IKON - Intelligente Betriebsführung durch Kommunikation von Produktion und Gebäudetechnik mit einem künstlichen neuronalen Netz

IKON - Intelligent Communication and Operation of Buildings by utilizing Artificial Neural Networks

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Essential project goals

Modelling the thermal behavior of a building is quite challenging not only because of the complications in energy transfer but also because of the uncertainties such as weather, occupancy and so on. The aim of this project is to build an Artificial Neural Network (ANN) model that is able to predict the thermal load of a building based on its historical data. This would lead to incorporate such ANN models into the control process of buildings and building systems where the energy consumption could be optimized.

1. Project details

<table>
<thead>
<tr>
<th>Funding</th>
<th>30,000 Euro</th>
</tr>
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<tr>
<td>Duration</td>
<td>June – December 2017</td>
</tr>
<tr>
<td>Faculty / Institute / Competence center</td>
<td>Institute for Energy and Building / Energy Campus Nürnberg (EnCN)</td>
</tr>
<tr>
<td>Project Management</td>
<td>Prof. Dr.-Ing. Arno Dentel</td>
</tr>
<tr>
<td>Contact details</td>
<td>E-Mail: <a href="mailto:arno.dentel@th-nuernberg.de">arno.dentel@th-nuernberg.de</a></td>
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2. Background and goal of the research

As the modern control and operation strategies for buildings and building components develop, it is inevitable to be able predict the energy demand of the future. Almost every modern day control and optimization strategies rely on such prediction data. More in particular, predicting the thermal load of a building plays a vital role towards making buildings energy efficient as they contribute to about 40% of global energy consumption.

There are various methods to predict the thermal load of a building. Classical modelling approaches use equations describing the physical behavior of a system to predict the output. Modern day data-driven approaches take advantage of the historical data from similar situations and use them with regression models to find appropriate relationship between the input and output.

Classical approach:

To model a building or a component using classical modelling approach all the internal details such as construction properties should be available. The energy transfer within the building as well as with the environment is modelled with the help of thermal resistances and capacitances. An example of such resistance-capacitance model of a building is shown below in Figure 1.
The complexity of such models depend on the chosen precision levels. Every constant or parameter associated with the model need to be calculated based on technical data. The higher the number of parameters are, the higher the source of error is [1].

Data-driven approach:
In contrast to classical modelling approach, data-driven approach creates a model describing the thermal behavior of a building based on available historical. Hence statistical and machine learning methods require collecting such historical data. These methods derive relationship between the thermal load of the building, and influential parameters such as weather information and room thermal conditions [2].

Machine learning approaches are a subset of such data-driven methods. They are used to devise complex models as well as prediction algorithms. Among the various methods available under the concept of machine learning, Artificial Neural Networks (ANNs) are one kind and they are inspired by the behavior of biological neural networks and how human brain processes information.

The goal of this research is to develop a model that can predict the thermal load of a building within acceptable limits based on data developed by a simulation of a real building. This would give a hands-on experience in learning about how ANN could be applied to forecast load of an actual building. Thus ultimately helping to develop control strategies of the building system and its components to improve energy efficiency.

3. Introduction to Artificial Neural Networks
As the name stands, artificial neurons are computational model inspired by natural neurons in human brain. Natural neurons receive signals through synapses located on the dendrites or membrane of the neuron. When the signals received are strong enough (surpass a certain threshold), the neuron is activated and emits a signal through the axon. This signal might be sent to another synapse, and might activate other neurons [3].
Artificial Neural Networks (ANNs) are composed of simple elements or neurons operating in parallel similar to the biological network. Each neuron receives an input signal multiplied by a weight and then activated by an activation function. The ANNs can be trained with particular set of inputs such that they adjust the weights between the connections so that they can perform a certain task [4].

In general, ANNs can be visualized as shown in Figure 3. They usually consist of one input and output layers and a number of hidden layers. The input layer takes all the inputs directly and multiplies a weight to it before forwarding it to the subsequent hidden layers. The main function of the hidden layer is to use the training algorithm to find a relationship between inputs and outputs by changing the weights and biases. Every layer has specified number of neurons and each neuron has weighted inputs coming into it and an activation function that fires the neuron hence connecting it to subsequent layer of the network. Most commonly three activation functions are widely preferred. Inputs to these functions are the weighted sum of the network inputs, possibly with or without biases depending on the application.

If $x_1, x_2, \ldots, x_n$ are inputs the weighted sum would be, $v = w_1 x_1 + w_2 x_2 + \cdots + w_n x_n$. And if output of a neuron is called $y$ then, $y = f(v)$

Here $f$ is the activation function. Commonly used activation functions are,
Linear function \[ f(v) = a + v \text{ where } a \text{ is a bias} \]

Step function \[ f(v) = \begin{cases} 1 & \text{if } v \geq a \\ 0 & \text{otherwise} \end{cases} \]

Sigmoid function \[ f(v) = \frac{1}{1+e^{-v}} \]

Table 1 Commonly used activation functions

4. Application of ANN to predict thermal load

One of the important requirements to be able to use ANN is to have sufficient amount of data to train and test the network for the application area. This is challenging if measured historical data are the only choice but the aim of this project is to test the abilities and accuracy of ANN in the field of buildings and building components. Taking advantage of simulation tools that has the ability to simulate actual buildings and its components with the original construction properties reduces the problem of data collection to a larger extent. TRNSYS [5] is such a software used extensively to simulate transient systems. A simple room model according to VDI 6007 [6] standard is built on TRNSYS and simulated to record data.

