A Linear Data-Driven System Identification Methodology for an Active/Passive Solar Thermal Storage System and Application to a Solar House

Amélie Allard, MASc, Eng.[1], Andreas K. Athienitis, PhD, Eng. [2]
[1]Research Assistant, Department of Building, Civil and Environmental Engineering.
Concordia University, Montréal, Canada.
[2]NSERC/Hydro Quebec Industrial Chair, Concordia University, Montréal, Canada.

Abstract

This paper presents a methodology developed to identify a parametric model of a thermally-activated building system (TABS) using a system identification (SI) tool. The model was identified with collected data from an energy efficient solar single-family residential building. The TABS is a ventilated concrete slab (VCS) serving as an energy storage medium for active and passive solar gains in the basement.

A data-driven system identification approach is used. Identifying a linear model and obtaining a low-order polynomial model were the main identification criteria. The paper addresses the issues of the monitoring sensor accuracy on the model parameters and how physical knowledge of the VCS dynamic system can be considered during its validation.

This paper also demonstrates that the identified linear polynomial model is an efficient tool to carry out redesign studies and possible control studies. An improved building integrated photovoltaic/thermal (BIPV/T) roof design is compared based on increased solar energy utilization potential and potential increase of collected thermal energy stored into the VCS.

1 Introduction

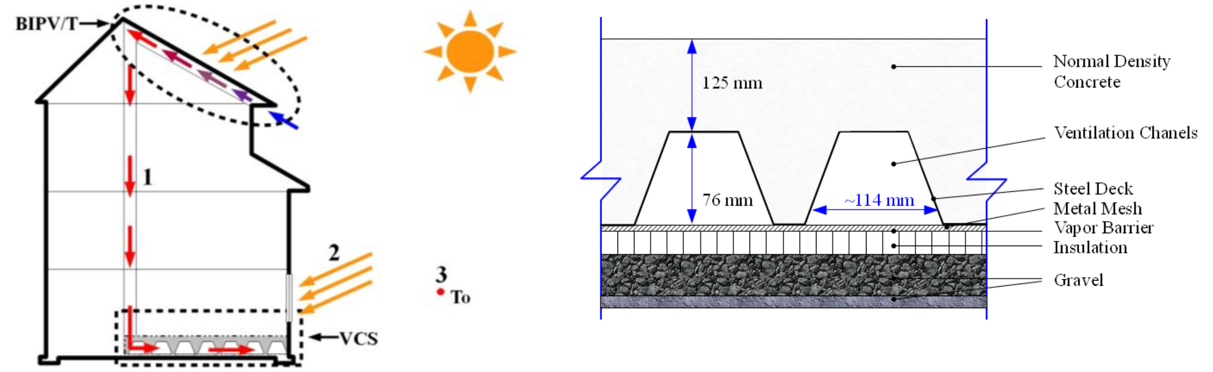
Comfort conditions in high performance buildings must remain satisfactory even while reducing the annual energy consumption and the peak loads. Similarly, to design high performance net-zero energy buildings (NZEBs) renewable energy generation such as that from BIPV/T systems needs to be optimally integrated with energy efficiency measures and HVAC systems. In that context, the control of building-integrated solar systems plays an important role. Therefore, these aspects should be considered when thermal performance simulations are completed.

Kummert et al. (2006) and Wang and Xu (2006) showed that with just a few parameters we can capture the essential behavior of building thermal systems. Candanedo and Athienitis (2011) demonstrated that simplified data-driven models facilitate the development of control strategies for thermal storage systems. This paper presents a methodology to identify a simplified model of an active/passive solar thermal storage system in order to build control strategies that will help optimize its operation by considering a near-net zero house – the Ecoterra™. The model was developed using inverse modelling technique and its mathematical description was obtained from measured data. It is demonstrated that it is an efficient tool to compare design and operation options for building system redesign studies.

The Ecoterra™ House

The Ecoterra™ house was the first of 15 demonstration houses to be built as part of the Equilibrium Sustainable Housing Demonstration Initiative sponsored by the Canadian Mortgage and Housing Corporation. It is a single-family detached dwelling having a total floor area of 211.1 m^2. This house is occupied since 2009 and is equipped with over 150 sensors measuring mainly climate variables, indoor conditions, temperatures, energy consumption of HVAC equipments, and flowrates.

Its main energy systems were designed to reduce the amount of energy dedicated to space heating and domestic hot water. In fact, the energy it annually consumes represents only 11% of the amount a typical Canadian home consumes for space heating and 20% of what it consumes for domestic hot water. Two strongly coupled solar systems of the Ecoterra™ house, illustrated in Figure 1a, were studied; its building integrated photovoltaic/thermal (BIPV/T) roof and the ventilated concrete slab (VCS) located in its basement.



(a) (b)

Figure 1: a) Solar systems of the Ecoterra™ house and three influencing energy inputs during solar dominated periods. b) Cross section of the ventilated concrete slab. Simplified schematic inspired from Y. Chen (2009, p. 92).

The VCS covers a floor area of 36 m^2. It consists of 19 steel channels embedded in approximately 5 m^3 of concrete and was directly placed on grade. The concrete layer above each channel is approximately 12.5 cm thick. The VCS forms a thermal storage system whose state is modified by controlled active solar charging, and by natural heat transfer phenomena such as the passive solar charging. In the basement, the solar radiation is transmitted through 3 south-facing tripled-glazed windows each having a glazing area of 1.8 m^2. The insulation under the basement slab is approximately RSI 1.3 (R7.8). At the time when the sensor data used in this study were recorded, no floor cover was installed and the house was not yet occupied.

