

The mapping of climate-dependent simplified thermal systems using state-space models

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The Mapping of Climate-Dependent Simplified Thermal Systems using State Space Models

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1. ABSTRACT

Performances of thermal systems are most of the time dependent on the external climate conditions. This means a high performance of a specific innovation in a certain part of Europe, does not imply the same performances in other regions. The mapping of simulated building performances at the EU scale could prevent the waste of potential good ideas by identifying the best region for a specific system. This paper presents a methodology for obtaining maps of performances of simplified thermal systems that are virtually spread over whole Europe using state space models. It is concluded that these maps are useful for finding regions at the EU where systems have the highest expected performances.

Keywords: mapping, modeling, building, performance, state space

2. INTRODUCTION

Due to energy efficiency, there exist a lot of studies on thermal buildings systems. The performances of these systems for example, plate & tube collectors, air heat collectors, PV panels, etc., are mostly dependent on the external climate conditions. This also means that a high performance of a specific system in a certain part of Europe, does not imply the same performances in other regions. Similar, systems that did not perform very well due to local climate conditions, and therefore not commercialised, could still perform quite well in other climates. The latter can be seen as ‘wasted’ innovations. The mapping of simulated building systems performances at the EU scale could prevent this wasting of potential good ideas by identifying the best region for a specific system. This paper presents a methodology for obtaining maps of performances of thermal building systems that are virtually spread over whole Europe using state space models. This work presents a new and important step towards mapping of building systems performances and is based on two recent publications of van Schijndel and Schellen (2013) and Kramer et al. (2012). These two publications are summarized below as background information. A comprehensive literature study with references is already presented in both mentioned publications and therefore marginally included in this paper.

2.1 Related work on maps by Schijndel and Schellen (2013)

Due to the climate change debate, a lot of research and maps of external climate parameters are available. However, maps of indoor climate performance parameters are still lacking. Van Schijndel and Schellen (2013) present a methodology for obtaining maps of performances of similar buildings that are virtually spread over whole Europe. The produced maps are useful for analyzing regional climate influence on building performance indicators such as energy use and indoor climate. This is shown using the Bestest building as a reference benchmark.

An important application of the mapping tool is the visualization of potential building measures over the EU. Also the performances of single building components can be simulated and mapped. It is concluded that the presented method is efficient as it takes less than 15 minutes to simulate and produce the maps on a 2.6GHz/4GB computer. Moreover, the approach is applicable for any type of building.

2.2 Related work on state space modeling by Kramer et al. (2012)

Kramer et al. (2012) provide a systematic literature review on simplified building models. Questions are answered like: what kind of modeling approaches are applied? What are their (dis)advantages? What are important modeling aspects? The review showed that simplified building models can be classified into neural network models (black-box), linear parametric models (black box or grey-box) and lumped capacitance models (white box). Research has mainly dealt with network topology, but more research is needed on the influence of input parameters. The review showed that particularly the modeling of the influence of sun irradiation and thermal capacitance is not performed consistently amongst researchers. Furthermore, a model with physical meaning, dealing with both temperature and relative humidity, is still lacking. Inverse modeling has been widely applied to determine models parameters. Different optimization algorithms have been used, but mainly the conventional Gaus-Newton and the newer Genetic Algorithms. However, the combination of algorithms to combine their strengths has not been researched. Despite all the attention for state of the art building performance simulation tools, simplified building models should not be forgotten since they have many useful applications.

2.3 Goal and Outline

The goal of this work is to present a methodology for producing performance maps of external climate related building systems by combining the above mentioned publications on mapping and state space modeling. Section 3 presents the mentioned methodology to produce maps of simplified thermal systems using state-space models based on a commercial case study. In Section 4, the conclusions and future research are provided.

3. CREATING MAPS OF SYSTEMS INNOVATIONS USING STATE-SPACE (SS)

A commercial case study is presented in this Section. Due to the patent protection of the industrial partner, some specific information is omitted without loss of generality. The innovation consists of a novel heat exchanger built inside a construction acting as a solar collector. Figure 1 shows the principle construction of the solar collector (in reality this is much more complicated). The solar collector will be used for the heating of water that directly can be used or stored for later use. Due to insulation, the heat exchange with the internal environment is negligible.

