Development of Reduced Order Thermal Network Models for Indian Wall Assemblies

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Abstract

Thermal network models simplify yet realistically represent various thermodynamic processes associated with the building. They enable estimation of building energy demand with relatively less computational resources compared to conventional simulations. Researchers have attempted to establish the tradeoff between model accuracy and computational intensity. There is a need to develop validated thermal network models for different wall assemblies. This paper presents thermal network models for various Indian wall assemblies with different U values.

A thermal network model of a residential building is developed in open modelica and validated using real time data from a test bed located in Hyderabad, India. According to Koppen Gieger classification Hyderabad has tropical wet and dry climate. The building is a residential test bed having an area of 40 sqm. Thermal network models of Indian wall assemblies are developed as per VDI 6007 guidelines. The 3R2C model of bedroom yields a MAE (Mean Absolute Error) value of 0.76 ˚C. The effect of model order reduction (5C, 4C, 3C, 2C) on prediction accuracy is discussed.

Key Innovations

- Thermal networks are a simplified way of developing building energy models.
- These models are computationally efficient and require lesser simulation time.

Practical Implications

The outcome of the study will benefit rapid energy demand prediction especially for community and city-scale applications. It will help in demand response management.

Introduction

Building sector is contributing around 40% to the total energy consumption globally. It is designated as a major contributor of carbon and greenhouse gas emissions (Frayssinet, et al., 2018). Reducing energy consumption and deriving suitable energy conservation methods for buildings has remained the research priority in the last two decades. However, modelling and simulation of the buildings can prove to be challenging because of increase in building complexity over time making it a resource intensive and time consuming process. So, there is a need for simplified models which can predict the thermal performance of buildings. However, simplifying a model leads to loss of data and accuracy.

For individual buildings a number of simulation tools such as ESP-r, EnergyPlus, TRNSYS are available which provide us precise thermal loads. Many building energy simulation programs for have been developed and validated against measurements (Henninger , Witte , & Crawley , 2004), (Kokogiannakis & Macdonald, 2008) and various standards are there to ensure their reliability (ASHRAE, 2011), (DIN, 2007).

Reduced order modelling is one technique which allows simplified representation of large scale buildings and complex geometries. Reduced order models have been demonstrated to generate results with reasonable accuracy. This technique can be used to study energy consumption and load profiles at a larger scale such as city district scale and also at individual building scale because of reduced complexity of building models.

The prediction accuracy of reduced order models is found to vary based on the building type, geometry and thermophysical property of the envelope. There is a dearth of literature on reduced order models in the Indian context especially in residential settings. In this context this article presents an application of reduced order models, particularly thermal network models for a residential building considering three alternate wall assemblies. The objectives of the study are to (a) develop a validated thermal network model of a building and evaluate its application for three different wall assemblies, (b) present the effect of model order reduction on the prediction accuracy. The study is limited to thermal network model of three widely used wall assemblies in India - AC (Aerated Concrete), brick and rubble masonry.

Methodology

Real time field measurements for a test bed located in Hyderabad, India (17.3850° N, 78.4867° E) were conducted for the year 2020. Building energy model of the test bed was developed using EnergyPlus and validated using real time field measurements. Thermal network model of the test bed was developed in accordance with VDI 6007 guidelines and validated using real time field measurements. Thermal network models of three widely used Indian wall assemblies: AC, brick and rubble masonry were developed using open modelica and their results were compared with the detailed model. Different order models (5C, 4C, 3C, 2C) of these wall assemblies were developed and prediction accuracy was compared. The following section presents a brief overview of reduced order modelling followed by the development and validation of energy simulation model and reduced order model.

Reduced Order Modelling

Reduced order models are a simplified version of complex models which can precisely predict thermal performance of the building. Such models require less input parameters and their main objective is to take in consideration all the dominant parameters which are affecting the building's behaviour and neglecting others. This significantly decreases the time involved in solving these equations (Lauster, Teichmann, Marcus, Streblow, & Mueller, 2014).

These models try to generate buildings having a lower order but almost same response which reduces the time required for its evaluation (Antoulas, Sorensen, & Gugercin, 2001). These models can be used for real time forecasting of energy consumption and demand.

When considering a reduced order model, some set of requirements should be met depending on the application (Rommes, 2007).

