A CRITICAL SOFTWARE REVIEW- HOW IS HOT WATER MODELLED IN CURRENT BUILDING SIMULATION?

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ABSTRACT

In a changing climate and with ever increasing energy standards that lead to low and zero energy buildings, the provision of hot water in buildings will become more significant in relation to the overall energy consumption. Higher demand on the provision of hot water consumption has been documented and will occur around activities such as laundry, dishwashing, food preparation, bathing and cleaning activities. The accurate prediction and simulation of hot water in building design is therefore crucial and we need to rethink how we estimate the amount of hot water in our buildings. This paper will investigate how hot water demand and provision in homes is simulated via a number of different tools. The input and output differences with respect to hot water are compared to measured data of a building in the UK.

INTRODUCTION

The need for reducing energy consumption and greenhouse gas (GHG) emissions is a key challenge. The UK Government has committed itself to reduce GHG by 80% in 2050 relative to the 1990 levels with the objective towards zero emission from the domestic sector DECC (2009). Based on this, building energy performance regulations and standards have been periodically updated introducing new performance values characterized by a very high level of thermal insulation, with the aim to design "zero energy" buildings EPBD (2010). As a consequence, buildings become more energy efficient and airtight, therefore the proportion of energy demand for space heating to energy demand for hot water production is decreasing (note: space heating is not considered in this paper). It is estimated that hot water production accounts for 26% of the total energy consumption in residential homes DECC (2012). Therefore, the accuracy of hot water demand estimation is an important factor in order to better design and plan our domestic heating systems and to predict more precisely the overall energy consumption. However, the methodologies (for estimating hot water) that are implemented in regulations and standards are often based on simplified methods and assumption.

The design and provision of domestic hot water and energy consumption is a challenging task as it depends on several unpredicted factors such as occupancy behaviour, appliances efficiency, mains supply line pressure, supply water temperatures, heat generation equipment, distribution system and other parameters that may vary from one household to another. The building regulations are in a constant flux and the need for better prediction of hot water demand is an important issue. In some cases monitored data has been used to create hot water demand profiles, however the level of detail of these models is not clear. From a literature review conducted in this paper it was found that simulated results often do not match well with monitored data. In most cases, the main factors that contribute to this discrepancy between simulated and measured results are not investigated.

The term 'hot water' in this paper refers to the hot water used/produced to a certain temperature that satisfies peoples comfort and hygiene requirements. The domestic hot water is mainly produced from the boiler and distributed via different devices such as taps, sinks shower/bath. There are however appliances such as dishwashing and washing machines which require hot water generation to accomplish the cleaning activities. These appliances although not connected to the boiler, are built to produce and use hot water. As a consequence they are seen as appliances that consume hot water and energy and therefore are considered in the measurements and models of this paper.

In this paper a literature review is carried out in order to investigate hot water demand assessment based on current regulations. Further, a case study is presented and a comparative analysis is carried out in order to compare the output of five different tools for a typical residential building. For reasons of sensitivity and fairness, we have chosen not to name the software tools used. We do not feel that this distracts from the scientific merits of the paper. The results include the volume of hot water, energy consumption, heat losses, equipment efficiency and water flow temperatures. In a critical review, we point out possible factors that influence the discrepancy between the measured and the simulated results. The overall aim of this paper is to address issues that can improve methods for models estimation and reduce software's simulation shortcomings.

METHODS

The research was carried out in two parts: a literature review, important to understand the context of current regulations and standards and a software review that investigated the features and capabilities of simulation softwares with respect to hot water demand.

Part 1: Literature Review

The European standards such as CEN and CENELEC define three tapping cycles and patterns ranging from

