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A novel ROM methodology to support the estimation of the energy savings under the Measurement and Verification protocol

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Abstract

This paper presents a novel Reduced Order grey box Model (ROM) methodology, based on a Resistor-Capacitor (RC) network, which supports the creation of the baseline energy consumption and the estimation of energy savings due to Energy Conservation Measures (ECMs) under the Measurement and Verification protocol. Within this scope, a description of the RC network, including a calculation of the parameters' needed to execute the ROM, are presented. This ROM methodology is demonstrated on an educational building located in Sant Cugat, Spain as part of the H2020 GEOFIT project. The results presented in this paper demonstrate that the ROM is sufficiently accurate for the creation of the baseline energy consumption and for estimating the energy savings of different ECMs.

Introduction

Energy efficiency of new buildings has improved significantly in recent decades due to more demanding design, construction and operation requirements. Nevertheless, achieving energy savings for existing building is a more challenging task, where uncertainty is a clear barrier to retrofit investments (Lee et al., 2015).

This research describes an innovative methodology and technology framework to overcome the barriers posed by uncertainty regarding post-renovation energy performance by utilising a novel standards-based Measurement and Verification (M&V) approach that leverages a Reduced Order grey box Model (ROM).

Guidelines regarding the M&V have been provided by various standardisation bodies. One of the most commonly used is the International Measurement and Verification Protocol (EVO, 2016).

IPMVP is widely recognised within the building industry and provides an effective instrument to measure and estimate the energy savings generated by Energy Conservation Measures (ECMs). IPMVP usually involves the utilisation of Whole Building Energy Simulation Modelling (WBEMS, White Box modelling) and whole building linear regression modelling (Black Box modelling) among other options to create the IPMVP Baseline Period Energy (BPE).

However, WBESM is time intensive, error-prone and the linear regression option tends to yield inaccurate results (Coakley et al., 2014).

The Reduced Order grey box Model methodology was selected and developed in this research due to its capability of estimating the energy consumption in a typical building energy system retrofit scenario, where the technical information about the building is often incomplete and there is high uncertainty in relation to the model parameters (Giretti et al. 2018).

Moreover, the grey box modelling approach was chosen because of a number of advantages over the white box models and black box models. Grey box models couple the physical meaning and structure from the white box paradigm and the statistical approach and parameter estimation from the black box approach.

In this way there is a physical meaning to most of the ROM's parameters. Thus, the model parameters are related to building elements and therefore, there is an opportunity to apply the model for different retrofitting packages.

In addition, the statistical approach and the restricted number of uncertain parameters simplify the model calibration procedures and provide a higher grade of model accuracy.

The parameters needed to setup the ROM were calculated using a supporting tool (ROMPar) developed as part of the research that uses information obtained through data collection and on-site surveys. Once the parameters were calculated they were inserted into the ROM model to run the initial simulation.

The calibration procedure consisted of systematically changing a restricted number of uncertain parameters within a specified range within a prechosen step in order to determine the relative impact of the parameters on the accuracy of the initial ROM.

To verify the accuracy of the ROM results and to demonstrate the advantages provided by the ROM method over existing modelling methods, this novel approach is demonstrated using a real building case scenario in Sant Cugat, Spain, where several ECMs have been installed and where a geothermal heat pump providing both heating and cooling will be deployed as part of the H2020 GEOFIT project (GEOFIT, 2018) pilot sites.

The final calibrated ROM will be integrated into the GEOFIT platform and utilised as an innovative tool for estimating the savings due to the installation of Geothermal Source Heat Pump (GSHP).

Methodology

Figure 1 shows an overview of the model usage process.

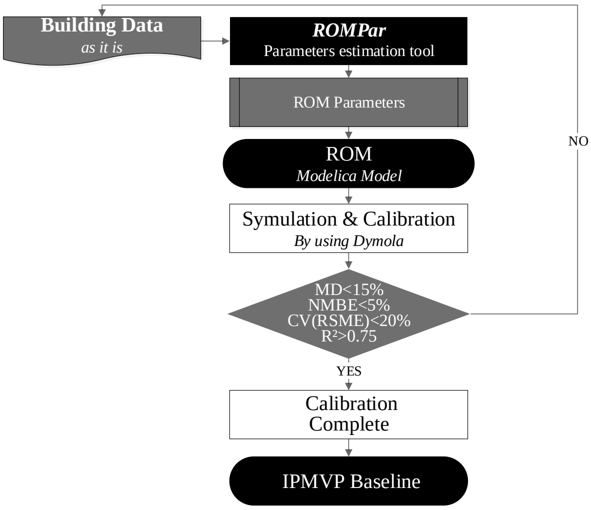

Figure 1 – ROM technologic framework

The process is composed of three main steps: (i) the tool for estimating ROM parameters (ROMPar) which receives building data as input; (ii) the Modelica model (ROM) which obtains as input the parameters calculated by ROMPar (iii) the ROM calibration and utilisation. The calibration procedure consists of systematically changing the uncertain parameters. The uncertain parameters are selected following the assumption made by Giretti et al. (2018) and they are the ones usually affected by some degree of uncertainty that derives from errors and approximations in data measurement, parameter values and model structure. Finally, following the steps outlined in the IPMVP protocol, the calibration is done by checking the statistical values' limits shown in Table 1.