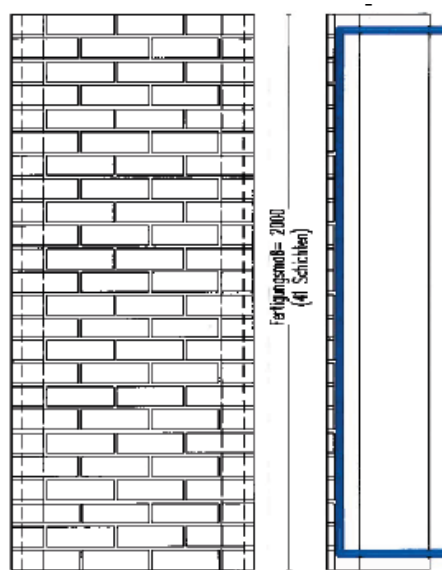


Figure 1 Construction of the solar collector

3.1 Modeling

A 3-State (3S) model was developed:

$$C_1 \frac{dT_1}{dt} = h A (T_{amb}(t) - T_1) - \frac{(T_1 - T_2)}{R_1} + a_1 A I(t) \quad (1)$$

$$C_2 \frac{dT_2}{dt} = \dot{m} c (T_{sup}(t) - T_2) + \frac{(T_1 - T_2)}{R_1} - \frac{(T_2 - T_3)}{R_2} \quad (2)$$

$$C_3 \frac{dT_3}{dt} = \frac{(T_2 - T_3)}{R_2} \quad (3)$$

Where

$T_{amb}(t)$ ambient (external) air temperature [$^{\circ}\text{C}$]

$T_{sup}(t)$ water supply temperature [$^{\circ}\text{C}$]

$I(t)$ external solar irradiance [W/m^2]

T_1 external surface temperature [$^{\circ}\text{C}$]

T_2 water return temperature [$^{\circ}\text{C}$]

T_3 internal wall temperature [$^{\circ}\text{C}$]

Parameters:

\dot{m} water mass flow [kg/s]

c	heat capacity of water [J/kgK]
a_1	solar absorption factor [-]
h	heat transfer surface coefficient [W/m ² C]
A	surface [m ²]
d1	distance pipe to surface [m]
d2	distance pipe to insulation [m]
k	heat conductivity of concrete [W/mK]
R_1	heat resistance [K/W] = $d_1/(kA)$
R_2	heat resistance [K/W] = $d_2/(kA)$
C_i	heat capacity [J/K]

The model was implemented using standard state-space modeling facilities of MatLab HAMLab (2014). The next Section shows the simulation and validations results.

3.2 Validation

Laboratory experiments were used to validate the models. We refer to the appendix for the details on the testing conditions. All experiments were simulated using the proper parameters and boundary conditions. The results were compared in order to evaluate the predictability of the model. In Figure 2 the results for a typical experiment A is shown.

