10° steps from 80° to -90° (-90° vertical upside out, 0 horizontal, +90° vertical upside in). The fraction f_{Bo} of outside direct solar irradiance on the facade goes from 0.01 to 0.99.

The transmittance of the non-shaded glazing evidently depends only on the sun position and the share of direct irradiance. With shading, the transmittance also depends on the slat angle. For sun elevation similar to the slat angle, the transmittance is close to the case without shading, because the sun rays are parallel to the slats and enter the room.

If applied to the state-space model, the effect of the *detailed façade model* –based on the characteristic map– can be observed in Fig. 5. The histograms show the frequency distribution of the temperature deviation, between the measurements and the model predictions, from two variants: the original state-space model with *simple façade model* in comparison to the state-space model with *detailed façade model.* The *simple façade model* obtains less than 0.5 °C deviation in 88 % of the time steps, compared to 90 % with the *detailed façade model.* The improvement of the overall performance of the model is very modest. This indicates that the *simple façade model* gives outstanding results in this building. This is probably reflecting the slat angle settings, which always block direct irradiance. So the assumption, in the *simple façade model*, of 0 % shading transmittance, is acceptable. The conclusion could be different with other shading control strategies.

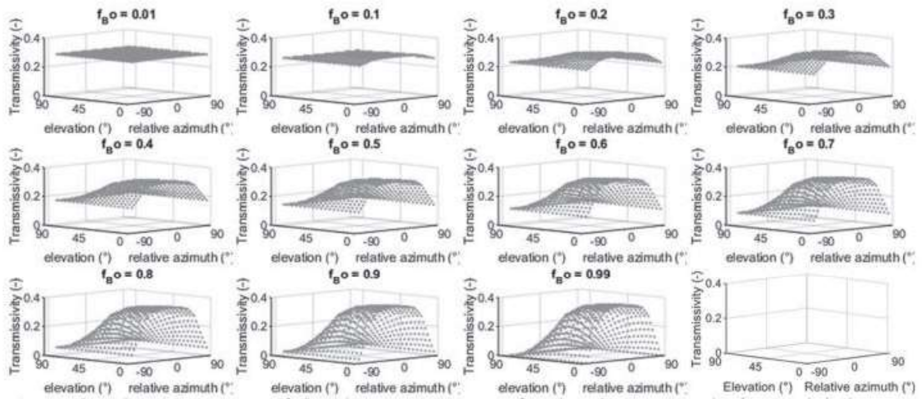

Fig. 3: Graphical overview of the characteristic map for the glazing (no shading): global transmittance τ_G in function of sun position (x and y-axis) with the fraction f_{Bo} varying through the diagrams.

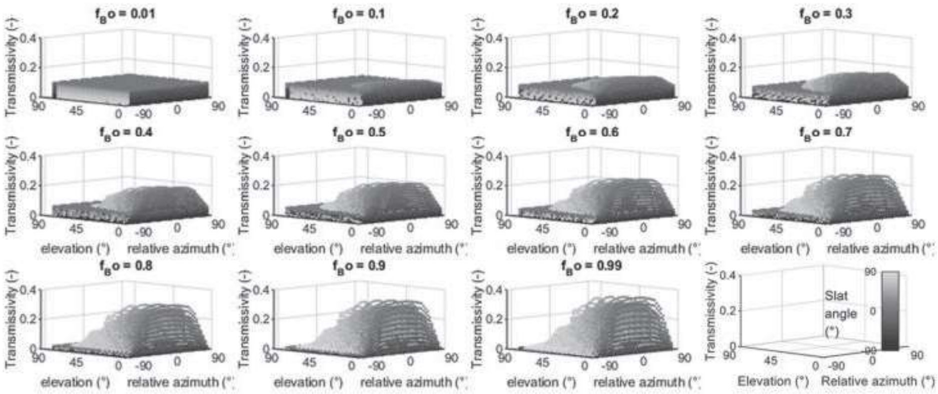

Fig. 4: Graphical overview of the characteristic map for the glazing with shutters: global transmittance τ_{Gs} in function of sun position (x and y-axis) and slat angle (colour scale) with the fraction f_{Bo} varying through the diagrams.

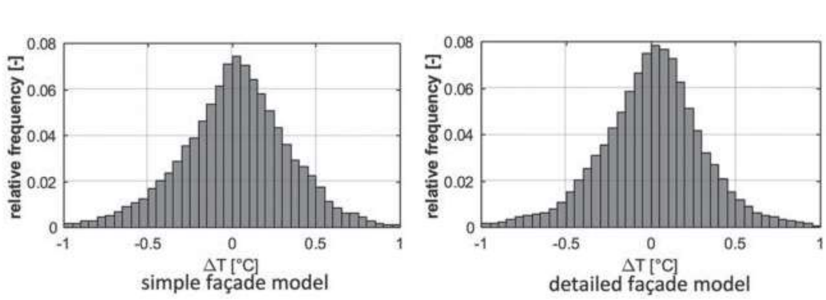

Fig. 5: Comparison of state-space model variants, with simple façade model and with detailed façade model (with the characteristic map): relative frequency distribution of the temperature deviation ΔT between the 24-hour forecast and the corresponding experimental data.

4. CONCLUSION AND PERSPECTIVES

With careful calibration, the white-box model offers a detailed physical representation of the reference building zone, with acceptable uncertainties. The characteristic map, derived from the white-box model, provides a *detailed façade model*, which can be integrated into the state-space model.

The results on the reference building show the detailed façade models only rises by 2 % the accuracy of the temperature prediction used in the MPC algorithm. This validates the use of the conventional grey-box model with its *simple façade model*, even in the case of complex glass facades. This opens exciting perspectives.

The characteristic map approach requires precise information on the facade for the detailed window and external shading model, even without developing an entire white-box model. Additional simulation effort is also needed because the optimisation setup must be problem-based (representing the objective and constraints symbolically). The required translation from problem form to matrix form leads to longer solving times.

The advantage of the conventional state-space model is that less information on the building is required, enabling an entirely data-driven parameter identification. As the structure of the model is more straightforward without the characteristic map, the state-space model can be transformed into a standardised matrix form. The solver-based optimisation problem setup is then possible (representing the objective and constraints as functions or matrices). This enables the use of well-established parameter identification and optimisation algorithms, based on more efficient solvers with shorter computational times.

Mind that the performance of the *simple façade model* might not be as good in all buildings. The characteristic map approach could still be helpful in some cases. It could, for example, help to model other variables, like longwave emissions or daylight illuminance levels.

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Contact:
François Veynandt
Steinamangerstraße 21
A-7423 Pinkafeld
Email: francois.veynandt@fh-burgenland.at