A Combination Of State Space and Mapping Functions In Matlab

Evaluation tool for climate related cases in the Netherlands
PREFACE

This report presents and discusses the results of my research for my second master project at the University of Technology Eindhoven. The purpose of this project is to gain specific competences with Matlab. The competences gained will be used during my master thesis, which preparations start directly after this project is finished.

The Matlab files are enclosed in a zip-file. The Matlab files only run when the System Identification and Mapping toolbox are installed.

Due my part time work at Deerns Nederland B.V., I had at irregular intervals gatherings with my supervisor, dr. ir. Jos van Schijndel. I would like to thank him, for his flexibility, support, and feedback.

Eindhoven, May 2013
SUMMARY

The main question of this study is whether Matlab is applicable as an evaluation tool for climate related cases. The cases climate change, wind turbine, and concrete brickwork wall collector are converted in a Matlab model to demonstrate the possibilities of Matlab as a quick evaluation tool.

The Matlab models are set up in state space, which greatly reduces the calculation time compared with traditional ordinary differential equations. Due the short calculation time, results are quickly obtained.

The visualisation time to create figures is rather long; however, after the visualisation is complete videos could be created with JPGvideo. The results in the figures should be critically examined, because the interpolation between the results could be wrong.

The study indicates that Matlab could be applied for climate related cases, but the results due interpolation should be evaluated.
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1 INTRODUCTION

Future outdoor climate scenarios indicate that the outdoor climate is changing and will continue to do so in the near future [1]. Effects of outdoor climate change on ecosystems and global economy have been researched intensively during the past decades [1]; however, the impact on climate related cases has not been investigated.

Ordinary differential equations (ODE’s) are traditionally applied in computer simulation models; however, this calculation method is rather slow [3]. A quicker evaluation tool to investigate the impact of outdoor climate by a combination of the state space functions and mapping toolbox in Matlab has not yet been developed.

The purpose of this study is to develop a Matlab model, where the results of climate related cases can be visualised over the Netherlands. Using three different cases, namely climate changes, wind turbines, and concrete brickwork solar collectors, the possibilities are demonstrated for visualisation. The visualisations of these aspects are made possible by calculations, which will be represented in state space form, in the Matlab model.

This research includes three state space models, which could serve as an example for other models. For each model, the method and results are presented and discussed. Finally, conclusions are drawn and recommendations for further research are provided.
2 METHOD

The first paragraph provides general information about the three models built in Matlab. From the second to the fifth paragraph, the three models are described. The three models are titled ‘Climate’, ‘Wind turbine’, and ‘Concrete brickwork solar collector’. The paragraphs mentioned describe the system and state space models.

Appendix I provides an extra case study about the internal temperature of the Kings chamber in the Castle of Amerongen.

2.1 General

This paragraph describes general information about the models and provides an explanation of the principle of state space models.

2.1.1 Model

A selection has been made of the weather stations located in the Netherlands, because some weather stations do not have climate parameters which are required for the simulations. The locations of the weather stations selected are presented in a map of the Netherlands with a dot and number in Figure 2-1.

![Figure 2-1: Location weather station selected](image)

The hourly data from the weather stations is stored in the online KNMI database. The KNMI data includes dates, weather station, and climate data. A program, which distinguishes data for HAMLab and the model of Kramer, has been developed to convert the KNMI data to Matlab data.
The data distinguished is used by the three models, which have been developed to evaluate the opportunities of mapping in Matlab.

2.1.2 State space

State space is derived from the state-variable method, which describes a dynamic system with a set of first-order differential equations in the vector-valued state. Higher order equations should be converted to multiple first-order equations. State space combines the set of first-order differential equations into matrices, which provides the possibility to work directly with the state-variable description of the system. Thus, the ordinary differential equations (ODEs) of dynamic systems can be transformed into state-variable form, which can be modified into state space.

The equations in the state-variable form can be represented as the vector equation

$$\dot{x}(t) = Ax(t) + Bu(t)$$

Where the input is $u$ and the output is

$$y(t) = Cx(t) + Du(t)$$

The column vector $x$ and $u$ are called the state and input of the system respectively. The quantity $A$ is a system matrix and $B$ is an input matrix. $C$ and $D$ are referred as the output matrix and the direct transmission term. Figure 2-2 shows the state space system in a block diagram.