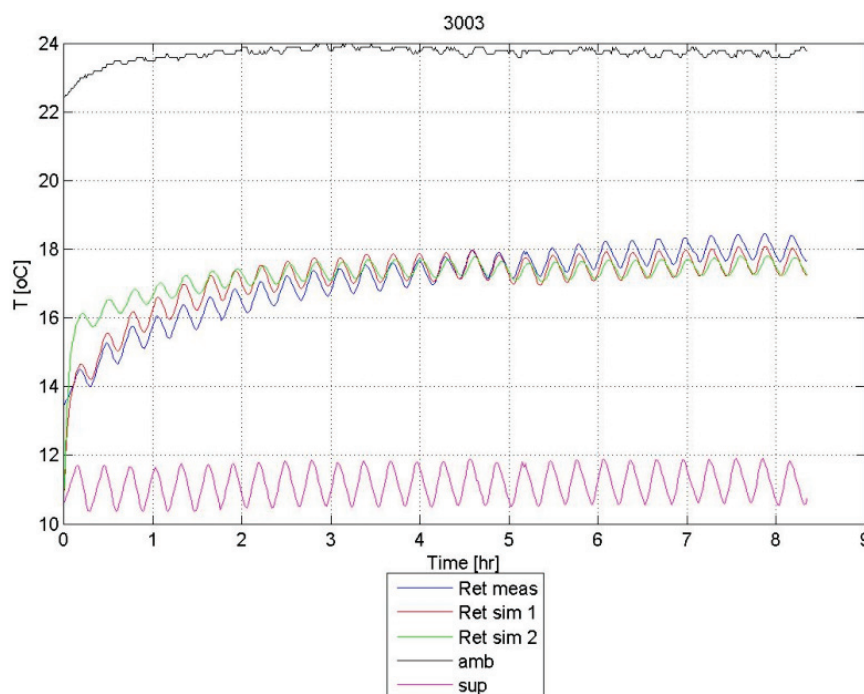


Figure 2. The simulation of experiment A: Temperatures vs time of the measured supply water(sup), the measured ambient air (amb), the simulated return water (Ret sim 1 & 2) and the measured return water (Ret).

From Figure 2 we observed that the predictability of model was satisfactory. All other tested configurations provided similar good results. Therefore we conclude that the model is quite usable for further use.

3.3 Simulation using a typical Dutch climate

The model configuration A was simulated using a reference standard Dutch climate of deBilt. Figure 3 presents the result.

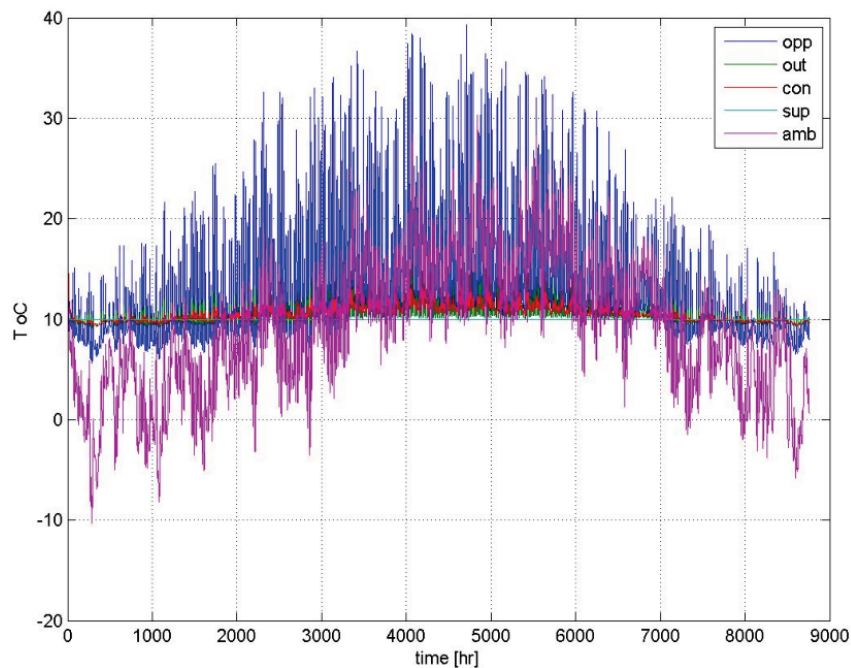


Figure 3. Simulation of model configuration A using a reference standard Dutch climate of deBilt. Temperatures versus time of the external wall surface (opp), the water return (out), the mid wall (con), the water supply (sup) and ambient air (amb).

The water supply temperature was constant held at 10 °C. The other two input signals: Ambient air temperature and solar irradiation were taken from the climate file. The main output signal is the return temperature (out). With this signal the output power can be calculated. This is shown in the next Section.

3.4 Performance evaluation

Figure 4 shows details of the model A configuration performance results.

