Building dynamic thermal model calibration using the Energy House facility at Salford

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Abstract: Thermal modelling tools have widely been used in the construction industry at the design stage, either for new build or retrofitting existing buildings, providing data for informed decision-making. The accuracy of thermal models has been subject of much research in recent decades due to the potential large difference between predicted and 'in-use' performance – the so called 'performance gap'. A number of studies suggested that better representation of building physics and operation details in thermal models can improve the accuracy of predictions. However, full-scale model calibration has always been challenging as it is difficult to measure all the necessary boundary conditions in an open environment. Thus, the Energy House facility at the University of Salford – a full-sized end terrace house constructed within an environmental chamber – presents a unique opportunity to conduct full-scale model calibration.

The aim of this research is to calibrate Energy House thermal models using various full-scale measurements. The measurements used in this research include the co-heating tests for a whole house retrofit case study, and thermal resistance from window coverings and heating controls with thermostatic radiator valves (TRVs). Thermal models were created using an IESVE (Integrated Environment Solutions Virtual Environment). IESVE is a well-established dynamic thermal simulation tool widely used in analysing the dynamic response of a building based on the hourly input of weather data. The evidence from this study suggests that thermal models using measured U-values and infiltration rates do perform better than the models using calculated thermal properties and assumed infiltration rates. The research suggests that better representations of building physics help thermal models reduce the performance gap. However, discrepancies still exist due to various other underlying uncertainties which need to be considered individually with each case. In relative terms, i.e. variations in percentage, the predictions from thermal models tend to be more reliable than predicting the absolute numbers.

Keywords: Model calibration, Dynamic thermal modelling, Co-heating, Retrofit, IESVE

1. INTRODUCTION

Dynamic thermal modelling tools have been particularly useful for building design and retrofit by enabling true what-if scenarios which often lead to, in theory, optimized design and retrofit solutions for buildings. Increasing evidence has shown that there are differences between the predicted and the 'in use' performances – the so called 'performance gap', which has been subject of much research in the past decades (Bordass et al 2001, Carbon Trust 2011 & Menezes et al 2012). The causes of the performance gap vary but can be characterised primarily by three categories: 1) how closely the building physics are represented by the model; 2) how accurate the operational inputs are against 'in use' operation of buildings; 3) the differences between the standardized weather data used in models and the actual weather condition post occupancy. Representing building physics has always been difficult, therefore, all models have to use assumptions. For example, in dynamic thermal models, building infiltration is represented as a constant background ventilation rate. While in reality, building infiltration is an instantaneous phenomenon depending on the air tightness of the building, instantaneous wind condition and the temperature differences between indoor space and outdoor environment. Air tightness of a building can be estimated through experiments under pressurized or depressurized conditions, however, the resulting infiltrate rate is an averaged rate rather than what happens in real time (CIBSE 2015 Guide A). Standard assumptions of thermal properties of building façades (i.e. used for simulation tools) can be quite different compared with the real thermal performances measured in practice (Francis et al 2015, Lucchi 2017). Very often when creating a building model using dynamic thermal simulation tools, construction details may be misrepresented due to a lack of understanding of the concerned building. The construction of walls in thermal models tend to be layer by layer with varying thicknesses, while in practice, materials used in construction can be mixed up together, thereby an approximation has to be made. The operational inputs of a building model include occupancy profiling, auto or manual controls of heating, cooling and ventilation of the building, etc. These would be assumed for modelling purpose, and in practice, these assumptions can be very different with the actual inputs when buildings are occupied. When a model is created at the design stage, standard weather data is often used to predict its likely performance, however, the standardized weather data can be quite different with the actual weather post occupancy. It is therefore not surprising that the performance gap exists. Eliminating the performance gap is somewhat unrealistic, however, reducing the gap through better representation of the building physics and operation is still very important to make the modelling outputs as informative as possible for building design and retrofit.

It is evident that calibrated thermal models can improve accuracy in predicting building performances, and are able to bridge or substantially reduce the performance gap (Monetti et al 2015, Paliouras et al 2015, Marshall et al 2017). However, full-scale model calibration has always been challenging as it is difficult to measure all necessary boundary conditions in an open environment, i.e. a building, on site, exposed to the natural environment. The IEA Annex 58 project was set up to examine the reliability of dynamic thermal modelling tools using full-scale twin houses in Holzkirchen, Germany (IEA58 2015). The detailed measurements from this project are believed to be the most comprehensive to date, as high quality field experiments for thermal model validation purposes tend to be expensive and time consuming. This research also illustrated the impacts of user errors which can be a key contributing factor in the difference on performance (Strachan et al 2015). Conventional methods of model calibration are limited by simple benchmarking settings, i.e. CIBSE TM33 (2006) and ASHRAE140 (2011). These benchmark cases are useful for comparative studies to identify programme errors and limitations, for example, the tests conducted for IESVE in accordance with ASHRAE 140 (IESVE report 2004). Although these benchmark cases have the benefits of simplicity, easier to make like-for-like comparisons (primarily for energy consumptions) between different programmes, they are far from realistic in practice, and are less useful in predicting building thermal comfort and energy use in real case scenarios. Research on full-scale model calibration or validation is still lacking and it is important to use more realistic case scenarios to carry out model calibration in order to raise the confidence of using such dynamic thermal models.

The Energy House (EH) facility at the University of Salford provides a unique opportunity to conduct thermal model calibration. The facility comprises of a full-sized Victorian end terrace house located within an environmental chamber. The chamber is able to provide fully-controlled conditions for the terrace house and various experiments are able to be conducted. This research aims to use some of the measured data under controlled conditions to validate the full house dynamic thermal model under controlled environment.

