syn.ikia

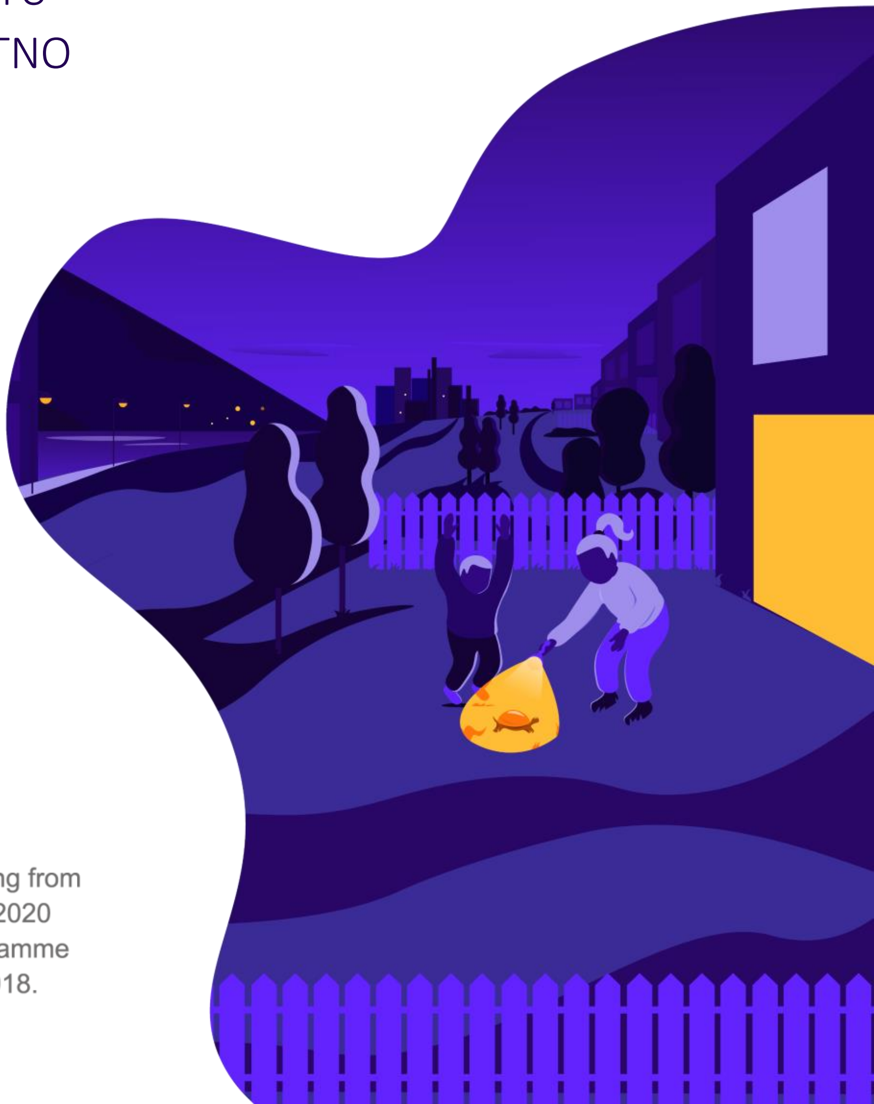
Sustainable
plus energy
neighbourhoods

WP4 - Flexibility measures in different climate zones & markets

D4.1 GREY BOX MODELS OF THE DEMONSTRATION CASES

Seyed Shahabaldin Tohidi - DTU
Behrouz Eslami Mossallam - TNO
Davide Calì - DTU

31.03.2022/M27



This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement N 869918.

1. Revision Log:

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published work has been properly cited.

PROJECT ACRONYM .... syn.ikia
PROJECT NUMBER 869918
PROJECT TITLE .... Sustainable Plus Energy Neighbourhoods
WEBSITE .... www.synikia.eu

2. Technical References

Deliverable (number)	D4.1			
Deliverable Name	Grey box models of the demonstration cases			
Work Package	WP4			
Task number and Title	Task 4.1, Grey box models of the demonstration case			
Dissemination Level	PU			
Date of Delivery	31.03.2022			
Lead Beneficiary	Seyed Shahabaldin Tohidi – DTU Davide Calì – DTU			
Contributors	Behrouz Eslami Mossallam - TNO			
Reviewers	Ruud van der Linden			
Status	Completed			
Document history	**V0**	Seyed Shahabaldin Tohidi – DTU Davide Calì – DTU Behrouz Eslami Mossallam - TNO	DTU / TNO	17-03-2022
	V1	Ruud van der Linden (review)	TNO	23-03-2022
	V2	Seyed Shahabaldin Tohidi, Davide Calì, Behrouz Eslami	DTU / TNO	28.03.2022

		Mossallam - TNO		
	V3	N. Gaitani (review)	NTNU	30.03.2022
	V4	Davide Calì	DTU	31.03.2022

3. Executive Summary

This report is a short-written description of deliverable 4.1, D4.1: the deliverable itself consists of the Grey-box models of the 4 demo sites in syn.ikia project.

Table of contents

syn.ikia

4. Roles and Responsibilities

Name	Role	Responsibility
DTU	Task 4.1 leader, coordinator of deliverable contents, contributor	Generating grey-box models of the four demo cases, evaluation of different models for each demo and correct model selection, coordinating the activities of the partners, design simulation scenarios for the white box models, so that the results from white box models can be used to fit the grey-box models.
TNO	Contributor	Generating specific simulation results from the white box models from the NL demo, generation of a digital twin, that can be used instead of a grey-box model in the NL case.
NTNU	Contributor	Generating specific simulation results from the white box models from the Norwegian demo
IREC	Contributor	Generating specific simulation results from the white box models from the Spanish demo
ABUD	Contributor	Generating specific simulation results from the white box models from the Austrian demo

5. Introduction

High quality models able to predict the future evolution of thermal dynamics, are required for the advanced model-based control implementation. In particular, these models should capture nonlinear behaviours of the thermal dynamics in the presence of process noise due to approximation errors or unmodelled inputs and measurement noise due to imperfect measurements.

The grey-box (GB) models, which consist of a set of stochastic differential equations (SDEs) that describe the dynamics of the system in continuous time and a set of discrete time measurement equations, allow incorporation of prior physical knowledge and utilization of statistical methods for parameter estimation. The physically meaningful parameters made these models a proper choice for control purposes.

Physical knowledge of buildings and the information embedded in the collected data from the buildings are two main requirements of establishing a grey-box model. The physical knowledge can be formulated by a set of first-order stochastic differential equations. Since the goal of finding a grey-box model is to design a controller, such as model predictive controller (MPC), it is meaningful to use the optimal simplified grey-box model which consists of a set of first-order linear stochastic differential equations.

In this mini-report, we describe briefly how we employed the generated data of white-box models for Spanish, Austrian, Norwegian and Dutch demos to estimate the parameters and find the best grey-box model for each demo. Statistical analyses were used to establish the model selection procedure (Bacher & Madsen, 2011) (Tohidi, Cali, Tamm, Ortiz, & Salom, 2022). A brief description of parameter estimation and model selection procedures are provided here:

Various electric circuits resembling the heat dynamics of buildings are considered and their dynamical equations are found. Then, a Kalman filter is applied to calculate the likelihood function, and an optimization problem is solved to maximize it. This can be done using the computer software CTSMR capable of calculating the maximum likelihood and estimating parameters of each model simultaneously (Juhl, Møller, & Madsen, 2016).

Once the parameters of each dynamical system were estimated, we proceeded with the selection of the best grey-box model per demo. To be mathematically rigorous, three statistical analyses were applied for model selection. These analyses are likelihood ratio test, Akaike's and Bayesian criteria. Likelihood ratio test finds the significant improvement between each two models with different number of parameters. Different from Likelihood ratio test, Akaike's and Bayesian criteria allocate a specific number to each model that simplifies the model selection decision making (Konishi & Kitagawa, 2008).