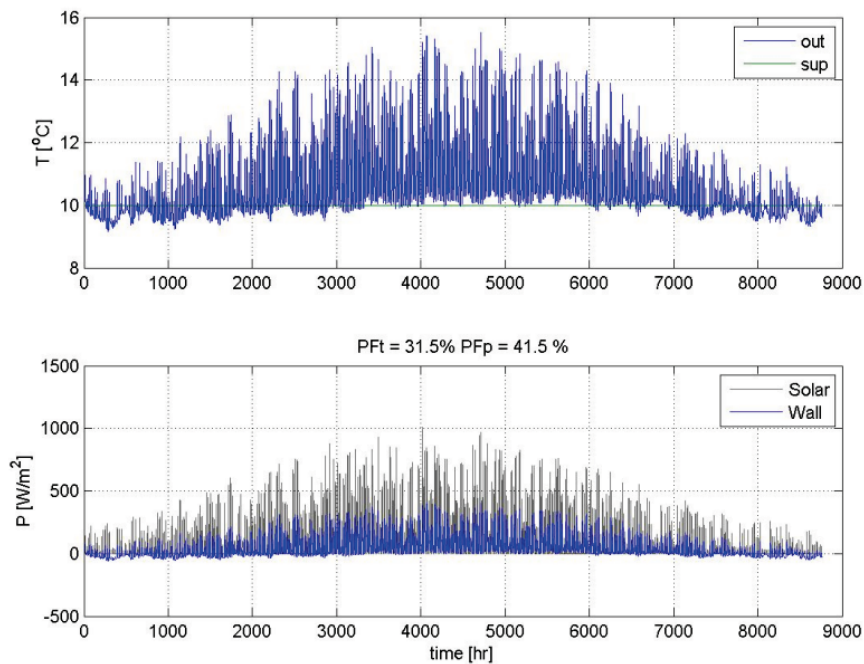


Figure 4. Performance evaluation. Top: The simulated supply and return water temperatures versus time. Bottom: The heat flux [W/m^2] of the incoming solar irradiation (Solar) and simulated output flux of the wall. 31.5 % of the year the wall system can be operated (P Ft) The yearly mean efficiency is 41.5 % (P Fp).

The output flux P_{out} is calculated by:

$$P_{out}(t) = (m) \cdot c \cdot (T_{ret}(t) - T_{sup}(t)) / A \quad (4)$$

The overall performance is evaluated as follows: Firstly, $P_{50}(t)$ is defined as $P_{out}(t)$ with a threshold of 50 W/m². Below 50W/m², the water return temperature drops below 10.7 oC and the wall system is too inefficient. For these values $P_{50}(t) = 0$. Secondly, two performance (PF) indicators are defined as follows:

$$P Ft = \text{Percentage of time of } P_{out}(t) \text{ above threshold of } 50 \text{ W} \quad (5)$$

i.e. percentage of time of possible operation [%].

$$P Fp = 100 \cdot \text{sum}(P_{50}(t)) / \text{sum}(I(t)) \quad (6)$$

i.e. the yearly mean efficiency [%]

From Figure 4 it follows for configuration A, $Pf_t=31.5\%$ and $Pf_p=41.5\%$. The main parameter that affects the simulated performances is the mass flow of the water. Figure 5 provides the simulated performances Pf_t and Pf_p as functions of the mass flow.

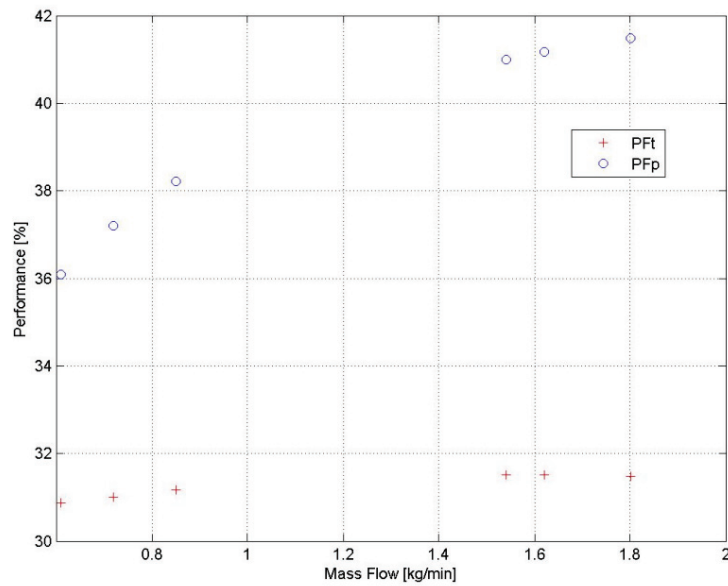


Figure 5. The simulated performances versus the mass flow.

Figure 6 presents the influence of the pump energy and surface heat transfer coefficient.

