Static and dynamic thermal properties of construction components: A comparison in idealized and experimental conditions using lumped parameter models

To cite this article: Lamberto Tronchin et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 609 072042

View the article online for updates and enhancements.
Static and dynamic thermal properties of construction components: A comparison in idealized and experimental conditions using lumped parameter models

Lamberto Tronchin1,*, Massimiliano Manfren2, Vincenzo Vodola1, Fabio Bisegna3, Fabio Nardecchia3

1 Department of Architecture (DA), University of Bologna, Via Cavalcavia 61, 47521 Cesena, Italy
2 Faculty of Engineering and Physical Sciences, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom
3 Department of Astronautical, Electrical Energy Engineering (DIAEE), Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy

* lamberto.tronchin@unibo.it

Abstract. The U values assumptions for construction components represent a significant source of uncertainty when estimating the energy performance of buildings. This uncertainty affects decision-making processes in multiple ways, from policy making to design of new and refurbished buildings. The correct estimation of both static (e.g. thermal transmittance) and dynamic thermal properties is crucial for quality assurance in building performance assessment. Further, while today many sophisticated simulators are available for building performance modelling, lumped parameter models can help reducing computational time for parametric simulation or optimization and enable inverse estimation of lumped thermal characteristics. A lumped parameter approach for construction components is proposed, for example, by the ISO 52016-1:2017 norm, introducing simplifications that are intrinsically dependent on component’s stratigraphy. This approach complements ISO 13786:2017 norm method, which is limited to steady-state periodic temperature and heat flux boundary conditions. In this research we consider these two different approaches, detailed and lumped modelling, comparing them first in idealized conditions and then in experimental conditions to analyse the robustness of methods.

1. Introduction

The U values assumptions for construction components represent a significant source of uncertainty when estimating the energy performance of buildings [1]. This uncertainty affects decision making processes in multiple ways, from policy making to design of new and refurbished buildings [2], including aspects such as indoor environmental quality [3], technical systems sizing [4] but also critical issues such as long-term preservation of historical heritage buildings [5]. Indeed, performance should be monitored during building life cycle, for example by using indicators for heating and cooling systems [6, 7], electricity and interaction with the grid [8] and primary energy consumption [9], comparing also design phase estimates and operation data [10], to learn from feedback and reduce progressively the performance gap [11, 12]. Considering the present necessity of linking calculation methodologies that are applied for performance assessment in different phases of building life cycle, we report in this paper preliminary results from a test facility, following an experimental campaign on different pre-fabricated (structural and anti-seismic) opaque construction components for high-efficiency and low-cost development in the Mediterranean area. More specifically, the research presented is part of a more general activity focused on modelling approaches for simulation and inverse estimation (using reduced order models) that could be easily employed in probabilistic simulation strategies [13, 14], to investigate
building technologies performance in terms of heat transfer [15], acoustics [16], as well as dynamic interaction with other innovative energy technologies [17, 18].

2. Methodology

Many sophisticated simulators are available today for building performance modelling, but a performance gap is generally observed empirically [11]. This gap between simulated and measured performance is due to the relevant uncertainties of the assumptions introduced in building performance assessment. Physical-statistical lumped parameter models can help reducing computational time in simulation (forward modelling) and enable also inverse parameter estimation (inverse modelling) [19].

In the recently introduce ISO 52016-1 standard [20] (which supersedes the consolidated ISO 13790) a lumped modelling approach for walls is proposed, with a classification based on walls’ stratigraphy. This approach is part of the strategy of ISO 52000 framework [21] that retains and updates other standards, for example ISO 6946 for construction component stationary thermal performance, and ISO 13786 [22] for dynamic construction components thermal performance. The approach proposed at the normative level for building performance simulation (ISO 52016-1) is substantially similar, in principles, to research focused on lumped parameter modelling using resistance-capacitance (RC) analogy [23] and analytical calculations [24, 25]. The conversion of RC models in state-space form and then in time series is described in detail in recent literature [15, 26]. Further, the correct identification of the impact of thermal capacity of building fabric (ideally represented as a lumped capacitance) is a relevant research issue [27]. Finally, the use of reduced order models for building performance simulation is an active research field at present, with multiple possible applications [28].