Table 1 – IPMVP Statistical values'limits used for the calibration

Statistical Value	Limit
NMBE - Normalised mean bias error	< 5%
CV(RMSE) - Coefficient of variation of root mean square error	< 20%,
$\mathbf{R^2}$ - Coefficient of determination	>0.75
MD - Monthly deviation	< 15%

If the calibrated models do not comply with the statistical values' limits, the building data must be manually adjusted, and the calibration process needs to be repeated. Otherwise, the model is considered calibrated and can be used as a Baseline Period Energy (BPE) for the IPMVP. The BPE can be then utilised to estimate the savings due to Energy Conservation Measures (ECMs) by comparing it with the actual Reporting Period Energy (RPE) and considering the calibration error as estimation precision.

$$\text{SAVINGS} = \text{BPE} - \text{Actual RPE} \pm \text{Calibration Error}$$

ROM - Description

The proposed ROM is based on a grey box modelling approach and is implemented using the Modelica programming language (Fritzson and Engelson, 1998) in the Dymola environment (Dassault Systèmes, 2020). Modelica was chosen as programming language because it allows to model complex dynamic energy system, recognises linear, non-linear and hybrid equations and finally it provide many open source library such as the IBPSA Project 1 Library (IBPSA, 2018), which has been implemented in the model. In particular, the ROM developed in this paper simplifies the physical description of the building using thermal network analogies and considers the system complexity as an electrical network problem by means of resistances and capacitances. Figure 2 shows the ROM as a RC-Network.

The Modelica ROM consists of four main components: (1) Building (RC-Network) (2) Internal Gains, (3) Heating and Cooling, and (4) Weather. A detailed description of these components was presented in a previous paper (Piccinini et al., 2019).

Building Component

The Building component is the main element of the ROM, which concerns all the physical structural/construction materials. This component is represented by the RC-network of Figure 2 and divides the building mass into four capacitances that represent the internal partitions (C_M), the external opaque envelopes (C_{WALL}), the floor slabs in contact with the ground (C_{GF}), and the room/building air capacitance (C_{AIR}) represented in Modelica using a "MixingVolume" element. The heat transfer between the nodes (e.g. T_{IN}) is divided into the radiative and convective heat transfer components. The high number of resistances are due to the division of each

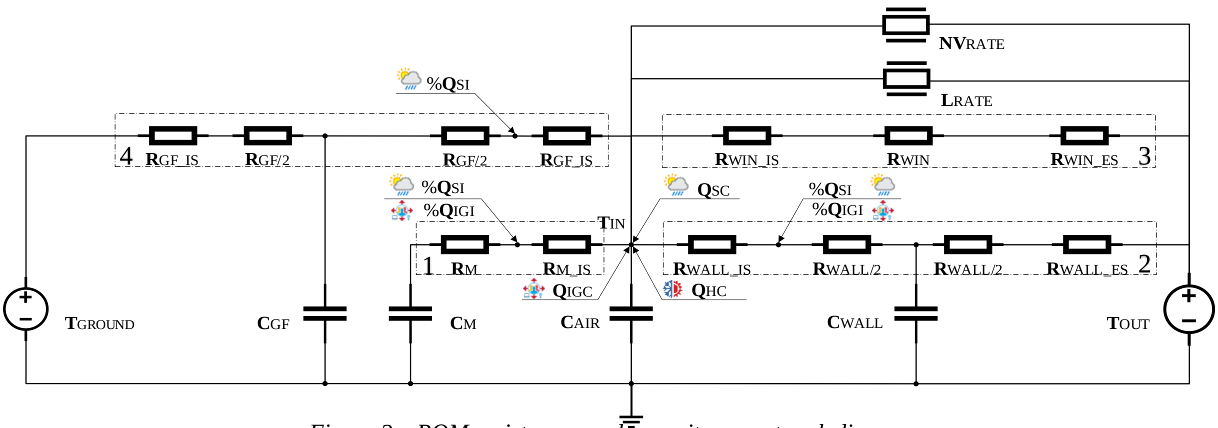

Figure 2 – ROM resistances and capacitance network diagram

resistance element into an internal surface resistance (e.g. R_{WALL_IS}), external surface resistance (e.g. R_{WALL_ES}) and thermal resistances of the solid wall materials (e.g. R_{WALL}). Thermal resistance is then divided two to assign the thermal capacitance at the middle point of the wall.

