

# EU maps of climate related building performances using state-space modeling

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## EU Maps of Climate Related Building Performances using State-Space Modeling

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**KEYWORDS:** *Climate, Map, State-Space, Building, Performance, Future*

### **SUMMARY:**

*Performances of building energy innovations 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 innovation. This paper presents a methodology for obtaining maps of performances of building innovations that are virtually spread over whole Europe. It is concluded that these maps are useful for finding regions at the EU where innovations have the highest expected performances.*

### **1. Introduction**

Due to energy efficiency, there exist a lot of studies on innovative buildings systems. The performances of these innovations are mostly very dependent on the external climate conditions. This also means that a high performance of a specific innovation in a certain part of Europe does not imply the same performances in other regions. Similar, innovations 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 innovation. This paper presents a methodology for obtaining maps of performances of building systems innovations that are virtually spread over whole Europe. This approach is based on previous research and literature: The model development, including State-Space models is presented in Kramer et al. (2012 & 2013). The use of Meteonorm (2013) climates files for generating maps is shown in van Schijndel & Schellen (2013). The computational tool HAMLab (2013) originating from van Schijndel (2007) was used to implement all models and climates. Finally the future climate files originates from the Regional Climate Model REMO by Jacob et al. (1997) and will become public available from July 2014 at the Max Planck Institute for Meteorology (2013).

The methodology consisted of (1) State-Space model development; (2) Validation with step-change experiments; (3) Simulation of one external climate; (4) Performance indicators; (5) Parameter study; (6) Mapping of using current external climates over the EU.

The above mentioned methodology covers a wide range of topics. Due to the length limitation of this paper, it is very difficult to provide all details for each topic. We try to focus on the most significant aspects taking the complete methodology into account. More details can be found in the references.

The next Section 2 demonstrates the method using a commercial case study. Section 3 presents a generalization of this approach by the development of a computational tool for simulation of performances using SS models and future climates. Section 4 provides the discussion and conclusions.

## 2. The simulated performance of a thermal active wall

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.

### 2.1 Modeling, validation and climate based performance

Figure 1 shows the principle construction of the solar collector (in reality this is much more complicated) and the involved mathematical model in the form of ordinary differential equations and State Space. The solar collector will be used for the heating of water that directly can be used or stored for later use.