Simulation results demonstrate that the one-step ahead error of the selected model for each demo has white-nose-like properties which indicates that these are appropriate models to be used for the control purposes. Prediction capabilities of the selected models for each demo are illustrated using cross-validation.

6. Spanish demo Grey-Box

The best model, selected for one specific apartment of Spanish demo, is found to be the following two-state grey-box model:

$$
\begin{aligned}
C_i dT_i &= \left(\Phi_\mathrm{h} + A_w \Phi_s + \frac{T_e - T_i}{R_{ie}}\right) dt + \sigma_i d\omega_i \\
C_e dT_e &= \left(\frac{T_i - T_e}{R_{ie}} + \frac{T_a - T_e}{R_{ea}}\right) dt + \sigma_e d\omega_e \\
Y_k &= T_{i,k} + e_k,
\end{aligned}
$$

where T_i and T_e are the states, that represent the interior and environment temperatures, respectively, C_i and C_e are the thermal capacities of interior and envelope, respectively, and R_{ea} and R_{ie} are the thermal resistances between ambient and envelope, and envelope and interior. Also, T_a is the ambient temperature, Φ_h is the total heat input, Φ_s is the solar irradiance, A_w is the effective window area and Y_k is the measured interior temperature. To represent the stochastic behaviour of the heat dynamics, we introduce ω_i and ω_e as standard Wiener processes, where σ_i^2 and σ_e^2 are the incremental variances of the Wiener processes. The deterministic part of the model is physically meaningful and can be considered as the following RC circuit.

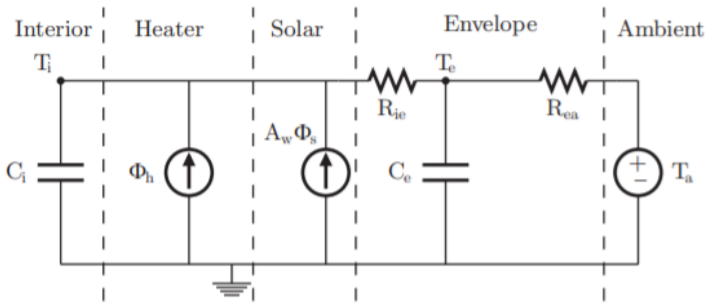


Figure 1. *RC circuit based on the deterministic thermal dynamics of Spanish demo.*

By comparing the measured and the modelled temperatures, Y_k and T_i, it is seen that the error, e_k, represents similar properties as the ones for white noise. Figure 2 demonstrates that the error is almost uncorrelated in time, its spectrum is uniformly spread across the frequencies, and the cumulative periodogram is close to the straight line. These are properties of a white noise (Ljung, 1998) (Madsen, 2007).

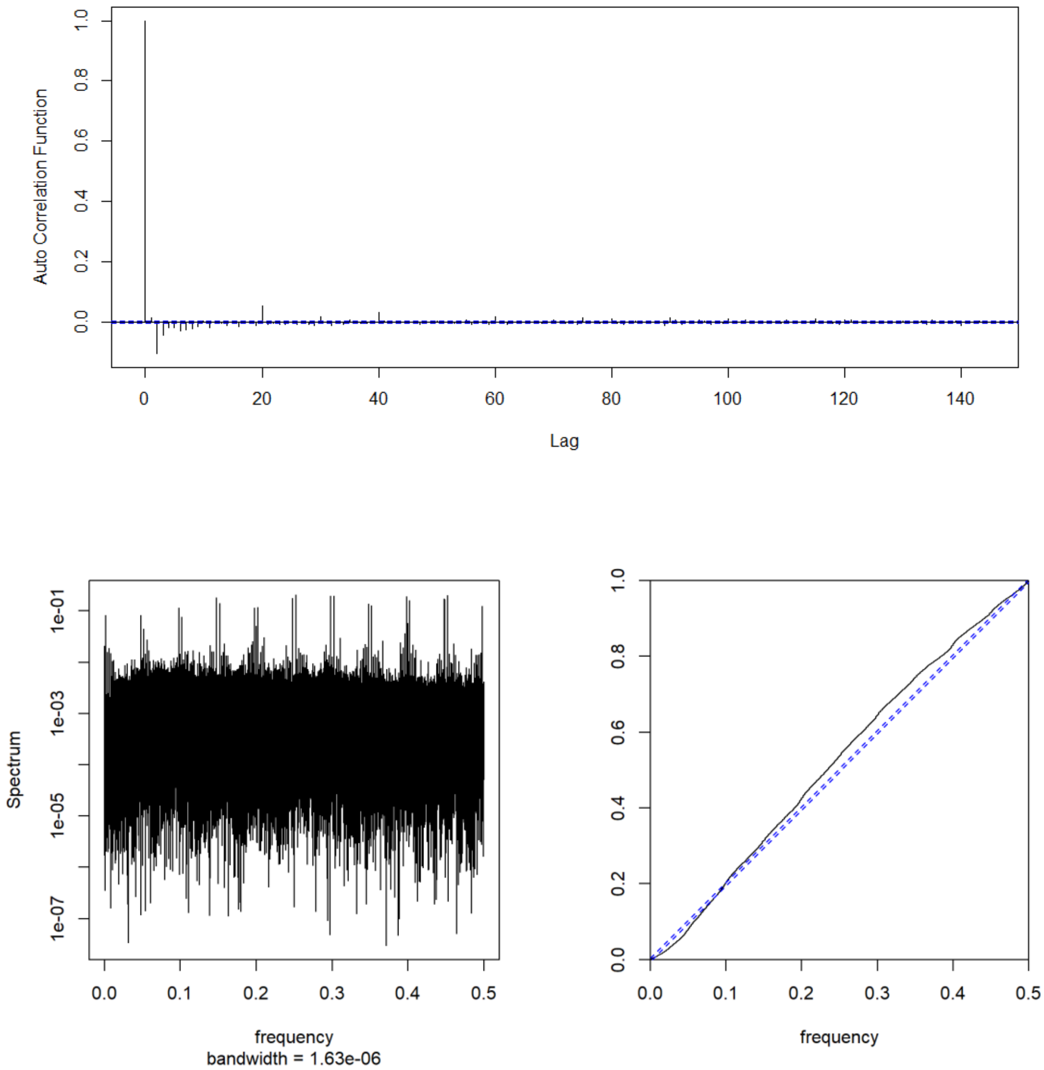


Figure 2. *Statistical properties of one-step-ahead error of the selected model.*

Figure 3 illustrates the 24-hours and 48-hours prediction capabilities of the selected model.