11 to 30 draw-offs per day. This is whilst the total volume of use ranges from 36 to 420 litres per day of hot water demand for a single household (European Commisison, 2002). The Code for Sustainable Homes (CSH) suggests that the assessment criteria for total (hot+cold) water consumption in new dwellings should range from 80 to 120 litre per person a day (DCLG, 2010). Burzynsky et al. (2010) reviewed methodologies used to estimate hot water demand and noted that there is only a limited number of methods. They considered the BREDEM model as the most advanced one. The hot water consumption according to the BS EN-8558 (2011) standard should be estimated between 35 to 45 litres per person per day. This is whilst BSRIA rules of thumb propose a daily hot water consumption between 80 to 120 litres per person per day (Hawkins, 2011) . The CEN Mandate 324 (2002) specifies a series of hot water run-off profiles over 24 hours period associated with the volume and energy consumed for each draw-off. According to this standard, the average energy consumption is about 4.3 kWh/day whilst the average volume of hot water use is about 116 litres/day. Jordan and Vajen (2005) developed a tool to generate DHW profiles based on IEA-SHC Task 26 and used statistical methods to distribute the draw-offs patterns. Garbai et al. (2014) used a methodology based on probability theory to predict hot water demand for a number of apartments considering quantity and intensity as stochastic variables. They found out that the quantity of hot water consumed in a peak period of discretionary duration resembles a normal distribution. Makki et al. (2013) used a linear multiple regression analysis to create a shower end use forecasting model and revealed that variables, such as household makeup, occupation status and shower-head efficiency are determinant variables for hot water use. A transient simulation program was developed by Rodriguez-Hidalgo et al. (2012) to obtain the dimensioning criteria of a domestic hot water solar plant and the size of the storage tank for a multi storey apartment building. Ayompe et al. (2011) validated a solar water heating systems modelled with TRNSYS against measured data and found out that mean absolute errors ranged from 7% to 18 %. Kenway et al. (2012) developed a detailed mathematical flow analysis model to estimate household water use. They found out that the model deviation error was within 20% of the monitored data. According to a study carried out by Bennett et al. (2013) the application of Artificial Neural Networks (ANN) based modelling is a feasible method of producing moderate accurate residential water demand end use forecasting models. Moreau (2011) simulated a storage water heating system with TRNSYS and validated simulated results against measured data. He found out that the model was able to accurately predict the electricity demand and the hot water temperature leaving the tank. Lutz (2010) evaluated the hot water temperatures and flow rates as calculated by the combined HWSim and TANK simulation models. His results revealed negligible differences.

Cahill et al. (2013) modelled and simulated hot water demand for a dwelling using end-water-use parameter probability distributions generated by Monte Carlo simulations. They found out that the results were comparable to their measurements. Lutz et al. (2013) used MODELLICA to model storage and instantaneous water heaters systems with the aim to improve models in existing libraries. The authors pointed out that the tool and existing models still needed to be improved, emphasizing system control and distribution system modelling. Ries et al. (2013) used the BEopt optimization software to simulate and predict the performance of a tankless water heater under retrofitting options. The authors pointed out that the demand patterns of hot water demand influence the feasibility of the energy reduction estimated from retrofitting. Wang et al. (2007) used ESP-r to model a gas-fired water storage tanks system and found that the model could predict the mean tank temperature well. However, dependent on the water drawing schedule the energy consumption was underestimated by ca. 8-15%. In a study by Clarke et al. (2009), they created hot water energy models and indicated that the optimization of hot water system design (such as boiler location, controls, cylinder sizing, distribution pipes and insulation) could provide significant reduction of hot water and energy consumption.

Part 2: Modelling Approach

The aim of the modelling approach is to estimate the hot water volume used and the energy consumption for hot water production in the home. This includes hot water from the taps, showering (boiler system), dishwashing, and washing machines (appliances). The estimation of energy consumption (gas for boiler and power for appliances) has been directly measured, whilst the hot water has been measured only for the boiler system. Meanwhile for the appliances an approximate estimation was made which is based on the measured power consumption technical data sheet information. For each created model, the input parameters such as draw-off profiles, boiler capacity/efficiency, supply temperatures are based on the default values for each of the chosen tools. The physical input parameters of the DHW system such as, distribution pipe length and diameter are based on the real measured values of the case study building, such as the total building floor area. In terms of the dishwasher (Zanussi 12001WA model as for this case study), the technical manual defines five different running cycles, each of which has a certain duration, energy consumption, temperature set point and hot water volume. Based on the cycles duration (estimated from the measured power), and information from the technical manuals, the hot water volume was estimated

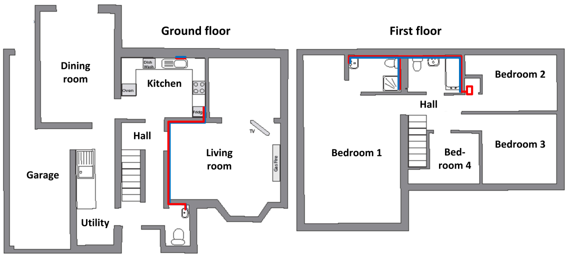

Figure 1: Internal layout of the building

Figure 2: Case study building (left) and simulated (right).

Table 1: Case study parameters of the monitored domestic hot water system that serve as input for the simulation models.