![Figure 2-2: Block diagram of a state space system](image)

The state space systems designed in the next paragraphs are a part of the total model, which is presented in Appendix II.

2.2 Climate change

Climate change is defined as a change in the statistical properties of the climate system during a certain period. For example, the change manifests in an increase or decrease of the average temperature and wind speed. The temperature and wind speed are the two parameters, which are implemented in the model.
2.2.1 Model

The temperature is a measurement in degrees Celsius or Kelvin of how warm or cold an object or location is. Temperature contains a real number and no direction; therefor temperature is a scalar. Wind speed is the rate which wind moves in meters per second. Wind speed is just as temperature a scalar; however, wind velocity is the wind speed in a particular direction and due the direction wind velocity is a vector. The model does not reckon with a direction, therefor the term wind speed is held.

2.2.2 State space

The values for temperature and wind speed are provided by the KNMI in tenth degrees Celsius and tenth meters per second respectively. The A, B, C and D matrices in state-variable form corresponded for the temperature (1) and wind speed (2) model are as follows:

\[
A_{1,2} = 0 \\
B_{1,2} = 0 \\
C_{1,2} = 0 \\
D_1 = 0.1 \text{ and } D_2 = 0.1
\]

2.3 Wind turbine

Wind energy is one of the most applied forms of sustainable energy in the Netherlands. The origin of wind is attributable to solar energy; nevertheless, wind is considered as a separate energy source.

Traditional wind mills, which convert wind energy into mechanical work, influence the sight of the landscape. Currently, the proceedings of the wind mills are done by other machines and the wind mills became monuments. Now, the wind is often used for electricity generation with wind turbines. An important reason to use wind energy is that while generating electricity no pollutants are emitted.

2.3.1 Model

The model uses wind speed in meters per second as a variable to calculate the energy generation in kilowatt hour, which is equal to 3.6 megajoules. The electricity generation by a wind turbine is determined by the following formula:

\[
P_{\text{turbine}} = C_p \cdot \frac{1}{2} \rho \cdot v^2 \cdot A
\]
The symbols have the following meanings:

- $P_{\text{turbine}}$ = Power generation of the wind turbine [W];
- $C_p$ = Coefficient of performance [-];
- $\rho$ = Density of air [kg/m$^3$];
- $v$ = Wind speed [m/s];
- $A$ = Sweap area of the rotor [m$^2$].

Two constraints are held by developing the model, namely a wind turbine generates electricity from a wind speed of 3 meters per second and the maximum wind speed is 12 meters per second.

### 2.3.2 State space

As shown in the formula, the wind speed is to the power three, while state space models are linear processes. The solution is to provide an input for the state space model which is already to the power three.

The A, B, C and D matrices belonged to the energy generation of a wind turbine are as follows:

$$
A = 0 \\
B = 0 \\
C = 0 \\
D = C_p \cdot \frac{1}{2} \rho \cdot A
$$

### 2.4 Concrete brickwork solar collector

The company ‘CRH clay solutions’ produces prefab brickwork elements and has developed a concrete brickwork solar collector. The solar collector contains a brickwork wall and pipes, which absorb the solar radiation, conduct the energy to the pipes and transport the energy collected with water into the building, where the heat will be used for heating purposes.
2.4.1 Model

The model uses two climate parameters, namely the hourly temperatures and solar radiation on a vertical surface positioned towards the South. The result of the simulation contains the energy generation by the concrete brickwork solar collector per hour.

Figure 2-4 shows a thermal model of the concrete brickwork solar collector.