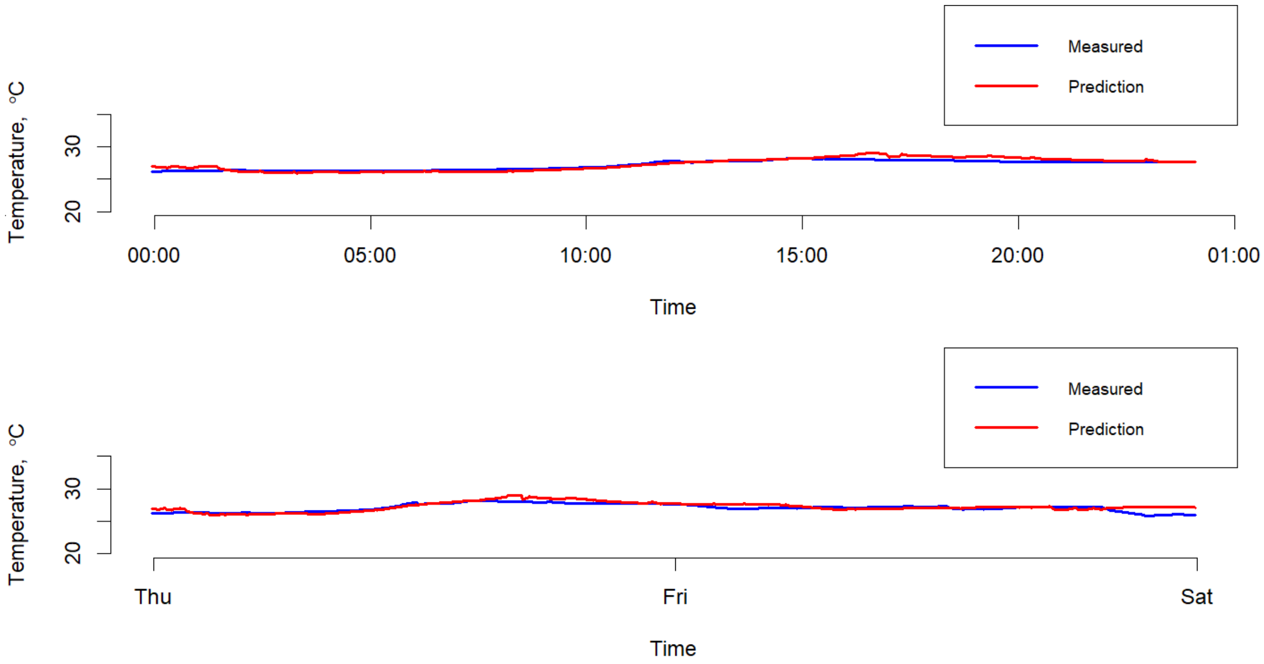


Figure 3. 24-hours (top) and 48-hours (bottom) ahead interior temperature prediction.

7. Austrian demo Grey-Box

The best model, selected for one specific apartment of Austrian demo, is found to be the following three-state grey-box model:

$$C_i dT_i = \left(-\frac{T_i - T_\mathrm{h}}{R_\mathrm{ih}} - \frac{T_i - T_e}{R_{ie}} + \frac{T_a - T_i}{R_{ia}} + A_w \Phi_s\right) \mathrm{dt} + \sigma_i d\omega_i$$

$$C_\mathrm{h} dT_h = \left(\frac{T_i - T_\mathrm{h}}{R_\mathrm{ih}} + \Phi_\mathrm{h}\right) \mathrm{dt} + \sigma_h d\omega_h$$

$$C_e dT_e = \left(\frac{T_i - T_e}{R_{ie}} + \frac{T_a - T_e}{R_{ea}}\right) \mathrm{dt} + \sigma_e d\omega_e$$

$$Y_k = T_{i,k} + e_k,$$

where T_i, T_h and T_e are the states of interior, heater and envelope temperatures, respectively. Also C_i, C_h and C_e are the thermal capacities of interior, heater and envelope, respectively. R_{ea}, R_{ie} and R_{ia} are the thermal resistances between ambient and envelope, envelope and interior, and ambient and interior, respectively, and R_{ih} is the heater resistance. Also, T_a is the ambient temperature, Φ_h is the total heat input, Φ_s is the solar irradiance, A_w is the effective window area and Y_k is the measured interior temperature. To represent the stochastic behaviour of the heat dynamics, we introduce ω_i, ω_h and ω_e as standard Wiener processes, where σ_i^2, σ_h^2 and σ_e^2 are the incremental variances of the Wiener processes. The deterministic part of the model is physically meaningful and can be considered as the following RC circuit.

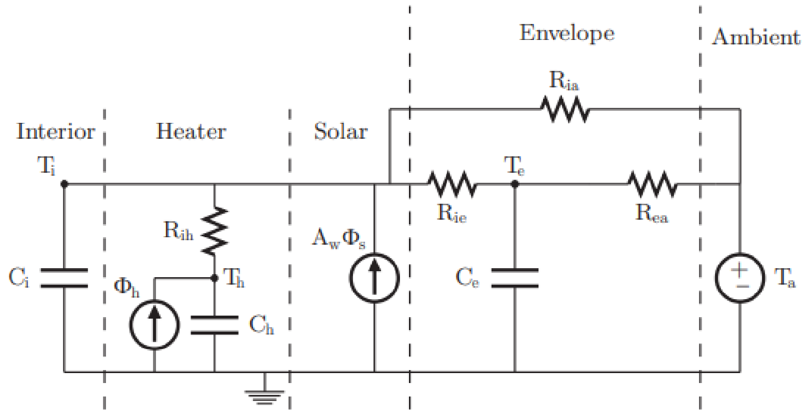


Figure 4. *RC circuit based on the deterministic thermal dynamics of Spanish demo.*

By comparing the measured and the modelled temperatures, Y_k and T_i, it is seen that the error, e_k, represents similar properties as the ones for white noise. Figure 5 demonstrates that the error is almost uncorrelated in time, its spectrum is uniformly spread across the frequencies, and the cumulative periodogram is close to the straight line. These are properties of a white noise (Ljung, 1998) (Madsen, 2007).

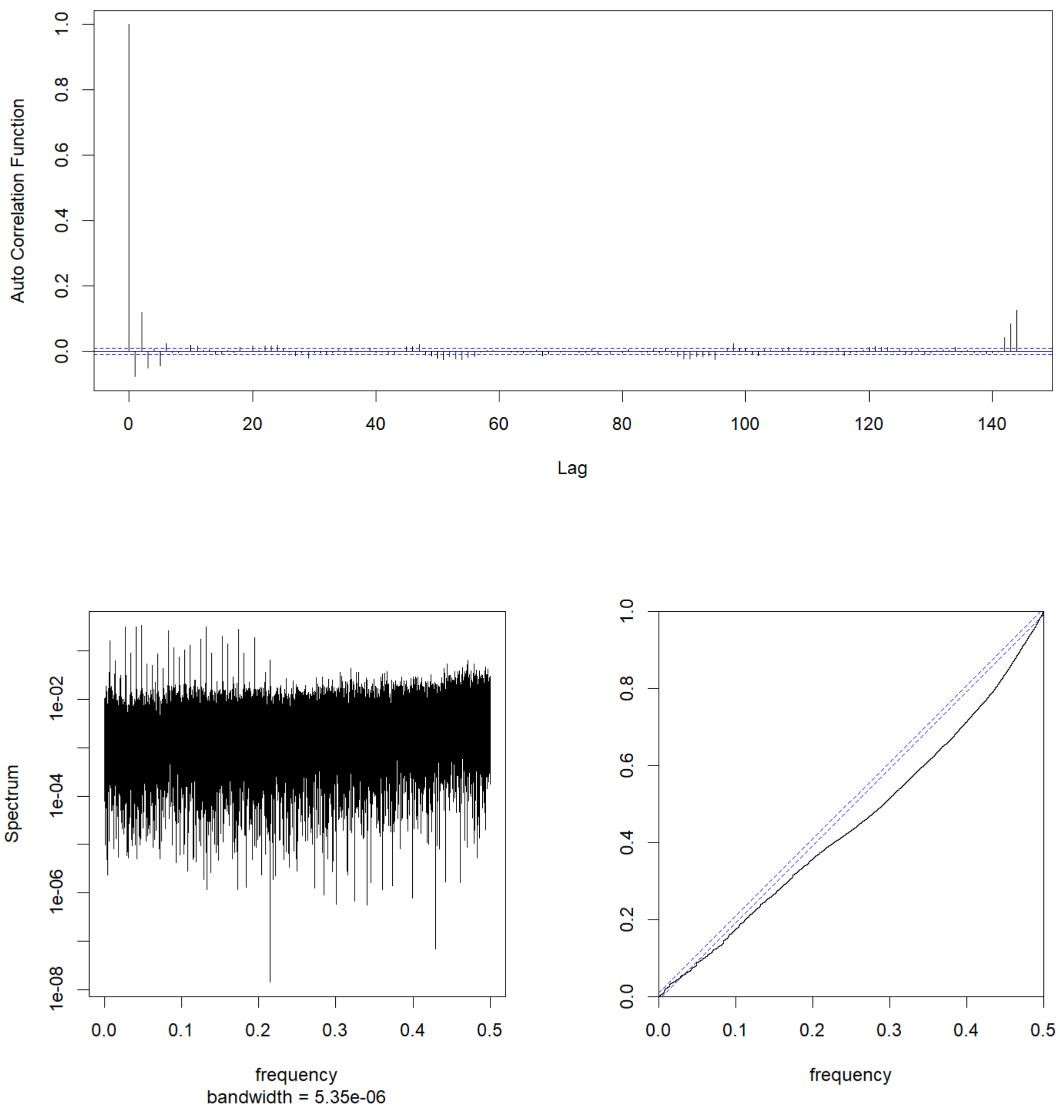


Figure 5. Statistical properties of one-step-ahead error of the selected model.