Parameter	Value	Unit
Boiler capacity (Max/Min)	29/10	kW
Boiler efficiency	87.1	-
Flow rates (Max/Min)	11/2	l/min
Distribution pipe inside diameter	0.0175	m
Distribution branches total length	15	m
Total Draw-off points	7	qty

(short cycles, as defined in the technical manual were considered as pre-wash and cold water is assumed to be used). The same approach was applied for the washing machine (Indesit WG1034 model).

Case study

A typical residential building located in Loughborough (UK) was considered for modelling and gathering the measured data. The building is a two storey building, constructed in the mid 1970's with four bedrooms covering 140m^2(Figure2). It has a filled cavity wall insulation and is double glazed throughout. The building is part of the LEEDR project which monitored the hot water and energy consumption in twenty homes at high resolution timestep. The heat generation and draw-off characteristics of hot water use were estimated for some homes and it was found that considerable (about eighteen percent) of total energy is consumed solely by the hot water production (Buswell et al., 2013).

Figure 1 shows the layout of the building and its domestic hot water system (red lines). The boiler is located on the first floor serving hot water bathroom taps on the same floor and kitchen and toilet taps on ground floor. Heating and hot water is provided instantaneously by a condensing combi-boiler (Vokera Compact 29H), serving radiators of varying size and style throughout the house. All radiators have manually controlled thermostatic radiator valves. The house is occupied by two adults and two children aged 11 and 8. Table 1 presents the main parameters of the monitored system. From the boiler technical datasheets, the capacity refers only to the hot water production (not including heating) as based on the water flow limits and on an average temperature rise (ΔT) 35℃. The rating efficiency is based on the technical manual and the average seasonal efficiency of the domestic boiler. The distribution of the hot water system is constructed from uninsulated copper pipe and seven draw-off points for different end use categories (such as one shower, five taps and one bath tube) are connected in total. Hot water is also used by other appliances in the home such as dishwasher and washing machine. However, these devices are not connected to the domestic hot water system. In terms of measurements for the case study, the hot water mass flow rate, mains (inlet) and supply (outlet) water temperatures in/out from the boiler are measured at a sample rate of every second, so that water volume, supplied thermal heat, mains supply and temperature rise (difference) for hot water can be estimated. The gas consumption from the boiler was measured at a secondly time step, while the power consumption of devices such as dishwasher and washing machines (and all other electrical devices in the home) were measured at minutely time step. Devices used and measured methods implemented in the case study are described in Marini et al. (2015).

OVERVIEW SOFTWARE TOOLS

We compared five different simulation tools with respect to the hot water demand and energy consumption based on different regulations and standards. Table 2 summarizes the results including capabilities and underlying methods of the tools with respect to hot water modelling as well as regulation compliances. In the following a brief overview of the simulation tools is presented.

Tool A is a free dynamic simulation software with its calculations based on BLAST and DOE-2 methods. The tool has been tested against the IEA BESTEST building load and HVAC tests. The simulation modules are integrated with a heat balance-based zone simulation, and input/output data structures are tailored to facilitate third party interface development. The accuracy and detailed simulation capabilities are considered as tool strengths. Figure 3 shows a scheme of domestic hot water generated by Tool A.

Tool B is a commercial dynamic simulation too. Its calculation is based on: UK National Calculation methodology (NCM), Part L, ASHRAE 55/ 90.1/62.1 calculation procedures. The tool has been validated and tested against several standards including ASHRAE 140/ BESTEST / CIBSE TM33 / EN13791. The tool can import files in different formats including gbXML, IFC, DXF files. The data input is managed through graphical interfaces and supported by databases and component libraries.

Tool C is a commercial tool that calculates the building energy demand in static regime in compliance with international standards (ISO 13790). It has been validated using dynamic simulation tools and measured data. The energy design and thermal comfort for high performance buildings, especially passive houses are considered as strengths of the tool whilst multizonal modelling for buildings and high need for control is not possible.

Tool D is a commercial static simulation tool where a spreadsheet is used to carry out the modelling and calculations. The procedure is consistent with the BS EN ISO 13790 standard. The tool is adopted by UK Government as the methodology and provides a framework for the calculation of energy use in dwellings.

Tool E is a free static simulation tool. Its calculations are based on the UK National Calculation Methodology (NCM) which was developed in compliance with Part L2A of the building regulation. The software makes use of standard data sets for different activity areas and calls on databases of construction and building service elements.