The main house energy system producing energy is the BIPV/T roof which forms the largest south-facing roof section. It produces electricity and thermal energy which actively charges the VCS. As shown in Figure 1b, outdoor air is drawn through a cavity (4 cm deep) under the PV system by a variable speed fan located in the mechanical room (basement) of the house. The air can be used for three purposes; preheat the domestic hot water system, dry clothes or actively charge the VCS. In this paper we consider mainly use of heat to charge the VCS. Doiron (2011) completed a whole building energy analysis for this house. The actual energy consumption of the Ecoterra™ house was compared against the modeled values determined prior to the construction and occupation. An important electricity production shortage was discovered due to a higher than expected snow cover on the PV arrays attributable to the less than optimal roof pitch. His work also allowed concluding that the VCS was not used at its full potential. For a similar building project, a more optimized BIPV/T system would allow to increase the house energy production and improving its operation would allow to store higher amounts of solar heat.

The house peak loads are an aspect as important as its net annual energy consumption. At the national level, this demand determines the total electricity capacity required to satisfy peak demands. Therefore, load management and interaction of the house with the electric grid are an important part of the design process of high performance buildings, and particular attention should be given to the coupling of the energy loads and renewable energy generation. Thermal storage, such as the VCS, is an important means to address this issue. It allows the house mechanical equipment size to be reduced at the design stage and the energy demand peaks to be lowered and shifted.

Therefore, a simplified thermal storage model would allow exploration of ways to modify the active charging operation in order to store higher amounts of solar gains. It would allow comparing improved BIPV/T roof designs based on the increase in collected solar energy utilization potential and the possible increase of the collected energy stored into the VCS.

2 Methodology

A methodology was developed in order to better understand and model the thermal behaviour of the ventilated concrete slab. Specifically, research efforts were focused to describe, using a mathematical model, how the active and passive charging of the ventilated concrete slab were influencing its surface temperature.

System identification methods were developed to build mathematical descriptions of the dynamic building response. Once identified, these mathematical models become useful tools for simulation, prediction and control of output variables of any type.

The system identification approach chosen to create the model of the VCS used inverse modeling techniques. The mathematical description the VCS dynamic system was obtained using measured data from the Ecoterrra™ house and statistical regression techniques.

Linearity Requirement and Modelling Assumptions

The modelling identification requirements were set in order to direct the modelling procedure towards a model well suited for thermal evaluations of retrofit solar system design. Therefore, this model had to respect linearity and low order requirements. Based on previous work (Athienitis et al. 1990, Chen, TY 2002 and Candanedo & Athienitis 2011), it is expected that models up to about 5th order (in frequency-Laplace domain) can generally account for the thermal dynamics of solar houses.

The linear description of the properties of a physical system is a mathematical idealization. However, linear models of dynamic systems are useful tools that suit the practical needs of building thermal evaluations.

The model was created for solar dominated conditions (a sequence of several clear days) so that it can be used to optimize the operation of the VCS with storage of heat from the BIPV/T system and its passive discharge. A solar dominated period is defined as a period during which the passive and active solar gains in the house are sufficiently high to maintain its indoor air temperature above the setpoint. It was consequently assumed that, during solar-dominated periods, the auxiliary heat inputs are negligible and that the two solar systems studied are used at their full potential. This assumption was supported with the measured data.

It was assumed that the room air temperature was not influencing significantly the VCS surface temperature during solar dominated periods and, consequently, that the convective heat transfer was mainly occurring from the slab surface to the room air. It was also assumed that the corresponding heat transfer coefficient and the difference of temperature between the room air and the concrete surface temperature remained relatively constant.

The influence of ground temperature was also neglected (the bottom of the VCS slab is insulated). It was assumed that since this temperature is varying with a low frequency (one year), it had no significant influence on the daily fluctuations of the slab surface temperature.

The Ventilated Concrete Slab System

An analysis of the ventilated concrete slab energy inputs and thermal zone energy flows allowed identifying three inputs influencing significantly the slab surface temperature output (y) during the solar dominated periods.

The first input is the heat absorbed by the VCS (u_1) when hot air (from the BIPV/T roof) is passed through its embedded channels (it is then exhausted to the outdoors). This hot air is drawn through the insulated manifold of the roof after it has traveled along its channels and been heated by the sun under the metal roof layer. Therefore, this active charging input can be identified as the only controlled input of the system because it is the only one that can be manipulated by the house control system. The active solar charging of the VCS (u_1) is the input of interest for this study since it represents the input over which operating strategies can be applied to optimize solar thermal storage in the slab.

Solar gains through the basement south windows correspond to the second significant input (u_2) influencing the VCS surface temperature. Passive charging of the slab can be qualified as a measured disturbance because the basement window did not have any controllable shading device.

The third input selected for the identification of the system was the influence of the exterior ambient temperature (u_3) by conduction heat exchanges through the building envelope and partitions. This input can also be qualified as a measured disturbance. Even though the house is highly insulated, it was assumed that the exterior temperature had an indirect impact on the slab surface temperature. As mentioned earlier, the convective heat losses of the slab were considered negligible and not included as an energy input for the slab system.

Data Selection

The signals used to estimate and validate the VCS surface system model were created with data recorded by sensors. Figure 2 shows the position of all the sensors used.