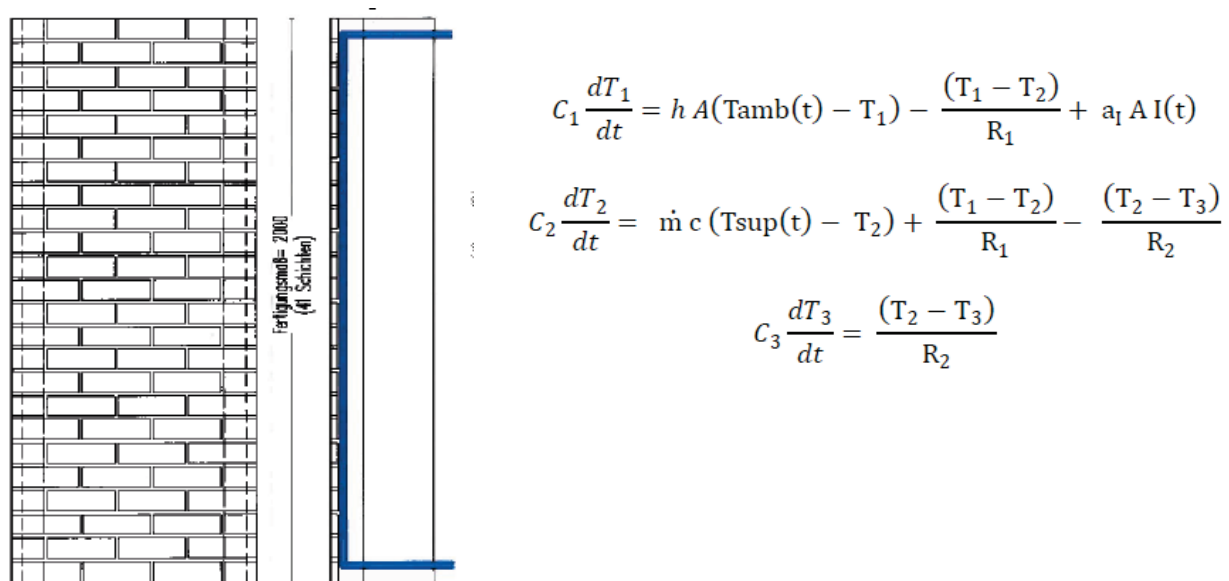


Figure 1. Construction of the solar collector (Left), the model representation in ODEs (Right)

Where *Inputs*  $T_{amb}(t)$  = ambient (external) air temperature [ $^{\circ}\text{C}$ ];  $T_{sup}(t)$  = water supply temperature [ $^{\circ}\text{C}$ ];  $I(t)$  = external solar irradiance [ $\text{W}/\text{m}^2$ ]; *States*  $T_1$  = 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 [ $\text{kg}/\text{s}$ ];  $c$  = heat capacity of water [ $\text{J}/\text{kgK}$ ];  $a_1$  = solar absorption factor [-];  $h$  = heat transfer surface coefficient [ $\text{W}/\text{m}^2\text{C}$ ];  $A$  = surface [ $\text{m}^2$ ];  $d_1$  = distance pipe to surface [ $\text{m}$ ];  $d_2$  = distance pipe to insulation [ $\text{m}$ ];  $k$  = heat conductivity of concrete [ $\text{W}/\text{mK}$ ];  $R_1$  = heat resistance [ $\text{K}/\text{W}$ ] =  $d_1/(kA)$ ;  $R_2$  = heat resistance [ $\text{K}/\text{W}$ ] =  $d_2/(kA)$ ;  $C_i$  = heat capacity [ $\text{J}/\text{K}$ ];

The model was implemented using standard state-space modeling facilities of MatLab. State-space models (see for example Kramer et al. (2012 & 2013)) contain variables and matrices. Regarding the variables: We have 3 variables: the state vector  $x$ , the input vector  $u$  and the output vector  $y$ . For the ODEs of Figure 1 this means that,  $x=[T_1;T_2;T_3]$ ,  $u=[T_{sup}(t); T_{amb}(t); I(t)]$  and we chose  $y=x$ . Regarding the matrices: **A,B,C,D** can be calculated as shown in Figure 2 by using  $dx/dt = Ax + Bu$  and  $y = Cx + Du$ . To simulate state-space models in MatLab, two commands are important: (I) creating a state-space system from the matrices:  $G=ss(A,B,C,D)$ ; (II) simulate the system (G) using input data  $u$ , time steps  $t$  and start values for  $x$ :  $lsim(G,InputData,t,Startvalues)$ .

```

A=[ -(hA+1/R1)/C1  1/(R1*C1)      0
      1/(R1*C2)    -(mdot*c+1/R1+1/R2)/C2  1/(R2*C2)
      0            1/(R2*C3)          -1/(R2*C3) ];

B=[ 0      hA/C1  arA/C1
      mdot*c/C2  0      0
      0          0      0];

C=eye(3);

D=[0 0 0
     0 0 0
     0 0 0];

G=ss(A,B,C,D);

lsim(G,InputData,t,Startvalues);

```

Figure 2. The state space representation and simulation in MatLab

The next part shows the simulation and validations results. Laboratory experiments were used to validate the models. 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 3 (Left) the results for a typical experiment, labeled A, is shown.