The input parameters (summarized in tables 3 and 4) for the simulation models, are based on: standards and regulations (see table 3, e.g. hot water demand, room temperatures, operational schedule), softwares default values (e.g. boiler efficiency, inlet/outlet supply temperatures; taps frequency; clothes and dishwashing frequency) and on the real case study or practitioner values (e.g. floor area, occupancy, boiler capacity, peak flow rate, pipe length/diameter and thermal conductivity). For each model, the input parameters are a mixture of these input categories.

Modelling setup

The simulation input parameters necessary from software's to calculate hot water demand and energy consumption for domestic hot water production are presented in Tables 3 and 4 . The domestic hot water profile represents the average water use and includes water used from all end-use categories such as showers, baths, sinks, dishwasher and washing machine. The water demand defined for Tool A based on a normalized hourly profile "masks" the boiler nominal design capacity as it does not specify the real peak flow rate. The peak flow rate is based on a normalized hourly load with a peak load of 20.2 l/hr (0.0056 l/s) it brings the design capacity up to an unrealistic value (900 W) for an assumed temperature rise of 35 ℃. As a consequence a maximum flow rate of 0.15 l/s or 9 l/min (i.e shower maximum flow) was assumed to estimate a realistic nominal capacity. Fractions of realistic design flow rate were calculated and inserted into the program in order to produce the normalized hot water demand profile as defined by the standard. The supply water

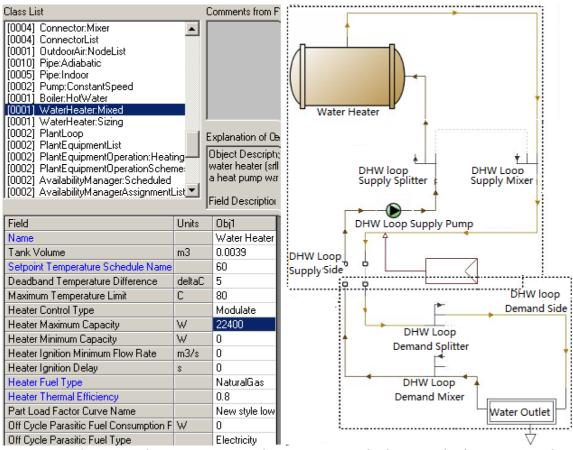

Figure 3: Tool A screen-shot input (left) and domestic hot water system diagram (right).

outlet temperature is considered on average 50℃ (hot water only) for all end use categories whilst the main water inlet supply temperature (Schedule-5) is calculated as a function of outdoor air temperature utilizing the calculation formula defined in the calculation manual of Tool A. Tool B estimates the hot water demand based on Part L2010 where each zone of the building has a different demand value (Design-1) and is a function of occupancy design level and operation schedules. The design values represent hot water demand for all end-use categories. The occupancy level varies between the zones (Design-3) and it varies throughout the day.

The domestic hot water system as part of the heating system is modelled in ApacheHVAC where standard boiler efficiency and performance curve parameters are selected from default values. The ApacheHVAC system (different from Apache which is a fully auto sized and ideally controlled system) allows detailed dynamic modelling of the system, equipment and controls to be fully integrated within the thermal simulation model at every time step. The supply temperatures from cold water mains and hot water outlet are defined constant through the simulations. Tool B estimates heat losses from storage tank and secondary circulations (not applicable for our case study) but it does not estimate the heat losses from the distribution system. Tool C for residential buildings assumes a default design value for hot water demand as defined in Table 3 and includes all end-use categories such as: taps, sink, shower and bath.

The defined boiler efficiency and supply (inlet/outlet) water temperatures are considered constant a throughout the entire period. The geometrical parameters of the distribution system, frequency of taps and room temperatures are used from the tool to estimate heat loss from dead-legs. The dishwasher and washing machine are considered as appliances that consume cold water by the software and are treated in separation. Tool C considered an average energy consumption of 1.1 kWh for the dishwasher and the washing machine

Table 2: Summary and overview of five different software tools used to predict hot water consumption.