2. THE WHOLE HOUSE FACILITY AND ITS DYNAMIC THERMAL MODEL

2.1 The whole house facility

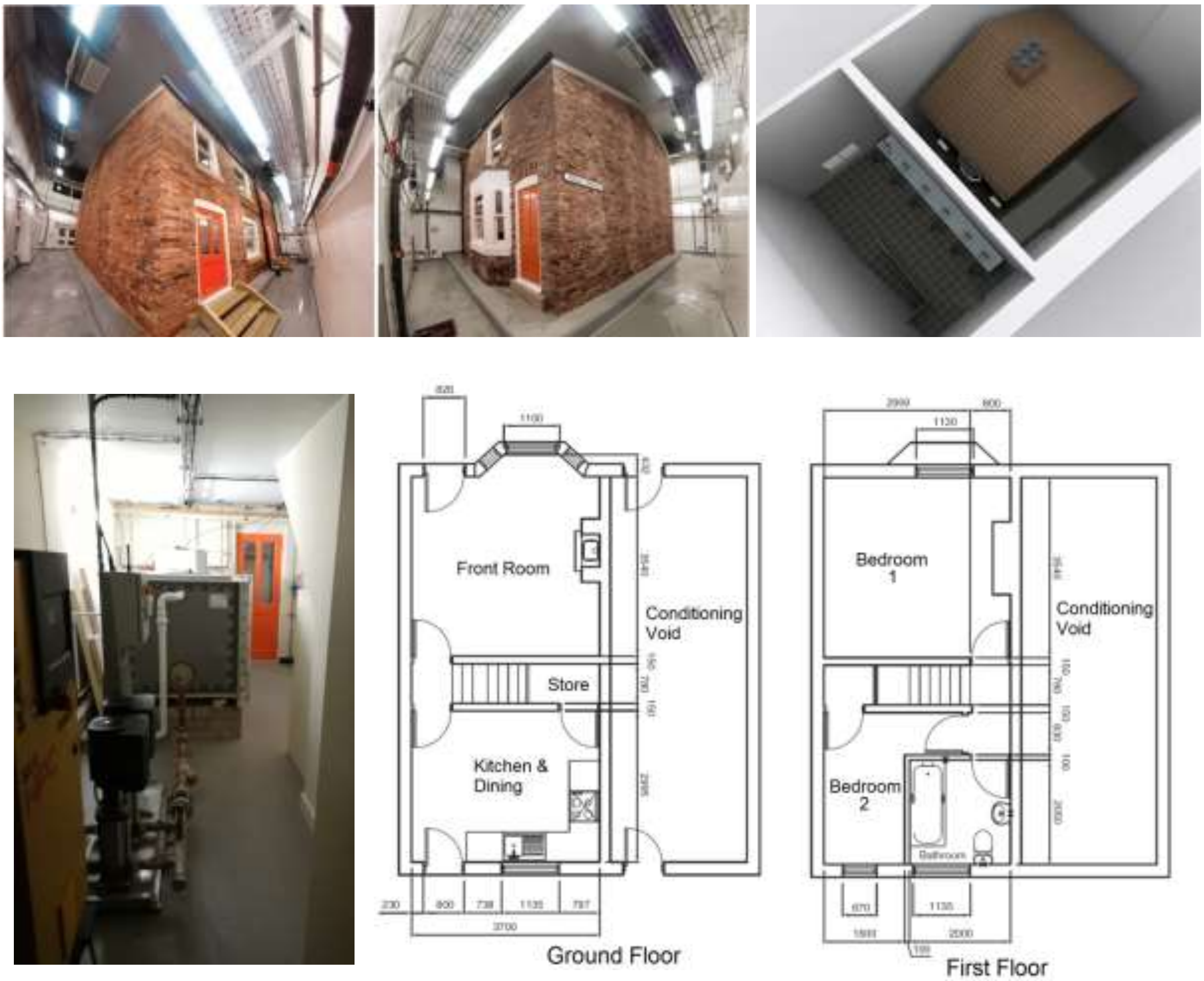

Figure 1 The Energy House – conditional void side, house side, spatial illustration of the house and its chamber, interior of the conditional void, and the floor plans for the Energy House

The Energy House is a full sized replica of a pre-1919 Victorian end terrace house. It was built with reclaimed materials and using the construction technologies at the time, mimicking the similar conditions of such houses on streets across the UK. It is estimated that such solid wall houses built during the late 18th and early 19th centuries represent approximately 30% of the existing housing stock, and these houses tend to be hard to treat in terms of improving their energy efficiency (BRE 2008). Figure 1 shows the house, interior of the conditioning void, and its internal two bedrooms layout. This house replica was built within an environmental chamber at the University of Salford. The chamber is a large concrete structure with 100mm PIR foam insulation to the walls and ceiling. To the floor there is expanded polystyrene insulation with 35mm thickness. The chamber is fully air conditioned with a total cooling capacity of 60KW. It is able to maintain the indoor temperature ranging from -12°C to 30°C with an accuracy of ±0.5°C (Farmer et al 2017).

The Energy House has been monitored extensively using various types of sensors. Some of the sensors referenced in this study are listed in Table 1. The sensors are always calibrated before taking measurements in order to make sure the accuracy of these instruments.

Table 1 Sensors used in the Energy House and their accuracy

Sensors	Model	Accuracy
Temperature sensor	Shielded 4-wire PT100 RTD	±0.1ºC
KWh meter	Elster A100C single phase meter	±1%
Heat Flux Plate	Hukseflux HFP-01	±3%
Pressure gauge	Energy Conservatory DG-700	±1%
Data Logger	DataTaker DT80	±0.1%

2.2 The dynamic thermal model

The thermal model of the Energy House was constructed using IESVE – Integrated Environmental Solutions Virtual Environment (IESVE 2017). IESVE is a well-established simulation tool analysing the dynamic thermal response and energy performance of buildings. The thermal model in Figure 2 illustrates the typical two bedroom end terrace house and its condition void which is used to mimic the condition of the adjacent terrace houses. The construction details assigned to the model are from the design specifications of the house, these are illustrated in Table 2 with the calculated U-values (the calculated U-values are from their default material thermal conductivities and their associated thicknesses of each material used for the energy house. In IESVE the U-values were calculated based on national and international standards).