3. Case study analysis

In this research we analyse two approaches, detailed and lumped parameters modelling, comparing them first in standard conditions and then in experimental conditions, considering the issues highlighted in Section 2. The experimental setup and the related lumped model are depicted in Figure 1.

![Figure 1. Experimental setup and simplified model considered for the analysis](image-url)
\[ U = \frac{\sum_{t=0}^{n} q_{in,n}}{\sum_{t=0}^{n} \Delta T_{n}} = \frac{1}{U_{1}} + \frac{1}{U_{2}} = \frac{1}{R_{1} + R_{2}} = \frac{1}{R} \]  

(1)

\[ C_{m} \frac{dT_{m}}{dt} = q_{in} - q_{out} \]  

(2)

\[ q_{in} = U_{1}(T_{i} - T_{m}) \]  

(3)

\[ q_{out} = U_{2}(T_{m} - T_{e}) \]  

(4)

\[ C_{m} \frac{dT_{m}}{dt} = U_{1}(T_{1} - T_{m}) + U_{2}(T_{e} - T_{m}) \]  

(5)

\[ T_{m,i+1} = T_{m,i} \left( 1 - \frac{(U_{1} \Delta t)}{C_{m}} - \frac{(U_{2} \Delta t)}{C_{m}} \right) + \left( \frac{U_{1} \Delta t}{C_{m}} \right) T_{i,i} + \left( \frac{U_{2} \Delta t}{C_{m}} \right) T_{e,i} \]  

(6)

where \( U \) (W/m²K) is thermal transmittance experimentally determined using ISO 9869, \( q_{in} \) (W/m²) is the heat flux entering in the lumped capacity of wall, \( q_{out} \) (W/m²) is the heat flux exiting from the lumped capacity of wall, \( n \) is the number of data points, \( U_{1} \) and \( U_{2} \) (W/m²K) are conductances on the internal and external side, \( R \) (m²K/W) is the total resistance, \( R_{1} \) and \( R_{2} \) (m²K/W) are thermal resistances on the internal and external side, \( T_{i} \) (°C) is internal air temperature, \( T_{e} \) (°C) is external air temperature, \( \Delta T = T_{i} - T_{e} \), \( C_{m} \) (J/m²K) is the lumped thermal capacity per unit of wall area, \( t \) (s) is time, \( i \) is a time index in the time series.

The time series model used for calculation (Equation 6) corresponds to the explicit discretization of Equation 5 in ARX (Autoregressive with Exogenous Input) form. Assumptions for the calculation of \( U_{i} \) has been made considering the thermal mass lumped on the internal side, as prescribed by ISO 52016-1 for the specific stratigraphy of our component (with insulation on external layer). Further, the lumped thermal capacity \( C_{m} \) assumed in simulation (estimated from regression coefficients) is very near to the internal areal heat capacity \( k_{1} \) calculated using ISO 13786, i.e. assuming sinusoidal periodic steady-state conditions. A detailed explanation on this assumption can be found in [26] and extensions in [31].

### 3.1. Initial research activity

As anticipated, the construction component tested is part of a test facility and has been design to adaptable in terms of insulation levels, for code compliance in different conditions. The stratigraphy of the component is reported in Table 1, where layers are defined from the internal to the external side.

| Table 1. Summary of assumptions on thermo-physical properties of construction component in design phase (before experimental activity) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Layers                          | Thickness (d)   | Conductivity (λ) | Density (ρ)    | Specific heat (c) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| 1 Internal coating              | 0.010           | 0.640           | 1500            | 1000            |
| 2 Lightweight brick             | 0.120           | 0.600           | 750             | 940             |
| 3 Reinforced concrete           | 0.160           | 1.800           | 2500            | 1000            |
| 4 EPS - thermal insulation      | 0.100           | 0.037           | 35              | 1480            |
| 5 External coating              | 0.010           | 0.640           | 1500            | 1000            |