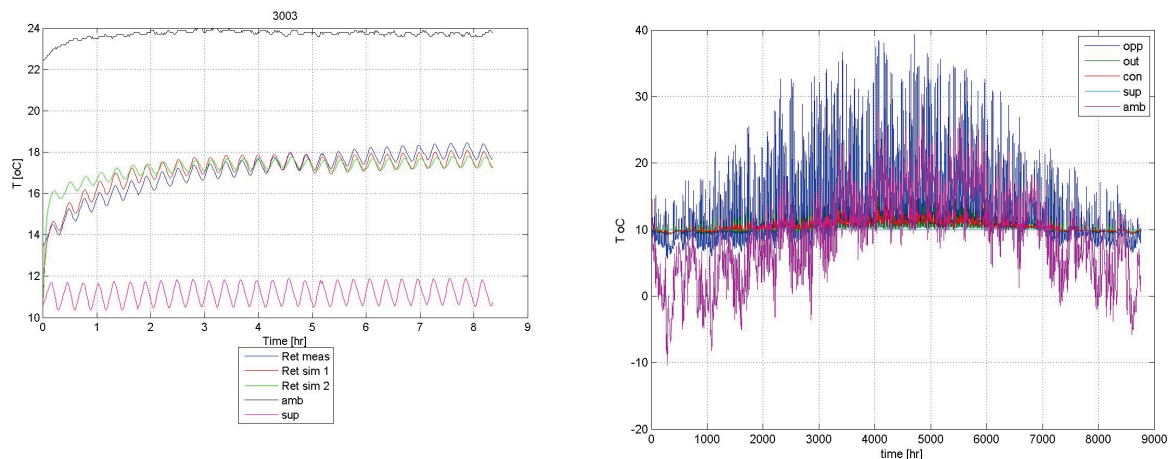


Figure 3. Temperatures vs time Left: Validation experiment A: The measured supply water(sup), the measured ambient air (amb), the simulated return water (Ret sim 1 & 2) and the measured return water (Ret). Right: Simulation of configuration A using a reference standard Dutch climate of deBilt. including the external wall surface (opp), the water return (out), the mid wall (con),

From Figure 3 left 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. The model configuration A was simulated using a reference standard Dutch climate of de Bilt. Figure 3 right presents the result. 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. Figure 4 shows details of the model A configuration performance results

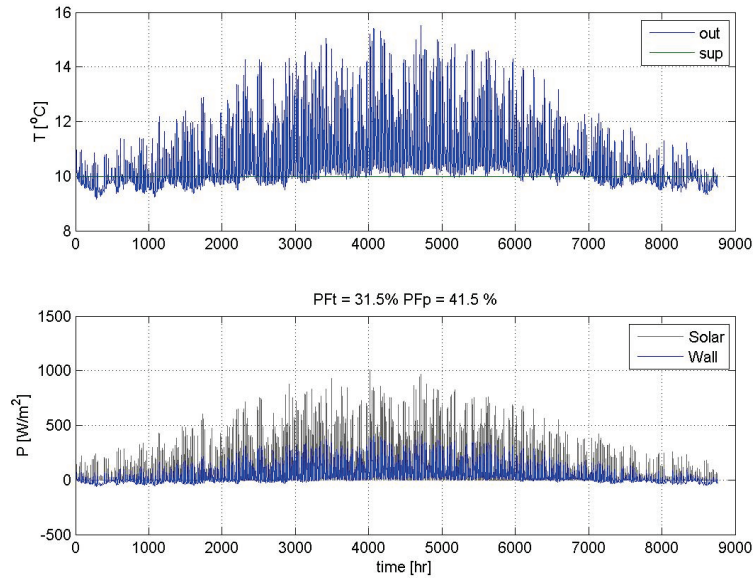


Figure 4. Performance evaluation. Top: The simulated supply and return water temperatures versus time. Bottom: The heat flux [ $W/m^2$ ] of the incoming solar irradiation (Solar) and simulated output flux of the wall. 31.5 % of the year the wall system can be operated (PFt) The yearly mean efficiency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