Therefore, the component is composed of 13 resistances and 4 capacitances that can be divided into four groups as numerated in Figure 2. The first group is used to combine the building internal partition and slabs (R_M, R_{M_IS}, C_M). The second group captures the whole building external envelope (R_{WALL_ES}, R_{WALL}, R_{WALL_IS}, C_{WALL}), the third represents the building external windows (R_{WIN_ES}, R_{WIN}, R_{WIN_IS}) and finally, the fourth group, considers the building ground floor (R_{GF_ES}, R_{GF}, R_{GF_IS}, C_{GF}). Finally, the components "L_{RATE}" and "NV_{RATE}" are developed in Modelica with the scope of simulating air infiltration and natural ventilation.

Internal Gain component

The two thermal power inputs "$\%Q_{IGI}$" and "Q_{IGC}" [W] in Figure 2 are the radiative and convective parts of the power heat gain due to the Internal Gain component that generates the heat gains from people, lighting and equipment in the building. The two input are controlled by the occupancy schedule that represent the people profile [0 to 1] and the equipment schedules that represent the equipment profile [0 to 1] in the building.

Heating and Cooling component

"Q_{HC}" is the power system thermal heat gain [W] which is generated by the Heating and Cooling component. The input generated by this block is controlled by the heating and cooling on/off switch [0 or 1], the heating and cooling set point [yearly variation of the setpoint temperature], and the occupancy schedule mentioned previously. The occupancy schedule is utilised only if there is a correlation between the system and the people in the building such as a thermostat controlled by the people.

Weather component

Finally, "%QSI" and "QSC" representing the radiative and convective thermal power heat gains [W] from the Weather Component. Moreover, this component includes the weather file in format .mo and the ground temperature with hourly basis that are used in the model by the Building Component and the HVAC System component

ROMPAr - Description

The four components described previously needs parameters in order to generate the input (e.g. Q_{HC}) and the building component needs also data to feed the RC-Network. To simplify the calculation of these parameters, a tool (ROMPAr), based on MS Excel, has been created.

ROMPAr uses information obtained during the tendering phase through data collection and on-site surveys. In case of missing or inaccurate data, standardised packages and associated parameter values are provided to support a good model parameters' estimation. The full list of the 48 parameters is presented in Table 5.

Building Component Parameters

The Building component requires 31 parameters. These parameters are the 13 resistances and 4 capacitances described in ROM - Description section.

All of these resistances and capacitances are calculated using formulae derived from international standards. For instance, the resistances of the building opaque envelopes are calculated using formulae that derive from the ISO 6946 (ISO,2007):

$$R_{WALL\_ES} = \sum_{i=1}^{n} \frac{0.043}{A_i} \qquad [K/W]$$

$$R_{WALL\_IS} = \sum_{i=1}^{n} \frac{0.043}{A_i} \qquad [K/W]$$

$$R_{WALL} = \frac{\sum_{i=1}^{n} R_i \ x \ A_i}{\sum_{i=1}^{n} (A_i)^2} \qquad [K/W]$$

Where:

A_i = Area of the envelope element i [m^2]

R_i = Resistance of the envelope element i [(m^2K)/W] = $\sum_{k=1}^{n} Thickness_{\ k} \ [m] \ / \ conducivity_{\ k} \ [W/mK]$

Where k= layer of the envelope element

All the formulae utilised to calculate the resistances and capacitances have been included in the tool. To simplify the data insertion, an interface has been created. In case of missing information about the building characteristics (e.g. layers of the walls), standard specifications are adopted based on the country building regulation and the year of construction of the building. These default values are derived from the outcomes of the Tabula project (TABULA WebTool, 2012).

Other parameters required for the building component are the building latitude (Latitude), building total volume [m^3] (Volume), window surface areas in different direction [m^2] (AWinSouth, AWinNorth, AWinWest, AWinEast, AWinRoof), g total value (total amount of solar entering through the glazing and the solar shading calculated with BS EN 13363-1 (BSI, 2003) of the windows for each direction (GtotWSouth, GtotWNorth, GtotWWest, GtotWEast, GtotWRoof). Finally, to complete the parameters needed for the Building component, the following data have to be specified: (i) the ratios between a building component surface and the total building surface areas (Ratio_m, Ratio_wall, Ratio_win, Ratio_g), values that are automatically calculated based on the surfaces input during the calculation of the building resistance and capacitance, and (ii) the infiltration rate [kg/s] (L_rate). The last is one of the parameters needed for the calibration process.

