First Building Simulation and Optimization Conference
Loughborough, UK
10-11 September 2012

INFLUENCE OF USER-BEHAVIOR ON THE PERFORMANCE OF THE BUILDING AND THE ENERGY SUPPLY SYSTEM: INVESTIGATION OF HEATING

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ABSTRACT

It is becoming conventional approach to evaluate the building envelop losses using detailed dynamic tools such as EnergyPlus, ESP-r and TRNSYS. However, the user-related loads (and their variations) in the building are usually over-simplified during performance evaluation of those buildings and associated HVAC systems. This paper presents a methodology to evaluate the performance of buildings and their energy supply systems while taking into account the user-related loads (non-HVAC & DHW) at individual household levels. For this purpose, a single family house (two different insulation cases) built in Oslo climate using an alternate duty air to water heat pump is used as a case study. The investigation shows that a large variation occurs in space heating needs for the same standard house when actual user loads are considered. The study also shows that the storage losses dominate the performance of total heat supply system in case of passive house insulation.

INTRODUCTION

In cold climates, net-zero emission buildings (Net-ZEB) are recognized as buildings having extremely insulated envelops. In such tightly insulated envelops, a large part of building losses is assumed to be covered from heat gains of electrical appliances and lighting services in the building (known as non-HVAC loads). However, these non-HVAC loads are uncertain in nature and depend strongly on the user. Studies by (Macdonald 2002; Eisenhower, O'Neill et al. 2011) have shown that uncertainity in these parameters could have strong influence on the energy needs in the building. Brohus (Brohus, Heiselberg et al. 2009) in his study found that uncertainity in the internal gains, the heating set-poins and the infiltration rate has the largest influence on the yearly energy consumption of the building. In common practice, the internal gains in the building are simplified assuming fixed values or at most fixed-time profiles neglecting actual user-behaviour. However, recent developments on modelling of occupant behaviour (Nicol 2001) and their inclusion in detailed building simulation (Hoes, Hensen et al. 2009) has shown large influence of user behaviour on building performance. Parys (Parys, Saelens et al. 2011) in his study has shown that integration of proper user behaviour in the building simulation is important. Nonetheless, most of these studies focus mainly on conventional non-residential buildings and are limited to building side only.

This study investigates the occupant influence in residential building and extends the investigation to the building energy systems. In the first part of this paper, particular focus is placed on elaborating the methodology: addressing the question of trade-off between detailed dynamic building simulations vs. simple hourly dynamic simulation and in the second part, preliminary results of the study are presented.

METHODOLOGY

In order to structurally incorporate the heat gains from user-related activities and hence study their influence on the performance of the building and the energy supply systems, two-separate models are employed as shown in Figure 1. In the first step, the profile for internal gains & DHW draw-offs are reconstructed using an open-source occupancy based model; developed by (Richardson, Thomson et al. 2010). In the second step, energy performance of building and system is evaluated using a model specially designed to provide reasonable trade-off between accuracy vs. computational effort.

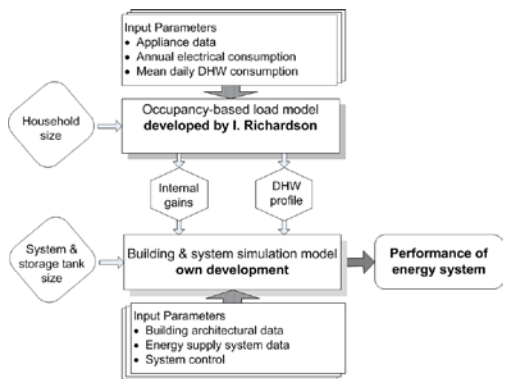

Figure 1: Methodological framework coupling occupant loads with building simulation

OCCUPANCY-BASED LOAD MODEL

The load model is used to obtain the hourly internal gains from non-HVAC loads and DHW draw-offs. Nonetheless, the non-HVAC loads in a household are strong function of user-behaviour, number of occupants (household size) and number and type of different appliance (appliance ownership) in the household (Yao and Steemers 2005). Significant efforts in modelling the household loads by various researchers (Walker and Pokoski 1985; Capasso, Grattieri et al. 1994; Paatero and Lund 2006) suggest that loads at utility scale flatten off the individual household peaks. The studies suggest that use of models based on bottom-up approach better represents the load-events in individual households. Therefore, a load generation model based on similar approach is employed in this study.