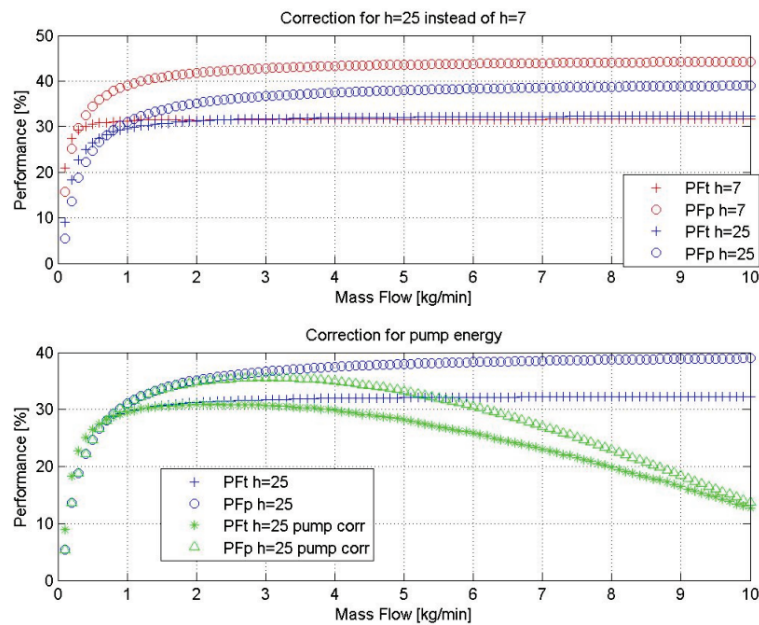


Figure 6. Influence of the pump energy and surface heat transfer coefficient. Top: The influence of a change in heat transfer surface coefficient. Bottom: Correction of the performances using pump energy.

For further simulations a more realistic surface heat transfer coefficient of 25 W/m²K is used instead of 7 W/m²K from the indoor experiment. The latter (i.e. $h=7$ W/m²K) was used for the validation of the experiments. Furthermore, for the water mass flow, values between 0.2 and 2 l/min are used.

3.5 Parameter study

During the project, the manufacturer of the solar collector wanted to know how the collector performed by changing the distance from the pipe to the surface and by changing the mass flow. Therefore the following parameters were varied for the parameter simulation study:

- * The distance from the pipe to the surface (default 35 mm) was varied: 20, 35 and 50 mm.
- * The mass flow (default 1 kg/min) was varied: 0.5, 1 and 2 kg/min.

The results of the nine simulations are shown in Table I and II.

Table I. Efficiency Performance

Simulated yearly mean efficiency PFp [%]			
	d=20 mm	d=35 mm	d=50 mm
MF=0.5 kg/min	30.6	24.7	20.2
MF= 1 kg/min	39.0	30.9	25.2
MF= 2 kg/min	44.3	34.8	28.0

Table II. Operation Time Performance

Simulated Operation time PFt [%]			
	d=20 mm	d=35 mm	d=50 mm
MF=0.5 kg/min	29.8	26.5	23.7
MF= 1 kg/min	33.1	29.5	26.5
MF= 2 kg/min	34.5	30.9	27.7

The increase of the efficiency performance by moving the pipe more towards the surface and the increase in mass flow is of course quite obvious. The efficiency performance for a Dutch climate is 44.3% with the accompanying mass flow of 2 kg/min and pipe depth of 20 mm. This is a significant increase compared with 30.9% (flow of 1 kg/min and pipe depth of 35 mm). However there is a limitation on the smallest distance because due to constructive reasons the depth can not be smaller as 20 mm. Therefore a pipe depth of 20 mm is optimal. From figure 6, it can be seen that a mass flow of 2 kg/min is also optimal, taking the pump energy into account.

3.6 EU Mapping of the standard configuration

By replacing the Dutch climate with the climates of weather stations presented in van Schijndel and Schellen (2013), it is quite easy to simulate the response of the system to each external climate using Meteonorm (2014). From the responses the performance indicators can be calculated (See previous Section). The results of the standard wall performances are shown in Figures 7 and 8. These results are still based on the standard wall configuration A.