Figure 6 illustrates the 24-hours and 48-hours prediction capabilities of the selected model.

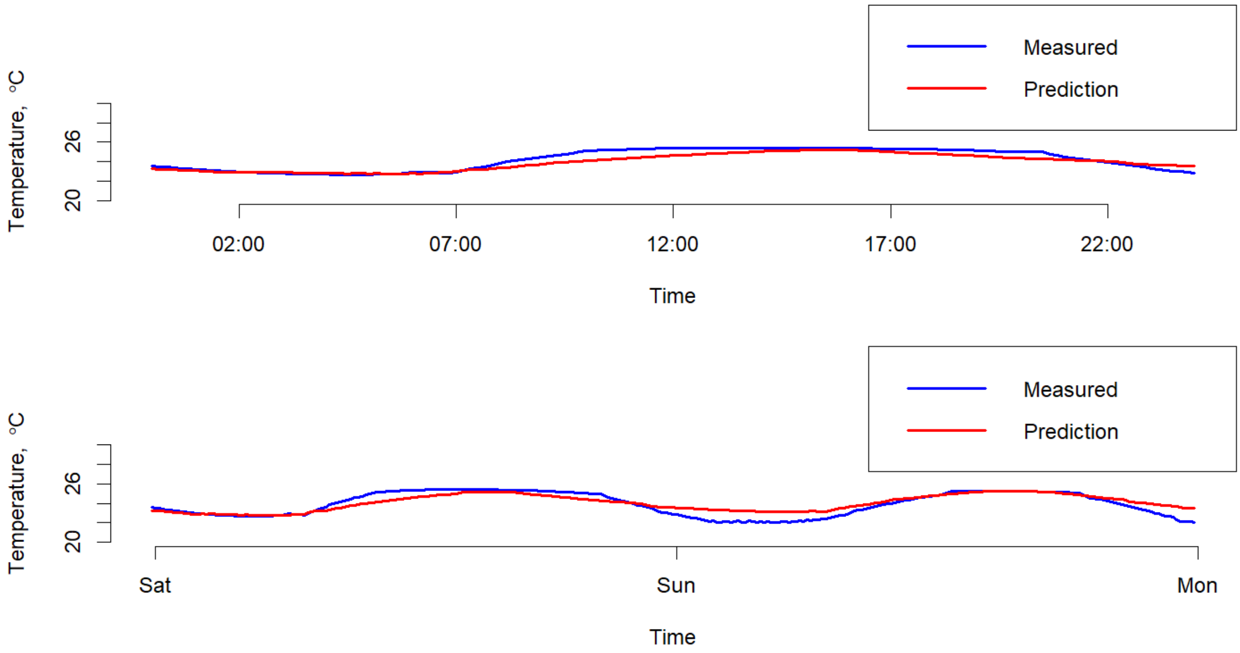


Figure 6. 24-hours (top) and 48-hours (bottom) ahead interior temperature prediction.

8. Norwegian demo Grey-Box

The best model, selected for one specific apartment of Norwegian demo, is found to be the following three-state grey-box model:

$$C_i dT_i = \left(\frac{-T_i + T_\mathrm{h}}{R_\mathrm{ih}} + \frac{-T_i + T_e}{R_{ie}} + A_w \Phi_s\right) dt + \sigma_i d\omega_i$$
$$C_\mathrm{h} dT_h = \left(\frac{T_i - T_\mathrm{h}}{R_\mathrm{ih}} + \Phi_\mathrm{h}\right) dt + \sigma_h d\omega_h$$
$$C_e dT_e = \left(\frac{T_i - T_e}{R_{ie}} + \frac{T_a - T_e}{R_{ea}}\right) dt + \sigma_e d\omega_e$$
$$Y_k = T_{i,k} + e_k,$$

where T_i, T_h and T_e are the states, that represent the interior, heater and envelope temperatures, respectively, C_i, C_h and C_e are the thermal capacities of interior, heater and envelope, respectively, and R_{ea} and R_{ie} are the thermal resistances between ambient and envelope, and envelope and interior. Also, R_{ih} is the heater thermal resistance, and T_a is the ambient temperature, Φ_h is the total heat input, Φ_s is the solar irradiance, A_w is the effective window area and Y_k is the measured interior temperature. To represent the stochastic behaviour of the heat dynamics, we introduce ω_i, ω_h and ω_e as standard Wiener processes, where σ_i^2, σ_h^2 and σ_e^2 are the incremental variances of the Wiener processes. The deterministic part of the model is physically meaningful and can be considered as the following RC circuit.

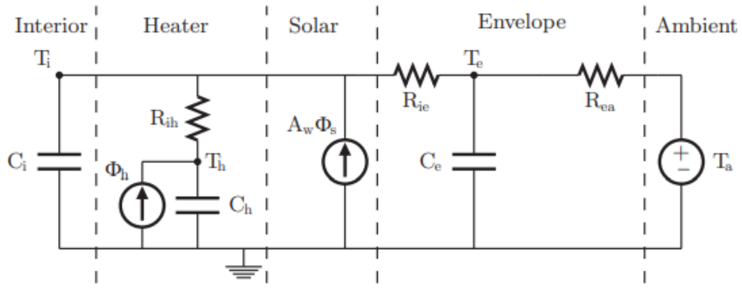


Figure 7. *RC circuit based on the deterministic thermal dynamics of Spanish demo.*

By comparing the measured and the modelled temperatures, Y_k and T_i, it is seen that the error, e_k, represents similar properties as the ones for white noise. Figure 8 demonstrates that the error is almost uncorrelated in time, its spectrum is uniformly spread across the frequencies, and the cumulative periodogram is close to the straight line. These are properties of a white noise (Ljung, 1998) (Madsen, 2007).