The employed model is developed by(Richardson, Thomson et al. 2010) at Loughborough university and generates the household load profiles using stochastically constructed occupancies. The occupancies are constructed using three occupant regimes defined by transition matrices of present and active, present and non-active, and absent where the matrices are extracted from 'time of use survey'. Since the model is originally built to represent household loads in UK, therefore, the parameters for appliances' ownership, annual consumption of each appliance, and mean annual household electrical consumption in the model are accustomed to represent the Norwegian household conditions. The values for these parameters are taken from a measurement campaign in Norway (Grinden and Feilberg ; Sæle, Rosenberg et al. 2010) and are shown in Table 3. Based on this data, the model stochastically populates the appliances in a household and generates the appliances profiles whereas for lighting loads, model uses additional information for relationship of indoor lighting. More detailed information about the model could be found at (Richardson, Thomson et al. 2009). Thus, using electrical load profiles generated from the model, the internal gains in the household are computed at hourly time step. The profiles for internal gains from human metabolism are also obtained from the same model. For this purpose, following assumptions are made:

i. During 0700 – 2300 hrs., house is occupied by a number of occupants given by the occupancy model and an average metabolism rate of 135 W/person is used
ii. During 2300 – 0700 hrs., house is occupied by occupants equal to household size and an average metabolism rate of 75 W/person is used

The available methodology in the occupancy load model provides only profile of electrical heater in a storage tank and does not provide the actual DHW draw-off events. In order to correctly establish the relation of occupant with system performance, the actual draw-off events are considered important in the study. Therefore, the model is modified to reconstruct DHW profiles. In the modification, four categories of DHW draw-off events (defined by Jordan and Vajen 2001) are introduced. The characteristics and probabilities of four categories are assumed according to the same study and are given in Table 1. The modification is made in order to correlate the DHW draw-off events with active occupancy which is not possible in case of Jordan's DHW model. The mean daily consumption for DHW draw-off is set at 55 l/day/person at 45^{0}C temperature rise which is in-line with findings for different countries presented at IEA ECBCS Task 42 (Knight, Kreutzer et al. 2007) and net-ZEB prescriptive requirements presented at IEA SHC task 40 (Sartori, Candanedo et al. 2010).

Table 1: Assumption for DHW load categories (Jordan and Vajen 2001)

Category	**Mean flow rate**	**Dura -tion**	**Draw-offs/day**	**Vol. drawn**	**Total vol.**
	[l/min]	[min]	-	[l/d]	[l]
short load	1	1	28	28	200
medium load	6	1	12	72	
bath	14	10	0.143	20	
shower	8	5	2	80	

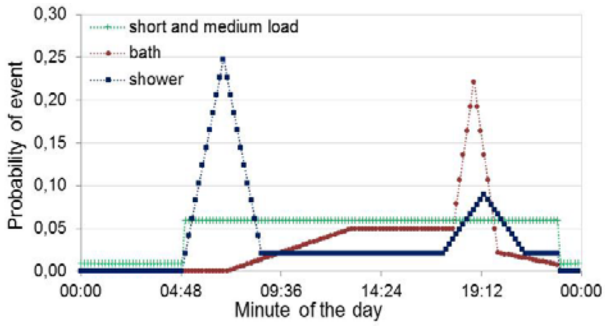

Figure 2: Assumed probability of DHW load events during a day(Jordan and Vajen 2001)

After setting up the model parameters, the model is run in order to generate profiles systematically into following four groups.

i. **User-behavior:** The user-behavior is not a fixed-time activity meaning that a same household with same number of occupants could have different non-HVAC loads and DHW consumption's profiles over different years. In order to assess this influence, profiles for both DHW and non-HVAC loads of same household (same appliances & number of occupants) are constructed for several years (10 years in this study) in this group.
ii. **Appliance ownership:** Statistics shows that a household with same number of occupants have different types and number of appliances which

influences both the profile as well as the total annual electrical consumption of non-HVAC loads. Therefore, a second group that represents households with different appliance ownerships is constructed.

iii. **Household size:** This group assesses the influence of household size meaning that a same house is occupied by different number of residents. The number of residents could have strong influence on the total non-HVAC electrical consumption as well as DHW consumption (Knight, Kreutzer et al. 2007). In order to study this effect, a third group of profiles is generated using a same household with number of residents from 1 to 5 (Population statistics 2011).

iv. **Aggregated influence:** This fourth group is generated covering above three categories together to represent an aggregated influence. A large number of households with different number of household sizes & ownerships are simulated in order to represent the aggregated effect. This group is used to investigate the performance of a standard designed building and energy supply system over a wide range of households.