In detailed simulations, to analyse the thermal performance and energy load profile of a building there is a need to know all the energy mechanisms happening throughout the structure. There is a need to physically model the energy conversion and transfer processes which can be conduction, convection, radiation, absorption. Then, these mechanisms are modelled in a mathematical way resulting in a number of differential equations which need to be solved using suitable methods and techniques (Rabenstein, 1994). Considering the level of detail in which building has been modelled with all its relevant properties, the resulting differential equation may be of a higher order which will require extensive resources to solve them (Rabenstein, 1994).

Reduced order models try to simulate and adjudge the thermal performance and load profiles of a building considering significantly lesser number of equations and maintaining the results within certain tolerance limits (Kim, He, Roux, Johannes, & Kuznik, 2019). This enables the user to perform such simulations with a reduced set of resources and lesser computational time. Due consideration is taken to maintain the quality standards of the simulations performed (Rabenstein, 1994).

Thermal Network Model

Thermal networks analyse building elements such as wall, window, roof etc. by breaking them down into a number of elements which will have a uniform temperature throughout.

Usually, the number of these broken-down elements is kept smaller to reduce the overall order of the system. These elements are then simulated for all the energy mechanisms (Gouda, Danaher, & Underwood, 2002). This makes the overall simulation process computationally efficient (Gouda, Danaher, & Underwood, 2002), (Boodi, Beddiar, Amirat, & Benbouzid, 2022).

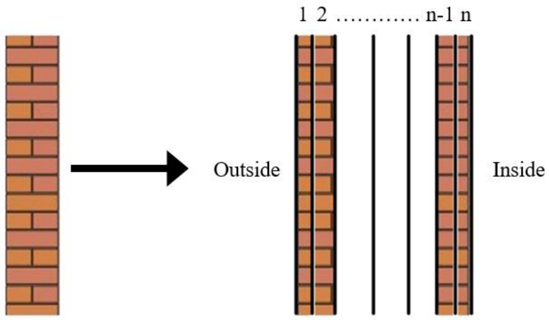

Figure 1: Breaking construction element into number of layers

Thermal network modelling makes use of RC (resistance-capacitance) networks to represent all the energy mechanisms in a building such as conduction, convection, radiation (Shamsi, Grady, Ali, & Donnell, 2014). All the building members are modelled as a combination of resistors and capacitors.

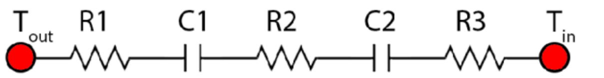

Figure 2: RC equivalent network of a wall (3R2C model)

R1: Resistance due to outside convection
R2: Resistance due to wall conduction
R3: Resistance due to inside convection
The resistors signify the resistance offered to heat transfer via the process of conduction, convection and radiation through various building elements. Capacitors basically represent the heat storing capability and thermal mass of respective building elements (Shamsi, Grady, Ali, & Donnell, 2014). These high-fidelity models provide detailed information but remain computationally efficient for real-time control design (Chinde, 2018).

Thermal Network Parameter Calculation

Material properties of building elements can be used to identify the parameters of the model. Following are the equations and methods used to calculate the total capacitance and resistance of the thermal network model (Chinde, 2018):

$$R_{total} = \left(\sum_{j=1}^{n} \frac{x_j}{k_j} / A \right)$$

$$C_{total} = A \sum_{j=1}^{n} x_j \rho_j c_{p,j}$$

Where,

j: Individual layer of the element;

x: Thickness of the layer

k: Layer R-value;

A: Area;

ρ: Layer density

$c_{p,j}$: Specific heat of each layer

These material properties are then used to calculate the parameters.

Thermal Network Model Order

With the increase in building size, the model order increases and poses challenges for real-time estimation and control applications. In order to handle this, several model reduction methods such as using constrained optimization (Gouda, Danaher, & Underwood, 2002), aggregation (Deng, Goyal, Barooah, & Mehta, 2014), balanced truncation (Goyal & Barooah, 2012) have been used to reduce the order of model.

The accuracy of thermal network model depends on the order of the model. Increasing model order increases the accuracy but also results in increased computational time.

The order of the model is represented by the number of capacitors used to represent the respective building element. A building can be modelled as a combination of building elements having the same model order or different model orders. Depending on the effect of a certain building element on simulation accuracy, the order of the model is decided.

Thermal Network Model of Residential Test Bed

The residential unit test bed is located in Hyderabad, India (17.3850° N, 78.4867° E). Hyderabad predominantly has a tropical wet and dry climate according to Koppen-Geiger climatic classification. The unit has a built-up area of 40 square meter (Figure 2).