Aggregated stationary (\( U \)) and dynamic (\(|Y|_{\Delta t}|, |\Delta t|, k_{1}\)) thermal properties have been calculated using data from Table 1 and ISO 6946 [29] and ISO 13786 [22] methodologies. The results are summarized in Table 2. In the same table, we compare the \( U \) value estimated in the design phase with the one determined experimentally following ISO 9869 [30] methodology. The initial estimate lays within the confidence interval of the experimental value.
Table 2. Result of performance calculation in design phase and experimental activity conducted using standard normative approaches

| Phase         | Technical standards | Thermal transmittance $(U)$ | Periodic thermal transmittance $(|Y_{ie}|)$ | Modulus of time lag of periodic thermal transmittance $(|\Delta t_f|)$ | Internal areal heat capacity $(k_i)$ |
|---------------|---------------------|-----------------------------|-------------------------------------|-------------------------------------------------|---------------------------------|
| Design        | ISO 6496, ISO 13786 | 0.31                        | 0.03                                | 10.05                                           | 48.58                           |
| Experimental  | ISO 9896            | $0.33 \pm 0.03$             | -                                   | -                                               | -                               |

3.2. Testing of simplified time series model for dynamic wall simulation

In this part of the research, the goal is simulating the dynamic behaviour with a simplified time series approach (Equation 6). Experimental (external and internal) air temperatures are presented in Figure 2.

Figure 2. External and internal air temperature for the experiment

As it can be noticed in Figure 2, internal air temperature is kept steadily increasing in our experiment, and data are collected for 80 hours (the minimum suggested time span for applying ISO 9869 is 72h, i.e. 3 days of measurements) with a temporal resolution of 1.5 minutes. In Figure 3 we compare the temperature of lumped thermal mass simulated by means of time series model (Equation 6) and calculated from filtered heat flux data (more details on heat flux measurement filtering can be found in
The goodness of fit of the time series models proposed is high for the construction component considered in this experiment, essentially confirming the validity of the simplification adopted in ISO 52016-1 standard and in recent research work on dynamic thermal behaviour of walls. Further research is will be necessary to improve model fitting by reducing deviations and identifying patterns in time, using both time and frequency domain analysis.

4. Conclusion

This research aims to present a simplified time series based approach compatible both with dynamic performance simulation in design phase and inverse model parameter estimates in operation phase. In this case study we conducted our analysis on a pre-fabricated opaque construction component, which is part of a test facility. The approach proposed can be used potentially for other types of components which present a similar stratigraphy, following the classification given in ISO 52016-1. The methodology presented aims to trace a line of continuity between design phase simulation and operation phase analysis (in situ measurement in this specific case), including extensions to regression-based methods for overall building performance analysis. The continuity in the use of models as well as their comparability and ease of use are important factors to reduce the performance gap and to improve the ability to learn from technology evolution on continuous base. The approach tested is a simple analytical approach using linear algebra and regression and its performance can be improved by further research focused on the reduction of deviations and on the identification of patterns in time, using both time and frequency domain analysis. In any case, the goodness of fit of the time series models proposed is adequate for the level of accuracy normally considered in building performance simulation, essentially confirming the validity of the simplification adopted by ISO 52016-1 standard and by recent research work on dynamic thermal behaviour of walls.