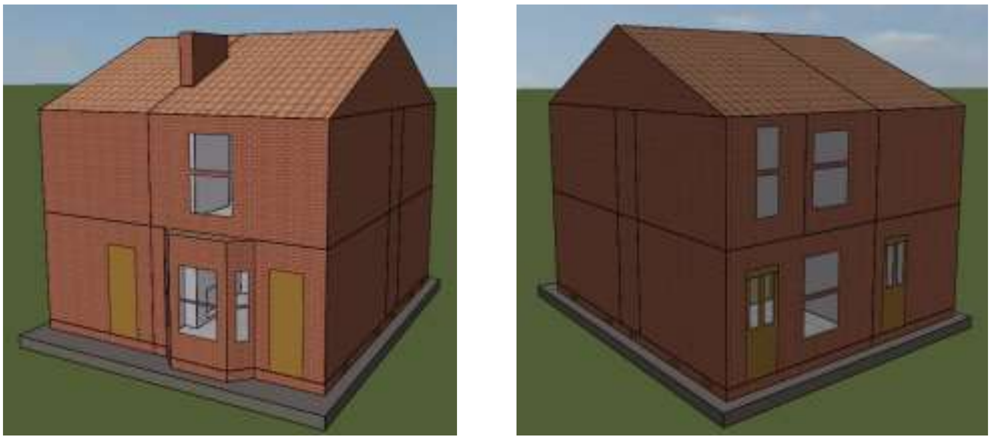

Figure 2 The Energy House model built in IESVE – Front façade (left) and Back façade (right)

Table 2 Materials (as built) used for the Energy House construction and the combined U-values

Structures	Details of construction	U-values (W/m^{2}K)*
Roof	Stone chipping + Felt/Bitumen Layers + Slate Tiles	6.05
External Walls	Terrace house: 225 mm brickwork + internal plastering Condition void: 225 mm brickwork + 45 mm EPS Slab	2.05 0.55
Glazing	6 mm Pilkington single glazing with timber sash windows	5.56
Ground Floor	Synthetic Carpet + timber flooring + Cavity + Cast Concrete (dense)	1.53
First Floor	Synthetic Carpet + timber flooring + Cavity + Plaster	1.39
First Ceiling	Timber board + Glass-Fibre Quilt (100 mm) + Cavity + Plaster	0.34
Internal Partition Walls	13 mm plastering + 115 mm brickwork + 13 mm plastering	1.97

**Three standards were used to calculate U-values of building structures: CIBSE, ASHRAE & EN-ISO, the values used in the table were from EN-ISO 6946 (2007): Building components and building elements -- Thermal resistance and thermal transmittance -- Calculation method.*

3. EXPERIMENTAL CASES DESCRIPTION

The cases selected for this study include two steady state experiments and one dynamic experiment using the Energy House. The first case is a co-heating experiment to examine the whole house's overall thermal performance before and after retrofit (Farmer et al 2017); the second case is the impact of window covering on energy performance (Fitton et al 2016); and the third case is a dynamic evaluation of heat dissipation through building fabric (unpublished in-house data).

3.1 The co-heating tests

The co-heating tests were carried out following the 2013 version of the test method (Johnston et al 2017), adapted to the Energy House facility condition (controlled environment). The overall Heat Transfer Coefficient (*HTC*) for the whole house is defined by:

$$HTC=Q/\Delta T \qquad (1)$$

where Q is the net power input and ΔT is the indoor and outdoor temperature difference under steady state condition.

Preliminary tests using the Energy House indicated that *HTC* is strictly correlated with the ratio between power inputs and temperature differences, i.e. *HTC* varies little with the variation of ΔT under steady state condition. This confirms that the overall heat transfer coefficient of the house is determined by the physical state of the house rather than the operation conditions. Therefore, given a fixed test condition, a staged retrofit process can be examined and the *HTC*s at different stages reflect the true nature of the thermal performances of that particular level of retrofit.

As shown in Table 3, for the convenience of putting up and taking down various retrofit measures used for the tests, the staged retrofit started from the 'full retrofit' (Stage1), and remove individual retrofit measures step-by-step until the all the measures were removed, the Energy House is then back to its baseline condition. Stage 6 in Table 3 is the baseline conditions for the co-heating tests. The construction details and calculated U-values at Stage 6 are from Table 2. During the retrofit experiments, the baseline condition for the glazing is 1980 style double glazing (**dg**) units, and was not the single glazed (**sg**) sash windows as what was installed for the Energy House originally (*ref*: Table 2). Stage 7 in Table 3 represents the original construction conditions of the Energy House. Table 3 shows the full retrofit stages, and during each stage, standard pressurised tests (@50Pa) were carried out to measure the permeability of the Energy House, the measurements were converted to the air change rate per hour (ach^{-1}) under normal condition as shown in the last column of Table 3 (CIBSE 2015 Guide A). The last row, stage 7, is from the preliminary tests using the original constructions (with the single glazed sash windows) as is, the pressure tests were not conducted under this condition, the infiltration is therefore assumed as 0.9ach^{-1} (relatively more ~~leaky~~ leakier compared the baseline case at 0.76ach^{-1} when the 1980 double glazing units were installed). All the tests were carried out with ΔT=15°C (indoor heating set point 20°C; environmental chamber temperature at 5°C).

Table 3 Retrofit cases considered (adapted from Farmer et al 2017)

Retrofit stages	Thermal elements				Measured infiltration (ach^{-1})
	External Wall	Roof	Ground floor	Glazing	
1	Side and rear wall: 90mm EPS (externally); front wall: 80mm PIR (internally)	270mm mineral wool	200mm mineral wool + membrane	A^{+++} glazing, low e, argon fill	0.38
2	Same as stage 1	Same as stage 1	Baseline	Same as stage 1	0.65
3	Same as stage 1	Baseline	Baseline	Baseline	0.70
4	Baseline	Baseline	Baseline	Same as Stage 1	0.70
5	Baseline	Same as stage 1	Baseline	Baseline	0.70
6	**Baseline**	**Baseline**	**Baseline**	**Baseline (1980 dg)**	**0.76**
7	Baseline	Baseline	Baseline	**sg** as in Table 2	0.9 (assumed)

The measured and calculated U-values for baseline case and retrofit cases are shown in Table 4. These details will be used for the two sets of IESVE models against the retrofit stages above, details will be discussed in section 4.1. For the measured U-value, it is calculated by U-value=q/ΔT, where q is the measured heat flux using Hukseflux-HFP01. The ΔT is the air to air temperature difference measured in the vicinity of each HFP location using PT100RTD temperature sensors During the retrofit experiments, 75 locations of were measured and the weighted U-values were used for individual thermal elements. Figure 3 shows the layout of the sensors used during the retrofit process (see Farmer et al 2017 for more details regarding the u-value measurements).