The output flux  $P_{out}$  is calculated by:  $P_{out}(t) = \dot{m} \cdot c \cdot (T_{ret}(t) - T_{sup}(t)) / A$  [ $W/m^2$ ]; The overall performance is evaluated as follows: Firstly,  $P_{50}(t)$  is defined as  $P_{out}(t)$  with a threshold of  $50 W/m^2$ . Below  $50 W/m^2$ , the water return temperature drops below  $10.7$  °C and the wall system is too inefficient. For these values  $P_{50}(t) = 0$ . Secondly, two performance (PF) indicators are defined as follows:  $PF_t =$  Percentage of time of  $P_{out}(t)$  above threshold of  $50 W$ , i.e. percentage of time of possible operation [%].  $PF_p = 100 \cdot \sum(P_{50}(t)) / \sum(I(t))$ , i.e. the yearly mean efficiency [%]. From Figure 4 it follows for configuration A,  $PF_t=31.5\%$  and  $PF_p=41.5\%$ .

## 2.2 Parameter study

The following parameters were varied for the parameter 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 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

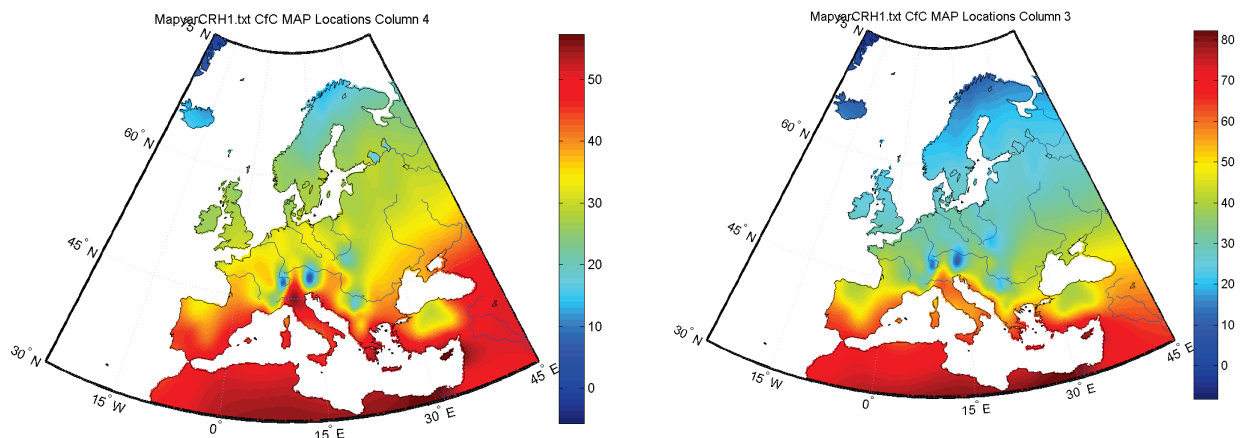
*Table II. Operation Time Performance*

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 optimal efficiency performance for a Dutch climate is 44.3% with the accompanying mass flow of 2 kg/min and pipe depth of 20 mm.

### 2.3 EU Mapping of the standard configuration

By replacing the Dutch climate with the climates of weather stations presented in Figure 3, it is quite easy to simulate the response of the system to each external climate. From the responses the performance indicators can be calculated (See previous Section). The results of the standard wall performances are shown in Figure 5. These results are still based on the standard wall configuration A.