Internal Gain component

The Internal Gain component requires 6 parameters. These parameters include maximum heat gains from people [W] (MLoadPeo), maximum heat gains from lighting [W] (MLoadLig), maximum heat gains from equipment [W](MLoadEqu) and heat gains from equipment on standby [W](SBLoad). To account for missing data, these parameters can be estimated using the ROMPar tool. In order to estimate them, the type, the use and the surface of the building have to be specified. The values provided can then be adjusted using the actual number of people present in the building. This estimation is based on the Ashrae Handbook Fundamentals (ASHRAE, 2013).

Finally, two other parameters are needed in the Internal Gain component: i.e. equipment efficiency / utilisation and lighting efficiency/utilisation (AlphaEqu, AlphaLig). These two parameters are usually equal to one and can vary between 0 and 3 with a step of 0.1 during the calibration process.

Heating and Cooling Component

The Heating and Cooling component requires 9 parameters. These include the maximum cooling power [W] (MCoolP), the maximum heating power [W] (MHeatP), the maximum power of the system equipment (HCEquP), the stand-by consumption of heating (SBHeat) such us the primary loop circulation pumps consumption, the standby consumption of cooling (SBCool) such us the primary loop circulation pumps consumption, and the possibility of the people switching off or control the thermostat in the building [True/False] (P_Switch). The other three parameters needed include the heating component efficiency/utilisation (AlphaHeat), the cooling component efficiency/utilisation (AlphaCool) and the influence of the people in the control (AlphaPeo). These three parameters are used in the calibration and are initially equal to one and can be changed between 0 and 5 with a step of 0.1 in the calibration process.

Weather Component figure

Only two parameters are required for this block, i.e. the ground temperature [°C] (GroundT) and the weather file (WeaFile). The weather file can be generated from an .epw (EnergyPlus, 2020) and converted into a .mos file to allow its usage in Modelica.

Pilot Description

Building Characterisation

This study researched the GEOFIT pilot case in Sant Cugat, Spain. The pilot is composed of a primary school, a sports pavilion and an administrative building constructed in 1975 (Figure 3).

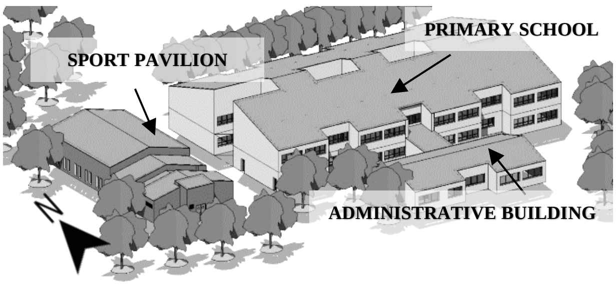

Figure 3- BIM model of the Sant Cugat pilot

Building data were collected directly from the BIM model provided by the GEOFIT partners. Furthermore, the data has been integrated through an interactive process of interviews and direct communication with the pilot building owners.

Building Fabric

Based on the BIM data, the primary school has a total floor plan area of 2900 m^2 distributed between two floors (3.5 m high). The administrative building floor plan area is 280 m^2 with an average floor to ceiling height of 3.5 m and the sport pavilion has a floor plan area of 450 m^2 with an average floor to ceiling height of 5.9 m.

The building's fabric specifications were extracted using the Autodesk Revit (Autodesk, 2020) function "Quantity Schedules". There were five different types of external walls and two internal partitions as shown in Table 2.

Table 2-Walls and partition specification of the Sant Cugat pilot

Walls and Partitions	**Area [m^2]**	**U-Value [W/(m^2·K)]**
Hollow bricks partition - 12cm	115.05	4.5
Hollow bricks partition - 10cm	1925.27	5.40
Concrete wall - 15cm	40.67	-
Brick wall - 30cm	67.37	1.80
Brick wall - 40cm	277.66	1.35
Brick wall - 50cm	220.68	1.08
School Brick wall - 30cm	2589.41	0.83

The floor slabs are made of concrete with a U-value of 2.66 W/m^{2}K.The roof covering is a steel structure cladded with clay tiles (total surface area of 2200 m^2). The windows are double glazed with a PVC frame and equipped with manually operable shutters. The total surface of the windows is 610 m^2. The 80% of the window openings face the North − South directions and the remaining 20% face the West-East directions. The ground floor is a concrete slab. The U-Values not specified in the BIM model were calculated using the ROMPar tool, as described in the previous section.

Occupancy Schedules and Internal Gains

Occupancy schedules were estimated by direct communication with the pilot building owners. The pilot is fully utilised from Monday to Friday from the middle of September to the middle of June, depending on the particular year. The primary school is occupied by 55 people from 7.30am to 9.30am, 350 people from 9am to 4.30pm and 45 people from 4.30pm to 6pm. The administrative building is occupied by 8 people from 7am to 6pm. Lastly, the sport pavilion is on average occupied by 52 people from 9am to 4.30pm and by 35 people from 4.30pm to 6pm. The internal gains from lighting, plug loads and people were calculated by the ROMPar tool, as described in the next section.