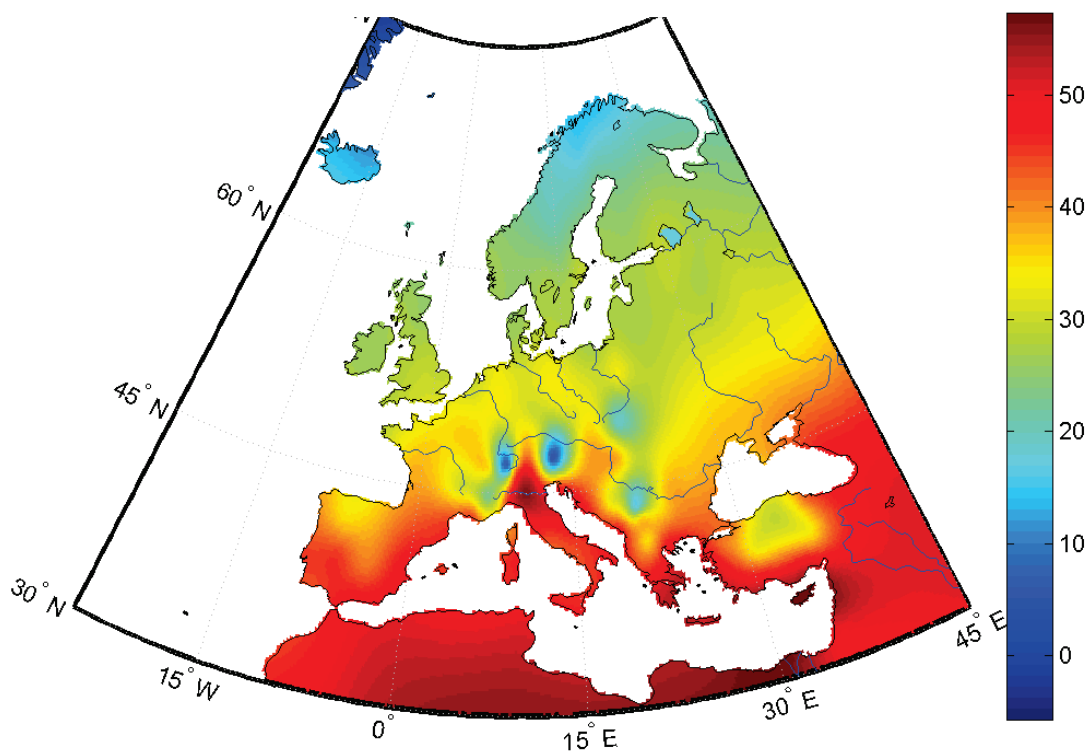


Figure 7. Efficiency (PFp) of the standard wall configuration.