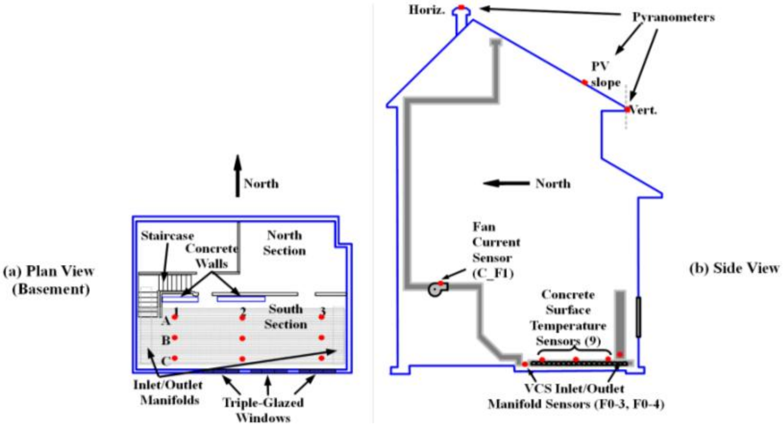
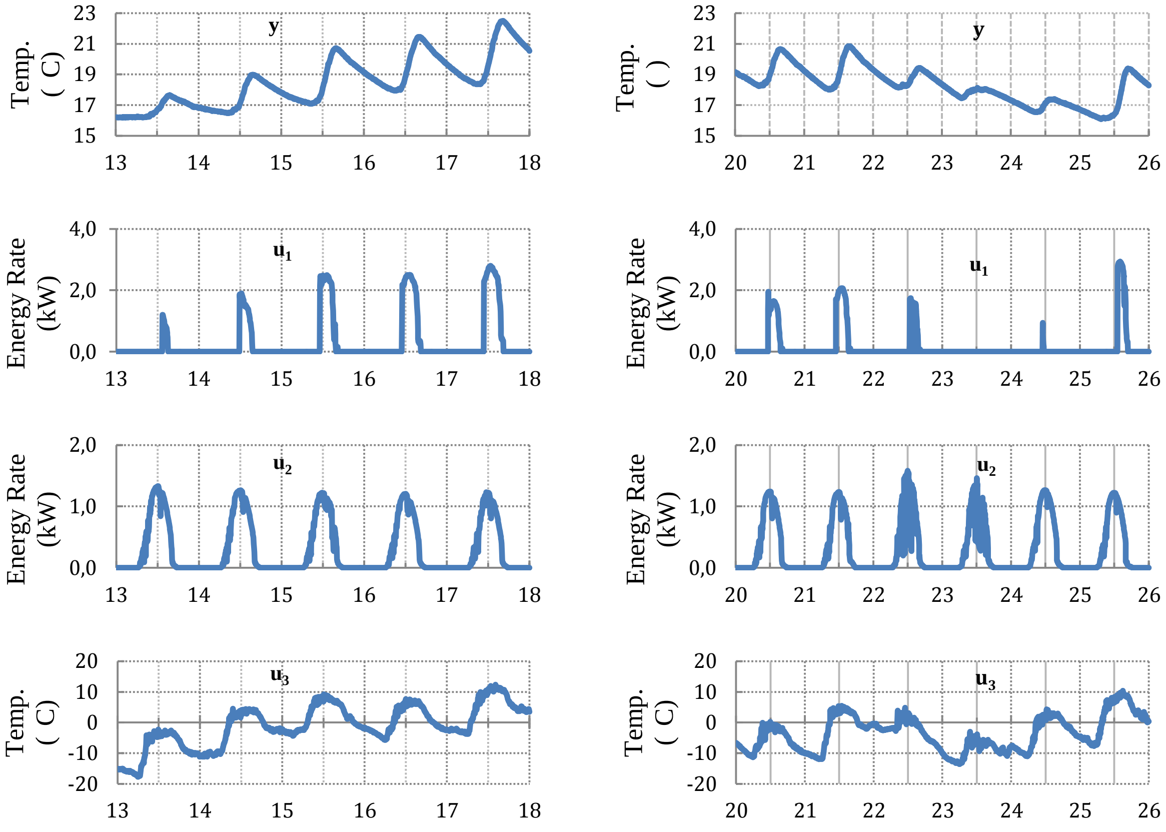


Figure 2: Basement floor plan (a) and side view of the Ecoterra™ house (b) with location of sensors.

The data from 9 VCS surface temperature sensors, two thermocouples recording the air temperature at the inlet and outlet VCS manifolds, by the fan current monitor, and by the three pyranometers located on the roof top were used.

The collected measured data from the Ecoterra™ house were carefully analysed to identify the most suitable monitoring periods for this solar dominated system identification study and two solar dominated periods of data were used to estimate and validate the statistically identified model of the VCS (Figure 3).



March 2009
(a)

March 2009
(b)

Figure 3: Input and output signals used to estimate (a) and validate (b) the VCS surface temperature model.

Model Estimation Procedure

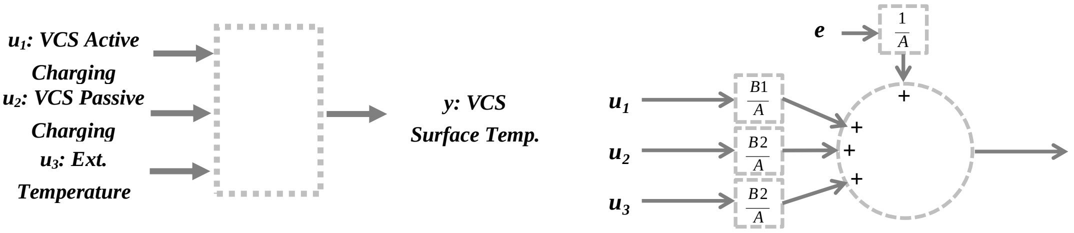
The creation of the linear polynomial model for the VCS was based on an iterative procedure. The search for the best model was restricted to one family of the linear parametric models, the auto-regressive models with an exogenous input (ARX). Therefore, the relationship between the VCS model inputs and output to identify had to respect the ARX structure described by (1) where $e(t)$ is the white noise term.

$$A(q)y(t) = B(q)u(t) + e(t) \tag{1}$$

In the case of VCS surface temperature dynamic system, the model to identify had three inputs- the active solar energy charging u_1, the passive solar energy charging u_2 and the exterior temperature u_3. As a result, the ARX model structure needed to be augmented to accommodate this multiple-input/single-output (MISO) system, as shown below in equation (2).

$$A(q)y(t) = B_1(q)u_1(t) + B_2(q)u_2(t) + B_3(q)u_3(t) + e(t) \tag{2}$$

Therefore, the parameters of four distinct time domain polynomials need to be identified. Figure 4a symbolically depicts the VCS dynamic thermal system and the structure of the model identified is schematized by Figure 4b, where B1/A, B2/A, B3/A, and 1/A represent the four transfer functions of the model (1/A represents the transfer function attributed to the white noise term).