*Figure 5. Left: Efficiency (PFp) of the standard wall configuration. Right: Percentage of time operation (PFt) of the standard wall configuration.*

## 2.4 Simulation of optimized wall configurations

All nine configurations of the parameter study (see Table II and III) 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 Figure 6

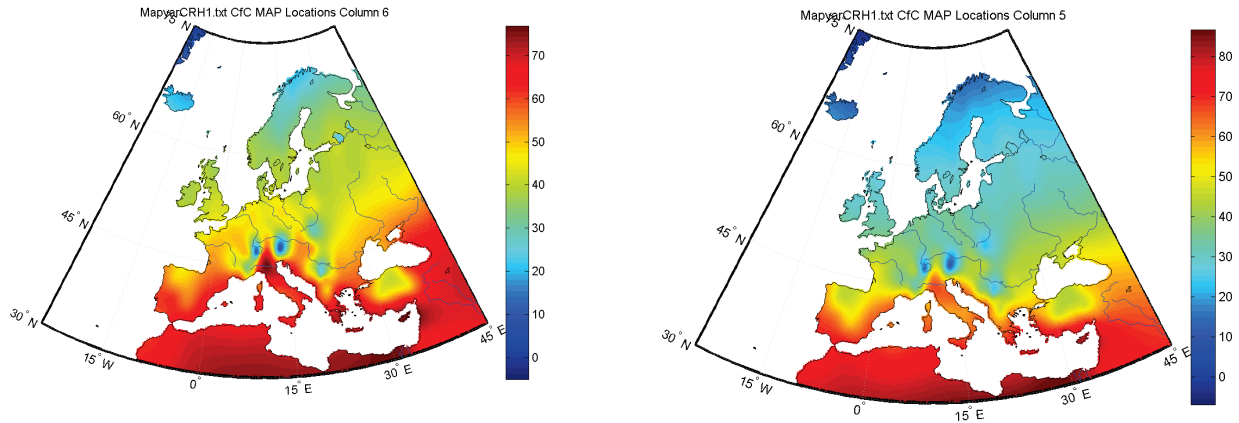


Figure 6. Left: Optimized wall configuration Efficiency (PFp). Right: Optimized wall configuration Percentage of time operation (PFt).

From Figure 6 left, it can be seen that large parts of Europe have efficiencies of at least 45%. From Figure 6 right, 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.

## 3. Towards a tool for State-Space model simulations with Future Climate

One of the benefits of simulating State-Space (SS) models is its outstanding computational efficiency. To illustrate this: It takes longer to plot the maps of figures 5&6 than simulating them. Due to this excellent computational performance a practical tool for general purpose of simulating SS models using hourly based future climates is developed and will be public available together with the availability of the future climate files by the REMO model (2013).

### 3.1 How to use future hourly-based climate files for building simulation

The EU-FP7 project Climate for Culture (2013) is one of the first projects where high resolution EU future climate files were used for building simulation. Due to the stochastic behaviour and the time scale of about 250 years of the REMO climate model, it is recommend use three 30-year-periods for comparison purposes: „Recent Past“ (1960 – 1990), „Near Future“ (2020 – 2050) und „Far Future“ (2070 – 2100). An example from Winkler (2013) is shown in Figure 7. The left part shows the mean indoor temperature from the recent Past of a reference building. To compare this with the Near Future, the Near Future was simulated and the recent Past was subtracted. This generates the middle figure Past to Recent Future. Similar the figure on the right Past to Far Future was obtained. The reader should notice that from the experiences of the above mentioned project, it was concluded that the one-year-periods includes too much noise to be useful for analyzing and comparing purposes.

