The Gap between Plan and Practice: Actual energy performance of the zero-energy refurbishment of a terraced house

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ABSTRACT Prêt-à-Loger, TU Delft's entry to the Solar Decathlon Europe 2014 (SDE2014), demonstrated the conversion of a common terraced house to energy neutrality, whilst adding value to its living quality. The house was retrofitted according to principles of smart & bioclimatic design, using local circumstances intelligently in the sustainable redesign. Basis of the Prêt-à-Loger concept is a new skin around the house: thermal insulation in the façade and roof, a greenhouse structure to the south-east, and phase change materials in the crawlspace. The project received a lot of acclaim and was awarded five prizes at SDE2014.

During SDE2014, under the circumstances of Versailles, France, the Prêt-à-Loger house proved to be energy producing, and simulations indicated that over a year's period it would be net zero energy. In spite of these promising results, there are several ways in which a zero-energy (re)design may perform differently than predicted, also in the case of Prêt-à-Loger. Firstly, there may be a difference between design and realisation. Secondly, simulation models may not predict the actual performance correctly. Thirdly, user behaviour can be a decisive factor.

With Prêt-à-Loger, the first category could be monitored by the team itself. The fact that the house was constructed three times could however cause small construction deviations from the ideal situation. The second category is the main topic of the research project presented in this paper. Real-time measurements in the house (reconstructed at the TU Delft campus) are executed to validate simulations. Different user behaviour is applied to test differences in actual energy performance, providing useful insight for millions of homes.

The results show, for building envelope characteristics, there is no significant difference between the simulations and reality.. A higher variation in the predicted energy can be accounted to user behaviour, specifically to experienced comfort and specific user actions.

KEYWORDS: Refurbishment; building performance simulation; zero-energy design; actual performance; model calibration.

Introduction

The Solar Decathlon is an open competition between higher education student-teams from all over the world, challenging them to design, build and operate a solar-powered 'green' house (US Department of Energy, 2014). Ten different sub-contests are included to ensure the design and construction (in ten days) of a well-integrated house that can be energy-efficient, attractive and affordable. In the last edition of the Solar Decathlon Europe 2014 (SDE2014) in Versailles, France, a multi-disciplinary team from TU Delft called Prêt-à-Loger (translated as "ready-to-inhabit") participated with a proposal focused on the existing housing stock rather than on a new house type. The starting-point for the team were post-war terraced houses (called row-houses) and the challenge to make them energy efficient while creating new quality space. The row-house typology is very common in the Netherlands, representing around 60% of residents' homes in the country (Eurostat, 2011).

In order to address this, as a case study a reference row-house was chosen from Honselersdijk, a small town south of The Hague. All features of the reference house were used for the SDE Prêt-à-Loger redesign, including its properties and relatively unfavourable south-eastern orientation. Based on the house's challenges, the team designed an external intervention system called "The Skin". The Skin combines heat loss reduction on the north-west elevation by applying PassivHaus standard external insulation and a light glasshouse structure to the south-east façade. This glasshouse is in fact an integrated system, combining energy production through PV panels on its roof and façade, reduction of heating requirement by forming a thermal buffer and the creation of an extra high-quality space, by forming a direct connection between exterior and interior. The Skin system was prototyped on a real-size replica of the prototype and participated in the competition, was awarded various prizes and took the third place overall, only 3 of the 1000 points behind the winner. After deconstruction, the house was transported to the campus premises of TU Delft, standing currently as a demonstration, education and research facility for the university. More details on the design process behind the system can be found in another AR2015 paper released in parallel (Dobbelsteen et al., submitted).

Problem statement - Methodology

In spite of promising design intentions and simulation results, there are several ways in which a zero-energy (re)design may perform differently than predicted, also in the case of Prêt-à-Loger. Firstly, there may be a difference between design and realisation: actual insulation thicknesses may be thinner; different building products may be used; onsite interventions – sometimes necessary – may change the original design. And for Prêt-a-Loger the fact that the demountable house was constructed three times may have led to construction imperfections, such as chinks and cracks. Secondly, simulation models may not predict the actual performance correctly, due to imperfections in the software or inaccurate input. Thirdly, user behaviour can be a decisive factor. Ecological awareness, active control, intensity of usage, individual preferences all play a role in the eventual energy performance. Since the Prêt-à-Loger house closely represents a newly refurbished post-war dwelling, featuring an extensive monitoring infrastructure, it can be suggested as a possible candidate to study the above effects.

Theoretically, the question can be quite simple: how close are the design assumptions and simulations to reality, at least as represented by the measurements of the monitoring system. Nonetheless, the real answer is complex. The performance of a building is affected by a multitude of interconnected parameters; the significance of them varies per building case, location, conditions, use profile etc. The large number of parameters create, as expected, a significant challenge in simulating the building's performance (Coakley et al., 2014). Even by using various assumptions and controlled use profile to limit the parameter list, still some of them are difficult to determine accurately; notably the U values of the walls, and the rates of natural ventilation and infiltration. These are also mentioned in the study by Majcen et al. (2013) as highly influential parameters for the typical Dutch dwellings. They are associated with heat losses through the building envelope, a key factor in estimating the energy needs of the house.