(a) (b)

Figure 4: Symbolic (a) and polynomial ARX transfer function model (b) representation of the VCS surface temperature dynamic system.

The system identification procedure was completed without restricting the model parameter values or integrating any physical insight to the model structure. The model was accepted only once it respected a predefined list of criteria concerning the fit with the validation data and the quality of the residuals.

The system identification procedure involved estimating the group of parameters that together formed the most suitable model for VCS surface temperature prediction. $\theta_{a,b}$ denotes the group of parameters to be determined:

$$\theta_{a,b} = [a_1 \ldots a_{n_a} \quad b1_1 \ldots b1_{n_{b1}} \quad b2_1 \ldots b2_{n_{b2}} \quad b3_1 \ldots b3_{n_{b3}}]^T \tag{3}$$

The coefficients of the polynomials (A, B_1, B_2 and B_3) were determined using the least-squares optimization method of the MATLAB System Identification Toolbox (Mathworks, 2012).

3 Results

The system identification process led to a model having 17 parameters. The iterative system identification process showed that a model made of an 8th order *A* polynomial and third order polynomials for *B1*, *B2* and *B3* respected the fit, stability and residual independence criteria. The fit is a scalar measurement of how well the selected model explains the data and it is calculated as the percentage of the output variations from the monitored data and calculated using (4).

$$FIT = \left(1 - \frac{(\sum_{n=1}^{N} (\mathrm{y(n)} - \hat{y}(n))^2)^{1/2}}{(\sum_{n=1}^{N} (\mathrm{y(n)} - \bar{y})^2)^{1/2}} \right) \cdot 100\% \tag{4}$$

Its fit exceeded 90% (91.6%). The identified time domain model is presented in the z-transform transfer function form as follows:

$$\frac{B_1(\mathrm{z})}{A(z)} = \frac{0.0002191z^{-1} - 7.094e^{05}z^{-2} - 2.453e^{-05}z^{-3}}{A(z)} \tag{5}$$

$$\frac{B_2(\mathrm{z})}{A(z)} = \frac{0.0002382z^{-1} - 1.607e^{05}z^{-2} - 6.719e^{-06}z^{-3}}{A(z)} \tag{6}$$

$$\frac{B_3(z)}{A(z)} = \frac{0.0116z^{-1} - 0.003392z^{-2} - 0.00788z^{-3}}{A(z)} \tag{7}$$

where the polynomial A(z) is presented by (8) and where z is the z-transform operator for discrete representations of Laplace transforms. In this case, the time step was 3600 seconds.

$$\begin{aligned} A(z) = 1 - 1.231z^{-1} - 0.005362z^{-2} + 0.6118z^{-3} + 0.4557z^{-4} + 0.004525z^{-5} \\ +0.1066z^{-6} + 0.02667z^{-7} - 0.05225z^{-8} \end{aligned} \tag{8}$$

Figure 5 shows a good fit between the recorded validation data and the predicted model output. The average absolute value of the model residuals is lower than 0.1 (0.062).

Therefore, it may be concluded that the VCS linear parametric model identified was a reasonable approximation of the true solar thermal storage system and that it was of an acceptable degree of simplicity considering that the VCS surface temperature system is a 3-inputs/1-output dynamic system.

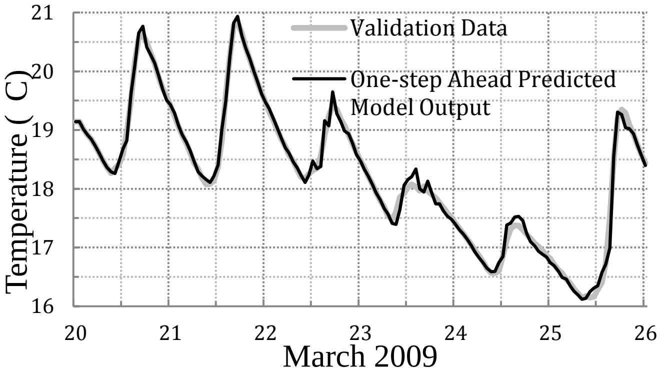


Figure 5: Comparison of the response of the VCS parametric model and monitored data used for validation.

4 Sensistivity Analysis

Data quality is an essential consideration in dynamic system identification applications. The VCS parametric linear model was identified with sensor data from the Ecoterra™ monitoring system and does not incorporate any data correction algorithm. The following table summarizes the accuracies of the sensors which recorded data used for this thesis.

Table 1: Measurement devices and their accuracies (Doiron, 2011, p. 53).

Measurement device	Accuracy
Type T Thermocouples	±0.5 °C
Pyranometers	± 5.0% of reading
Amp Meters	±0.05% of reading + 0.06

An analysis was completed in order to evaluate the effect of the sensor accuracy on the parameters of the ARX VCS surface temperature model. The estimation and validation data used in the system identification procedure presented in the previous chapter were modified in order to simulate the lower and upper bounds of each sensor accuracy range. The transformed data sets were then used to estimate two additional parametric linear models. The same model structure was chosen (ARX) while the polynomial orders and input delays were kept identical. The parameters amplitudes of the two new models were compared to those of the original model. It can be observed from Figure 6 that the amplitudes of the two new model parameters remain similar when they are compared to the parameters of the original VCS surface temperature model. This demonstrates that the system identification procedure presented is, to a small extent only, sensitive to input data imperfections.