Features and Capabilities	**Simulation Software**				
	Tool A	**Tool B**	**Tool C**	**Tool D**	**Tool E**
Version	8.0.0	2014.6.5.0	8.5	9.92	5.2.d
Availability	Free	Commercial	Commercial	Commercial	Free
User Interface	TextInput	Tabular/Graphical	Tabular	Tabular	Tabular
Regulation Compliance	ASHRAE[1]	PartL/CIBSE[2]/ASHRAE	ISO[3] 13790	EPBD[4]	PartL/EPBD
Calculation Methodology	BLAST[5]/DOE[6]	UK NCM [7] /ASHRAE	ISO 13790	BREDEM [8]	UKNCM/CEN[9]
Simulation Engine	DOE	ApacheSim	Excel	Excel	Excel
Simulation Regime	Dynamic	Dynamic	Static	Static	Static
Simulation Timestep	Minutely	Minutely	Hourly	Daily	Hourly
Outputs Interface	CSV/Tabular.	Tabular/Graphical	Spreadsheet	Spreadsheet	Spreadsheet
Outputs Timestep	Minutely	Minutely	Monthly	Monthly	Monthly
System Simulation (T/S)[10]	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes
Heat Losses (D/S/C)[11]	Yes/Yes/No	No/Yes/Yes	Yes/Yes/Yes	Yes/Yes/No	Yes/Yes/Yes

[1] American Society of Heating, Refrigerating, and Air-Conditioning Engineers;[2] Chartered Institution of Building Services Engineers; [3] International Organization for Standardization;[4] Energy Performance Building Directive; [5] Building Loads Analysis and Systems thermodynamics;[6] US Department of Energy; 7 United Kingdom National Calculation Method 8 Building Research Establishment Domestic Energy Model; 9 European Committee for Standardization; [10] T-Tank; S-Solar;; [11] D-Distribution; S-Storage; C-Secondary circulation

Table 3: Design input parameters for the five simulated models.

Parameter	**Unit**	**Tool A**	**Tool B**	**Tool C**	**Tool D**	**Tool E**
Hot Water Demand	Litres/hour Litres/Person/hour Litre/Person/Day Litre/Day Litre/day/m^2	Schedule-1	Design-1[a]	25	109[b]Schedule-2 [c]	Design-2
Floor Area	m^2	143	143	143	143	143
Occupancy	Person	4	Design-3[d]	4	2.9	Design-3
Boiler Capacity	kW	22.4	22.4	autosize	-[e]	-
Boiler Efficiency	-	0.8	0.81	0.84	Schedule-3	0.81
Peak Flow Rate	m^3/s	0.00015	-	-	-	-
Boiler PLR Efficiency Curve	-	Cubic	Cubic	-	-	-
Outlet Supply Temperature	^0C	50	60	60	Schedule-4[f]	60
Inlet Supply Temperature	^0C	Schedule-5	10	11.2	-	10
Pipe Length	m	15	-	15	-	-
Pipe Inside Diameter	m	0.018	-	0.018	-	-
Pipe Outside Diameter	m	0.020	-	0.020	-	-
Pipe Thermal Conductivity	W/(mK)	384	-	384	-	-
Room Temperature	^0C	Schedule-6 [g]	-	20	-	-
Taps Frequency	Times/Person/day	-	-	3	-	-
ClotheWashing/DishWashing Frequency	Times/Person/year	-	-	57/65	-	-

	Building Zones						
	Dining	Kitchen	Longue	Bedroom	Bathroom	Toilet	Common/Circulation areas
Design-1	11.8	11.8	6.6	2.5	14.9	37.9	0/45
Design-2	1.05	1.05	0.72	0.53	1.05	4.85	0/2.6
Design-3	59	42	53.3	43.6	50.3	41	9.4/11.2
Schedule-Fractions [h]	SchF-Din	SchF-Kit	SchF-Lon	SchF-Bed	SchF-Bath	SchF-Toi	SchF-Cir

[a] Design values according zones ; [b] Volume derived from occupancy and zones floor area; [c] Schedule fractions of monthly hot water use ; [d] Design occupancy level for each zone of building ($m^2/person$); [e] (-) Parameter not input in softwares for DHW system calculations; [f] Temperature rise of hot water production ΔT (not outlet supply); [g] Design heating set-point temperatures (used to calculate heat losses) [h] Schedules fractions (SchF-Din –SchF-Cir) of zones occupancy level used from Tool B and Tool E software

Table 4: Operation schedules for the five simulated models.