The ordinary differential equations (ODE’s) corresponded to the thermal model are as follows:

\[
C_1 \frac{dT_1}{dt} = hA(T_e - T_1) - \frac{T_1 - T_2}{R_1} + \alpha A I
\]

\[
C_2 \frac{dT_2}{dt} = \dot{m}c(T_{sup} - T_2) + \frac{T_1 - T_2}{R_1} - \frac{T_2 - T_3}{R_2}
\]
\[ C_3 \frac{dT_3}{dt} = \frac{T_2 - T_3}{R_2} \]

The symbols have the following meanings:

- **A** = Surface \([\text{m}^2]\);
- **c** = Heat capacity \([\text{J/kg} \cdot \text{K}]\);
- **C_i** = Heat capacity \([\text{J/K}]\);
- **h** = Heat transfer coefficient \([\text{W/m}^2 \cdot \text{K}]\);
- **I** = Irradiance \([\text{W/m}^2]\);
- **ṁ** = Water mass flow \([\text{kg/s}]\);
- **R_1** = Heat resistance \([\text{K/W}]\);
- **R_2** = Heat resistance \([\text{K/W}]\);
- **t** = time \([\text{s}]\);
- **T_e** = External temperature \([\circ \text{C}]\);
- **T_{sup}** = Water supply temperature \([\circ \text{C}]\);
- **T_1** = External surface temperature \([\circ \text{C}]\);
- **T_2** = Water return temperature \([\circ \text{C}]\);
- **T_3** = Internal wall temperature \([\circ \text{C}]\);
- **α** = Solar absorption coefficient \([-]\);

### 2.4.2 State space

The ODE’s are converted in state space matrices, which are as follows:

\[
A = \begin{bmatrix}
-hA - \frac{1}{R_1} & \frac{1}{R_1} & 0 \\
\frac{C_1}{R_1} & \frac{1}{C_1} & 0 \\
\frac{1}{C_2} & -mc \frac{1}{R_1} - \frac{1}{R_2} & \frac{1}{R_2} \\
0 & \frac{1}{R_2} & -\frac{1}{R_2} \\
0 & 0 & 0 \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{hA}{C_1} & 0 & \alpha A \\
0 & \frac{mc}{C_2} & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\]
\[
C = \begin{bmatrix}
0 & 0 & 0 \\
0 & \dot{mc} & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

\[
D = \begin{bmatrix}
0 & 0 & 0 \\
0 & \dot{mc} & 0 \\
0 & 0 & 0
\end{bmatrix}
\]
3 RESULTS

General results of the total model developed in Matlab are provided in the first paragraph. The results of the three models are presented in the second to the fifth paragraph.

Appendix II and III provide an overview of the Matlab models to convert KNMI data to Matlab and calculate the state space models respectively.

3.1 General

Traditional, the simulations for building physics and services applications are performed by ODE’s. ODE’s are much slower than state space models, because ODE’s interpolate ion between the time steps. State space models calculate with the given time step without loss of accuracy compared to ODE’s. The calculation time of the total Matlab model is less than 20 seconds.

The complexity of a model is less important regarding the simulation time than the number of output parameters. Due the standard vector and output equation with only differences in the $A$, $B$, $C$ and $D$ matrices, the simulation time is more depended on the number of output parameters.

3.2 Climate change

Figure 3-1 illustrates the average temperature and wind speed in the Netherlands during the year 2000. As shown in the figure, the outer weather stations have been connected by a border. The results outside this border are due extrapolation unrepresentative. Inside this border the results are obtained by interpolation and are more reliable than the results outside this border; however, at a significant distance between the weather stations the interpolation causes also unreliable results. This could occur for example in the province Gelderland, where lower temperatures and wind speeds are visualized than the weather stations surrounded.

*Figure 3-1: Average temperature and wind speed in 2000*
As mentioned in the previous chapter, climate change is defined as a change in the statistical properties of the climate system during a certain period. This period could range from decades to millions of years. The calculation period is eleven years, which is too short to make well-founded conclusions about climate change; however, the possibilities for visualisation are good.

Appendix III provides all figures of the average temperature and wind speed from the year 2000 to 2010. Also two videos, which are created by JPGVideo, of these figures are included in Appendix III.

3.3 Wind turbine

The results provided by Matlab are presented in figures per month, which is an average of the year 2000 to 2010. Figure 3-2 shows four figures of the energy generation of a wind turbine for the second (February), fifth (May), eighth (August), and eleventh (November) month.