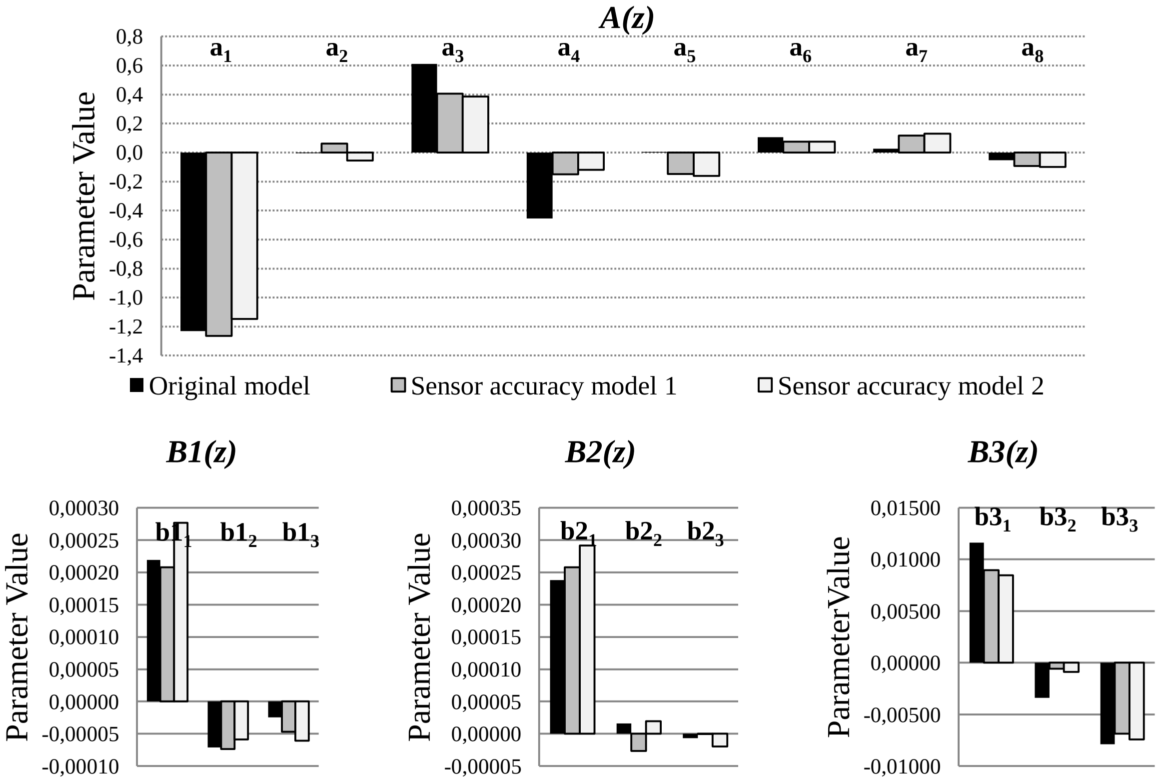


Figure 6: Effect of sensor accuracy on the linear model parameter values.

5 Relative Weight of each input

The system identification process is highly related to its application. Therefore, an insight into the model characteristics remains a crucial step in order to accept the model as a suitable representation of a physical system. Using the three transfer functions of the VCS polynomial model, it was possible to quantify the relative importance of each input variables influencing its surface temperature. Figure 7 shows that inputs u_1 and u_2 have the most important contributions to the concrete surface temperature rise.

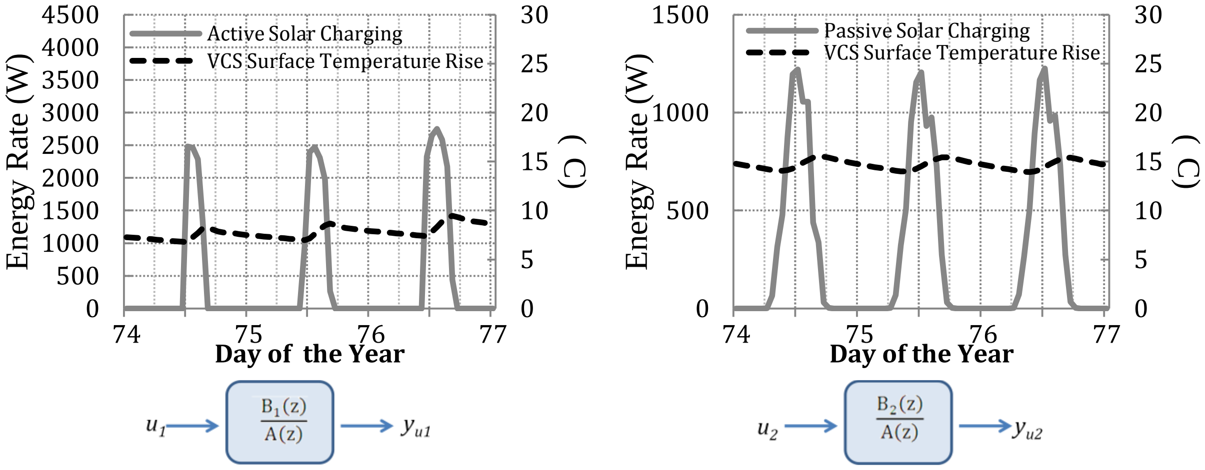


Figure 7: Relative weight of u_1 and u_2 on the surface temperature of the ventilated concrete slab.

The exterior temperature input (u_3) has very little impact on the fluctuation and total temperature response of the slab (Figure 8). The way the ambient temperature influences the amount of energy collected through the BIPV / T system is not considered in this input since it is included in u_1. These results indicate that, for solar dominated periods, the ventilated concrete slab surface temperature is heavily dependent on the passive solar gains and the active solar energy input from the BIPV/T roof through the 19 embedded air channels. The high insulation value of the house and its relatively high air-tightness explain the negligible impact of the exterior temperature on the VCS surface temperature.

