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The adjacent walls effects in simplified thermal model of buildings

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Abstract

The thermal network method is a reliable approach to study the thermal performance of buildings. It is able to simulate the indoor temperature, heating and cooling loads by means of a set of ordinary differential equations. In this work, a 4R3C thermal network has been proposed to study a detached building. Combinations of thermal networks are addressed in order to consider the effects of adjacent walls in other typologies (semi-attached and terraced). Corresponding models, generated by the TRNSYS software, provide the training data used to identify the parameters in the thermal networks. At the end, the accuracy of the model's output and identified parameters is discussed.

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Keywords: Thermal networks, System identification, Adjacent wall, Building's simplified model

1. Introduction

Buildings consume around 40% of the total energy in Europe with residential and commercial sectors. They are the fastest growing sector of energy usage: energy consumption in the building sector is even more than in transportation and industrial sectors [1]. This has raised interest to study new fields in the energy sector for buildings, such as

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renewable resources and net zero energy buildings (NZEB) [2] or districts (NZED) [3]. Minimizing the energy consumption in buildings is a complicated problem which is made up of the interactions between the building envelope, its geometry, occupant profiles, heating systems, energy production and control systems [4]. Building thermal models are strong tools for engineers to determine the total energy consumption at small and large scales. Among various methods, simplified models are an alternative which can represent the physics of the system with accurate outputs [5,6]. The simplified model presented here is based on electrical analogy; it is called thermal network or RC model (resistances and capacitances). The thermal network method is based on the lumped capacitance assumption. This method assumes that the total mass of a system is accumulated in a finite number of nodes and the accumulated mass in each node has the same temperature [7]. The energy is stored in the capacitance of each node and the heat transfer between two nodes is occurring through thermal resistances.

The thermal network method has been used in many studies to simulate and predict the thermal performance of different buildings, especially to study the energy demand and the indoor air temperature profiles [8]. In addition, some work has been done to study various thermal branch complexities (2R1C, 1R2C, 3R2C, and 3R4C) to represent a plane wall [9]. These were also used to optimize different structures in multilayer walls [10] or to estimate buildings' U values [11]. These studies confirmed the capability of thermal networks to be used as an alternative method to other white and black box models, for simulating the thermal performance of buildings. Considering the internal mass effects and appliances [12] in thermal networks by means of system identification methods [13] enhanced their functionality for more complicated problems. The thermal network model has been already used for multi-zone simulations [14], but not many studies have addressed the interactions in multi-zone or district simulations. In the case of district studies, the focus is on detached, semi attached, and terraced buildings as the main typologies.

In this paper, the thermal network method and system identification approach are therefore used to study detached, semi attached and terraced buildings. For this purpose, a 4R3C model is proposed as the thermal model of a detached building. In order to study other typologies (semi-attached and terraced buildings) the 4R3C model is duplicated, and a 2R1C branch is used to connect each 4R3C network to another. The effects of adjacent walls (for semi-attached and terraced buildings) in the thermal interactions of buildings are addressed. It will be laid out that the thermal networks are reliable enough to represent the thermal performance of various typologies while the identified parameters for the envelope, adjacent walls resistances and thermal masses may not fully meet the expectations. The aim of the present work, part of the RESIZED project [3], is to obtain reliable resistances and capacitances for simplified models of various buildings from a limited knowledge about buildings. The system is modelled in MATLAB and we used system identification toolbox [15] for determining the model's parameters.

2. Thermal network and system identification approach

A 4R3C model is used to simulate the indoor air temperature of a detached building; this model is developed from the 4R2C model in [16]. The added capacitance for the indoor air temperature makes the model more stable for a larger set of initial values (for the heavy structured buildings tested so far). In this 4R3C model, one 2R1C branch represents the parts of the building which are in contact with outdoor temperature (external walls, roof and windows). A similar 2R1C branch represents the heat transfer between indoor air temperature and the ground, which gives the 4R3C model (Figure 1b). In order to study other typologies, 2R1C branches are added in place of the adjacent walls. For instance, semi-attached buildings have just one adjacent wall, therefore one 2R1C branch is added to two 4R3C models. Figures 1 and 2 represent the general schemes of detached and semi-attached buildings alongside with their proposed thermal networks. The terraced building model is developed with the same procedure.