Heating Systems

The pilot is equipped with three non-condensing natural gas boilers with a thermal capacity of 1 x 125 kW and 2 x 110 kW, with a fourth and boiler of 110 kW kept in reserve. The heat is distributed by radiators with a maximum supply temperature of 70°C.Cooling units are only present in the sport pavilion and in the computer labs of the primary school. The sport pavilion is equipped with three 12 kW air source heat pump units and four 5.2 kW split units, while the computer labs are equipped with four 3.3 kW dual split units. The heating season generally occurs between the end of October to the end of May, depending on the year analysed. The cooling is estimated to be always on.

The indoor set point temperatures are constant, i.e. 22 °C for heating and 26°C for cooling.

Weather data

The Sant Cugat average outdoor air temperature ranges between 20 - 29°C in the summer to 7 -16°C in winter.

The MERRA 2 application (Gelaro et al., 2017) was utilised to extract 2017 – 2019 weather data, including air temperature, relative humidity, barometric pressure and solar radiation needed for the model development.

Elements (Big Ladder Software, 2020) was used to create the .epw file. Then, the .epw file was converted in a .mos file to allow its usage in the ROM.

Utility Bills analysis

A full review of all energy bills retrieved from the electricity provider and the gas meter for the boilers was carried out. Table 3 shows monthly electrical energy bills and monthly gas readings used to develop the M&V baseline created in the ROM and to estimate the energy savings generated by the ECMs.

Table 3- Monthly electricity and natural gas energy consumption of the Sant Cugat Pilot

	Electricity [kWh]			Gas [kWh]		
	2017	**2018**	**2019**	**2017**	**2018**	**2019**
Jan	12,766	11,659	9,472	60,237	62,680	57,377
Feb	11,335	10,571	9,406	34,196	58,647	50,889
Mar	11,041	9,997	7,745	22,732	29,459	27,538
Apr	8,360	9,176	6,512	13,712	19,086	21,837
May	10,146	9,507	5,846	6,386	4,069	11,490
Jun	9,066	8,702	5,59	0	0	0
Jul	6,644	5,833	4,74	0	0	0
Aug	6,611	4,241	3,049	0	0	0
Sep	9,548	7,733	4,928	0	0	0
Oct	10,970	9,195	6,932	0	7,949	623
Nov	10,800	9,954	7,8	23,297	22,179	22,038
Dec	9,634	8,427	---	40,607	35,773	18,921
Tot	**116,921**	**104,995**	**72,020**	**201,167**	**239,842**	**210,713**

Buildings upgrades

Since 2018, the pilot buildings have been upgraded with several ECMs. A new lighting system based on LED bulbs and photovoltaic (PV) panels were installed in December 2018. All of the external opaque building external envelope were retrofitted with an External Thermal Insulation Composite System (ETICS). These works started in February 2019 and finished in July 2019. The new U-values of the walls are shown in Table 4.

Table 4 – San Cugat Renovated walls' U-Value

Walls	**Area [m²]**	**U-Value [W/(m²·K)]**	
		Pre	**Post**
Renovated Concrete wall - 15cm	40.67	6.5	0.29
School Renovated Brick wall - 30cm	2589.41	0.83	0.27

Result and Discussion

By following the workflow described in Methodology section, the ROMPar was populated with the data collected from the Sant Cugat demonstrator. Next, each parameter estimated by the ROMPar tool was inserted into the Modelica ROM. Table 5 shows the full list of model parameters calculated by ROMPar.

Table 5- ROM Parameters for the Sant Cugat pilot

	Value	Unit		Value	Unit
Latitude	41.4776	-	R_M	1.17E-04	K/W
Volume	13547	m³	C_M	2.52E+09	J/K
$AWin_{South}$	255.75	m²	R_{GF_IS}	6.57E-05	K/W
$AWin_{North}$	237.51	m²	R_{GF}	2.83E-04	K/W
$AWin_{West}$	60.9	m²	R_{GF_ES}	2.02E-05	K/W
$AWin_{East}$	54.81	m²	C_{GF}	1.51E+09	J/K
$AWin_{Roof}$	0		$L_{\_RATE}$	3	kg/s
$GtotW_{South}$	0.75	-	**WeaFile**	SantCugat	-
$GtotW_{North}$	0.75	-	**GroundT**	20	℃
$GtotW_{West}$	0.75	-	$MLoad_{Peo}$	32756	W
$GtotW_{East}$	0.75	-	$MLoad_{Lig}$	42280	W
$GtotW_{Roof}$	0	-	$MLoad_{Equ}$	6724	W
$Ratio_{\_m}$	0.381	-	**SBLoad**	0	W
$Ratio_{\_wall}$	0.424	-	$Alpha_{Lig}$	1 (1 to 3)	-
$Ratio_{\_win}$	0.046	-	$Alpha_{Equ}$	1 (1 to 3)	-
$Ratio_{\_gf}$	0.149	-	**MCoolP**	70000	W
R_{WALL_IS}	2.31E-05	K/W	**MHeatP**	345000	W
R_{WALL}	4.9E-04	K/W	**HCEqiP**	8000	W
R_{WALL_ES}	7.10E-06	K/W	**SBHeat**	5000	W
C_{WALL}	7.99E+08	J/K	**SBCool**	0	W
R_{WIN_IS}	2.13E-04	K/W	$P_{\_Switch}$	FALSE	-
R_{WIN}	6.33E-04	K/W	$Alpha_{Peo}$	1 (1 to 5)	-
R_{WIN_ES}	6.56E-05	K/W	$Alpha_{Heat}$	1 (1 to 5)	-
R_{M_IS}	2.56E-05	K/W	$Alpha_{Cool}$	1 (1 to 5)	-

