Simplified Model of HVAC Load Prediction for Urban Building Districts

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Abstract

HVAC load dynamic prediction of building districts is fundamental in the field of urban energy planning. A new physical model of HVAC load prediction for the individual building is developed, with the open source library of BERKELEY LAB's Modelica Buildings Library in the environment of Dymola. On this base, this study explores the model further for the HVAC load prediction of urban building districts. The results shows that the method can ensure the accuracy of the results by the validation, and the calculation speed for building district is also very fast, as the input parameters for the HVAC load calculation of each building are reduced to six parameters.

1. Introduction

The load prediction of energy supply system is essentially important to the urban energy planning. Some statistical models and steady-state models have been used to calculate the load of a large number of buildings, but only annual or monthly energy consumption predictions are available with these approaches. Fu Lin et al. have put forward the concept of integrated method for urban energy planning based on the dynamic and spatial distribution. They suggest considering the dynamic feature of energy demands from the perspective of temporal and spatial
distribution so that the energy can be allocated rationally and used efficiently. The development of numerical simulation technology in the building energy-planning field has made it possible for energy consumption predictions. Many experts proposed a wide range of building energy consumption prediction models that are relatively accurate. However, these models can only be used for predicting the energy consumption of individual building on account of its computationally expensiveness and complexity. Existing building models are usually either too complex for city-oriented energy simulation or too simple to adequately predict a precise urban load profile.

Aiming at this, in our previous research, Eui-Jong Kim[2] developed a simplified model to predict the cooling load of individual buildings with enough accuracy, by using the reduction technique used in the Grey Boxes model[3]. However, the EDF (Electricite De France) library used in the model is not available to the public, which becomes a big constraint for the application of models. So the aim of this work is to develop the simplified model of HVAC load dynamic prediction with the open source library of BERKELEY LAB’s Modelica Buildings Library in the environment of Dymola, and further explore the model for the HVAC load prediction for urban building districts.

2. Physical models

2.1. Description of the detailed model

To deduce the simplified model (SM), the detailed model (DM) should be presented firstly. The following hypotheses have been made to simplify the calculation of DM:

- One single thermal zone for any building type;
- One-dimensional component of walls and windows;
- Conductive and convective heat transfer coefficients are assumed constant;
- The transmittance rate of window is variable in function of the solar incident angle;
- The solar radiation transmitted through windows is assumed entirely absorbed on the floor;
- The surrounding solar masks are ignored;
- The equipment and human activities are not taken into account.

For a building of n wall-orientations (including the roof), 3n solar radiation information should be given to the model as seen in Fig.1: $\Phi_{dir}$ – direct, $\Phi_{dif}$ – diffuse, $cosi$ – cosine of the incident angle. Together with the outdoor and sky temperatures, the overall thermal input ($P$) provided from internal gains and air-conditioning systems, for one single zone 3n+3 inputs are required.

![Fig. 1. Inputs to the DM model (n-orientation single zone case)](image)

The DM model can be expressed as a state-space representation, shown as Function (1) [5]:

$$\begin{cases} \dot{T} = A(T)T + B(T,U)U \\ Y = C(T)T + D(U) 
\end{cases}$$

(1)

Where, $T$ indicates temperatures of the thermal nodes of walls, windows and indoor air. $U$ represents the inputs to
the model and $Y$ the output variables, the indoor zone temperature in this model. $C$ is relative to the thermal capacity of thermal nodes and it is constant. Some of terms in the matrices $A$ and $B$ are variable in function of node temperatures to account for the long-wave heat transfer. In addition, $B$ is time-variable as some of the terms include a time-variable function that is used to calculate effective transmittance rates. All terms of the matrices $J$ and $D$ are constant for typical output variables.