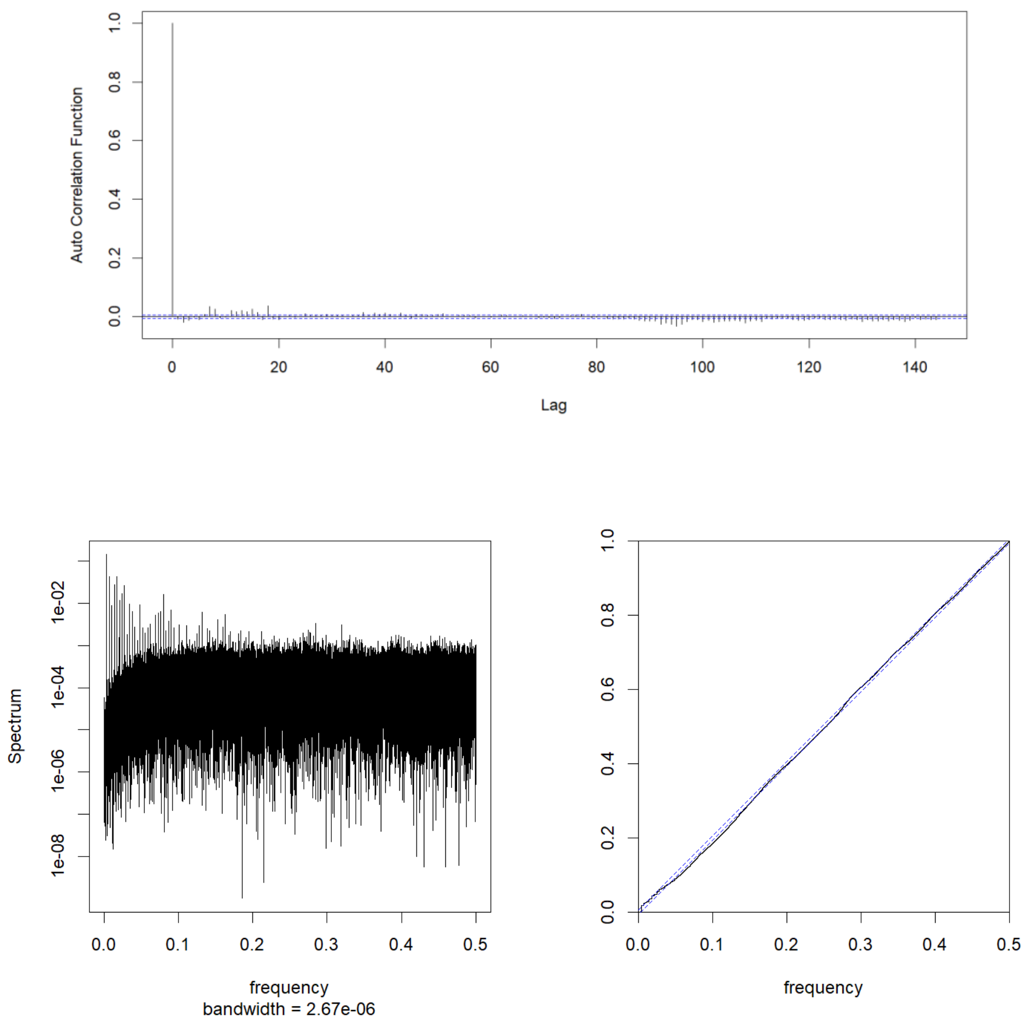
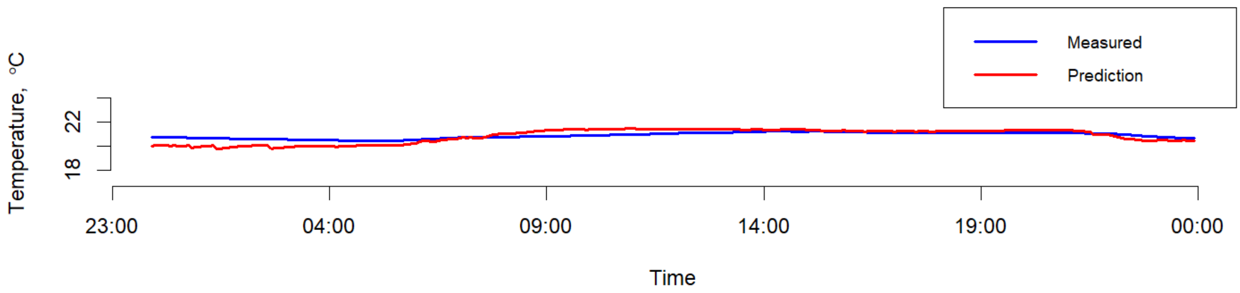


Figure 8. Statistical properties of one-step-ahead error of the selected model.

Figure 9 illustrates the 24-hours and 48-hours prediction capabilities of the selected model.



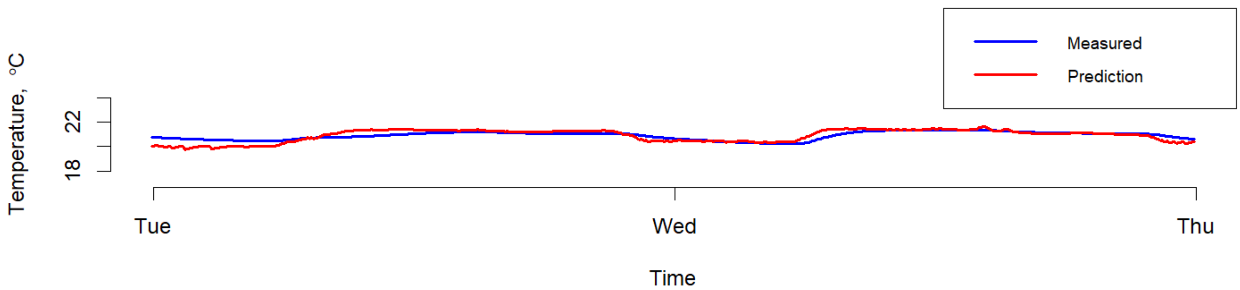


Figure 9. 24-hours (top) and 48-hours (bottom) ahead interior temperature prediction.

9. Dutch demo Grey-Box

The best model, selected for one specific apartment of Dutch demo, is found to be the following two-state grey-box model:

$$
\begin{aligned}
C_i dT_i &= \left(\frac{-T_i + T_\mathrm{h}}{R_\mathrm{ih}} + \frac{-T_i + T_a}{R_{ia}} + A_{w,W}\Phi_{s,W} + A_{w,E}\Phi_{s,E}\right) dt + \sigma_i d\omega_i \\
C_\mathrm{h} dT_h &= \left(\frac{T_i - T_\mathrm{h}}{R_\mathrm{ih}} + \Phi_\mathrm{h}\right) dt + \sigma_h d\omega_h \\
Y_k &= T_{i,k} + e_k,
\end{aligned}
$$

where T_i and T_h are the states, that represent the interior and the heater temperatures, respectively, C_i and C_h are the thermal capacities of interior and heater, and R_{ia} and R_{ih} are the envelope and the heater temperatures. Also, R_{ih} is the heater resistance, and T_a is the ambient temperature, Φ_h is the total heat input, $\Phi_{s,W}$ and $\Phi_{s,E}$ are the solar irradiances from West and East, $A_{w,W}$ and $A_{w,E}$ are the west and east sides effective window areas and Y_k is the measured interior temperature. It is noted that the Dutch demo uses both heating and cooling, therefore positive and negative values of Φ_h are related to the heating and cooling processes, respectively. To represent the stochastic behaviour of the heat dynamics, we introduce ω_i, ω_h and ω_e as standard Wiener processes, where σ_i^2, σ_h^2 and σ_e^2 are the incremental variances of the Wiener processes. The deterministic part of the model is physically meaningful and can be considered as the following RC circuit.

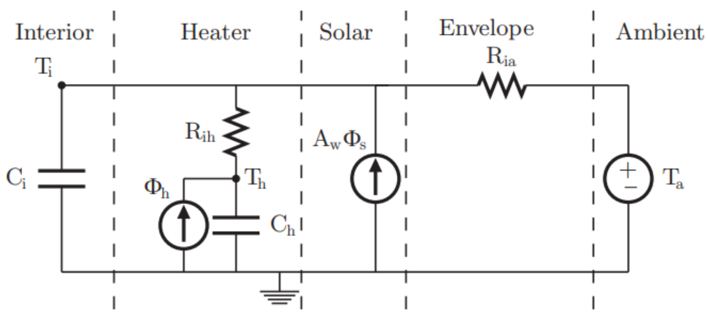


Figure 10. *RC circuit based on the deterministic thermal dynamics of Spanish demo.*

By comparing the measured and the modelled temperatures, Y_k and T_i, it is seen that the error, e_k, represents similar properties as the ones for white noise. Figure 11 demonstrates that the error is almost uncorrelated in time, its spectrum is uniformly spread across the frequencies, and the cumulative periodogram is close to the straight line. These are properties of a white noise (Ljung, 1998) (Madsen, 2007).