BUILDING AND SYSTEM SIMULATION MODEL

The selection of methodology for modelling of the building and the HVAC systems is made based on the trade-off between the accuracy versus the computational effort. The trade-off is made on the fact that, although detailed numerical modelling for the building are considered providing better accuracies, they require a large number of parameters. This leads to higher risks of errors (Déqué, Ollivier et al. 2000) and requires large computational efforts. On the contrary, simple dynamic modelling of the building results into relatively low accuracy. However, this approach requires limited number of parameters and provides transparent and robust results (ISO-13790 2008). Since the objective of this study is to assess the difference in predicted performance of the same building under user-influence instead of focusing on the absolute values, the "simplified" approach is considered sufficient to provide required results. The HVAC systems are modelled using quasi-steady state approach specified by the European standard 15316. The approach permits the analysis of different energy sub-systems and their impact on the overall energy performance of the building (EN-15316-1 2007). Different segments of the energy supply system including heating, distribution, control and emission are strictly followed as described by the relevant norms. The exception is made on the modelling of the storage tank. Contrary to above-mentioned normative method that represents the storage tank by an average temperature, a detailed fully dynamic model based on TRNSYS approach (TRNSYS-17 ; Newton 1995) is implemented in this methodology. This addition enabled the model to evaluate the influence of different DHW draw-off profiles (Spur, Fiala et al. 2006) on the performance of energy system which is very important in case of solar assisted systems.

Figure 1 shows the framework of building energy calculation that is developed based on approach described in European standard (EN-15603 2008). In the first step, building energy needs are computed using standard internal gains from appliances, lighting and human metabolism. In the second step, based on these energy needs, the energy requirement of heating emission, control, distribution and supply are computed. The recoverable losses from different segments of heating systems and storage tank are also computed in this step. In the third step, different recoverable losses are treated as internal gains in the building and energy needs for the building are recomputed. The iteration is made over first three steps to achieve the required convergence. Upon convergence, recovered part of losses is computed as the difference between the newly computed energy needs and energy needs without considering system losses. Finally, the building energy consumption is computed by adding the non-recovered part of losses to the iteratively computed building energy needs.

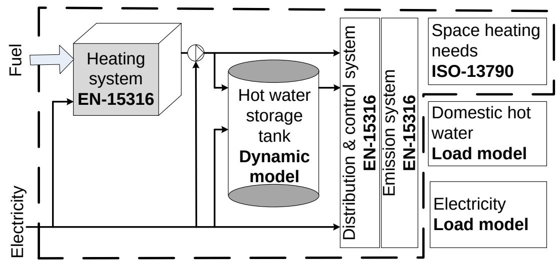

Figure 3: Generic energy flow diagram: Calculation started from left side where energy needs for space heating are computed and then different systems losses are taken into account. Profile for DHW draw-off and internal heat gains from non-HVAC electrical loads are generated using an external model.

The models are implemented in Matlab© using object-oriented-programming that could fully utilize the advantages of logical structuring while handling large complex problems(Mathworks) and provide opportunity to employ parallel computing techniques.

CASE STUDY

A typical two storey Norwegian single family house with total heated area of 160 m^2 is considered in this investigation. The insulation and air tightness for the house are assumed to meet two different energy levels: Norwegian passive house standard (SH20) and low energy level 2 (SH54) defined by Norwegian standard (NS-3700 2010) and are given in Table 2.