Table 4: Calculated and measured U-values for the Energy House facades

Building façade elements	U-values (W/m^{2}K)			
	Baseline calculated	Baseline measured	Retrofit calculated	Retrofit measured
First floor ceiling (between joints)	0.34	0.35±0.01	0.139	0.16±0.07
Side and rear external walls	2.05	1.74±0.06	0.324	0.33±0.01
Front external walls	2.05	1.84±0.08	0.269	0.22±0.01
Ground floor (between joists)	1.53	0.61±0.01	0.177	0.13±0.03
Glazing (measured at central pane)	2.86	2.39±0.09 (**dg**)	1.600	1.34±0.05

Figure 3 Heat flux and temperature sensors and their layout within the Energy House facility during the retrofit process

3.2 Curtain energy saving potentials

A series of experiments were carried out measuring the energy saving potentials of window covering using the Energy House facility (Fitton et al 2017). Existing research studies on window covering were often done through a hotbox or small climatic chamber environment (Fang 2001, Garber-Slaght & Craven 2012). The in-situ measurements from the Energy House are more realistic due to the nature of the facility. The test cases used in this research are those with electric heating to maintain a temperature difference of 20°C between the indoor and the environment chamber, with indoor set point at 25ºC and chamber temperature 5±0.5ºC (during heating season in the UK, the outdoor average temperature is around 5ºC). For both with and without window covering cases, the tests were run 3 full days in order to ensure the steady state conditions were achieved. The detailed window covering used for the tests and the measured U values without and with window coverings are shown in Table 5 (for detailed window covering materials, and their locations in relevance to the position of radiators, please refer the appendix of Fitton et al 2017). The windows glazings are the same for all the 5 spaces examined and the experimental uncertainty was around 5.75%. It is worth noting that the U-value of the living room is obviously larger than other spaces which are within the measurement uncertainty. It was thought to be due to the influence of airflow within the chamber, i.e. the bay window of the living room protrudes into the environment while other windows are recessed into the wall, and their exposure (to airflow) differences may have caused the variation of air flow intensities among these windows.

Table 5: Window covering types and location in relation to radiator, and measured U values (adapted from Fitton et al 2017)

	Living Room	Bedroom 1	Bedroom 2	Kitchen	Bathroom
Window covering materials	Lined curtain: Cotton lining, synthetic face materials			Roller Blind: Polyester	
Position of windows	Above radiator	Not adjacent to radiator	Not adjacent to radiator	Not adjacent to radiator	Above radiator
In use window covering	Curtains tucked behind radiator	Curtain drape 25cm below windowsill	Curtain drape 15cm below windowsill	Blind rests on windowsill	Blind rests on windowsill
U-value (W/m^{2}K, **without** covering)	5.10	4.5	4.45	4.32	4.43
U-value (W/m^{2}K, **with** covering)	4.13	3.93	3.96	3.40	3.49
U-value difference(W/m^{2}K)	0.97	0.57	0.49	0.93	0.93
U-value reduction (%)	19	13	11	22	21

3.3 Dynamic thermal responses under controlled conditions

The dynamic thermal response case came from a particular test on thermostatic radiator valves (TRV). TRVs can be installed on the inflow pipe of radiators in individual rooms which help regulate indoor temperature on an individual room basis. These valves can sense the air temperature around them and respond to their settings by controlling the volume flow rate of hot water within a central heating system, i.e. if the pre-set temperature is achieved for an individual room, the valve can cut off the hot water supply to the radiator serving that room. The accuracy of TRVs is around 2°C to 3°C, not scientifically accurate but are sufficient for domestic household zoning controls of temperature. As shown in Figure ~~3~~4, the 15 days tests include different intermittent heating patterns, set points and different type of TRVs. The living room temperatures were recorded every minute and the instantaneous power inputs for the whole house were also measured.

The first two cases discussed in early sections are both steady state tests where energy demand or system loads are the central focus. This TRV test case was used to examine the dynamic thermal response of the facility under fixed environmental temperature of the chamber.

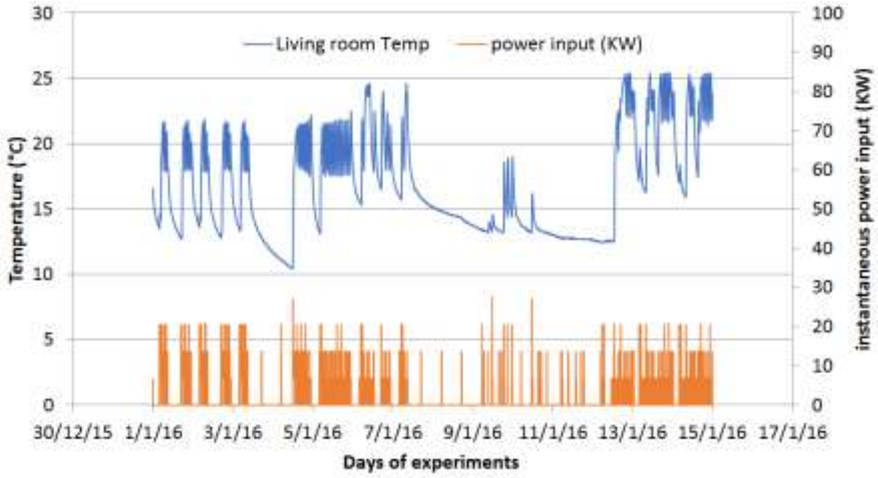

Figure ~~3~~4: The 15 days test on heating controls

4. RESULTS AND DISCUSSIONS

The Energy House itself is a fully functional house with all the necessities installed for occupants, for example, sofa, armchair, coffee table in the living room; fully fitted kitchen and bathroom and furnished bedrooms, but no one is able to actually live in the house due to safety reasons. The operational aspects of the house can be accurately represented, i.e. outdoor environment is tightly controlled, no occupancy profiling needed and controls in terms of space conditioning can be dealt through heating/cooling set points. Due to this uniqueness of the Energy House facility, the calibration of the thermal model can focus on the representation of the building structure details. In order to examine the system errors and the deviation between modelled data and measured data, two statistical quantities are also included in the analysis when measured and modelled data are compared. They are the Mean Bias Error (MBE – a measure of overall systematic error in percentage) and Root Mean Square Error (RMSE – measuring average deviation from the true value in percentage), expressed as follows:

$$MBE = \frac{1}{N}\sum_i^N \frac{x_i - x_m}{x_m} \qquad (2) \qquad\qquad RMSE = \sqrt{\frac{1}{N}\sum_i^N \left(\frac{x_i - x_m}{x_m}\right)^2} \qquad (3)$$

where N is the number of measurements, x_i is the modelled output, x_m is the measured output for under the same condition of x_i.