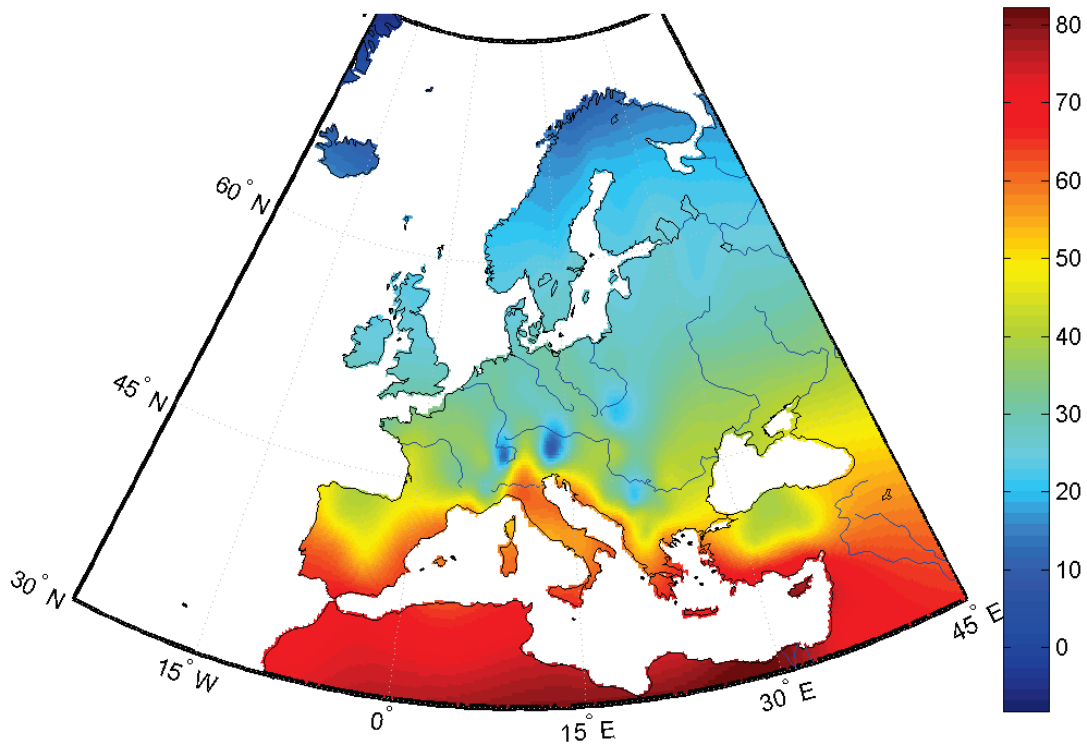


Figure 8. Percentage of time operation (PFt) of the standard wall configuration.

3.7 Simulation of optimized wall configurations

All nine configurations of the parameter study (see Table I and II) were also simulated on the EU scale. For each weather station the best configuration out of nine was selected. These optimized wall configuration performances are presented in Figures 9 and 10.

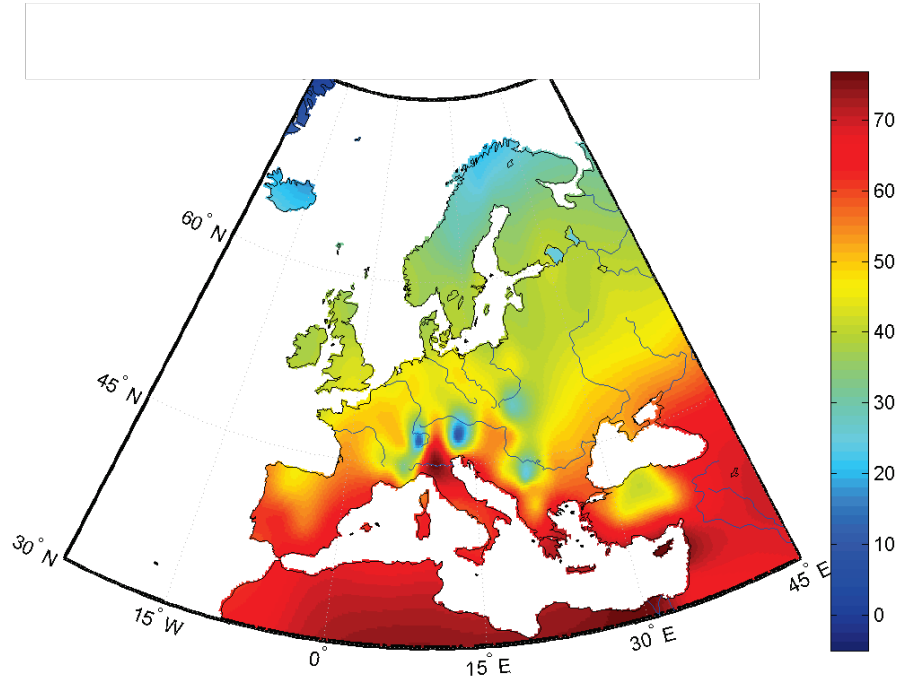


Figure 9. Optimized wall configuration Efficiency (PFp).