References

[1] Berardi U, Tronchin L, Manfren M and Nastasi B 2018 On the effects of variation of thermal conductivity in buildings in the Italian construction sector Energies 11 872
[2] De Santoli L, Mancini F, Nastasi B and Ridolfi S 2017 Energy retrofitting of dwellings from the 40’s in Borgata Trullo-Rome Energy Procedia 133 281-9
[3] Fabbri K and Tronchin L 2015 Indoor environmental quality in low energy buildings Energy Procedia 78 2778-83
[4] De Santoli L, Basso G L and Nastasi B 2017 Innovative Hybrid CHP systems for high temperature heating plant in existing buildings Energy Procedia 133 207-18
[5] Tronchin L and Fabbri K 2017 Energy and Microclimate Simulation in a Heritage Building: Further Studies on the Malatestiana Library Energies 10 1621
[6] Noussan M and Nastasi B 2018 Data analysis of heating systems for buildings—A tool for energy planning, policies and systems simulation Energies 11 233
[7] Tronchin L, Manfren M and Nastasi B 2019 Energy analytics for supporting built environment decarbonisation Energy Procedia 157 1486-93
[8] Manfren M 2012 Multi-commodity network flow models for dynamic energy management—Mathematical formulation Energy Procedia 14 1380-5
[9] Noussan M, Roberto R and Nastasi B 2018 Performance indicators of electricity generation at country level—The case of Italy Energies 11 650
[10] Tronchin L, Manfren M and James P A 2018 Linking design and operation performance analysis through model calibration: Parametric assessment on a Passive House building Energy 165 26-40
[11] Imam S, Coley D A and Walker I 2017 The building performance gap: Are modellers literate? Building Services Engineering Research and Technology 38 351-75
[12] Allard I, Olofsson T and Nair G 2018 Energy evaluation of residential buildings: Performance gap analysis incorporating uncertainties in the evaluation methods Building Simulation 11 725-37
[13] Cecconi F R, Manfren M, Tagliabue L C, Ciribini A L C and De Angelis E 2017 Probabilistic behavioral modeling in building performance simulation: A Monte Carlo approach Energy and Buildings 148 128-41
[14] Tagliabue L C, Manfren M, Ciribini A L C and De Angelis E 2016 Probabilistic behavioural modeling in building performance simulation—The Brescia eLUX lab Energy and Buildings 128 119-31
[15] Raillon L and Ghiaus C 2017 Study of Error Propagation in the Transformations of Dynamic Thermal Models of Buildings Journal of Control Science and Engineering 2017 15
[16] Tronchin L 2013 Francesco Milizia (1725-1798) and the Acoustics of his Teatro Ideale (1773) Acta Acustica United with Acustica 99 91-7
[17] Castellani B, Morini E, Nastasi B, Nicolini A and Rossi F 2018 Small-Scale Compressed Air Energy Storage Application for Renewable Energy Integration in a Listed Building Energies 11 1921
[18] Nastasi B, Basso G L, Garcia D A, Cumo F and de Santoli L 2018 Power-to-gas leverage effect on power-to-heat application for urban renewable thermal energy systems International Journal of Hydrogen Energy 43 23076-90
[19] Hong T and Lee S H 2019 Integrating physics-based models with sensor data: An inverse modeling approach Building and Environment 154 23-31
[20] ISO/FDIS 52016-1:2016 Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent head loads - Part 1: Calculation procedures (final draft).
[21] ISO/DIS 52000-1:2017, Energy performance of buildings — Overarching EPB assessment – Part 1: General framework and procedures (draft).
[22] ISO 13786:2017, Thermal performance of building components - Dynamic thermal characteristics - Calculation methods.
[23] Gori V, Marincioni V, Biddulph P and Elwell C A 2017 Inferring the thermal resistance and effective thermal mass distribution of a wall from in situ measurements to characterise heat transfer at both the interior and exterior surfaces Energy and Buildings 135 398-409
[24] Fraisse G, Viardot C, Lafabrie O and Achard G 2002 Development of a simplified and accurate building model based on electrical analogy Energy and Buildings 34 1017-31
[25] Ramallo-González A P, Eames M E and Coley D A 2013 Lumped parameter models for building thermal modelling: An analytic approach to simplifying complex multi-layered constructions Energy and Buildings 60 174-84
[26] Naveros I, Ghiaus C, Ruiz D P and Castaño S 2015 Physical parameters identification of walls using ARX models obtained by deduction Energy and Buildings 108 317-29
[27] Mantesi E, Hopfe C J, Cook M J, Glass J and Strachan P 2018 The modelling gap: Quantifying the discrepancy in the representation of thermal mass in building simulation Building and Environment 131 74-98
[28] Kramer R, van Schijndel J and Schellen H 2012 Simplified thermal and hygric building models: A literature review Frontiers of Architectural Research 1 318-25
[29] ISO 6946:2017, Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.
[30] ISO 9869-1:2014, Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance - Part 1: Heat flow meter method.
[31] Gasparella A, Pernigotto G, Baratieri M and Baggio P 2011 Thermal dynamic transfer properties of the opaque envelope: Analytical and numerical tools for the assessment of the response to summer outdoor conditions Energy and Buildings 43 2509-17
[32] Bishara N, Prada A, Pernigotto G, Baratieri M and Gasparella A 2016 Analysis of the Measurements Reliability in Dynamic Test of the Opaque Envelope. In: International High Performance Buildings Conference.