The ROM updated with the calculated parameters (Table 5) was then calibrated using the 2017 data. The calibration procedure consisted of changing a restricted number of uncertain parameters (underlined in Table 5) within a specified range. Next, the calibrated ROM was validated with the 2018 data. The validation is a cross checking made to verify the capability of the ROM in forecasting the energy and gas consumption of the building. Finally, using the formula described in the in Methodology section, the calibrated ROM was used to create gas and electricity Baseline Period Energy (BPE) for year 2019 with the scope of estimating the savings due to the ECMs installed at the end of 2018 and during 2019.

ROM Calibration

After the insertion of the parameters into the Modelica ROM, the 2017 schedules for occupancy, equipment, cooling, heating and set points were created (in .txt format) and used in the model. To support the creation of these schedules ROMPar had a capability of creating yearly schedules by specifying the weekly utilisation and holidays. The first simulation ran based on the parameters listed in Table 5. The simulation results were then compared with the actual gas readings and electrical bills from the demonstrator using the statistical indices (Methodology section). Table 6 shows the statistical indices calculated from the first simulation. These values indicated that the ROM prediction of electricity consumption was relatively good. However, this was not the case for the gas consumption where the statistical indices greatly exceeded the IPMVP criteria (Table 1).

Table 6 - IPMVP statistical indices of the not calibrated model

Model 2017	ROM Gas	ROM Ele
Total energy	96302 kWh	129223 kWh
NMBE	86.87%	-11.48%
CV(RMSE)	83.07%	18.55%
R2	0.99	0.87

The under-prediction in gas consumption can be attributed to different factors such as the system's efficiency, the system utilisation and the presence of unheated spaces. For this reason, in order to calibrate the model, the values underlined in Table 5 had to be changed until the comparison of the BPE created with the ROM and the actual energy consumption of the building was within the IPMVP statistical criteria.

Since there is no interaction of the people in the building system because the system control is centralised, the AlphaPeo can be omitted. The calibration consisted an iterative procedure in which the five parameters described in Table 7 are being changed until the IPMVP statistical indices are respected. Table 7 also illustrates the final parameter values in the calibrated ROM.

Table 7 – Parameters used in the calibrated ROM

Parameter	Description	Value
$Alpha_{Heat}$	Heating - efficiency/utilisation	2.2
$Alpha_{Cool}$	Cooling - efficiency/utilisation	0.2
L_rate	Air infiltration rate [kg/s]	3
$Alpha_{Equ}$	Equipment - efficiency/utilisation	1.1
$Alpha_{Lig}$	Lighting - efficiency/utilisation	0.5

Whit this values, the calibrated ROM satisfied all the calibration criteria (Table 8), giving a yearly precision of 4.14% for the gas and 3.65% for the electricity with a level of confidence of 90%.

Table 8- IPMVP statistical indices of the calibrated model

Model 2017	ROM Gas	ROM Ele
Total energy	96302 kWh	115011 kWh
NMBE	-0.67%	1.31%
CV(RMSE)	7.98%	7.08%
R^2	0.99	0.89
Monthly precision @90%	±14.35% (±1152 kWh)	±12.66% (±1213 kWh)
Yearly precision @90%	±4.14% (±3987 kWh)	±3.65% (±4198 kWh)

Figure 4 and Figure 5 outline the simulated energy consumption against the real energy consumption with the associated monthly deviation. The results show also that the ROM meet the IPMVP monthly deviation criteria as the values of are within the 15% recommended.