4.1 Calibration on the co-heating tests

In the IESVE model, the indoor air temperature is set to be 20°C, the adjacent condition void has the same heating set point during the retrofit tests. It is reasonable to assume there is no heat transfer through the shared wall therefore an adiabatic condition is given to the wall between the Energy House and its adjacent condition void. Simulations were carried out using IESVE to repeat the retrofit cases step by step. Two sets of simulation cases were considered – the first one is to use the calculated U-values for the construction materials for the baseline case (*ref*: Table 2, Table 4). The calculated U-values were also used for the proposed retrofit measures at each stage. The relevant materials were selected from the system material library from IESVE. The averaged background infiltration is assumed at 0.9ach^{-1}(Table 3), which is typical for an end terrace house of this age. The second set of simulation cases is to use in-situ measurements wherever possible. Using the same materials but their U-values were adjusted to meet the measurements from Table 4, and during each stage of retrofit the infiltration level is given based on the airtightness test results (measured infiltration rates under normal condition are shown in Table 3).

Table 6 The measured HTC at each retrofit stages compared with the corresponding modelled HTC

Retrofit stages	Measured *HTC* (W/K)	Modelled *HTC* using calculated U-values (W/K)	% departure from measured *HTC*	MBE/ RSME (%)	Modelled *HTC* using measured U-values (W/K)	% departure from measured *HTC*	MBE/ RSME (%)
1 (full retrofit)	**69.7**	103.3	48%		73.3	5%	
2 (full retrofit with original floor)	**82.7**	127.2	**54%**		99.4	20%	
3 (Solid walls only)	**103.6**	142.9	38%		116.1	12%	
4 (A^{+++} glazing only)	**174.2**	253.9	46%	42/43	211.0	21%	15/16
5 (Roof only)	**180.5**	257.3	43%		213.5	18%	
6 (baseline with 1980 dg)	**187.5**	263.1	40%		222.1	18%	
7 (With original sg sash windows)	**220**	279.2	27%		242.4	10%	

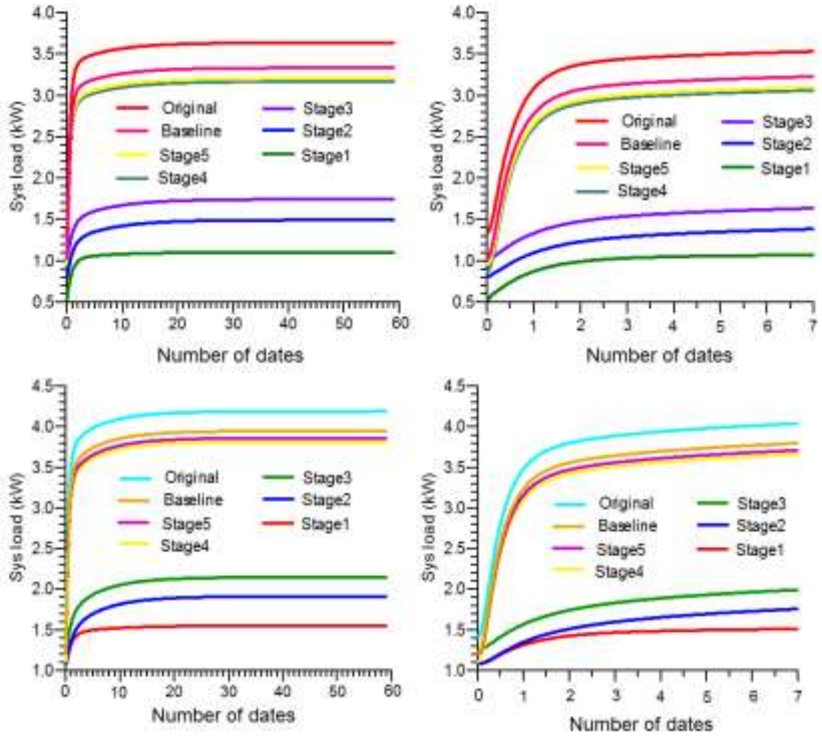

Figure 45: The total system loads (power inputs) through the energy house model for various retrofit stages – top two images (data for 60 days and first 7 days) are for models with measured U-values and infiltration rates; bottom two images (data for 60 days and first 7 days) are those with calculated U-values and assumed infiltration rate.

Table 6 shows the measured heat transfer coefficients (*HTCs*) from co-heating tests and the modelled *HTCs*. Broadly speaking, the modelled *HTC*s were all over-predicated by the thermal models. Using the calculated U-values (the default thermal properties from IESVE system libraries) and assumed infiltration at 0.9ach^{-1}, much higher *HTC*s were resulted compared with the measured *HTC*s for all the retrofit stages. Discrepancies are ranging from 27% with the original case to 54% with stage 2 retrofit. While with the measured U-values and infiltration rates at each retrofit stage, the discrepancies are ranging from 5% for the full retrofit case to 21% for the retrofit stage 4. Mean Bias Errors on *HTC*s differ from 42% to 15% between models with calculated U-values and assumed infiltration and measured U-values and measured infiltrations. For Root Mean Square Errors (RMSE), the differences of which were 43% and 16%. It is evident that by using the measured inputs for the thermal model, the accuracy of model predictions improved significantly. However, the departure from measured data at different stages is random in nature for both calculated and measured inputs. The largest discrepancy at 54% at stage 2 could be primarily attributed to the ground floor U-value. The calculated U-value for the original ground floor is 1.53W/m^{2}K (Table 2), while the measured U-value is 0.61W/m^{2}K (Table 4). Comparing Table 2 and

Table 4 for the baseline case, differences between calculated and measured U-values for individual thermal elements are expected, however, the difference for the ground floor appears to be unrealistically large.