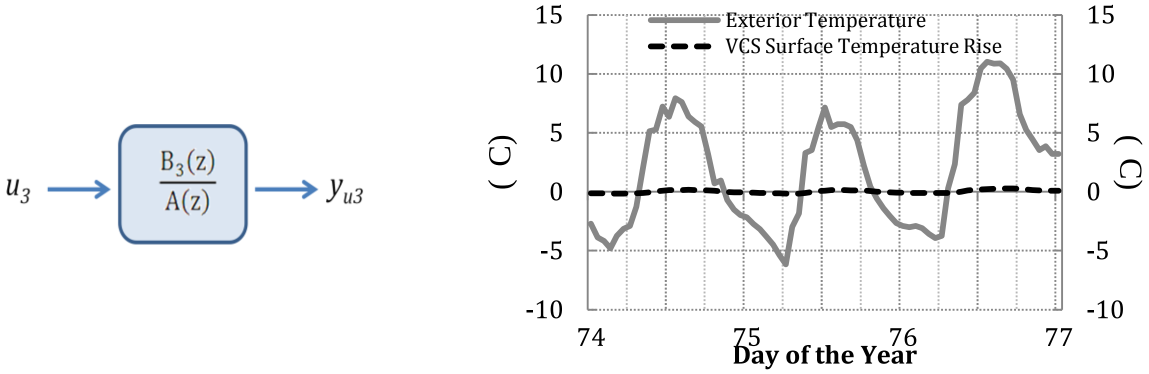


Figure 8: Influence of u_3 (outdoor air temperature) on the surface temperature of the ventilated concrete slab.

Although the data-driven process of system identification was completed without applying any constraints to the polynomial identification, these observations indicate that the VCS parametric model identified adequately models the thermal charging and discharging dynamics of the VCS.

These results also suggest that the VCS surface temperature model could be further simplified by neglecting the exterior temperature as an input to the dynamic system without jeopardizing the validity of the model.

6 Simulation Study Using the Model

An improved BIPV/T design was considered to increase the solar heat (and electricity) available from the roof and its utilization. The identified parametric model, in its transfer function form, was used to study its possible storage into the ventilated concrete slab. As a tool, another model developed by Candanedo (2011) was used for the calculation of the outlet air temperature at the exit manifold of the BIPV/T roof. The simulations were carried out for a typical clear cold day of March using measured data - a day in which no auxiliary heating is required for the house and in which it is desirable to store heat collected from the BIPV/T system for later use (discharge) at night.

Thermal Energy Collection

The effect of modifying the roof angle and including a glazing section was analyzed to explore ways of improving the collection and its possible subsequent heat storage into the slab. A 1.23m vertical glazing section was included in the suggested design to benefit from low solar angles in winter and the increased roof tilt (β=45°) to reduce the accumulation of snow during winter (Figure 9). Candanedo carried out detailed simulations to evaluate the solar energy output of BIPV/T roof configurations including PV and glazing sections. He found that this portion of the BIPV/T structure is thermally beneficial and increases the exit air temperature. While most of the solar radiation is transmitted through the glass of the glazing section, it is captured by the bottom absorber plate.

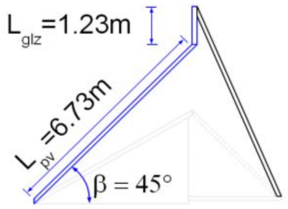


Figure 9: Schematic of the alternative BIPV/T roof design studied to increase solar energy collection and utilization.

The model created by Candanedo used for open-loop building-integrated photovoltaic/thermal systems, was adapted to respect the roof description of Ecoterra™. It allows a steady-state analysis of the roof thermal dynamic phenomena. As presented by Figure 10, the results have confirmed that the new design is highly beneficial for the thermal energy collection.

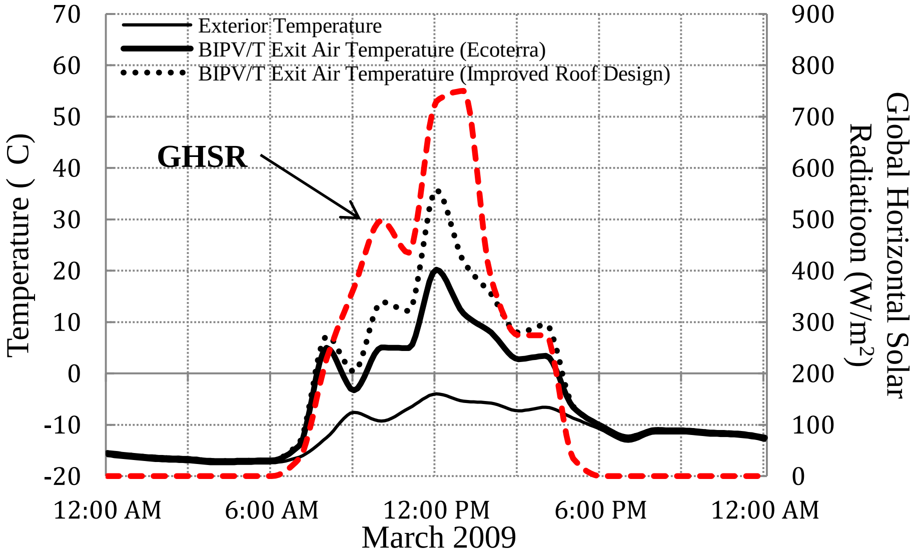


Figure 10: Exit air temperature for the actual Ecoterra™ BIPV/T roof and the design alternative studied, global horizontal solar radiation and exterior temperature.