	Time of Day (hr)																							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Schedule-1	1.5	0.8	0.2	0.2	1.1	5.1	18.9	20.2	19.2	17.1	15.4	12.3	10.6	9.6	8.4	9.6	10.8	14.7	17.4	16.4	14.9	12.1	10.6	5.8
SchF-Din	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1	1	1	1	0.65	0
SchF-Kit	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0
SchF-Lon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1	1	1	1	0.65	0
SchF-Bed	1	1	1	1	1	1	1	0.5	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.75
SchF-Bath	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0
SchF-Toi	0	0.8	0	0	0	0	0.5	1	1	0.25	0	0	0	0	0	0	0	0	0.5	1	1	0.3	0	0
SchF-Cir	0	0	0	0	0	0	0	0.5	0.5	0.25	0	0	0	0	0	0	0.2	0.75	1	0.5	0.4	0.2	0.2	0

	Month of Year											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Schedule-2	1.10	1.06	1.02	0.98	0.94	0.90	0.90	0.94	0.98	1.02	1.06	1.10
Schedule-3	0.84	0.84	0.84	0.84	0.84	0.75	0.75	0.75	0.75	0.84	0.84	0.84
Schedule-4	41.2	41.4	40.1	37.6	36.4	33.9	30.4	33.4	33.5	36.3	39.4	39.9
Schedule-5	6.0	5.1	7.8	8.8	12.4	15.6	18.6	17.7	14.5	11.3	8.3	6.4
Schedule-6	20	20	20	20	25	25	25	25	25	20	20	20

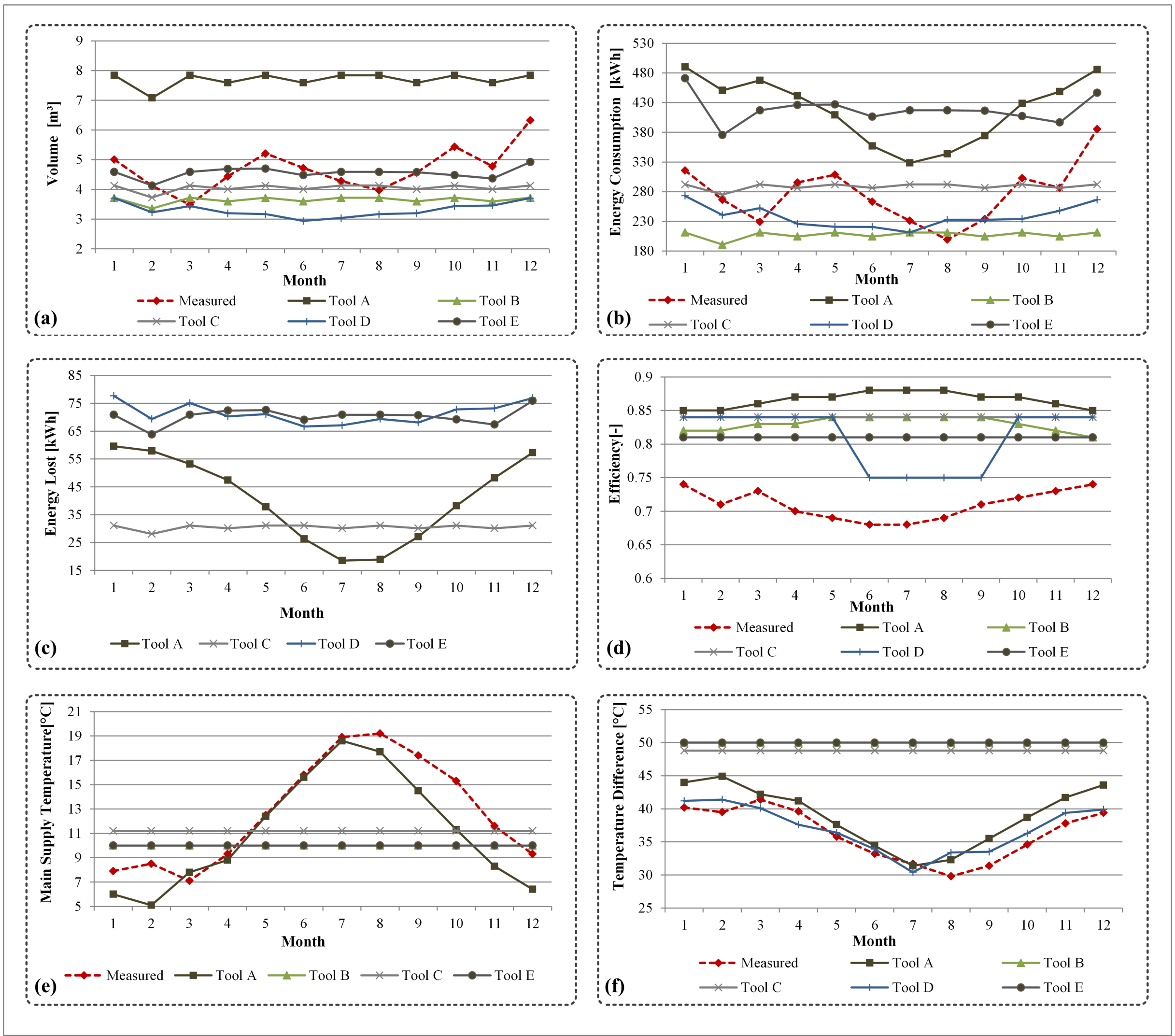

Figure 4: Estimated results comparing the measured data with the output of the five simulation tools; showing the results for (a) Volume [m^3], (b) Energy Consumption [kWh/m^2], (c) Energy Losses [kWh], (d) Efficiency [-], (e) Main Supply Temperature [^0C], (f) Temperature Difference [^0C].