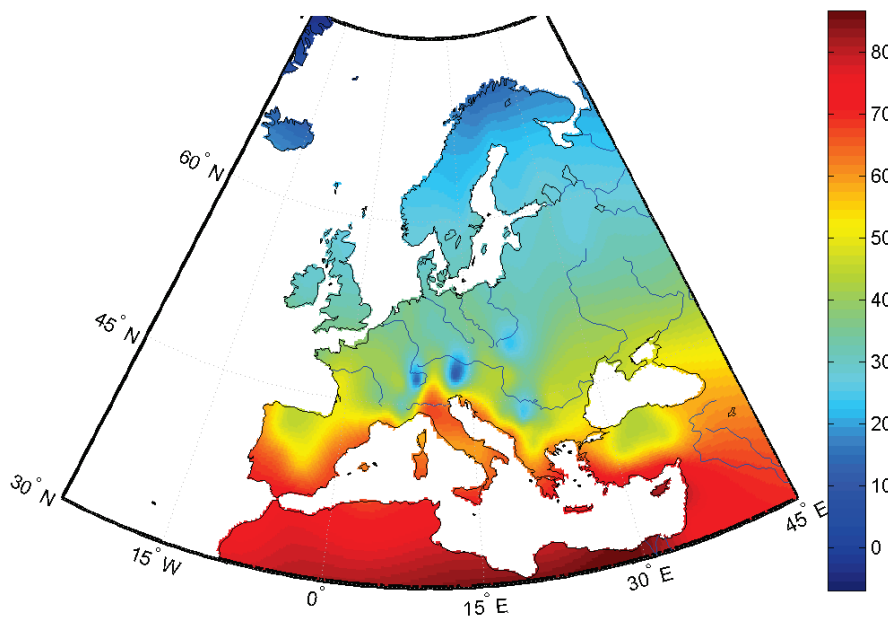


Figure 10. Optimized wall configuration Percentage of time operation (PFt).

From figure 10 it can be seen that large parts of Europe have efficiencies of at least 45%. From figure 10 it can be seen that the areas near the Mediterranean have percentages of time of operation above 60%. The latter means that the wall collector is also operational during parts of the night.

4. DISCUSSION AND CONCLUSIONS

In this paper a methodology was presented, for producing maps of external climate dependent simplified thermal systems, based on state-space models. The approach was successfully applied for a commercial case where, the main objective was to simulate and optimize the thermal performance of solar wall collector under different EU climate conditions using state space modeling:

- (1) The solar collector was successfully modelled;
- (2) The validation of this model using existing measurements was satisfactory;
- (3) The solar collector model was successfully simulation using 130 EU weather stations;
- (4) Estimation of minimal and maximal performance was done by a parameter study;
- (5) EU Maps of the performance were created.

Large parts of Europe have solar collector efficiencies of at least 45%, the exact details are provided in Figure 9. Furthermore, areas near the Mediterranean have percentages of time of operation above 60% (exact details are shown in Figure 10). The latter means that the solar collector is even operational during parts of the night. It is concluded that this study shows that the solar collector could be applicable in large parts of Europe.

Limitations.

However, the reader should notice that the solar collector simulation results in this study are based on two assumptions: The supply water temperature is constant at 10 °C and all heat produced by the wall collector is usable at any time. Under most circumstances this is not very realistic. Therefore it is recommended to include buildings, systems and controllers details into the modeling for more realistic performance simulations and design of promising integrated configurations.

Benefits.

Currently we are working on a more general state space mapping tool in MatLab. This tool will become public available. With this tool the performances of any state-space can be mapped.

5. REFERENCES

HAMLab (2014), <http://archbps1.campus.tue.nl/bpswiki/index.php/Hamlab>

Kramer, R.P., Schijndel, A.W.M. van & Schellen, H.L. (2012). Simplified thermal and hygric building models : a literature review. *Frontiers of Architectural Research*, 1(4), 318-325.

Meteonorm (2014).<http://meteonorm.com/>

Schijndel, A.W.M. van & Schellen, H.L. (2013). The simulation and mapping of building performance indicators based on European weather stations. *Frontiers of Architectural Research*, 2, 121-133.

APPENDIX Testing Conditions

To reach the main objective of providing a first estimate of the efficiency numerous experimental measurements are executed. A test setup was build at the laboratory consisting of an array of infrared lamps, a cold water machine, pump with flow adjustment valves, temperature sensor in the ingoing flow and outgoing flow, four temperature sensors inside the solar collector, an air temperature sensor, pyrano meter and a balance for measurement of the flow quantity . Photo 1, 2 and 3 give an impression of the test setup. Each configuration has been measured for at least 5 hours to ensure that a stationary state was reached.



Photo 1 Array with IR lamps



Photo 2 Front side of collector



Photo 3 back site of collector with cool water unit, circulation pump and temperature sensors

The settings for a typical experiment in the stationary part (between 350 and 525 minutes) were:

- Radiation average 964 W/m^2
- Flow average state $1,80 \text{ kg/min}$
- Average water temperature supply $11,2 \text{ }^\circ\text{C}$
- Average air temperature $23.7 \text{ }^\circ\text{c}$

The results of the experiment in the stationary part (between 350 and 525 minutes) were:

- Average temperature return $18,0 \text{ }^\circ\text{c}$
- Average power out. 491 W/m^2
- Average efficiency $51,0\%$