2.2. Description of the simplified model

To simplify the DM and changes it to a linear and time-invariant (LTI) model, these matrices $C$, $A$, $B$, $J$ and $D$ should be turned into constant. The long-wave radiation heat transfer is defined according to non-linear function. For linearization this part of heat exchange, the average annual temperatures $T_{sky}$ and $T_s$ are used to make

$$\frac{1}{2} = \frac{1}{2} \left( T_{sky}^2 + T_s^2 \right) = \frac{1}{2} \left( T_{sky} + T_s \right)$$

constant. This approximation makes the matrices $A(T)$ and $B(T,t)$ into $A$ and $B(t)$. As mentioned earlier, the transmittance rate of window is variable in function of the solar incident angle. It’s a non-linear process. To derive the DM into a LTI system, the solar transmittance is externalized in pre-processing phase. It means that the solar radiation transmitted through all windows is separately calculated using the variable transmittance rates. Thus, the average value of total solar transmitted flux through all windows becomes one of the input variables to the simplified model. With these simplifications above, the state-space matrices $C$, $A$, $B$, $J$ and $D$ become constant.

To further simplify the DM model, equivalent envelopes are used for the SM model. With the equivalent envelope, just one wall and one window component is required in SM model to treat all the cases of various building type. It means that each solar absorbed irradiation on opaque walls and windows is averaged for the SM model as the mean transmitted flux is calculated. The SM model has the same outside surface temperature of walls and windows as they are exposed to the same boundary condition of the average solar irradiation. The simplification principal of the SM model is shown in Fig.2. Since the target variable of the building model is the indoor temperature relatively apart from the outside of walls, this simplification would not much affect the results. And in this way, the SM model becomes orientation-independent.

Thus, for SM model just 6 input variables (mean transmitted irradiance, mean absorbed irradiance on windows, mean absorbed irradiance on opaque walls, the outdoor and sky temperatures and the overall thermal input) are required instead of $3n+3$ for DM model. In case of a multi-story building, an additional fictive floor component will be added to the SM model to take into account the thermal inertia of floors between stories.

3. Numerical models

3.1. Establishment of numerical model for the SM

Modelica®, an acausal modeling language, is used in this work. Modelica® [4] is an object-oriented, declarative, multi-domain modeling language for component-oriented modeling of complex systems. Amongst other advantages, an acausal modeling language allows to modify easily pre-defined component models as the numerical algorithm for
resolution is separated from the modeling part. Dymola®, known as dynamic modeling laboratory, is a commercial modeling and simulation environment based on the open Modelica® language.

In our previous research, Kim has developed the model based on “BuildSysPro” Library, which is not open to the public, and hence it becomes a big constraint for its application. Aiming at this, this study will use the fully open source “Buildings Library” to develop the SM, to replace the “BuildSysPro” Library, as shown in Fig.3. And as the reference model, the existing SM model developed with EDF’s “BuildSysPro” library is used to validate the SM model developed with “Buildings” library.

Fig. 3. The schematic diagram for calculation of SM based “Buildings” library

The "Buildings Library" contains HVAC system, building envelope components, control system, heat exchange components, ventilation, etc. This library can be used to describe the heat exchange and control processes between the building envelope and the outside.

Before the modeling of SM, the pre-processing model (the left part in the figure 3) should be developed firstly. As shown in the Fig. 4, from the weather connector, the pre-processing model can read the meteorological data and then calculate and export the 3 mean irradiance flux required.

Fig. 4. The pre-processing model
The main part of SM model consists of four major components: wall, window, floor and air volume. Taking the wall component as an example, as seen in the Fig. 5, the module accounts for conductive heat transfer between inner computation nodes, the convective heat exchange with the ambient air and the long-wave radiation heat exchanges.