Figure 3-2: Simulation results of the months February, May, August and November
Derived from Figure 3-2, it could be stated that the electricity generation near the coast is higher than landward. Appendix III provides all figures and a video of the electricity generation by a wind turbine. The average wind speed, wind energy, efficiency, and operation time of the wind turbine are also included in Appendix III.

Based on these aspects, a location of a new wind turbine can be proposed. Also an advice can be made for a maintenance planning, where the electricity generation is less influenced.

3.4 Concrete brickwork solar collector

Figure 3-4 presents the collected solar radiation by the wall on 1 March, 1 June, 1 September, and 1 December at noon. The results are simulated in hourly values; nevertheless it could also be presented in daily, monthly, seasonally and yearly values to make another comparison between the results. The displayed results should depend on the desired presentation; for example, to investigate the behaviour of a concrete brickwork solar collector during a day, it is inappropriate to use yearly results.

As presented in Figure 3-4, during a summer day the chance to collect more radiation by the concrete brickwork wall is higher than during a winter day. However, during the summer less heat is required than in the winter. An energy buffer will provide a solution to store the heat for future use. To optimize the system, the results could be extended in efficiency, operation time and cooling capabilities. Also the required pump, which creates a water flow, could be implemented in the model.

![Figure 3-3 (1): Collected power by the concrete solar wall collector on 1 March and 1 June at noon](image-url)
Figure 3-4 (2): Collected power by the concrete solar wall collector on 1 September and 1 December at noon

State space models are unable to use variable parameters, which discusses the fixed value of absorptivity in the state space model, because it varies in time due variation in solar radiation, external and medium temperature. The absorptivity is higher if the solar radiation is higher and a lower external temperature or higher medium temperature decreases the absorptivity [2].

However, an inverse modelling approach could identify the parameter values of the model by repeatedly trying different parameter values and comparing the simulated output with the measured output [3].
4 CONCLUSION

This report has indicated that Matlab is applicable for evaluating various subjects; for example, indoor and outdoor climate change and performance of building physics and services.

Using state space models instead of ordinary differential equations reduces the calculation time to obtain results; however, visualising the results in a figure is rather long. The figures visualised could be converted in a video using JPGvideo for a dynamic presentation.

The disadvantage of models in state space form is that variables, which change in time, can not be implemented. If a variable could be estimated by an optimisation toolbox, the results will be more accurate.

The type of results and time scales should be discussed before developing a model. Without these preparations, the evaluation of the results will be more difficult or even impossible.

The research performed will be extended with smart data centres. This new research will contain a cooling concept for data centres named ‘Cloud control’ and a new concept named ‘Guiding the cloud’, which have both been developed by Deerns. These concepts will save money on data centre electricity costs, but the amount of savings has not been investigated.
5 REFERENCES

[1] www.climateforculture.eu
APPENDIX I – CASTLE OF AMERONGEN

Method

The Castle of Amerongen is a 17th century castle and is situated in Amerongen. The Castle of Amerongen is surrounded by a canal and contains thick massive walls, varying from 0.7 to 1.5 meters thick. The main building materials contain brick, wood and slate roof covering.

One room of the Castle of Amerongen is named Kings chamber, which is located on the second floor and has windows oriented to the South and East. Although the windows are relatively large, sun irradiation is limited by fixed external sun blinds.

The data available for this research is measured in the year 2009. During 2009 the main part of the Castle was free floating, which means no climate conditioning was applied, however some rooms had limited dehumidification (7 kg/day) and heating.

An important aspect is that adjacent rooms of the Kings chamber are not free floating, but have limited heating (set point 10°C). This affects the thermal indoor climate of the Kings chamber.

Model

Kramer [3] has performed a research, where inverse modelling can be applied successfully to reproduce the indoor climate of buildings. During Kramer’s research, the performances of multiple thermal models are studied. The study indicates that the best thermal model is a 3S11P-model (a) and is presented in Figure 5-1. The thermal model contains 3 states and 11 parameters. The parameter values, which are implemented in the Matlab model, are obtained by an inverse modelling approach.