Equation 1 calculates the energy balance in each node: C_n is the capacitance of each node, T_n is the temperature, $R_{n\text{-}n'}$ is the thermal resistance between two nodes, and finally $\dot{Q}_n$ represents the heat flux rate, which can be solar radiation, heating load, ventilation, and infiltration (Figures 1b and 2b). After developing the system of equations, all the equations are represented in state space matrices, as demonstrated in Equation 2. In state space representation, all the derivative terms form the states of the system. A, B, C, and D matrices are state space matrices and their components can be extracted by expanding Equation 1 for each node. The **u** vector represents the inputs of the model and the **y** vector is the model outputs. The state space matrices and their components for this model have been introduced in [16]. When the model is generated in state space format, the system identification toolbox in Matlab is used to identify the parameters for each model.

$$C_n\dot{T}_n = \sum_{n'=1}^{N}\frac{T_{n'}-T_n}{R_{n-n'}} + \dot{Q}_n \tag{1}$$

$$\begin{cases}\dot{\boldsymbol{T}} = A \times \boldsymbol{T} + B \times \boldsymbol{u}\\ \boldsymbol{y} = C \times \boldsymbol{T} + D \times \boldsymbol{u}\end{cases} \tag{2}$$

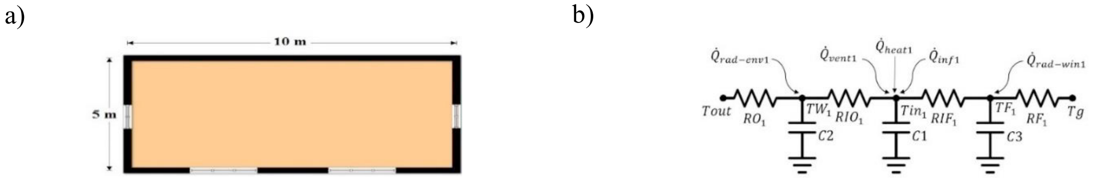

Figure 1. a) Scheme of the detached building, b) the proposed thermal network

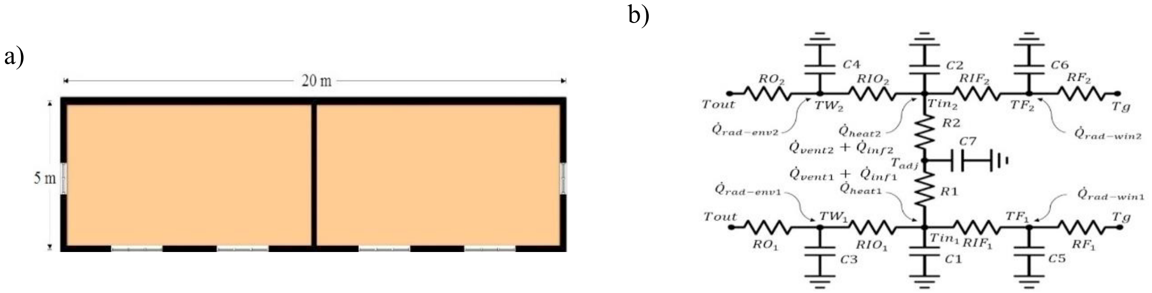

Figure 2. a) Scheme of the semi-attached building, b) the proposed thermal network

System identification algorithms require an information matrix (training data) to train the model. The information matrix contains data related to the outputs and inputs of the model. To identify the parameters of the proposed thermal networks, indoor temperatures are the outputs of the model (**y**), while the weather data (including outdoor temperature, solar radiation, and ground temperature), the heating profiles (heating load, ventilation, and infiltration), and some geometrical information such as walls, roof areas, and windows to wall ratio are considered as inputs.

The training data in the information matrix is generated from TRNSYS software. TRNSYS includes detailed libraries for different structures and contains Meteonorm information for various cities. In this paper, the considered buildings are located in Belgium and the weather data corresponds to the Uccle weather station. The detached building is a simplified office building with 50 m^2 of net floor area, heavy structured and south faced. There are 4 m^2 of windows on the south wall and 1 m^2 on east and west walls. The detailed information of the walls, roof, floor, and windows are available in [16].

It has been assumed that the adjacent walls in the semi-attached and terraced buildings have a unique layer of concrete (thickness: 30cm), and the connected buildings are similar: i.e. in the semi-attached simulation, two 50 m^2 offices are connected to each other as shown in Figure 2a.