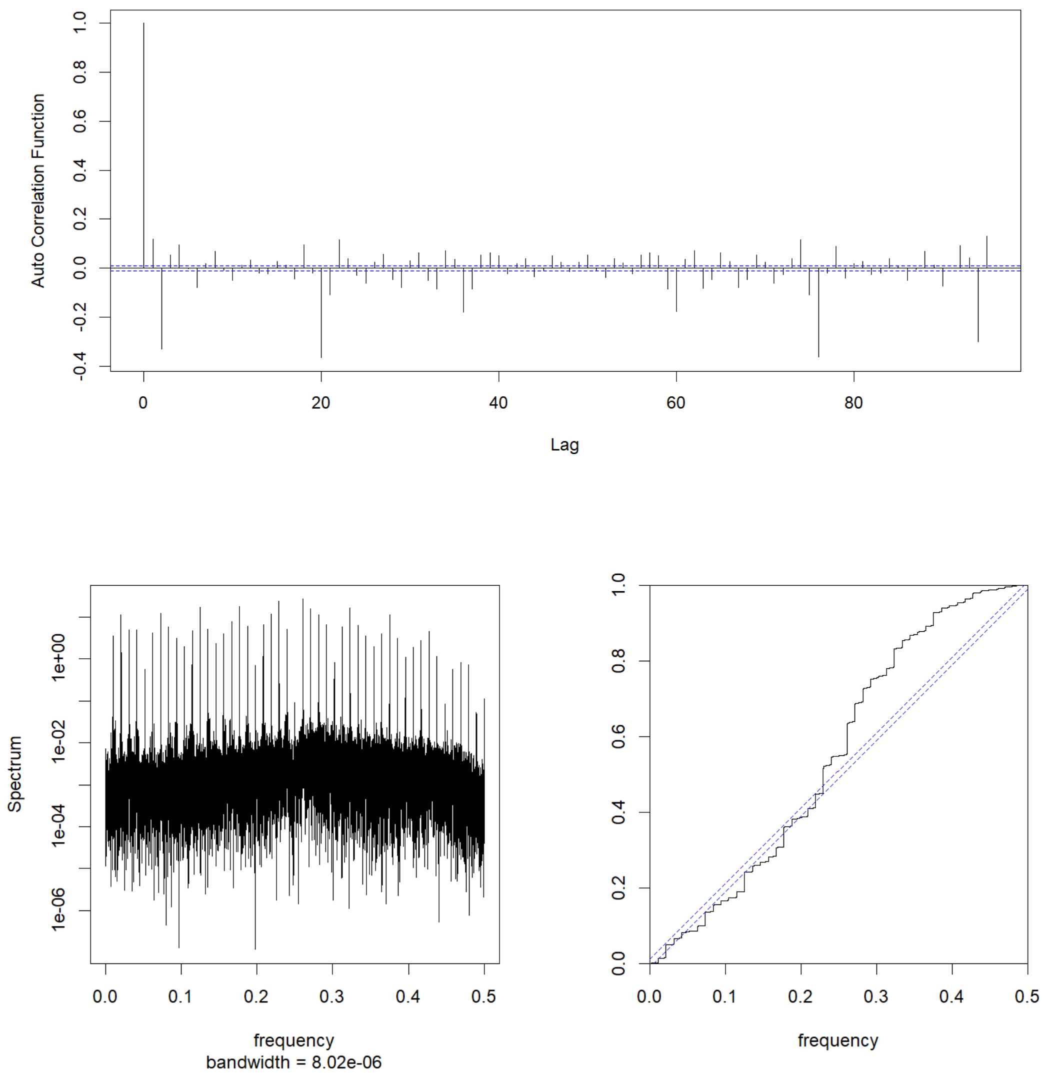


Figure 11. Statistical properties of one-step-ahead error of the selected model.

Figure 12 illustrates the 24-hours and 48-hours prediction capabilities of the selected model.

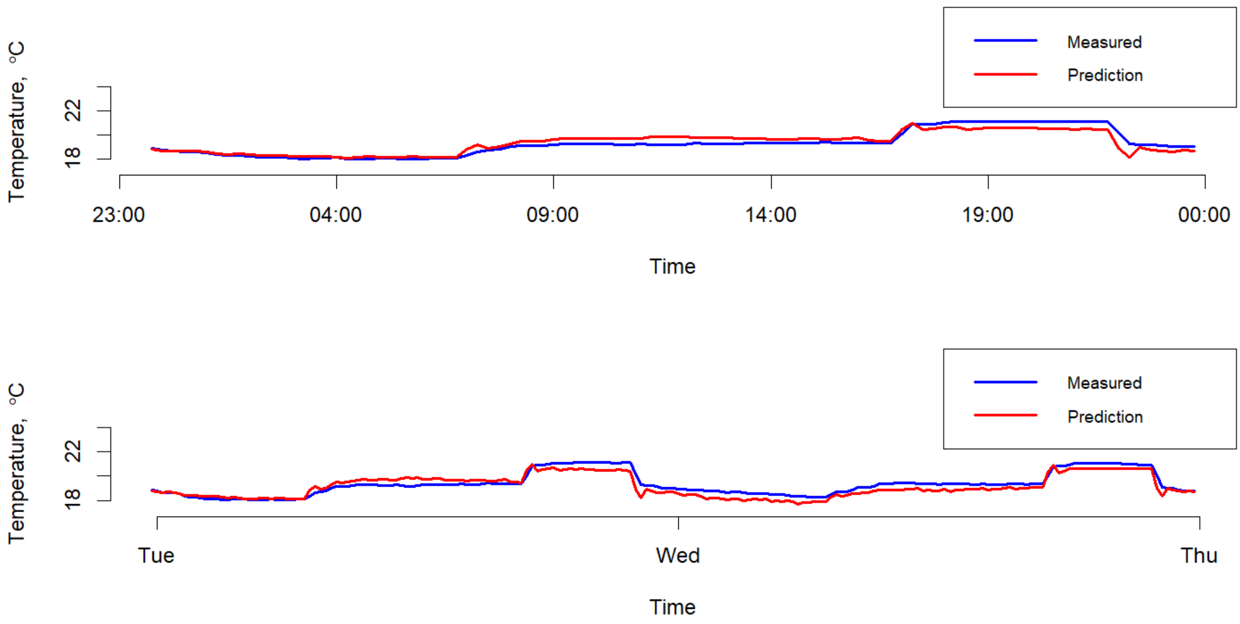


Figure 12. 24-hours (top) and 48-hours (bottom) ahead interior temperature prediction.

10. Dutch demo simplified White-Box

The Dutch demo is modelled in SirinE, a hybrid predictive digital twin for buildings. SirinE consists of a physical building model which solves the heat flow balance equations, and a data-driven occupant model which models the interaction of the occupants with the building components (e.g., thermostats, windows, electric appliances, etc.) and includes the effect of occupants' actions in the heat flow balance equations.