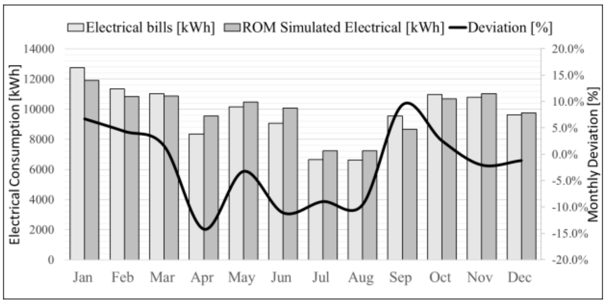

Figure 4 - Comparison of the electrical bills and the ROM electrical energy consumption with monthly deviation for year 2017

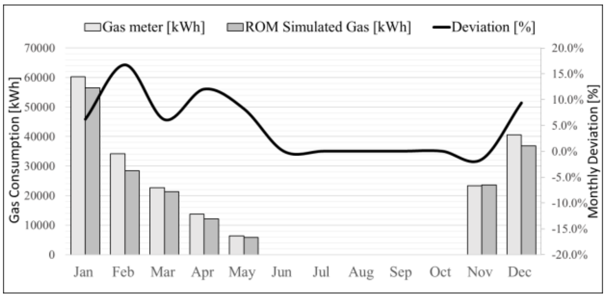

Figure 5 - Comparison of the natural gas bills and the ROM gas energy consumption with monthly deviation for year 2017

ROM Validation

The calibrated 2017 ROM was validated utilising the 2018 data. The parameters used in the 2017 calibrated model were maintained while the weather file, the internal gains schedules and the system schedules were updated with the 2018 data.

As showed in Table 9, the results obtained satisfy the calibration criteria demonstrating the capability of the ROM forecast the electrical and gas energy consumptions of buildings in a scenario where some of the technical information was incomplete, and uncertainties in model parameters were present. Hence, ROM may provide a credible solution for the creation of the IPMVP BPE.

Table 9 - IPMVP statistical indices of the calibrated model tested with the 2018 data

Model 2018	ROM Gas	ROM Ele
Total energy	96302 kWh	116410 kWh
NMBE	4.99	3.47
CV(RMSE)	9.77	8.81
R^2	0.98	0.83

Furthermore, Figure 6 shows reduction in the electricity consumption in December 2018. This is due to the PV panels and the LED bulbs installed during this month, this reduction will reflect the savings that will be calculated in the next section

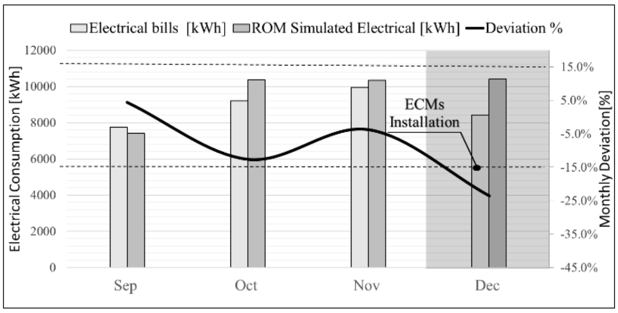

Figure 6 - Comparison of the electrical bills and the ROM electrical energy consumption with monthly deviation for the year 2018

ECMs Savings estimation

Finally, to demonstrate the capability of the ROM to be used as IPMVP BPE and, thus, to estimate energy savings using the IPMVP formula (Methodology section), the model was used to create gas and electricity baseline energy for year 2019. Also in this case, the only data changed were the weather file, the internal gains schedules and the system schedules. All remaining parameters were kept the same as in the 2017 calibrated ROM. Figure 7 displays the ROM adjusted BPE in comparison with the RPE for electricity. ROM adjusted BPE is the baseline period energy consumption modified as part of routine and non-routine adjustments to account for changes in the reporting period, so is the building consumption as if the ECMs were not installed. This allows to calculate the real energy savings considering the boundary condition (e.g. weather file, different occupancy, etc.) of the year considered. The savings generated (or avoided energy consumption) shown in Figure 7 are due to the new PV panels system and the LED bulbs installed in December 2018 (ECMs installation).

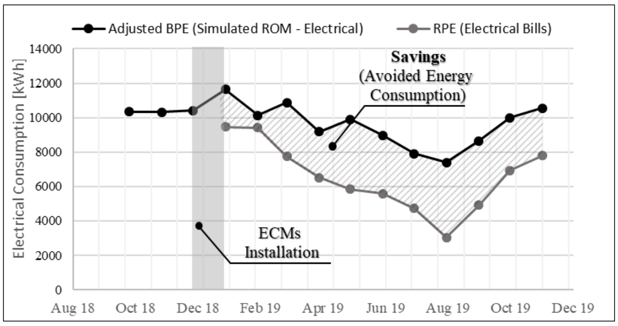

Figure 7 - ROM adjusted electrical BPE in comparison with the electrical RPE for year 2019.