The consistent over-predictions of *HTC*s could be due to two key reasons: the uniformity of indoor air temperature and the thermal lag from the IESVE model. In the IESVE model, once the heating set point is set at 20ºC, the spaces with heating elements will remain 20ºC which is an ideal uniform condition numerically. During the actual experiments, the temperature sensors within the Energy House tend to be located in the spatial centre for all the concerned spaces, these are point measurements which may not be representing the spatial average so the actual average temperature of the testing facility could be lower than the set point leading to smaller overall heat flux through the whole house (ref: equation 1 where ΔT is fixed). While this is hard to prove unless high density measurements (many more sensors for one space) were carried out. The thermal capacity of the Energy House represented by the IESVE model seems to be taking much longer to settle. The in-situ tests were running for 72 hours in order to meet the steady state requirement based on ISO 9251 (BSI 1987), from the moving average data (Farmer et al 2017), the power output and the indoor air temperature are fairly steady which indicates that the steady state was achieved. However, numerically it took up to 30 days to reach steady state in which the total power inputs (system loads in KW) for the Energy House models at various retrofit stages become constant (Figure ~~4~~5). If we were taking data on the third day (In IESVE model, the initial indoor temperature is set at 20ºC, only the structure thermal capacity takes time to reach steady state), the *HTCs* with “calculated U-values and assumed infiltrate rate” and “measured U-values and measured infiltration rates” at various retrofit stages would have been closer to the in-situ measurements. The reasons for the long thermal lag are primarily from dynamic heat exchanges between different spaces/zones of the model. Spaces with heating elements (Ground floor living room, kitchen, first floor two bedrooms and bath room) are controlled by the heating set point. Indoor air temperatures for these spaces reach the set point temperature instantly, the initial temperature was set to 20°C. For other spaces such as ground/first floor storage space, landing, staircase, base void, loft, etc., although the initial air temperature was 20°C, the time taken for these spaces to settle is consistent with the settling time of the system loads shown in Figure 5. In IESVE model, there is no assisted circulation within the house, the heat exchanges between internal spaces rely on natural convection and conduction only, which was one of the reasons why it took longer for the IESVE model to settle. It is therefore important to note that ~~T~~the data presented in Table 6 were derived from the steady state condition for all the retrofit stages in order to compare the like.

~~One of the~~Other reasons for the slow progress to steady state from the thermal models ~~is~~ may include the simulation input conditions. ~~-~~As indicated in Farmer et al (2017), the wind speed in the environment chamber is assumed to be zero. The wind speed (caused by the chamber air handling system) measurements were not taken during the staged retrofit tests carried out by Farmer et al (2017). For the dynamic thermal models, the environment inputs from the chamber only considered air temperature which is set to be constant at 5°C to mimic the experimental setting (wind speed is set to be zero). The input conditions for the thermal models include external convection model which involves wind speed in McAdam’s empirical equation (IESVE User Manual 2018). This led to a discrepancy on the convective heat transfer coefficient among the external facades to the chamber environment increasing the time to reach steady state. The unintended consequence of this observation is that the resulted *HTCs* from the thermal models should be smaller than actual measurement, which is certainly not the case as all the thermal models over-predict the *HTCs*. Due to the nature of co-heating tests which consider only the overall heat transfer coefficient, the underlying uncertainties from various aspects are hidden from this single number representation of thermal performance for the whole house. The uncertainties could come from: wind velocity uncertainty is ranging from ±2% (calm conditions which fits the chamber conditions) to ±16 (6.0m/s) (Persily 1982); accuracy for co-heating tests ranges from ±8% to ±10% (Jack et al 2018); the uncertainty of in-situ U-value measurements in accordance with ISO 9869 is ±14% (BSI 2014); during the tests when the temperature difference ΔT was remained constant, the tolerance of variation for heat flow rate Q is ±5% (Farmer et al 2017); and other uncertainties include infiltration blower door tests, thermal bridging and uneven heat loss across the ground floor of the facility (Pelsmakers et al 2017). These uncertainties were not able to be mitigated through the use of dynamic thermal models, thus, discrepancies between measurements and modelling outputs are unavoidable.

Table 7 shows the whole house heat transfer coefficient reduction against the baseline condition and the percentage contribution to that reduction from individual thermal elements. Although the absolute numbers look quite different between the measured data and the modelled data, the percentage contribution on reduction remains relatively consistent, in particular for the solid wall insulation at Stage 3 – the percentage contribution towards full retrofit *HTC* is both 71% for measured *HTC* and modelled *HTC* using measured U-values. Even with calculated U-values, the difference is small (71% verses 75%). The largest relative difference (7%) happens for the stage 2 retrofit where the original floor was used. As indicated earlier (table 2 & table 4), the measured and calculated U-values did have a relative large difference. Again using the measured U-values and infiltration data, both absolute and percentage reduction data from the IESVE models are closer to the measured data compared with the IESVE models with the calculated U-values and assumed infiltration. In theory, the full retrofit reduction (stage 1) should equal the sum of the *HTC* reductions from individual thermal elements (stages 2 to 5). Both the measure data and the modelled data showed some slight discrepancies, i.e. 117.8W/K vs 117.2W/K; 159.8W/K vs 158.9W/K; 148.8W/K vs 151.8W/K, which is the reason why the added percentage contribution is not exactly 100% in the third and seventh columns.

Table 7 HTC reductions on baseline stage 6 and percentage contribution from each thermal element towards full HTC reductions (W/K)

Retrofit stages	Measured *HTC* (W/K)	Modelled *HTC* using calculated U-values (W/K)	Modelled *HTC* using measured U-values (W/K)

	Reduction on baseline stage 6	% contribution towards full retrofit HTC	Reduction on baseline stage 6	% contribution towards full retrofit HTC	Reduction on baseline stage 6	% contribution towards full retrofit HTC
1 (full retrofit)	**117.8**	N/A	159.8	N/A	148.8	N/A
2 (full retrofit with original floor)	**13**	11%	23.9	15%	26.1	18%
3 (Solid walls only)	**83.9**	71%	120.1	75%	106.1	71%
4 (A^{+++} glazing only)	**13.3**	11%	9.1	6%	11.1	7%
5 (Roof only)	**7**	6%	5.8	4%	8.6	6%
6 (baseline with 1980 dg)	**N/A**	N/A	N/A	N/A	N/A	N/A