All the simulated buildings are considered as single zone buildings. When two buildings are semi-attached, the first building is labeled as “Room1” and the second “Room2”. If we assume that all buildings are kept at the same temperatures, then the heat transfer rate between two buildings will be zero and thereby the estimation of the thermal resistance of the adjacent wall will not be reliable. Thus, different heating schedules have been assumed to keep each building at a different temperature. The heating schedules are presented in Appendix A. Different set-point profiles with ideal control and infinite heating power are used to make the simulations in TRNSYS. The simulations of different typologies were performed in TRNSYS for one month according to these assumptions. In the next section, the results of different identifications and simulations will be presented.

3. Results and discussions

In the system identification, the accordance between model output and the training data has a great importance. Equation 3 calculates the model fitness between the RC model output and the training data (TRNSYS results). In Equation 3, y is the training data and ŷ is the output of the model. A comparison between the model's outputs and the training data, for the semi-attached buildings is represented in the Figure 3. According to Figure 3, the indoor air temperatures for both buildings have been identified accurately and the RC model can follow TRNSYS results with more than 84% of fitness. Almost the same results were achieved for the detached and terraced buildings. Therefore, the proposed structure for the thermal network is a responsive model to training data to regenerate the same outputs as TRNSYS software for different typologies.

$$fit = 100 \times \left(1 - \frac{\|y-\hat{y}\|}{\|y-mean(y)\|}\right) \qquad (3)$$

Furthermore, the prediction of the thermal performance of buildings is the main key to optimize buildings' energy consumption. For testing purposes, the identified RC models were used to predict the indoor air temperature for one week after the training data period. The input data contains weather data, heating load, ventilation and infiltration loads for the next week in order to predict the indoor air temperature. According to Figure 4, the model is predicting the indoor air temperature accurately and the model fitness is more than 80% compared to TRNSYS data.

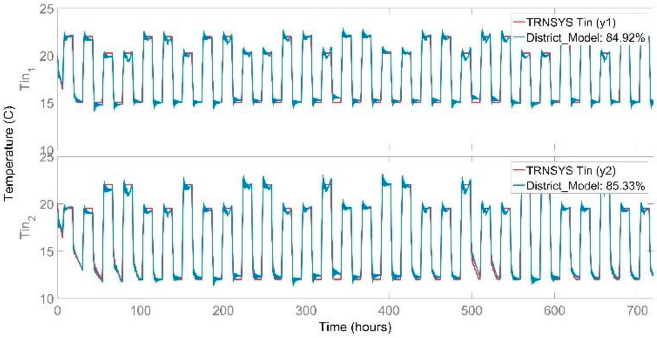

Figure 3. Semi-attached building with 720-hour data set: comparison of the training data (TRNSYS) and the identified temperature profile

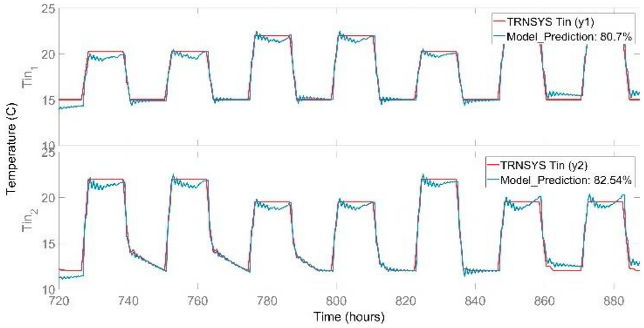

Figure 4. One-week ahead prediction for the semi-attached building compared to TRNSYS results

Until now, it has been shown that the proposed RC models are reliable models to simulate and predict the thermal performance of different typologies. In terms of an improved perception of the thermal networks, the identified parameters for each typology are presented in Table 1. The TRNSYS columns are the calculated parameters according to physical and geometrical properties of each layer, represented in [16], and the following columns are their identified values for the thermal network. In Table 1, The RENV represents the thermal resistance of the envelope. The convective and radiative heat transfer rate on inner and outer surfaces of the wall and roof are assumed to be constant and equal to 8 and 23 W/m^{2}K. Finally, the absorbed solar radiation by the window's frame is neglected and all the solar radiation through the windows heats the ground.