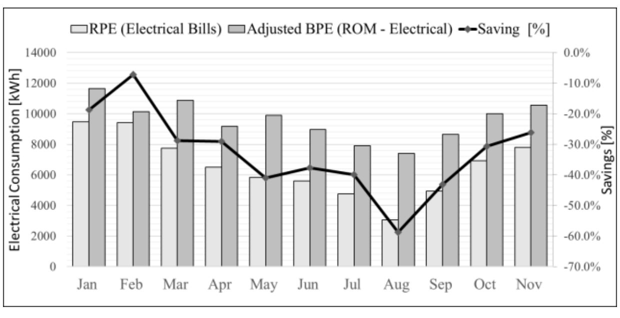

Figure 8 - Comparison of the electrical bills and the ROM electrical energy consumption with savings for year 2019

As shown in Figure 8, the savings during year 2019 have a peak in the summer period, probably due to the higher PV panels' electrical energy production.

Figure 9 shows the Gas ROM adjusted BPE in comparison with the RPE from the gas meters. In this case, the savings are due to the installation of the external insulation between February and July 2019. The period is too brief to provide a good estimation of the annual gas savings, but the effects of the ECM in the months of November and December 2019 generate savings of 6512.96 kWh. Therefore, with a level of confidence of 90%, the monthly savings generated by the external insulation for the months of November and December 2019 are equal to 3256 kWh ± 1152 kWh (35%).

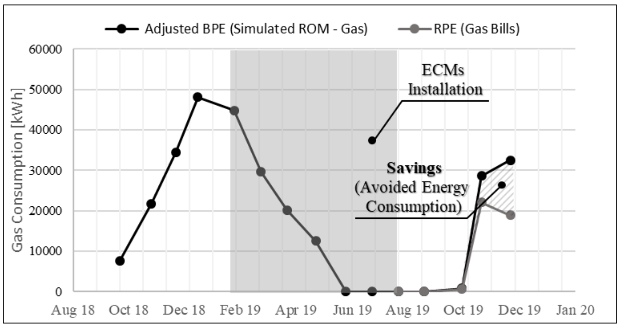

Figure 9 - ROM adjusted gas BPE in comparison with the gas RPE for the year 2019.

Geothermal heat pump savings estimation

The same procedure will be used in the GEOFIT project to estimate the savings due to the application of an innovative GSHP that will be installed in the Sant Cugat pilot at the end of 2020. In order to evaluate the savings, the model will be calibrated again with the 2020 data, the resistances and capacitances of the external envelope will be re-calculated with the ROMPar tool considering the renovated packages with new U-values. Then, following the methodology explained in 'ECMs Savings estimation' section of this paper, a comparison between the BPE and RPE will be performed and savings calculated with relative uncertainty.

Conclusion

This paper uses a novel methodology to support the creation of IPMVP Baseline Period Energy (BPE) and to systematically quantify the energy savings achieved through Energy Conservation Measures (ECMs) utilising a workflow based on a Reduced Order Model (ROM).

Modelica and Dymola were used to develop the ROM based on the grey-box modelling approach. The Model uses a thermal network with 13 resistances and 4 capacitances considering the building system as an electrical problem.

The ROMPar tool, used to calculate 48 parameters needed for ROM development, is described in this paper. The data needed to populate ROMPar was gathered from available technical information, surveys and interviews. The remaining uncertain parameters were assigned specific values, and then adjusted throughout a simplified calibration process.

To demonstrate the accuracy of the methodology, the ROM described in the paper was applied to an educational building located in Sant Cugat, Spain. The building was one of the five pilots of the GEOFIT project. The aim of the GEOFIT project is to provide a cost effective enhanced geothermal system for energy efficient building retrofitting.

This paper concludes that the ROM is accurate enough to being utilised as IPMVP® Baseline Period Energy consumption. The model calibration was carried out with the 2017 data, achieved a yearly NMBE = -0.67%, a CV-RMSE = 7.98% and a R^2=0.99 for the gas consumption and a yearly NMBE = 1.31%, a CV-RMSE = 7.08% and a R^2=0.89 for electricity consumption. Furthermore, the accuracy of the ROM was verified by forecasting the energy and gas consumption for year 2018. Also in this case, the model maintained the statistical values under the IPMVP criteria.

Finally, the ROM was used to create the BPEs of gas and electricity for the year 2019. These were utilised to estimate the saving due to different ECMs applied into the building during the same year.

The yearly savings generated by the ECMs were of 43608 kWh ± 4198 kWh (9.6%) with a level of confidence of 90% for the electricity and a monthly saving of 3256 kWh ± 1152 kWh (35%) for the gas with the same level of confidence for the gas.

The methodology presented here will be utilised to estimate the savings due to retrofitting with a novel Geothermal Source Heat Pump (GSHP) under the GEOFIT project.

Further research is needed to:

- apply the methodology to other buildings;
- create a standalone or web interface to use the ROM and improve the calibration engine;
- create an automatic calibration engine for the calibration parameters.

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