A multizone model for the Dutch Demo is constructed, where each room is considered a thermal zone. Each zone z_i is represented by a temperature node T_{zi} in the heat network. Each physical layer of boundary surfaces (i.e., walls, floor, ceiling and roofs) constitutes a temperature node in the heat network. For kth layer of the jth boundary surface $S_{j,k}$ ($k = 1$ corresponds to the innermost layer, $k = n$ to the outermost one), a temperature node $T_{Sj,k}$ is added to the heat network. In addition, all boundaries (outdoor environment, ground etc.) are represented by a temperature node. The heat flow balance equations can be summarized as follows:

- For the zone z_i:

$$C_{zi}\frac{\partial}{\partial t}T_{zi} = \sum_{S_j \in z_i} A_j h_{\mathrm{int}}^{\mathrm{surf}}(T_{Sj,n} - T_{zi}) + Q_{zi,vent} + Q_{zi,int} + Q_{zi,sol} + Q_{zi,heat/cool}$$

- For the innermost surface layer $S_{j,1}$ of the boundary surface S_j which is in direct contact with the zone z_i:

$$C_{Sj,1}\frac{\partial}{\partial t}T_{Sj,1} = A_j h_{\mathrm{int}}^{\mathrm{surf}}(T_{zi} - T_{Sj,1}) + A_j h_{2,1}^{(j)}(T_{Sj,2} - T_{Sj,1})$$

- For the internal layers of the surface S_j

$$C_{Sj,k}\frac{\partial}{\partial t}T_{Sj,k} = A_j h_{k,k-1}^{(j)}\left(T_{Sj,k-1} - T_{Sj,k}\right) + A_j h_{k+1,k}^{(j)}\left(T_{Sj,k+1} - T_{Sj,k}\right)$$

- For the outermost surface layer $S_{j,n}$ in contact with the outside environment:

$$\begin{aligned}C_{Sj,n}\frac{\partial}{\partial t}T_{Sj,n} = {} & A_j h_{n,n-1}^{(j)}\left(T_{Sj,n-1} - T_{Sj,n}\right) + A_j h_{\text{ext-conv}}^{\text{surf}}\left(T_{out} - T_{Sj,n}\right) \\ & + A_j h_{\text{ext-rad}}^{\text{surf}}\left(T_{out} - T_{Sj,n}\right) \\ & + A_j F_{sky_j} h_{\text{ext-rad}}^{\text{surf}}\left(T_{Sky} - T_{out}\right) + Q_{Sj,sol}\end{aligned}$$

The parameters in the above equations are defined as:

- C_{zi}: thermal mass of zone z_i.
- $C_{Sj,\text{k}}$: thermal mass of surface layer $S_{j,k}$ of the boundary surface S_j.
- A_j: the area of the boundary surface S_j.
- $h_{\text{int}}^{\text{surf}}$: the internal surface heat transmission coefficient, including both the convective and radiative transmissions.
- $h_{\text{ext-conv}}^{\text{surf}}$: the external convective surface heat transmission coefficient.
- $h_{\text{ext-rad}}^{\text{surf}}$: the external radiative surface heat transmission coefficient.
- $h_{k+1,k}^{(j)}$: conductive heat transmission coefficient between the kth and $(k+1)$th layers of the boundary surface S_j.
- T_{out}: outdoor temperature.
- T_{Sky}: apparent sky temperature.
- F_{sky_j}: view factor to the sky for the boundary surface S_j.
- $Q_{zi,vent}$: ventilation heat flow for the zone z_i. In SirinE this is calculated by solving the steady-state airflow balance equations.
- $Q_{zi,int}$: internal heat flow for the zone z_i due to occupants and house appliances.
- $Q_{zi,sol}$: solar heat flow for the zone z_i via the windows.
- $Q_{Sj,sol}$: absorbed solar power by the external boundary surface S_j.
- $Q_{zi,heat/cool}$: heating or cooling flow delivered to zone z_i via the floor heating system. In SirinE this is calculated by modelling a plant loop system, which includes a heat pump, a source-side pump, a load-side pump and a ground heat exchanger and solving the steady-state flow and heat flow balance equations.

In addition to the building model, a combined tank and heat pump model is used to simulate the production of the domestic hot water (DHW). The model solves the heat flow balance equations between the layers of hot water inside the tank taking into account the heat stratification in the water volume.

The simulation is performed using a heat pump control comparable to the real installation control (which uses an on-off controlled heat pump for both heating the building as for heating of domestic water)

Figures 13 and 14 show the simulated temperature profiles as well as the electric power consumption by the heat pump during a whole year for the Dutch demo.

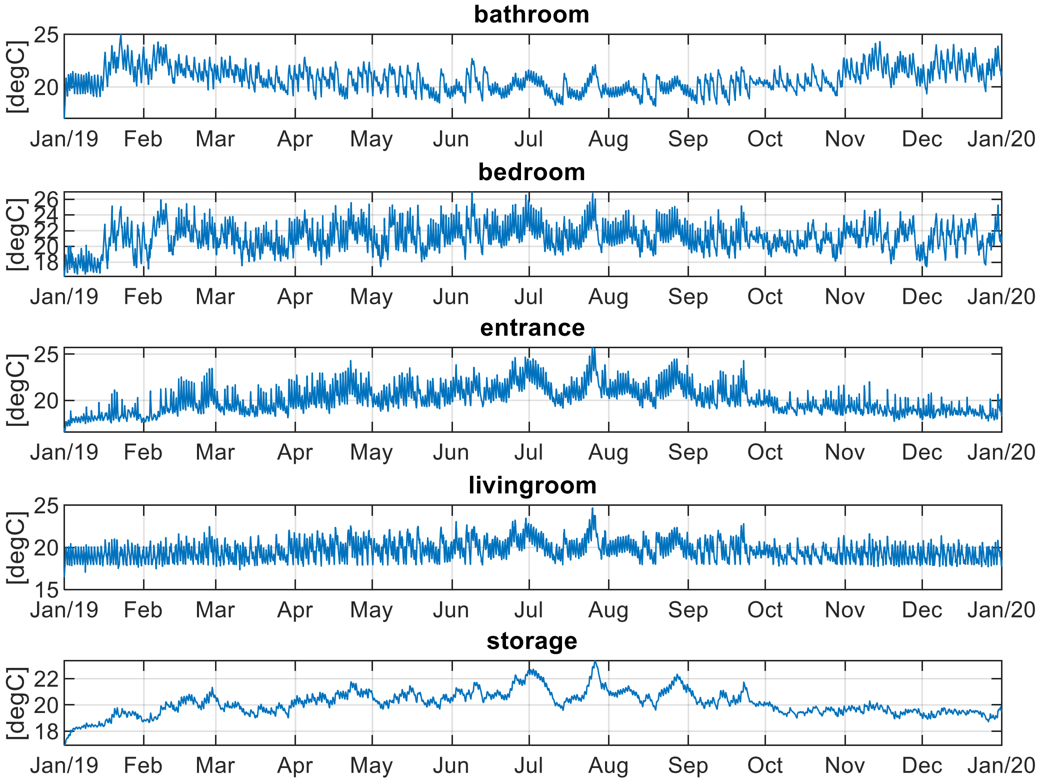


Figure 13: Simulated temperature profiles during a whole year for all rooms in the Dutch demo.