Table 2: Architectural data for the case study

Heated floor area	160 m²	
Roof area	80 m²	
Window area	32 m²	
Air volume	480 m³	
	SH20	SH54
Net Energy Needs for Space Heating [kWh/(m².yr]	≤ 20	≤ 54
U-value	[W/(m².K)]	
Walls	0.11	0.22
Floor	0.13	0.18
Roof	0.13	0.18
Windows	0.80	1.20
Doors	0.80	1.20
Thermal bridges	0.03	0.04
Ventilation		
Infiltration, n_{50} [h^{-1}]	0.60	2.50
Heat recovery; [%]	85	70
SFP ventilation fan [kW/(m³/s)]	1.5	2.5

The house is simulated for the Oslo climate presenting outdoor design temperature of -20°C and an annual mean temperature of 6.3°C. The space heating needs of the house are fulfilled using a hydronic floor heating system. The hydronic system is designed to operate at low temperature (with supply temperature of 40 °C). The heating needs of the building are supplied with a state-of-the-art alternative duty inverter type air to water heat pump system. The performance of the heat pump is defined using standard test points (EN-14511-4 2007) provided by manufacturer as shown in Figures 3-4 below. The heat pump is designed to cover 100% of the heating duty for both space heating and domestic hot water storage tank and worked in the alternative mode. The chosen heat pump is able to operate down to -25 °C therefore; no back-up system is used. The system employed inverter controlled compressor that resulted into better performance and reduction the on/off cycles and hence, energy losses related to this cycling process. The system is assumed to be able to modulate down to 30%.

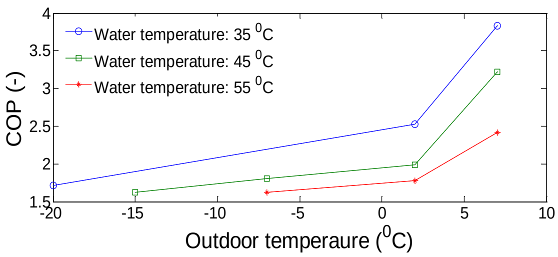

Figure 4: Coefficient of performance (COP) of the heat pump at standard test points(Mitsubishi Electric)

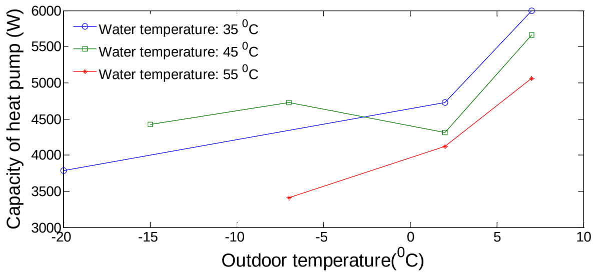

Figure 5: Heating capacity of the heat pump at standard test points (Mitsubishi Electric)

The emission, distribution and control systems for the house in order to supply both the DHW and the space heating needs are defined using default configurations suggested by relevant standards as mentioned in Figure 3. The hot water needs are covered using a stratified hot water storage tank. The storage tank is heated by a heat exchanger and the storage tank temperature is limited by the maximum temperature limit of the heat pump dependent upon outdoor air temperature. A 200L storage tank with insulation of 5cm thickness and thermal conductivity of 0.042 W/(m².K) is assumed as a standard practice for single family houses in this case study.

Prior to investigate the influence of user on building energy needs, the results obtained from building model are compared to the results obtained by "SIMIEN" - a commonly used simulation tool in Norway (Dokka and Dokka 2012). For this purpose, the internal gains are defined by a fixed values and a fixed operating schedule given in Table 3. Both models resulted into similar values of energy needs for space heating – 20 kWh/(m².y) for SH20 and 54 kWh/(m².y) for SH54. Then investigation of user influence on building and system performance is carried out using method described in Figure 3.

Table 3: Electrical & DHW loads and internal heat gains for residential building (NS-3700 2010)

Electrical loads [W/m²] (percent contribution to internal gains)		**Annual energy consumption [kWh]**	
		Normative (NS 3700)	**Measurement campaign†**
Lighting *	1.95 (100%)	1824	1000
Appliances *	3.00 (60%)	2800	2492
Domestic hot water *	5.10 (0 %)	4770	2539 †
Metabolism**	1.50 (100%)	2100	-

With operating schedule: * 16/7/52 ; ** 16/7/52

† Result of measurement campaign (Grinden and Feilberg)

† This value is not used in this study. Instead a mean daily DHW consumption of 55 l/d/person with 45 °C temperature rise is assumed

RESULTS AND DISCUSSION

Table 4 gives results of space heating and seasonal performance factor (SPF) for the four above-mentioned user groups. The variation of results over both the heating needs as well as SPF is reported using average value and percentage deviation of all the simulation runs within the studied group. The SPF for the energy system (in this case heat pump) is reported in form of generation system and total heat supply system. For generation system, boundaries are placed around the heat pump and therefore, the SPF is evaluated based on the ratio of output energy to input energy to only heat pump. However, the SPF for total heat supply system takes also the distribution, emission and control, and storage systems into account and therefore, represents the ratio of actual energy needs of the user (i.e. building & DHW) to the actual energy input to the overall energy supply system. The thermal comfort in all simulation is kept a constraint and is fully met using a back-up electrical heater is used to cover the un-met space heating and domestic hot water needs.