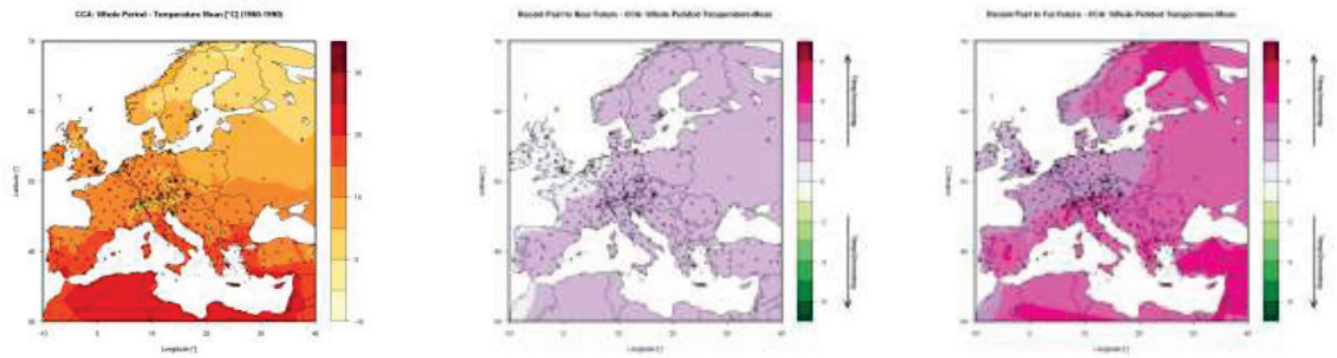


Figure 7. An example of the use of 30-year periods for comparison purposes of the indoor temperature of a reference room: Left: Recent Past, Middle: Past to Near fur, Right: Past to Far Future from Winkler (2013)

### 3.2 Current mapping visualisation tool

A MatLab mfile was developed for visualisation of EU maps. The input of this tool is in a single text file with performances related to longitudes and latitudes of the locations of the climate files. An example is shown in Figure 8. Here, over 130 external hourly based climate files were produced using commercially available software (Meteonorm 2013) using the so-called wac format. Figure 8 presents the distribution of the locations over Europe.

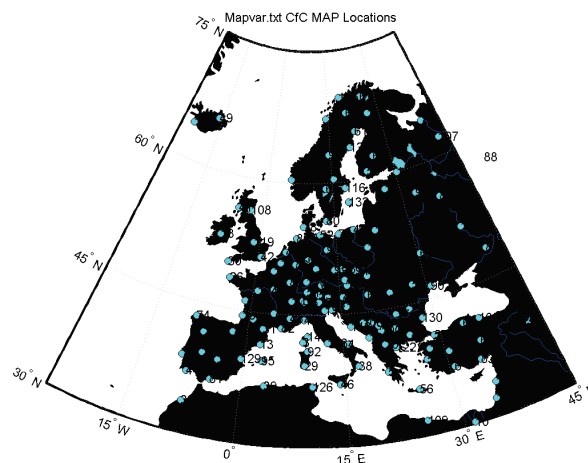


Figure 8. The distributions of the locations of the external climates in Europe.

Each climate file includes hourly based values for the common used external climate parameters: Horizontal global solar radiation [ $W/m^2$ ] (ISGH), Diffuse solar radiation [ $W/m^2$ ] (ISD), Cloud cover [0-1] (CI), Air temperature [ $^{\circ}C$ ] (TA), Relative humidity [%] (HREL), Wind speed [m/s] (WS), Wind direction [0-360 $^{\circ}$ ] (WD), Rain intensity [mm/h] (RN), Long wave radiation [ $W/m^2$ ] (ILAH). Each can be used as input file to simulate building energy performances for location. For the exact details of this mfile, we refer to the HAMLab website (HAMLab 2013).

### 3.3 State-space modeling and simulation tool

MatLab has been a very successful modeling tool for simulating state space systems over the last 20 years. For a recent built environment application, we refer to Kramer (2013).



## 4. Discussion and Conclusions

### 4.1 EU performance of the solar collector

Large parts of Europe have solar collector efficiencies of at least 45%, the exact details are provided in Figure 6. Furthermore, areas near the Mediterranean have percentages of time of operation above 60% (exact details are shown in Figure 6). 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. 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.

### 4.2 State-Space modeling tool using Future Climates

The main three work packages: (1) State-space modeling and simulation; (2) Getting reliable future hourly based climate data over the EU and appropriate use of them; (3) Visualisation of maps, are all implemented in MatLab. The complete tool, including climate files, will become public available after the official ending of the Climate for Culture project (2013). This is expected at July 2014.

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