Solar Heat Storage in the Ventilated Concrete Slab

The most important role of the ventilated concrete slab is to store and release thermal energy, at a desirable rate, in order to reduce the need for space heating. The u_1 transfer function ($G_{BIPV/T}$) from the VCS polynomial model was used to calculate the amount of energy available for storage and the amount of energy that can actually be stored in the ventilated slab. These two quantities were calculated according to equations (9) and (10) using the values of Table 2:

$$\dot{Q}_{avail,stor} = \dot{m}_{air} \cdot c_{p,air} \cdot \rho_{air} \cdot (T_{outlet,bipv/t} - T_{VCS.surf}) \tag{9}$$

$$Q_{stored,VCS} = \rho_{conc} \cdot V_{tot,conc} \cdot c_{p,conc} \cdot \Delta T_{surf,VCS} \tag{10}$$

where $\Delta T_{surf,VCS}$ is the difference between the lowest and peak surface temperatures on the VCS surface temperature fluctuation curve (Figure 12) for the active charging input (u_1). This curve was obtained by using the transfer function B_1/A for input u_1.

Table 2: Values and properties used in the BIPV/T and VCS energy calculations

	Symbol	Value
Specific heat of air at atmospheric pressure, 300K (J/kg·K)	$c_{p,air}$	1007
Density of air at atmospheric pressure, 300K (kg/m^3)	ρ_{air}	1.16
Specific heat of concrete (J/kg·K)	$c_{p,conc}$	900
Total volume of concrete in VCS (m^3)	$V_{tot,conc}$	5
Density of concrete, 300K (kg/m^3)	ρ_{conc}	2300

The results of these calculations for March 4th 2009 are presented in Figure 11. It can be observed that the amount of thermal energy collected by BIPV/T improved design is approximately twice the amount collected by the Ecoterra™ roof. The same observation can be made for the thermal energy available for storage into the VCS.

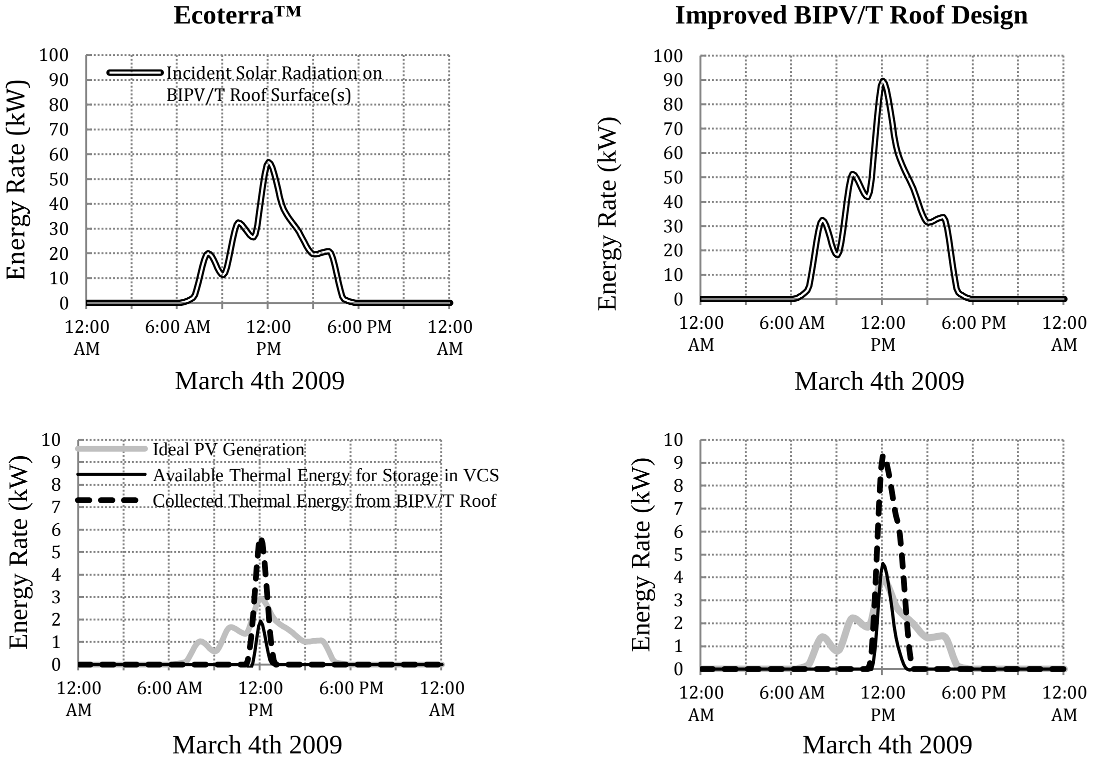


Figure 11: Energy performance results for the actual BIPV/T roof of the Ecoterra™ house and for the improved design.

The simulation results, presented in Figure 13, showed that it is possible to collect 175% more thermal energy with the improved BIPV/T roof design when the actual Ecoterra™ BIPV/T roof is used for comparison. Moreover, it allows to store 183% more energy in the slab than the actual BIPV/T roof configuration when its current state of charge is considered. Furthermore, the daily heat storage numbers obtained using the VCS polynomial model allowed to determine that the percentage of heat collected from the BIPV/T roof effectively stored in the slab is approximately 22%.

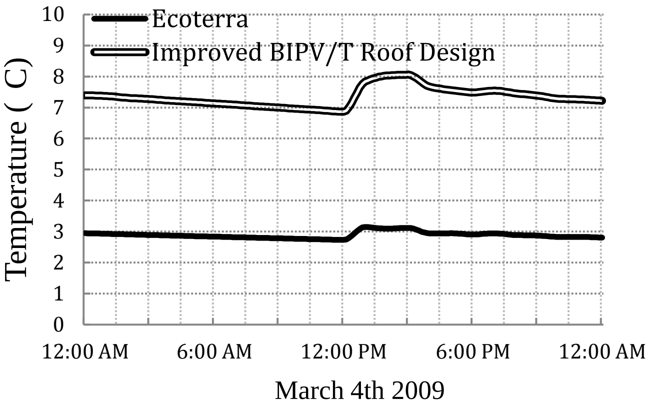


Figure 12: Simulated ventilated concrete slab surface temperature fluctuation due to the active solar charging from the actual BIPV/T roof of the Ecoterra™ house and from the improved BIPV/T roof design.