In order to avoid large sets of simulation runs, first two groups are simulated only for a 2-resident household and is assumed to represent the national average i.e. 2.2-residents.

Table 4: Summary of user influence on performance of building and generation system

Group number	User-effect	Approach	Internal gains	DHW draw-off	Norm	SH Needs		SPF			
								Generation system		Total heat supply system	
						mean	dev.	mean	dev.	mean	dev.
						kWh/m^2	%	-	%	-	%
001	User behavior	Normative	fixed value with schedule	fixed value with schedule	SH20	27.0	-	2.80	-	2.21	-
					SH54	60.4	-	3.02	-	2.62	-
		Fixed profile	1- day fixed profile	1- day fixed profile	SH20	21.6	-	2.72	-	2.11	-
					SH54	53.9	-	3.01	-	2.57	-
		Partially stochastic	10 sample years	1- day fixed profile	SH20	22.0	1.6	2.74	0.3	2.21	0.5
					SH54	54.2	0.7	3.00	0.1	2.62	0.2
		Fully stochastic	10 sample years	10 sample years	SH20	22.1	1.6	2.72	0.7	2.11	0.7
					SH54	54.4	0.7	3.01	0.1	2.59	0.2
002	Appliance ownership	Fixed profile	1- day fixed profile	1- day fixed profile	SH20	27.0	-	2.80	-	2.21	-
					SH54	60.5	-	3.02	-	2.62	-
		Fully stochastic	100 households' sample	100 households' sample	SH20	22.8	12.3	2.73	1.5	2.13	3.0
					SH54	55.2	6.4	3.01	0.6	2.59	1.2
003	Household size	Partially stochastic	stochastic	1 - day fixed profile	SH20	21.9	14.1	2.66	5.7	2.12	1.8
					SH54	53.8	7.0	2.93	4.8	2.54	3.8
004	Aggregated	Fully stochastic	300 households' sample	300 households' sample	SH20	23.4	18.0	2.74	5.1	2.15	3.0
					SH54	55.9	9.4	3.01	4.4	2.59	3.8

Mean	represents the mean value of results of different simulation runs
Deviation	represents the percent standard deviation of results from the mean value i.e. dev = (standard deviation / mean x 100) %
Fixed value with schedule	represents a fixed value extracted from the sample data corresponding to same group and applied with normative method of 16 h operation for appliances and light and 24 h operation for human metabolism (NS3031)
1-day fixed profile	represents the averaged profile extracted from the sample data corresponding to same group over 1 day
Stochastic	represents the internal gains and DHW draw-off events generated by the probability based occupancy model

i. **User-behavior:** User-behavior leads to highly stochastic profiles. Figure 6 shows an example week profiles of internal heat gains for a 2-resident household where thick-line shows averaged internal gains over 10 years. The grey scatter around thick line shows that a large variation in loads occurs over different years due to user-behavior. Since this group investigates only user-behavior therefore, the load model is used only to simulate the behavioral aspect and not the user attitude towards energy consumption. Therefore, the variation in annual electrical consumption (±2%) and DHW use (±4%) is rather small. The influence of user-behavior is studied using different resolutions of profiles being presented by four sets of simulation runs. For the first and the second sets, the profiles pre-determined based on custom resolution whereas for last two sets, fully stochastic annual resolution is used. The results in Table 4 shows that pre-determined fixed value with fixed schedule overestimates both the space heating needs as well as heat pump performance. However, a 1-day fixed profile shows results that are close to average of fully stochastic resolution. Looking at the influence of user-behavior, it is found that although, a strong link between internal gains and space heating loads exits as shown in Figure 7, this does not significantly influence the annual space heating (1.6%) and SPF (0.7%) given in Table 4. Further investigation reveals that even the slighter variations in annual heating needs and SPF are actually caused by the variation in annual internal gains and are not result of stochasticity in load profiles.