4.2 Calibration for window covering cases

The IESVE model for the curtain case uses the Energy House original state where the single glazed sash windows were present. For this setting, the infiltration rate was assumed as 0.9ach^{-1}, same as in section 4.1 to keep consistency. U-values used for all the thermal elements are from measurements wherever possible (Table 4, loft, external walls, ground floor, window and window glazing). The heating set point was 25ºC with external chamber temperature at 5ºC in order to achieve a 20ºC temperature difference to meet the measurement conditions. In the IESVE model, the concerned spaces are the first floor bedroom 1 and the ground floor kitchen. These two spaces were isolated out by 'turning off' all the other spaces to achieve adiabatic condition for all the internal partitions, floor and ceilings. This is a common practice when conducting dynamic thermal modelling – when internal spaces have the same air temperature, there would be no heat transfer through partition walls, it is therefore logical to assign an adiabatic condition in order to simplify the calculation process. The overall heat losses through both rooms were recorded under three scenarios: (1) 'as is' scenario to calculate the total power input (power input equals heat loss under steady state condition) through exposed facades for both rooms; (2), repeat scenario (1) with window covering, the thermal resistances of window coverings are given based on the measurements from the heat flux transducers used in the experiments (Hukseflux HPF-01, Table 1), the measured resistances R values are 0.03m^{2}K/W for the Bedroom 1 and 0.06m^{2}K/W for the Kitchen, the power input differences between the first two scenarios are the heat loss reductions due to window covering; (3) blocking all the windows to make sure no heat flow through the window areas and remain all other exposed areas are the same condition. The overall power input difference between scenario (1) and scenario (3) is the heat loss through windows without covering; the difference between scenario (2) and scenario (3) is the heat loss through windows with covering. In Figure ~~5~~6, the line graphs show the power inputs calculated for Bedroom 1 and Kitchen, the bar chart is the comparison between the measured and modelled heat fluxes (the modelled heat fluxes are derived from the power inputs over the window areas). It is evident the heat fluxes through windows were under-predicted by the thermal model. The heat flux transducers measure heat flux at a specific point of a surface – for the cases considered here it is the central pane of windows. This point (small area – smaller than one's palm) heat flux is used to represent the heat flux across the full glass surface. In the IESVE model, the glazing areas include the contribution from the window frames. They are relatively larger than the actual glazing size, which could contribute the under-prediction of the heat flux. The other possible reason for the under-prediction of the heat flux through windows was the established experimental condition. During the experiments of Fitton et al (2017), the 60 minutes moving average of indoor air temperature was slightly more than 25ºC, and the moving average of chamber temperature is less than 5ºC, which could have resulted a temperature difference of more than 20ºC, a slightly higher heat flux than the set condition is therefore expected. It is worth noting that the time taken to reach steady state is much faster than modelling the full Energy House model. When Bedroom 1 and Kitchen were isolated by 'turning off' other spaces to achieve adiabatic condition for internal shared partition/ceiling/floor, the thermal mass of all other parts of the building was not taken into account during the numerical calculation, so the time taken to reach the steady state numerically become similar with the experiments.

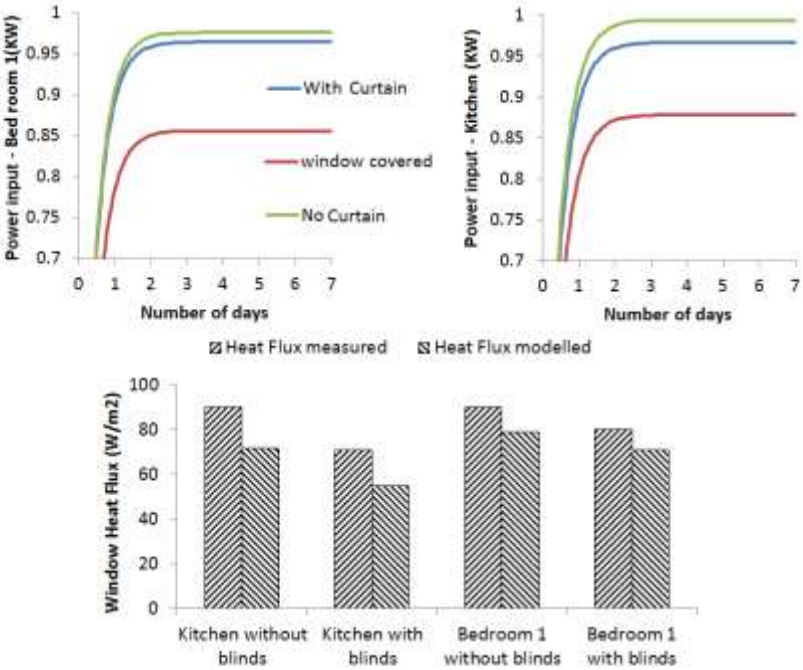

Figure ~~5~~6: The power inputs through bedroom 1 and kitchen for the three testing scenarios (no curtain, with curtain & covered windows) and the heat fluxes comparisons between measured and modelled data.

4.3 Calibration dynamic heat dissipation

The living room air temperature measurements in Figure ~~3~~ 4 were taken under the original Energy House setting with single glazed sash windows (retrofit stage 7 as discussed in section 4.1). For comparison purpose the first 5 days data in Figure ~~3~~ 4 were used. The heating schedules for the first 5 days vary, i.e. for day 1 and day 2, intermittent heating is on from 4am to 9am and then on again from 5pm to 11pm; for day 3, heating is on from 4am to 9am only; for day 4, heating is on from 12 noon to 11pm; and day 5, heating is on from 4am until midnight. As the room temperature is controlled by TRVs, there are clear 'overshoot' and 'undershoot' in temperatures (Figure ~~3~~ 4 & ~~6~~7), the set point is roughly 20ºC by the setting on the TRV but the controlled temperature is about 19.5ºC in average during heating. In IESVE model, a heating set point of 19.5ºC was used and the heating profile was set based on the heating schedule explained above. When the central heating is on the measured heating output from the radiator in the living room is 1.63KW in average so the heating capacity of the living room is set to 1.63KW in IESVE model (Ji et al 2014). Due to the nature (overshooting and undershooting in temperatures) of the TRV controls, IESVE model is not able to replicate the TRV's behaviour therefore a fixed heating set point was used. In the IESVE model, once the heating set point is reached, the temperature will stay at this set point, which is the reason why the air temperatures from the IESVE models tend to be a straight line when heating is on (Figure ~~6~~7).