for each time of use. This is converted into primary energy consumption utilizing a conversion factor of 2.6 as defined in the calculation spreadsheet. Tool D estimates hot water demand based on the number of people. This parameter is calculated as a function of the total building floor area. The model assumes a variability of hot water demand over the months and this variation is considered in the calculations as utilization factors (Schedule-2). The efficiency of boilers and temperature rise (ΔT) are considered differently for each month and are presented in Schedule-3 and Schedule-4 respectively. The calculation equations for hot water demand are described in the Tool D manual BRE (2012) whilst the software assumes 15% of total head demand for hot water production for distribution heat loss.

Tool E estimates the hot water demand based on the Building Research Establishment (BRE) method. For residential buildings the estimation method provides the design values (Design-2) for each zone. The boiler efficiency and supply inlet/outlet temperatures (as defined in the technical manual) are considered constant over the entire year BRE (2014). The heat loss from the distribution system are estimated by the software assuming 17% of total heat demand for hot water production. The energy consumption from condensing boiler, hot water flow rate and supply/outlet temperatures were measured at secondly timestep. The power consumed from dishwasher and washing machines are measured by using CT devices at minutely timestep.

The volume of water consumed by these devices has been estimated based on measured power consumption and assumed water temperature rise as based on the technical manuals. An in-situ measurement calibration process was carried out in order to validate the accuracy of measuring for water flow and temperature sensors. For water flow sensor was found that the error gap was ±7% whilst for the temperature sensor the error was lower than ±1K. The measured gas consumption was compared to meter readings and an error deviation of +5.5% was found. The measured data were corrected with the coefficient factors found from the calibration process.

RESULTS and DISCUSSION

Figure 4 presents the estimated results from measurements and the results from simulated models. The results are presented on a monthly basis for each estimated variable.

From the observed result it was found that Tool A overestimated the hot water demand and the energy consumption considerably compared to the measured data. The other tools (especially Tool D) underestimated the hot water demand whilst the energy consumption was overestimated considerably by Tool E. The mains cold water temperature was estimated slightly lower for each model as compared to the measurements whilst the temperature difference was considerably higher in Tools B and E.

The estimated efficiencies of the DHW system from measurements and simulation tools at monthly level are presented in Figure 4 (d). On average, the estimated efficiency was found to be 71% from the measurements, 87% for Tool A; 83% for Tool B; 84% for Tool C and 81% for Tool D and E. The considered efficiency from the models was found to be overestimated by around 14% to 22% as compared to the estimated efficiency from the measurements.

Tool B and Tool D were found to have a more accurate estimation regarding the litres of hot water demand per person per day but apparently the occupancy level as based on the softwares calculation methodology was underestimated. From measurements it was found that about 0.058 kWh energy was consumed by the production of one litre hot water at an average temperature of 49℃ whilst in the simulated model the consumption varied between 0.054 and 0.091 kWh/litre. This difference is mainly attributed to the overestimated assumed efficiency and the water flow temperatures (mains supply/temperature difference) between measured and model considerations.

Figure 5 on the top plot shows the normalised hourly hot water demand profiles estimated from: measured data (blue line), Tool A (red line) and Tool B (green line). Tool A shows clearly a higher demand profile compared to the measured profile, except for the late night hours.