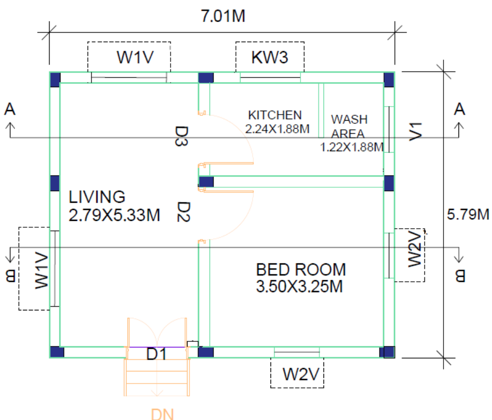

Figure 3: Floor Plan of Building

Measurements of indoor and outdoor environmental variables: dry bulb temperature, surface temperature, zone temperature, humidity were recorded in real time for the year 2020.

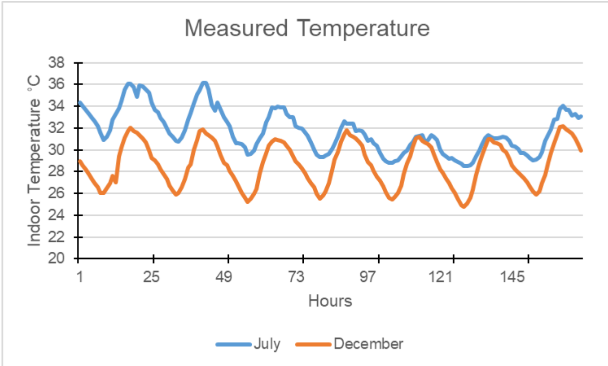

Figure 4 Measured Temperature of Bedroom

Figure 4 depicts the measured indoor air temperature of bedroom for first week of July and December.

Detailed model of bedroom was developed in EnergyPlus. The simulated and measured indoor air temperature was compared as shown in figure 5. It yielded a MAE of 0.82˚C.

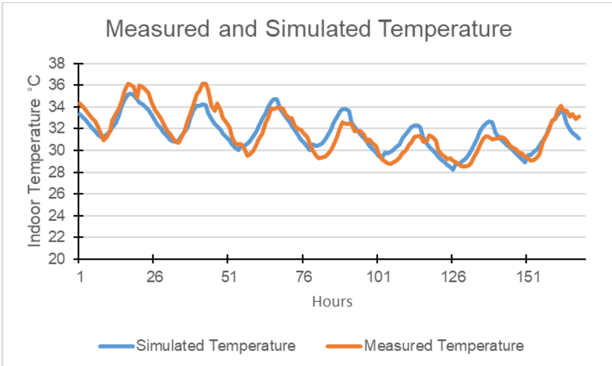

Figure 5 Measured and simulated temperature

Thermal network model of the unit was developed using open modelica. Various components such as external walls, internal walls, windows, roof were modelled using thermal network model. The value of resistors and capacitors were calculated using thermal properties of respective material. The indoor temperature of bedroom was estimated using thermal network model.

Figure 6: Residential Test Bed

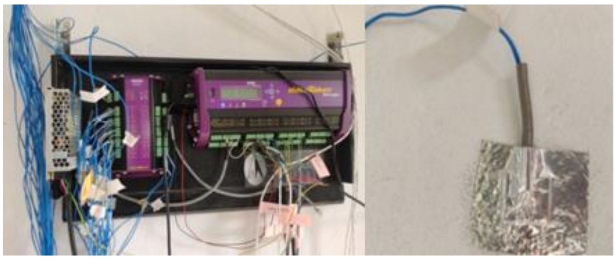

Figure 7: Installed Sensors

Figure 6 presents the residential test bed. Figure 7 depicts the installed sensors in test bed.

Thermal Network Model of Bedroom

Thermal network model of bedroom was developed in accordance to VDI 6007 standards (German Association of Engineers, 2015).