By means of these assumptions, the identified parameters for the envelope of different typologies are around 30% higher than the corresponding ones in TRNSYS. In addition, the floor resistances (RFLO) are identified almost equal to TRNSYS data. The summation of R1 and R2 in Figure 2b is equal to the adjacent wall resistance which is shown by RADJ1 in Table 1. It can be observed that the thermal resistance of the first adjacent wall, for the semi-attached building, is close to the value calculated from TRNSYS data. By contrast, the resistances of the adjacent walls for terraced buildings are larger than TRNSYS data, and more specifically, the identified value for the second adjacent wall is almost twice. Overall, it can be concluded that the envelope and floor resistances were identified more accurately than the corresponding values for adjacent walls. In addition, the indoor air capacitances (CIN) are identified around 100 Wh/K more than the TRNSYS values, although they are consistent and almost equal for three different typologies. On the other hand, the identified capacitances for envelope (CENV), floor (CFLO) and adjacent walls (CADJW) are varying significantly compared to TRNSYS data. These variations in identified capacitances occurred in other studies too [9,12]. It is possible that the information matrices containing more hours of data with higher sample rates ranges could prove more adequate for training the examined model.

Table 1. Identified resistances for three different typologies

Rs (K/W)	TRNSYS-Terraced	Terraced	TRNSYS-Semi-attached	Semi-Attached	TRNSYS-Detached	Detached
RENV1	0.0168	0.0225	0.0168	0.0232	0.0145	0.0197
RENV2	0.0198	0.0266	0.0168	0.0233	0	0
RENV3	0.0168	0.0222	0	0	0	0
RFLO1	0.0067	0.0068	0.0067	0.0069	0.0067	0.0067
RFLO2	0.0067	0.0066	0.0067	0.0065	0	0
RFLO3	0.0067	0.0065	0	0	0	0
RADJ1	0.0321	0.0490	0.0321	0.0332	0	0
RADJ2	0.0321	0.0637	0	0	0	0

Table 2. Identified capacitances for three different typologies

Cs (Wh/K)	TRNSYS-Terraced	Terraced	TRNSYS-Semi-attached	Semi-Attached	TRNSYS-Detached	Detached
CIN1	50.75	152.7	50.75	117.4	50.75	169.1
CIN2	50.75	152.8	50.75	117.3		
CIN3	50.75	151.4				
CENV1	5615.5	31372.3	5615.5	33523.8	6738.67	796.5
CENV2	4492.44	20651.5	5615.5	26158.2		
CENV3	5615.5	24999.7				
CFLO1	2846.67	6641.0	2846.67	5782.3		19230.7
CFLO2	2846.67	6643.2	2846.67	6010.7	2846.67	
CFLO3	2846.67	6268.9				
CADJW1	1900	8230.4	1900	54320.4		
CADJW2	1900	4746.5				

4. Conclusion

In this work, we tried to study the application of thermal networks and system identification approach as an alternative method for simulating indoor air temperature for detached, semi-attached and terraced buildings. It was shown that the model is able to follow the training data and accurately predict the indoor air temperature for the next week. In addition, the reliability of identified parameters was considered, and it was shown that the identified resistances for the envelope and floor for the proposed models are more accurate than the resistances for adjacent walls. To increase the reliability of identified parameters for resistances other data sets with a wider time span and different sample rates, containing more conditions for different indoor air temperature peaks and periods, can be useful. Moreover, the indoor air capacitances were comparable to TRNSYS data, whereas the envelope and floor capacitances were identified larger or smaller than TRNSYS. In conclusion, this paper has investigated the reliability of the thermal network method to simulate thermal performance of buildings. Further data collection is required to determine more accurate parameters.

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Appendix A. Load schedules and temperature set-points

$$heat\ 1 \rightarrow T_1 = 7 \times ROOM1 + 15\ [°C],\ heat\ 2 \rightarrow T_2 = 10 \times ROOM2 + 12\ [°C],\ heat\ 3 \rightarrow T_3 = 12 \times ROOM3 + 10\ [°C] \quad \text{(A-1)}$$

$$Infiltration = 0.24[ach] \quad \text{(A-2)}$$

$$Vent - Zone - i = 2 \times ROOMi + 1\ (i = zone\ number)[ach] \quad \text{(A-3)}$$

Table A1. Daily Schedule for controlling the indoor air temperature

Day times	0-6	6-18	18-24
DAY1	0	1	0
DAY2	0	0.75	0

Table A2. Weekly Schedule

Week days	Day1	Day2	Day3	Day4	Day5	Day6	Day7
ROOM1	DAY1	DAY1	DAY2	DAY2	DAY1	DAY1	DAY2
ROOM2	DAY2	DAY2	DAY1	DAY1	DAY2	DAY2	DAY1
ROOM3	DAY1	DAY2	DAY1	DAY2	DAY1	DAY2	DAY1

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