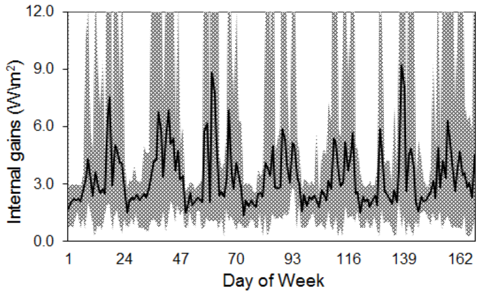

Figure 6: Example week: Variation of internal gains of a household (scatter shows variation over years)

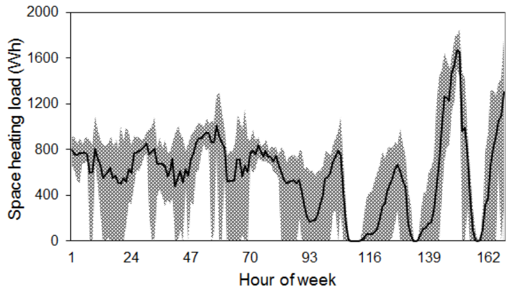

Figure 7: Example week: Variation of space heating loads (scatter shows variation over different years)

ii. **Appliance ownership:** In appliance ownership group, although stochastic behavior is similar to that of user-behavior however, the variation in annual internal gains (±15%) are rather large this time showing the effect of appliances' ownership as shown in Figure 8. In this group, two sets of runs are made: first using 1-day fixed profile (extracted by averaging of sample stochastic profiles) and the second using original sample of stochastic profiles. The results in Table 4 show that 1-day fixed profile could not correctly estimates both the building as well as system performance in case of large variation in annual internal gains. Nonetheless, the variation in space heating needs follows similar trend and stays within similar order of magnitude (±12.3%) as of internal gains in case of SH20 and variations get halved in case of SH54 (±6.4%). The effect of input variations on system performance is also more obvious in this group. The performance of heat generation system and total heat supply system shows a variation of ±1.5% and ±3.0 % respectively for SH20 which is halved in case of SH54. This particular trend in results shows that the total annual internal gains play more influencing on the performance of both space heating and energy supply system than the stochastic behavior of these gains.

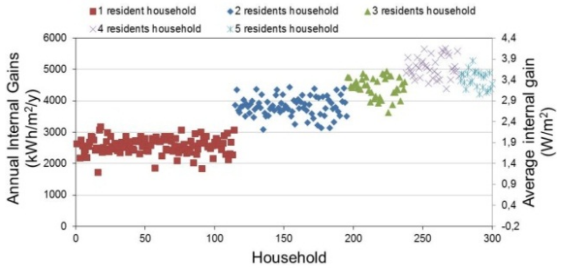

Figure 8: Annual internal gains for household (sorted after number of occupants)

iii. **Household size:** This group investigates the influence of variation in number of household residents using a set of 1 to 5 residents' households. The results show that the variation in space heating follows similar trend and is strongly dependent on internal gains. Nonetheless, the SPF, that has shown little effect in previous two groups, shows an obvious variation (±5.7% for SH20 & ±4.8% for SH54) in this case. Figure 9 shows that with less number of residents (i.e. lower DHW consumption), the SPF of generation system and total heat supply system starts to improve in case of SH54 but in case of SH20; limited improvement in SPF of total heat supply system is noticed. This trend could be explained such that in case of SH20, the losses form so large portion of actual heating needs that performance of total heat supply system is mainly decided by the system losses instead of heating loads. It is further important to mention that all the storage tank losses in this investigation are assumed to be recoverable losses. The finding therefore, underlines the importance of a careful sizing of storage tank size (and number of storage tanks) and better insulation meaning that a simple approach of oversizing DHW storage tank with high temperature could result as a penalty on the system performance.