Figure 5-1: Thermal model
The ordinary differential equations, which correspond to the thermal model, are as follows:

\[
\begin{align*}
C_w \frac{dT_w}{dt} &= G_w(T_e - T_w) - G_i(T_w - T_i) \\
C_i \frac{dT_i}{dt} &= G_i(T_w - T_i) - G_f(T_f - T_i) - G_{int}(T_i - T_{int}) + G_{fast}(T_e - T_i) \\
C_{int} \frac{dT_{int}}{dt} &= G_{int}(T_i - T_{int}) + \bar{f} \cdot \text{Irrad}
\end{align*}
\]

The symbols have the following meanings:

- \( C_i \) = Indoor air capacitance [J/K]
- \( C_{int} \) = Interior air capacitance [J/K]
- \( C_w \) = Enveloper capacitance [J/K]
- \( f_I \) = Effective irradiance [m²]
- \( G_{fast} \) = Conductance from indoor air to outdoor air [W/K]
- \( G_i \) = Conductance from indoor air to envelope [W/K]
- \( G_{int} \) = Conductance from indoor air to interior [W/K]
- \( G_w \) = Conductance from envelope to outdoor air [W/K]
- \( \text{Irrad} \) = Solar irradiation [W/m²]
- \( t \) = time [s];
- \( T_e \) = External temperature [°C];
- \( T_f \) = Fixed temperature [°C];
- \( T_i \) = Internal temperature [°C];
- \( T_{int} \) = Internal temperature [°C];
- \( T_w \) = Wall temperature [°C];

**State space**

The ODE’s are converted in state space matrices, which are as follows:

\[
A = \begin{bmatrix}
-\frac{G_w}{C_w} & -\frac{G_i}{C_i} & 0 \\
\frac{G_w}{C_w} & -\frac{G_i - G_f - G_{int} - G_{fast}}{C_i} & -\frac{G_{int}}{C_{int}} \\
0 & \frac{G_i}{C_i} & -\frac{G_{int}}{C_{int}} \\
0 & \frac{G_{int}}{C_{int}} & -\frac{G_{int}}{C_{int}}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{G_w}{C_w} & 0 & 0 & 0 & 0 & 0 \\
\frac{G_{fast}}{C_i} & 0 & 0 & 0 & 0 & \frac{G_f}{C_i} \\
0 & \frac{f_I_1}{C_{int}} & \frac{f_I_2}{C_{int}} & \frac{f_I_3}{C_{int}} & \frac{f_I_4}{C_{int}} & 0
\end{bmatrix}
\]
\begin{align*}
C &= \begin{bmatrix}
0 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 0
\end{bmatrix} \\
D &= \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{align*}

Results

Kramer has estimated the building characteristics of the Kings chamber with an optimisation toolbox in Matlab; however, these characteristics can also be implemented by the developer. Variant characteristics will provide different results, which can be used to compare the performance of the building physic components implemented.

The results of the Matlab model are provided in hourly values and figures. As mentioned in paragraph 3.1, the simulation time is less than 10 seconds; however, the visualisation time for creating figures will take more than 50 days. Figure 5-3 represents on 1 March, 1 June, 1 September, and 1 December at noon with their corresponding indoor temperatures of the Kings chamber.

Figure 5-2 (1): Indoor temperature in the King’s chamber on 1 March and 1 June at noon
Figure 5-3 (2): Indoor temperature in the King’s chamber on 1 September and 1 December at noon
APPENDIX II – CONVERSION KNMI DATA TO MATLAB DATA

The main script is named ‘NL_0_FvS_A’ and is presented in the first column. The functions called by the main script are shown in the second column. The third column provides an overview of the sub functions, which are called by the functions. In order to perform these calculations, only the main script should be started.

<table>
<thead>
<tr>
<th>Main script</th>
<th>Function</th>
<th>Sub function</th>
</tr>
</thead>
<tbody>
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APPENDIX III – MATLAB CODE MODEL

The main script is named ‘NL_0_FvS_B’ and is presented in the first column. The functions called by the main script are shown in the second column. The third column provides an overview of the state space models, which are called by the functions. In order to perform these calculations, only the main script should be started.

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<th>Main script</th>
<th>Function</th>
<th>State space models</th>
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APPENDIX IV – MATLAB RESULTS