Tool Bs hot water demand is directly depended on the occupancy profile. It can be noted that from 10:00 to 16:00 there is no consumption as the tool assumed that there are no people in the home during this time. The measured data showed an unexpected demand profile for the late night hours (00:00 to 05:00). The hot water consumption during this period was attributed to washing machine and dishwasher appliances. These devices were used mostly during the night time. This unexpected pattern for these appliances was believed to be caused by the energy price policy (lower rates

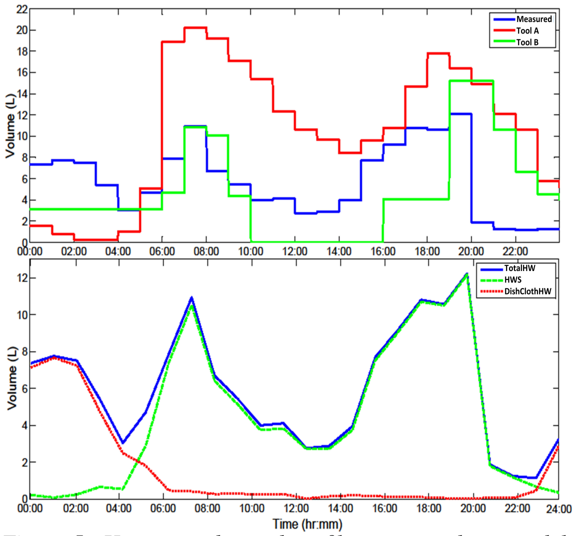

Figure 5: Hot water demand profiles measured vs. models (top plot) measured categories (bottom plot).

for night hours usage). The bottom plot shows the breakdown of the normalized measured hot water demand profile: the blue line represents the total hot water use in the home from all end use devices and appliances; the green line represents the demand profile from the hot water system only (boiler supply) and the red line shows the sum of hot water used from washing machine and dishwasher usage. The normalized term (used here and across the paper) describes the average hot water use for each specific hour of the day as derived from the arithmetic mean 365 days of the year, representing an average normalized hourly hot water use for each our of the day throughout the year.

CONCLUSIONS

In this study five simulation tools were used to model a DHW system and compared based on respective software regulation compliances and calculation methodologies. The simulated results were compared against real measured data gathered from a case study. The variables included hot water volume, energy consumption/losses, system efficiency, cold water supply temperature from mains and temperature rise (difference) for hot water production. It was found that the tools underestimated the hot water demand by about -30% and overestimated up to 40% as compared to the measured data.

The considered efficiency from the models was found to be overestimated by 14-22% as compared to the estimated efficiency from the measurements. The measured supply water temperature from mains supply pipeline on average was about 1.4-2.7℃ higher than what was considered by the simulation models. Meanwhile the temperature difference was found to be overestimated by 1.2 to 14℃ compared to the design temperatures considered by the simulation models. The temperature difference is considered as a constant value in each month by some software tools and

Table 5: Difference percentage between measured and simulated for unit of volume and energy

Estimated Variable	**Unit**	**Measured**	**Simulated Values**					**Difference measured vs. simulated (%)**				
			Tool A	Tool B	Tool C	Tool D	Tool E	Tool A	Tool B	Tool C	Tool D	Tool E
Volume	l/day	154	253	119	134	109	150	-39.1	22.7	12.9	29.2	2.5
	l/person/day	38	63	37	33	37.5	47	-39.1	2.6	15.1	1.3	-19.1
Energy Consumption	kWh/day	9.1	13.8	6.8	9.5	7.8	13.6	-34.3	22.7	12.9	29.2	2.5
	kWh/litre	0.058	0.054	0.056	0.071	0.072	0.091	7.4	3.5	-18.3	-19.4	-36.2
Energy Losses	kWh/day	-	1.3	-	1.0	2.3	2.3	-	-	-30	43.4	43.4
	kWh/litre	-	0.005	-	0.071	0.072	0.091	-	-	29.5	30	45.1

therefore leads to an overestimation of the energy consumption.

It can be concluded that: (a) The accuracy of hot water (i.e. daily consumption) is not explicitly dependent on the simulation tool and whether it is dynamic or steady state. It rather depends on the considered design values estimation procedure. For example, it was found that tool A (which is based on the US standard) significantly overestimated the hot water consumption compared to measurements and tools where the estimation is based on the UK standard; (b) Dynamic tools estimated the supply and temperature differences more accurately (i.e. monthly estimation opposed to a yearly estimation of the steady state tools); and (c) Dynamic tools estimated the energy consumption and energy losses per unit of hot water use more accurately. In summary, dynamic simulation tools can predict the results more accurately (with input and output parameters at an hourly or less time step), however the scale of the accuracy is dependent on the respective standards.

The fact that some of the results suggest an increased efficiency and at the same time more energy consumption (Table 5), is likely caused by two main factors: the considered inlet/outlet design supply temperatures (consequently temperature difference) and the estimated energy losses. For example, although the steady state tools C, D, E have a higher efficiency, the temperature differences are higher as well and constant throughout the year, causing an overestimation of the predicted energy consumption (Figure 4 and Table 5).

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