The current setting of the IESVE model provides a finite heating capacity (at 1.63KW); it takes time for the room air temperature to reach the set point (by default, IESVE models use a heating system with unlimited capacity, it can lift the temperature straight to the set point as soon as heating is on). This is clearly shown on day 4, at 12 noon after a longer break of heating from previous day, heating is on but it took hours before the room air temperature can reach the set point indicating the thermal lag in numerical calculation; other days behave similarly but is not as obvious. Due to the nature of how heating is managed by the TRV and the model setting, it is not as useful to compare the data during heating period. During the times when heating is off, the Energy House will be dissipating heat through its façade fabrics and ventilation (background infiltration through natural convection only as no external wind is considered). In principle, the heating dissipation process for both the in-situ measurements and the IESVE model are the same so meaningful comparisons can then be made. As shown in Figure ~~6~~7, the IESVE model with calculated U-values does seem to dissipate heat much faster than the measurement consistently. This was due to fact that U-values of the building thermal elements (i.e. walls, ceilings/floors, windows, etc) were largely over-estimated by the default thermal properties from the IESVE system material library. When using the measured thermal U-values for the Energy House building façades, the comparisons between the measured and model temperatures show much better agreement. Discrepancies still remain even using the measured U-values. This is consistent with the comparisons between the full retrofit *HTC* measurements and the modelled *HTC*s discussed in section 4.1 (modelled *HTC*s are consistently higher than measured *HTCs*, thus quicker heat dissipation through building fabric and infiltration). Apart from the over predicted *HTCs*, the discrepancies can also be due to the differences of heating behaviour between a real central heating system and IESVE model. When the central heating system stops, the radiator has residual heat which would normally last about 30 to 40 minutes before the temperature of the radiator reaches room temperature, during the time the radiator still releases heat to the designated space. While for the IESVE models, once scheduled heating stops there will be no residual energy into the room to resist the temperature drop.

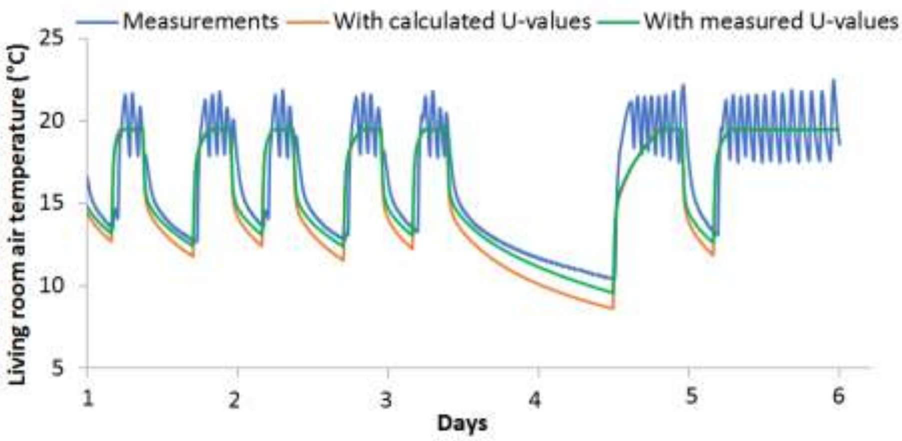

Figure ~~6~~7: The living room air temperature for 5 days using TRV heating controls – measurements compared with IESVE models: model with calculated U-values and model with measured U-values.

5. CONCLUSIONS

This paper reports the calibration of dynamic thermal models using the unique Energy House facility at the University of Salford. The two steady state cases presented here were the co-heating tests and the window curtain tests conducted at the Energy House previously. The third case was testing heating controls (TRVs) and the dynamic data of room air temperatures were used. Various IESVE models were developed against the experiments settings and comparisons were made between the measured and the modelled data.

For the co-heating tests, the overall heat transfer coefficients (*HTC*s) were all over-predicted by the IESVE models. The models with calculated U-values and assumed infiltration rates had larger discrepancies compared with the measured data. Significant improvements were observed from the IESVE models when the measured U-values and infiltration rates were used as inputs. It is evident that better representation of the building physics (construction details) in thermal models can improve accuracy. The calculated U-values for the building thermal elements using their material default properties are consistently higher than the measured U-values, which was the key reason resulting the over-prediction of the *HTC*s. These default material properties (i.e. thermal conductivities) from the IESVE material library were the reflection of the true thermal property under homogeneous conditions. There are always differences in practice (uneven thickness, mortar, edging, framing, etc). The measured U-values, although discrete with finite number of measurements, still present a better representation of the real building physics then IESVE default. The exact reasons for the discrepancies between the measured *HTC*s and modelled *HTC*s with measured inputs (U-values and infiltrations at various retrofit stages) are complex. This could be further investigated by re-designing the model calibration process, i.e. by separating the contributions of *HTC* reduction between thermal elements and infiltration rates at each retrofit stage. This will help identify the dominant reasons contributing the difference between measured and predicted *HTC*s. The *HTC* reduction comparisons confirm the large discrepancies in the predictions of absolute numbers, however, in relative terms – the percentage contribution towards full retrofit *HTC*s, the measured data and the modelled data agreed each other well. Therefore, comparative studies using numerical models are more reliable than predicting the actual performances.

The curtain case was compared only with the models with measured U-values wherever possible. The modelled heat fluxes were under-predicted for both Bedroom 1 and the Kitchen. The differences were thought to be primarily due to the window areas used in the IESVE models and the higher temperature differences in the experiments. For the dynamic case, representing the TRVs using a fixed heating set point in the IESVE models is unrealistic due to the accuracy of the TRV controls (2 to 3°C). However, the dynamic heat dissipation in the IESVE models should represent the actual heat dissipation through the Energy House from experiments closely when the heating is off. With calculated U-values, the IESVE models dissipated heat much faster than the experiments, which results in much lower temperatures before the next heating cycle starts. With measured U-values in the IESVE models, the heat dissipation rates are much closer to the measurements. The remaining discrepancies are thought to be primarily due to the residual heat from radiators during the experiments and the over-predictions of *HTC*s from the IESVE models in general.

The evidence from this study suggests that closely representing building physics does improve the accuracy of thermal models. In practice, when a dynamic thermal model is created, very often there were no physical measurements available to use as model inputs. Given the fact the calculated and measured difference in U-values can be large (i.e. for the ground floor – measured 0.61 W/m^{2}K verses calculated 1.53 W/m^{2}K), the model prediction of absolute terms can often be biased, hence the performance gap. While in relative terms, these discrepancies tend to be less obvious.

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As requested from 'Guide for Authors'

Highlights

- Full scale measurements were used for thermal model calibration
- The measurements were made under controlled condition
- Three different case scenarios were modelled and comparisons were made
- Measured inputs can improve the accuracy of thermal models

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