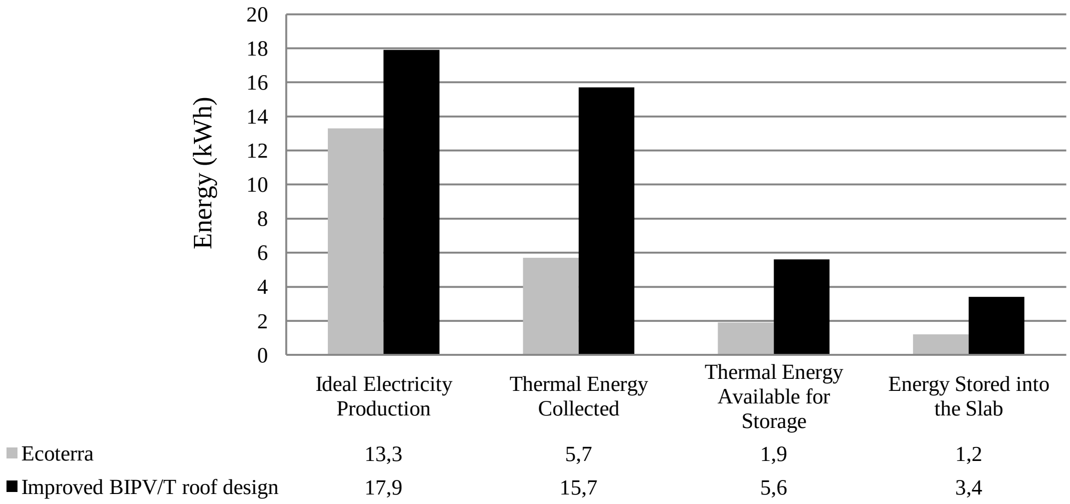


Figure 13: BIPV/T roof energy production and ventilated concrete slab energy storage for the actual Ecoterra™ roof and studied design (March 4th 2009).

7 Conclusion

A methodology was developed to enable the identification of a parametric model of a system with active thermal charging and passive discharge (a ventilated concrete slab system) with 17 time domain (z-transfer function) parameters. This model was estimated and validated using monitored data from the Ecoterra™ house. A statistical regression (modified least squares) approach was used to identify this model. Its number of parameters can be considered very low as compared to the number of parameters required when similar building system models are created with detailed energy simulation tools.

The identified parametric model for the VCS surface temperature was linear. The validation process proved that the linear assumption made during the system identification procedure was reasonable to model the charge/discharge process of the thermal storage.

The relative weight of the three inputs of the VCS system on the surface temperature response was compared. The active solar charging and the passive solar charging of the VCS were confirmed as the inputs having the most important contributors to the increase of the concrete surface temperature. It was found that the exterior temperature input (u_3) has very little impact on the fluctuation and total temperature response of the slab. This means that the exterior temperature has a negligible effect on the performance of TES systems in well-insulated energy efficient solar houses having a high air-tightness.

Based on the results of a sensitivity analysis, it was determined that the accuracy of the monitoring sensors does not have a significant impact on the value of the identified model parameters or on the simulation results when the model is used to carry out thermal evaluations.

An improved BIPV/T roof configuration for the Ecoterra™ house was evaluated based on its active thermal charging capacity when coupled to the ventilated concrete slab (VCS) in the basement. A previously identified VCS linear parametric model was used in the thermal simulations. It was found that this design leads to a significant increase in the amount of energy stored in the concrete during cold sunny days.

Finally, the linear parametric data-driven model of the VCS was shown to be an efficient tool for comparing different design and operation options. Results can be easily obtained with this model, enabling an efficient comparison of different solar thermal systems. It was demonstrated that this modelling approach is a useful and simple tool for thermal evaluations when VCS's are connected to active solar systems such as a BIPV/T roof. Moreover, it is a more efficient and faster alternative to whole building detailed simulations, particularly when comparing design and operation options. The presented technique can also be applied to model the operation of other configurations of solar collection and storage systems for solar buildings and NZEBs.

8 Nomenclature

$A(q), B(q)$	Polynomials in terms of q^{-1}
$a_1 ... a_8$	Parameters of the A polynomial of the ARX statistical model identified
$b1_1 ... b1_3$	Parameters of the B_1 polynomial of the ARX statistical model identified
$b2_1 ... b2_3$	Parameters of the B_2 polynomial of the ARX statistical model identified
$b3_1 ... b3_3$	Parameters of the B_3 polynomial of the ARX statistical model identified
$e(t)$	Disturbance at time t
$\dot{m}_{air}$	Volumetric flow rate of the heated air drawn from the BIPV/T roof
q	Forward shift operator
$\dot{Q}_{avail,stor}$	Thermal energy available for storage in the ventilated concrete slab
$Q_{stored,VCS}$	Thermal energy stored into the ventilated concrete slab
$u_1, u_2, u_3, u(t)$	Inputs of the VCS dynamic system and input at time t
$T_{VCS,surf}$	Surface temperature of the ventilated concrete slab
$T_{outlet,bipv/t}$	Exit air temperature from the BIPV/T roof
To	Outdoor temperature
$y(t)$, y	Output of the VCS dynamic system at time t and surface temperature output of the VCS dynamic system

y_{u1}, y_{u2}, y_{u3}	Response of the VCS system to input u_1, u_2, and u_3
$y(\mathrm{n}), \hat{y}(\mathrm{n}), \bar{y}$	Measured output value, output value calculated by the model, and arithmetic mean of the model output

9 References

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