Table 1 Thermal Capacitance and Resistance of Bedroom

	Thermal Conductivity (W/m-K)	Thickness (m)	Area (sqm.)	Density (kg/cubic m)	Specific Heat Capacity (J/Kg-K)	R (K/W)	C (J/K)
Roof	2.27	0.1524	13.806	2321.4	837.36	0.005	4089922
South Wall							
Plaster	0.72	0.01	10.332	1760	840	0.001	152748
Brick	0.72	0.21	10.332	1920	840	0.028	3499324
Plaster	0.72	0.01	10.332	1760	840	0.001	152748
Wall Total						0.031	3804821
West Wall							
Plaster	0.72	0.01	12.031	1760	840	0.001	177866
Brick	0.72	0.21	12.031	1920	840	0.024	4074755
Plaster	0.72	0.01	12.031	1760	840	0.001	177866
Wall Total						0.027	4430488
Living/Bedroom Wall							
Plaster	0.72	0.01	11.831	1760	840	0.001	174910
Brick	0.72	0.21	11.831	1920	840	0.025	4007018
Plaster	0.72	0.01	11.831	1760	840	0.001	174910
Wall Total						0.027	4356837
Kitchen/Bedroom Wall							
Plaster	0.72	0.01	13.518	1760	840	0.001	199850
Brick	0.72	0.21	13.518	1920	840	0.022	4578384
Plaster	0.72	0.01	13.518	1760	840	0.001	199850
Wall Total						0.024	4978085
West Window	1	0.003	1.487			0.002	
South Window	1	0.003	1.499			0.002	

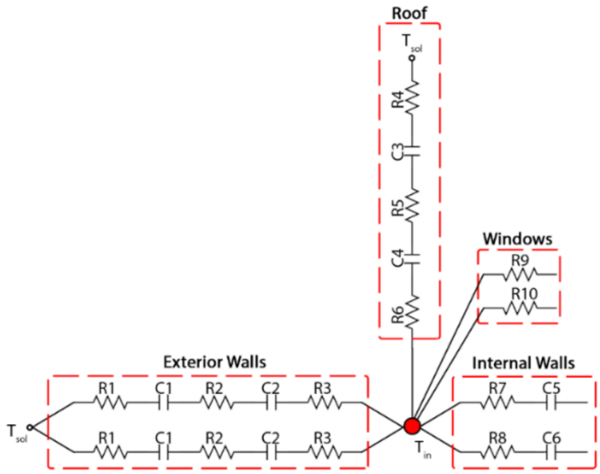

Figure 8 Thermal Network Model of Bedroom (3R2C)

T_{sol}: sol air temperature

T_{in}: Indoor air temperature

R1: Resistance due to outdoor convection

R2: Resistance due to wall conduction

R3: Resistance due to inside convection

C1, C2: Thermal capacitance of wall

R4: Resistance due to outdoor convection

R5: Resistance due to roof conduction

R6: Resistance due to inside convection

C3, C4: Thermal capacitance of roof

R7, R8: Resistance due to wall conduction

C5, C6: Thermal capacitance of internal walls

R9, R10: Resistance due to window

Figure 8 depicts the thermal network model of the bedroom.

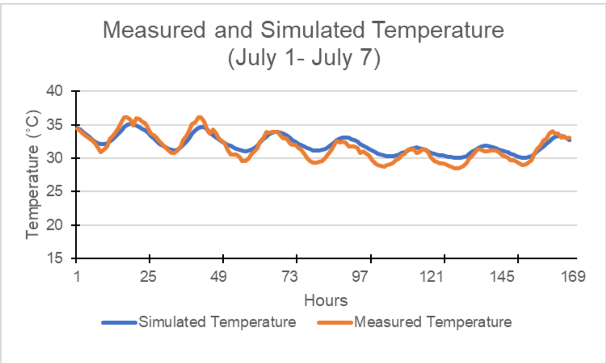

Figure 9 Measured and Simulated Temperature of Bedroom

Figure 9 depicts the comparison between measured and simulated indoor air temperature for thermal network model. A 3R2C model yielded a MAE of 0.76 ˚C as shown in figure 9. Thermal network model was able to predict indoor air temperature upto a reasonable accuracy.

Thermal Network Model for Different Indian Wall Assemblies

Thermal network model for the test bed was prepared to simulate the indoor mean temperature. Three wall assemblies were chosen which are as follows: rubble masonry, brick, aerated concrete (AC). The material properties are as shown in table 2.

Table 2 Material Properties

	Thermal Conductivity (W/m-K)	Thickness (m)	Density (Kg/cubic m)	Specific Heat Capacity (J/Kg-K)	U Value (W/m^2-K)
Rubble Masonry	2.3	0.3	2600	1000	3.329
Brick	0.72	0.21	1920	840	2.043
AC	0.11	0.2	2800	896	0.503

For all the three wall assemblies, model of different orders (3R2C, 4R3C, 5R4C, 6R5C) were developed.