Building model:

The room geometry is shown in Figure 4 and it is in accordance with the standard VDI 6007. The VDI room model emulates the thermal behavior of the building components with sufficient precision by considering convective and radiative heat exchanges (both internal and external) and by taking into account actual wall structure.

Weather data:

This model on TRNSYS accepts weather data according Test Reference Year (TRY) standard [7]. Versatile weather data for various locations across Germany is used to simulate the building under various conditions. The model is equipped with an ideal heating or cooling meaning that it would always achieve the defined set-point thermal conditions of the room. The simulation environment in TRNSYS is visualized as shown in Figure 5.
Next step is building the network that accepts certain number of inputs and predict the thermal load of the aforementioned model. Among the various types of neural network architecture available, feed-forward neural network (FNN) is considered suitable to predict the hourly thermal load based on historical data.

The network model is created on MATLAB environment. Feed-forward neural network is simple and one-directional. The output of one layer is forwarded to the layer next to it and has no influence on the current layer or the ones before. This type of neural network is generally used to find relationship between inputs and outputs. The representation shown in Figure 3 is a feed-forward network and the overview of the network created on MATLAB is shown below.

<table>
<thead>
<tr>
<th>Time data</th>
<th>Weather data</th>
<th>Building thermal data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day of the year</td>
<td>Ambient temperature</td>
<td>Room operating temperature</td>
</tr>
<tr>
<td>Day of the week</td>
<td>Global radiation on the horizontal surface</td>
<td>Temperature of the building surfaces</td>
</tr>
<tr>
<td>Hour of the day</td>
<td></td>
<td>Thermal load</td>
</tr>
</tbody>
</table>

Table 2 Training data
The network is trained with Levenberg-Marquardt backpropagation algorithm where the neuron and bias values are updated according to Levenberg-Marquardt optimization. It is the fastest and highly recommended backpropagation algorithm from MATLAB [4]. The training data is fed to the network in the form of a matrix. This matrix is then separated into three categories to train, test and validate the network within the training phase. Testing and validation in this aspect means the iterative procedure when the configured network tries to find a relationship between input and output by using the specified training algorithm. The random sampling of training data is done in such a way that,
- 70% is used for training
- 15% is used for testing
- 15% is used for validation
The performance function by default is the mean squared error function.

5. Results and discussion
The simulation of VDI room model in TRNSYS is done with various weather data from TRY. The resulting output data for 5 years (5 different weather data from TRY) are used for the training the network. To validate the network, output for a different weather data is generated.
The selection of number of neurons is tricky for each application and they also depend on the data used for training. Based on a parametric study, different number of neurons are tested and Figure 7 shows the prediction for 24 hours obtained for different number of neurons (from 10 to 33) As mentioned above, predictions are compared with the simulated thermal load of the building for the corresponding date and time.

![Figure 7 Prediction of thermal load for 24 hours (different number of neurons)](image)

To compare the accuracy of the prediction, Root-mean-square error (RMSE) is calculated for the same and the results are,
<table>
<thead>
<tr>
<th>Number of neurons</th>
<th>Prediction horizon</th>
<th>RMSE</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>24</td>
<td>4.86</td>
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<tr>
<td>20</td>
<td>24</td>
<td>0.21</td>
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<tr>
<td>30</td>
<td>24</td>
<td>3.74</td>
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<tr>
<td>33</td>
<td>24</td>
<td>7.84</td>
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</table>

Table 3 Root-mean-square error

It is evident that using 20 neurons yields good results. Using the same network configuration, a random day in summer is chosen and the prediction is done. The result is shown in Figure 8 and as seen, the cooling load is shown as negative value in the figure.

![Figure 8 Prediction of thermal load for a summer day (with 20 neurons)](image)

6. Exploitation

With the knowledge gained during this project, it is intended to make bigger projects possibly with industrial collaborations. A project proposal application is successfully submitted (Projektträger Jülich). The title of the proposal application is "KMU+ - Development of a modular and cost-effective energy management solution for small and medium-sized enterprises in the course of holistic digital transformation". Alongside THN, the planned project partners are,

- BROCHIER Consulting + Innovation GmbH
- TREvisto AG
- Best Practice KMU
- Fraunhofer Institut für integrierte Schaltungen

Apart from the project proposal, two abstracts have been submitted on the title “Comparison of different modeling approaches to predict thermal load of a building” and waiting for further notifications. The conferences are,

- iSEnEC – Integration of Sustainable EnergyConference (July 2018)
- BAUSiM 2018 (September 2018)
7. Literature