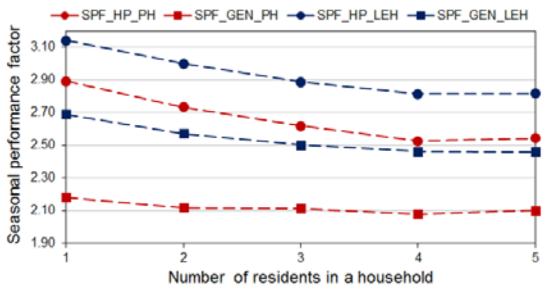

Figure 9: Seasonal performance of generation system and total heat supply system

iv. **Aggregated:** In this group, different user-effects related to behavior, appliance ownership, and household size are aggregated. A sample of 300 households; limited by the computer simulation time; is chosen in this study. The distribution of household sizes (1-5) is chosen to represent the Norwegian national average of 2.22 residents per household (Population statistics 2011). The annual sum of internal gains of profiles obtained from this household sample shows a variation of ±27%. The sample is simulated to assess the performance of building and energy system under this large variation and some of results are shown in Figure 10 to 12. Table 4 shows that a standard built SH20 could have ±18% deviation around the mean space heating needs and around ±3% deviation around mean SPF of total heat supply system. This leads to an important conclusion that although a large cluster of households could lead to a mean space heating value that is close to normative energy requirement however there is a large portion of households that do not actually follow the standard designed conditions and therefore lead poorly performing systems.

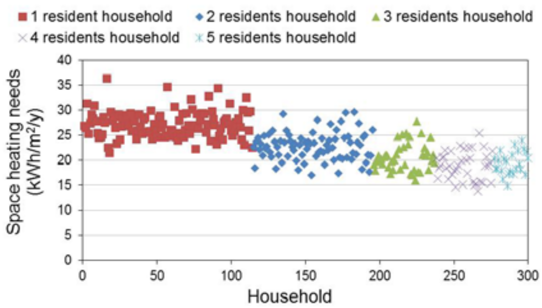

Figure 10: Space heating needs for different households having different number of residents and appliance ownerships

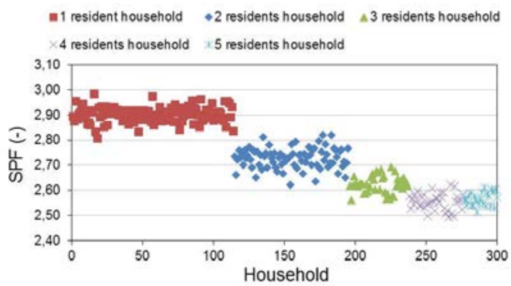

Figure 11: Seasonal performance factor of generation system for different households

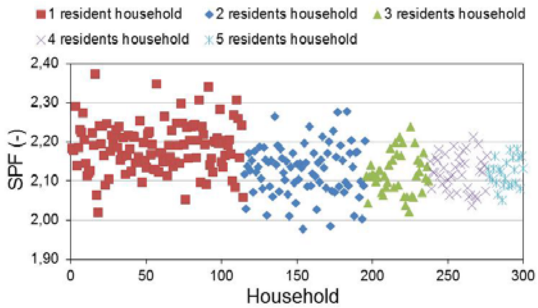

Figure 12: Seasonal performance factor of total heat supply system for different household

CONCLUSION & FUTURE RESEARCH

The study confirms the important hypothesis about significance of internal gains in case of highly insulated building envelops. The study of user-influence using systematic grouping shows that the variations in occurrence of events (stochastic profiles with similar total annual internal gains and total annual DHW consumption) does not have any significant influence on the performance of the investigated system. The performance is mainly affected by the difference in the total annual internal gains and/or the total annual DHW consumption. It is also shown that the conventional methodologies i.e. a fixed value with schedule and 1-day fixed profile to represent internal gains or DHW loads are not able to correctly represent the user-behavior. Study shows that the storage losses form a significant large portion of total energy need in case of highly insulated envelop (SH20 compared to SH54). Therefore, the performance of total energy supply system shows little improvement with increasing energy demand – a trend which is normally observed in case of poorly insulated envelops – as shown in Figure 12. This leads to the conclusion that the performance of total energy supply system is dominantly influenced by the storage tank losses and not the heating demand itself. This point underlines the importance of strategy involved in sizing of storage tank. This study is performed to test the methodology and therefore a rather simple system configuration is chosen. The influence of DHW draw-offs is less profound due to the fact that system is charging the storage tank volume within controlled temperature range. The approach will be extended to include more systems e.g. solar thermal where the influence of draw-off profiles is expected to be more profound.

ACKNOWLEDGEMENT

The authors want to thank the Norwegian Research Council for their support, as this work is performed in the framework of the Research Center for Zero Emission Buildings (ZEB).

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