With all major components, the SM model is shown as the figure 6. The output of SM model is the indoor temperature. With the PID (Proportion, Integration and Differentiation) temperature controller\(^6\), the load required can be calculated from the indoor temperature. The initial load value is 0 and the initial indoor air temperature can be calculated. By comparing the initial indoor air temperature with the upper and lower limits set by the temperature controller, the load required can be predicted through calculation. For example, assuming that the temperature allowed is between 20 to 26 degrees centigrade. When the temperature is higher than 26 degrees, the system automatically calculates the load required for refrigeration. Conversely, when the temperature is lower than 20 degrees, the system calculates the load required for heating in order to maintain the temperature at 20 degrees centigrade.
3.2. The validation of SM based "Buildings" Library

The simulation results of the simplified model for one building using the BERKELEY LAB’s Library shows a good match with that of the reference models using the EDF’s library, seen as the figure 7. That means that the SM based on "Buildings" library can give a satisfying result for individual building.

Fig. 7. Result of validation of SM model based “Buildings” library

3.3. CASE STUDY OF ONE BUILDING DISTRICT

On the basis of the SM model above, a case of 10 buildings is studied to explore the feasibility of SM model in the HVAC load prediction for building districts. Five buildings with insulation and five without insulation constitute this buildings district. Tables 1 to 4 show the characteristics of building envelopes.

Table 1. Physical characteristics of test cases

|                | Building 1 | Building 2 | Building 3 | Building 4 | Building 5 |
|----------------|------------|------------|------------|------------|------------|
| Storey         | 2          | 2          | 5          | 10         |
| Length / Width (m) | 6           | 12         | 15         | 12         | 15         |
| Storey height (m) | 2.5         | 2.5        | 2.5        | 2.5        | 2.5        |
| Air volume(m³)  | 180        | 720        | 1125       | 1800       | 5625       |
| Total floor area (m²) | 72          | 288        | 450        | 720        | 2250       |
| Window area (m²) | 45          | 80         | 150        | 180        | 420        |
| Wall-sky factor | 0.66        | 0.7        | 0.8        | 0.66       | 0.66       |
| Window ratio   | 0.38        | 0.33       | 0.50       | 0.30       | 0.28       |

Table 2. Performance of envelope materials

| Material | Concrete | Insulation | Timber | plastering |
|----------|----------|------------|--------|------------|
| λ  W/mK  | 1.75     | 0.041      | 1.3    | 0.35       |
| ρ kg/m³  | 2450     | 20         | 800    | 900        |
| c J/kgK  | 920      | 1210       | 850    | 837        |

Table 3. Envelope structure of the five buildings with insulation

| Composition | Layer | Concrete(mm) | Insulation (mm) | Plastering(mm) |
|-------------|-------|--------------|-----------------|-----------------|
| Wall with insulation | 3     | 200          | 140              | 10              |
| Composition | Layer | Concrete(mm) | Insulation (mm) | Plastering(mm) |
| Floor with insulation | 3     | 160          | 200              | 10              |
Table 4. Envelope structure of the five buildings without insulation

| Composition      | Layer | Concrete (mm) | Plastering (mm) |
|------------------|-------|---------------|-----------------|
| Wall without insulation | 2     | 200           | 10              |
| Floor without insulation | 2     | 200           | 10              |

The SM model using in building district is shown as the figure 8. For the case of multi-buildings, one improvement has been made for the pre-processing model to export 3 mean irradiance flux required for each building without increasing the number of equations.

For this building district, there are 5 groups of meteorological data inputs for these 10 different buildings, which can be calculated by the pre-processing model. Thus, there are 10 indoor temperature output corresponding to each building. With the PID temperature controller for each thermal zone, the SM model can export the load required for the whole district.

4. Results

The case study of 10 buildings shows the feasibility of SM to extend to a building district as shown in figure 9. We set the simulation time 1st-8th June as an example. The result can reflect dynamic feature of energy demands. In terms of computations time, the SM model shows its advantage for the prediction of building districts, with the value of 168 seconds for 10 buildings for the annual energy consumption prediction.
5. Conclusions

One simplified model using the open source “Buildings” library is proposed and validated in this paper, and it is further explored to be used in the prediction for building districts with an acceptable feasibility. The results show that the method can not only ensure the accuracy of the results, but also reduce the calculation time, as the input parameters for the HVAC load calculation of each building are reduced to six parameters.

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