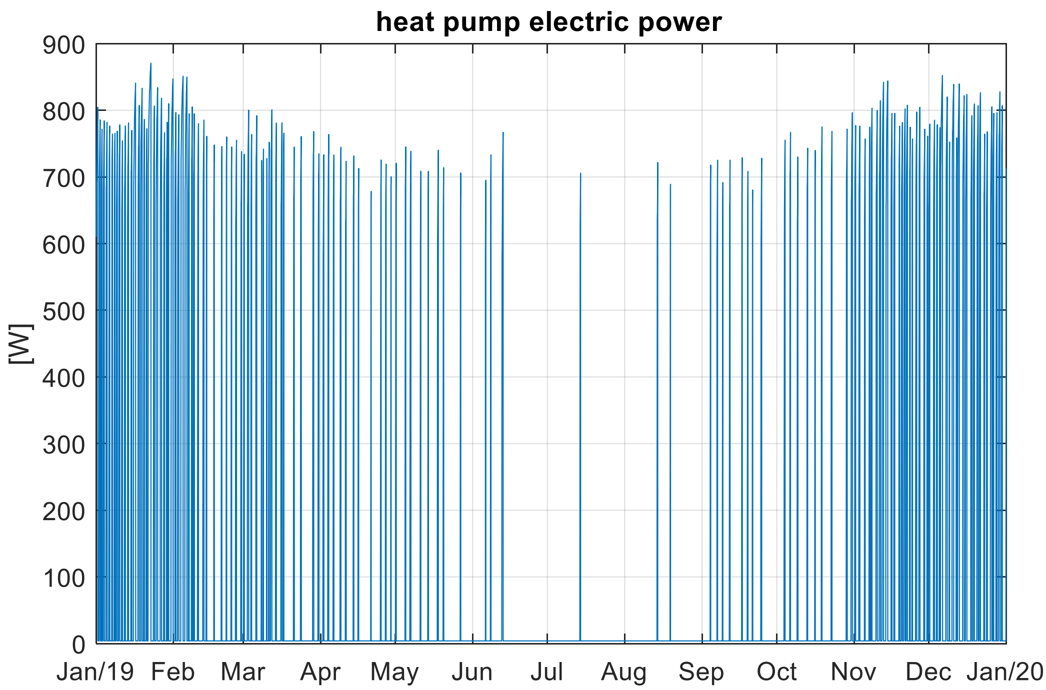


Figure 14: Simulated electric power consumption by the heat pump during a whole year for the Dutch demo.

11. Outlook

This report provides a brief discussion and simulation results of the grey-box models estimated for Spanish, Austrian, Norwegian and Dutch demos. To find the best model capable of representing the thermal dynamics of each demo, data generated by white-box modes has been used. The selected grey-box model can then be utilized for the model predictive control design purposes of task 4.5. In the task 4.2 the grey-box models will be finetuned according to different occupant behaviours.

In addition to the grey-box models, a simplified white-box model for the Dutch demo has also been presented. Compared to the grey-box model, a (simplified) white-box model requires a deeper knowledge of the buildings' structure and geometry: In white-box models, most parameters are estimated based on previous knowledge, not based on measurements and telemetry data from buildings.

Both white-box and grey-box models can be used for control purposes, e.g., in a model predictive control approach, as a stand-alone, or even be combined: grey-box models are typically much faster than white-box models due to their smaller dimension. White-box models, on the other hand, are more accurate.

12. References

Bacher, P., & Madsen, H. (2011). Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings*, 1511--1522.

Juhl, R., Møller, J. K., & Madsen, H. (2016). CTSMR-Continuous time stochastic modeling in R. *arXiv preprint arXiv:1606.00242*.

Konishi, S., & Kitagawa, G. (2008). *Information criteria and statistical modeling.* Springer.

Ljung, L. (1998). *System identification.* Boston, MA: Birkhäuser.

Madsen, H. (2007). *Time series analysis.* Chapman and Hall/CRC.

Tohidi, S. S., Cali, D., Tamm, M., Ortiz, J., & Salom, J. (2022). From white-box to grey-box modelling of the heat dynamics of buildings. *BuildSim Nordic.* Copenhagen: accepted for publication.

13. Appendix A – Glossary of Terms:

GB: grey-box

MPC: model predictive controller

SDE: stochastic differential equations

“This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 869918”.

NTNU
Norwegian University of Science and Technology

DTU
Technical University of Denmark

BPIE

SINTEF

HOUSING EUROPE

IREC
Shaping Energy for a Sustainable Future

OBOS

area

INCASÒL
Institut Català del Sòl

TNO innovation for life

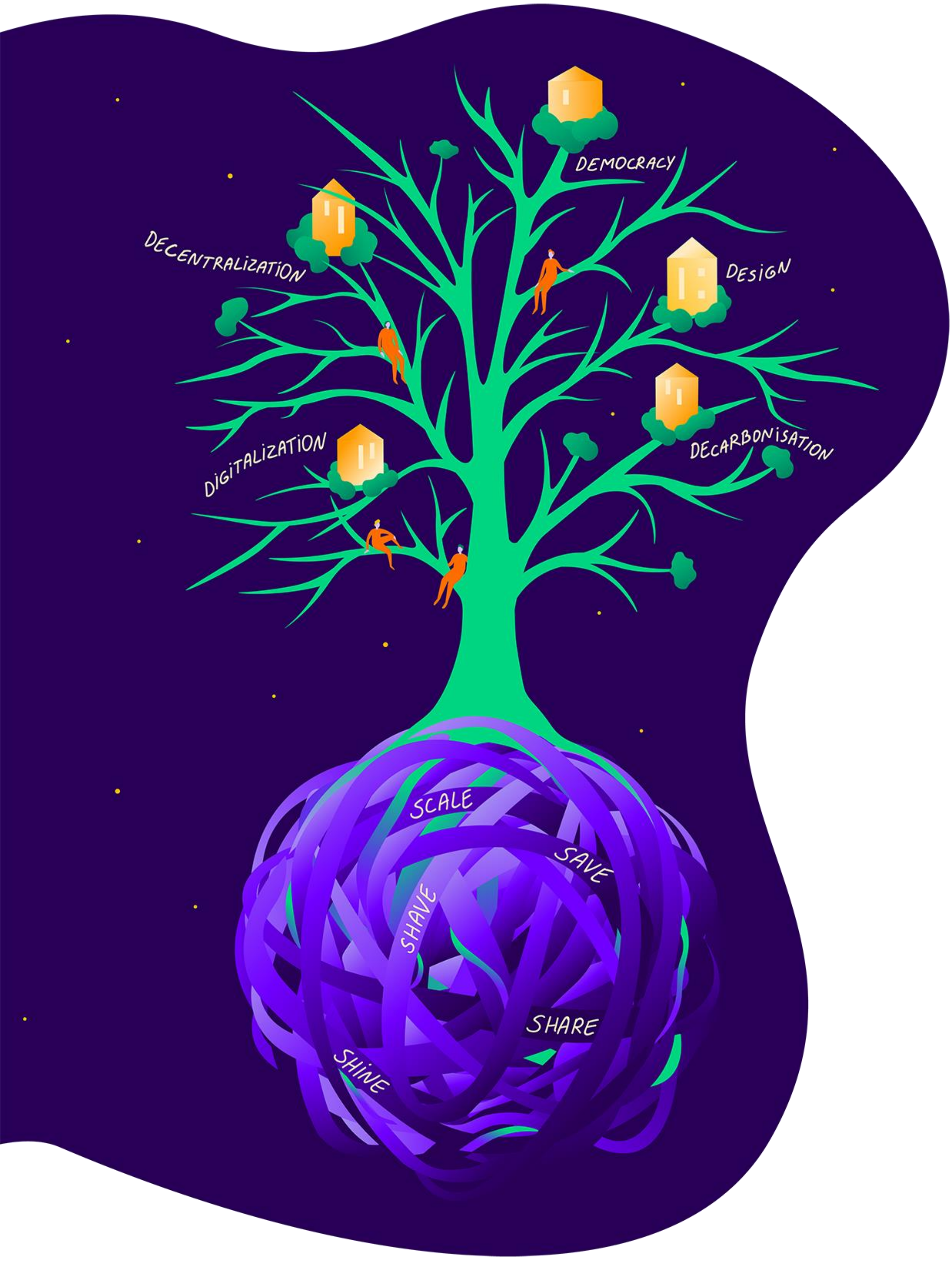
ENFOR

ABUD
Advanced Building & Urban Design

HEIMAT ÖSTERREICH

SIR
SALZBURGER INSTITUT FÜR RAUMORDNUNG & WOHNEN

ECA
ENERGY CONSULTING AUSTRIA


DEMOCRACY
DECENTRALIZATION
DESIGN
DIGITALIZATION
DECARBONISATION
SCALE
SAVE
SHAVE
SHARE
SHINE

syn.ikia