The prediction accuracy of these model orders was compared using one way ANOVA test. There were no statistically significant differences between group means as determined by one-way ANOVA ($F = 0.01$, $p = .999$) in case of AC. The results for brick and rubble masonry were similar.

MAE of different models are shown in table 3.

Table 3 Mean Absolute Error (˚C)

	AC	**Brick**	**Rubble Masonry**
3R2C	0.610	0.638	1.116
4R3C	0.653	0.658	1.123
5R4C	0.659	0.661	1.125
6R5C	0.656	0.661	1.126

As per literature and VDI 6007 guidelines (German Association of Engineers, 2015), 3R2C models are mostly preferred.

Figure 10 represents the comparison of indoor dry bulb temperature predicted using thermal network model (3R2C) and detailed model in case of AC wall assembly. It yielded a MAE of 0.61˚C. The maximum temperature of thermal network model is corresponding to maximum temperature of detailed model, however minimum temperature are unequal. Thermal network model estimates lesser heat loss when compared to detailed model.

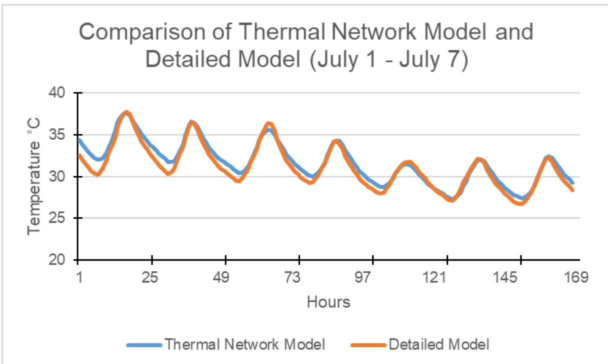

Figure 10 Comparison of Thermal Network Model and Detailed Model in case of AC

Figure 11 represents the comparison of indoor dry bulb temperature predicted using thermal network model (3R2C) and detailed model in case of brick. It yielded a MAE of 0.638˚C. The minimum temperature of thermal network model is corresponding to minimum temperature of detailed model, however maximum temperature are unequal. Thermal network model estimates more heat gain when compared to detailed model.

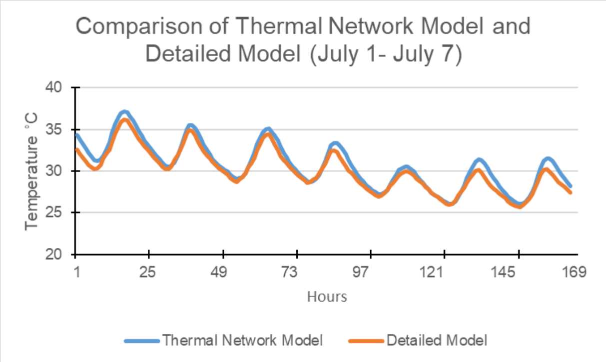

Figure 11 Comparison of Thermal Network Model and Detailed Model in case of Brick

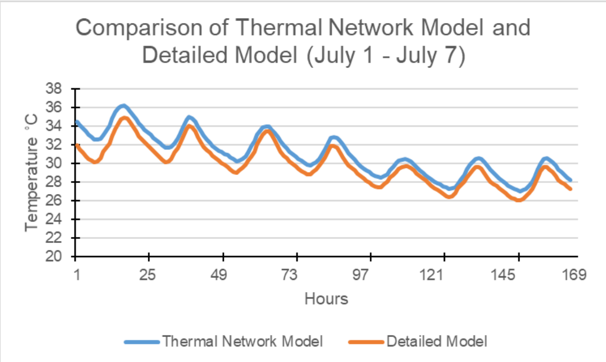

Figure 12 Comparison of Thermal Network Model and Detailed Model in case of Rubble Masonry

Figure 12 represents the comparison of indoor dry bulb temperature predicted using thermal network model (3R2C) and detailed model in case of rubble masonry. It yielded a MAE of 1.116˚C. The maximum temperature and minimum temperature in case of thermal network model and detailed model are not corresponding. Thermal network model is estimating more heat gain and less heat loss when compared to detailed model.

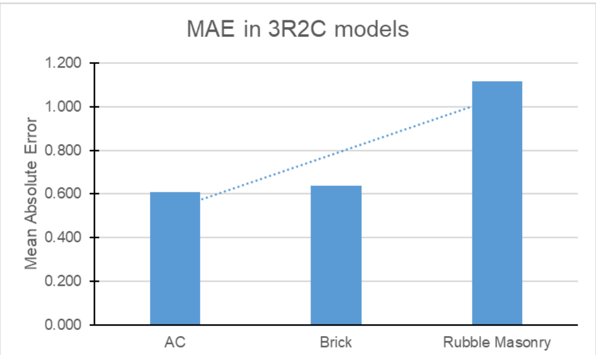

Figure 13 Mean Absolute Error in case of different materials

Mean absolute error of models of different materials were compared. As the U value and thermal mass increases the mean absolute error increases. Thermal mass is associated with thermal capacitance, so a correction factor needs to be developed for thermal capacitance in case of high thermal mass materials.

Conclusion

The study presented the thermal network model of three widely used Indian wall assemblies- AC, brick and rubble masonry. Thermal network model of a test bed was developed and validated (MAE: 0.76˚C). The MAE of second order thermal network model (3R2C) for the three wall assemblies ranged between 0.61 to 1.116 ˚C. Prediction accuracy of different orders was tested. No significant difference was found between prediction accuracy of different order models for the test bed under consideration. Significant difference might occur with increase in building complexity and scale. The prediction accuracy of thermal network model increased with increase in U value. The prediction accuracy of thermal network model of low thermal mass materials was higher compared to high thermal mass materials. Further work is required to investigate composite wall assemblies and complex building geometries.

References

Antoulas, A., Sorensen, D., & Gugercin, S. (2001). A survey of model reduction methods for large-scale systems. *Contemporary Math*, 193-219.

ASHRAE. (2011). *Standard 140-2011-Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs.*

Boodi, A., Beddiar, K., Amirat, Y., & Benbouzid, M. (2022). Building Thermal-Network Models: A Comparative Analysis, Recommendations, and Perspectives. *Energies*.

Chinde, V. (2018). *Modeling and control of complex building energy systems.* Iowa: Iowa State University.

Deng, K., Goyal, S., Barooah, P., & Mehta, P. G. (2014). Structure-preserving model reduction of nonlinear building thermal models. *Automatica*, 1188-1195.

DIN. (2007). *Energy Performance of Buildings - Calculation of Energy Needs for Space Heating and Cooling Using Dynamic Methods.*

Frayssinet, L., Merlier, L., Kuznik, F., Hubert, J.-L., Milliez, M., & Roux, J.-J. (2018). Modeling the heating and cooling energy demand of urban buildings at city scale. *Renewable and Sustainable Energy Reviews, 81*, 2318-2327.

German Association of Engineers. (2015). *Calculation of transient thermal response of rooms and buildings - Modelling of rooms (VDI 6007-1).*

Gouda, M. M., Danaher, S., & Underwood, C. (2002). Building thermal model reduction using nonlinear constrained optimization. *Building and Environment*, 1255-1265.

Goyal, S., & Barooah, P. (2012). A method for model-reduction of non-linear thermal dynamics of multi-zone buildings. *Energy and Buildings*, 332-340.

Henninger , R. H., Witte , M. J., & Crawley , D. B. (2004). Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100–E200 test suite. *Energy and Buildings*, 855-863.

Kim, E.-J., He, X., Roux, J.-J., Johannes, K., & Kuznik, F. (2019). Fast and accurate district heating and cooling energy demand and load calculations using reduced-order modelling. *Applied Energy, 238*, 963-971.

Kokogiannakis, G., & Macdonald, I. A. (2008). History and development of validation with the ESP-r simulation program. *Building and Environment* , 601-609.

Lauster, M., Teichmann, J., Marcus, F., Streblow, R., & Mueller, D. (2014). Low order thermal network models for dynamic simulations of buildings on city district scale. *Building and Environment*, 223-231.

Rabenstein, R. (1994). Application of model reduction techniques to building energy simulation. *Solar Energy*, 289-299.

Rommes, J. (2007). *Methods for eigenvalue problems with applications in model order reduction.* Utrecht: University of Utrecht.

Shamsi, M. H., Grady, W. O., Ali, U., & Donnell, O. J. (2014). A generalization approach for reduced order modelling of commercial buildings. *CISBAT 2017 International Conference Future Buildings & Districts Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland*, 901-906.