Taking the above into account, a strategy was devised to try to study the reality and model convergence for the Prêt-à-Loger house. It is based on separating the influential parameters in the analysis, in order to minimise the coupling of their inaccuracies. Firstly, the envelope heat loss parameters are validated against measured data, appropriately filtered to avoid local disturbances in the interior. That can illustrate the real effectiveness of the building envelope to retain the heat and verify the design of the component U values and infiltration rate. Then, by using this validated model as basis, the user behaviour and installation performance can be studied and provide a more realistic estimation of the energy use.

The simulation, measured data filtering and comparison are performed by a custom automated process, allowing large amounts of data to be analysed and compared in a short amount of time.

Carbon neutrality target

The Prêt-à-Loger proposal for Solar Decathlon 2014 included a detailed sustainability analysis (Prêt-à-Loger, 2014), for which it was awarded the first prize on this specific sub-contest. The analysis included strategies on energy and carbon neutrality for the house and urban scale. 116,350 kg of CO_2 equivalent emissions were calculated with the "IPCC GWP 100a" method, for a lifetime of 50 years after the Skin application. The greatest share was made up from the transportation of the users (82%), mainly with personal cars. Therefore, the strategies focused on reducing this share by promoting the use of electric vehicles (and especially electric bikes) from the excess energy produced by the PV panels. From simulations, the energy consumption for the house was estimated to 3200 kWh annually, allowing for 500 kWh of energy for transportation, which can limit CO_2 emissions significantly. Nevertheless, this again depends on the difference between simulated and actual energy consumption of the house, underlining its significance even further.

Climate and monitoring system description

The design of the climate and installation system is based in making the existing house effectively adaptive for the different seasons in a year. As expected for a north-western European country, the focus of the system is on anticipating the low winter temperatures and minimising the heating requirements. The main solution introduced for this is the glasshouse on the south-east side, functioning as a thermal buffer, effectively reducing the energy demand by 34% (from design phase simulations). Combined with double-E glazing windows, thick thermal envelope insulation and improved airtightness, it results in a total energy reduction of 79%. A solar thermal system is used, in which thermodynamic panels extract the heat from the glasshouse and transport it towards a heat pump. This heats a 300 litre water tank to 55°C, which can then warm the 6 radiators of the house and provide hot tap water. The mechanical ventilation system is supported by using pre-heated air from the glasshouse when appropriate and a Heat Recovery Unit of 96% efficiency. The balanced ventilation is CO2 driven and controlled by the home automation system.

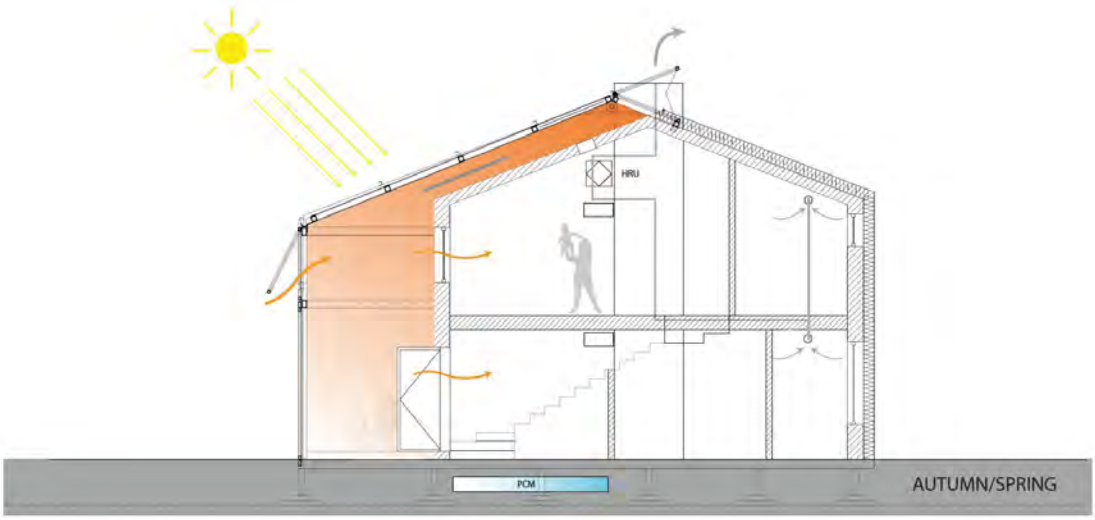

FIg. 1. Section of the Prêt-à-Loger house, explaining the climate system in spring/autumn.

In the mild and wet seasons of autumn and spring, the glasshouse can harvest the heat from the increased sunshine, allowing for the passive heating of the house, by opening the intermediate doors and windows (Fig. 1). Temperature monitoring in all spaces, as well as CO2 and VOC measurements, constitute the driver of the home automation system, in order to optimise the interior climate. For example, it can ventilate on high CO2 levels or open the glasshouse windows on overheating. It can also report and advise the user, who is allowed to manually override the system per comfort preference.

In summer the system's function is to retain comfortable temperatures in the house while producing the bulk of energy to render it zero-energy on yearly basis. The 4.9 kWp total power, is estimated to produce over 3.700 kWh yearly. Finally for avoiding overheating, the ventilation system attracts fresh air via phase-changing materials (PCMs) in the crawl space, in order to pre-cool the air.

Comparison on building envelope characteristics

The data collected by the monitoring system from October till March are filtered to avoid periods of occupation or energy use for heating. Specifically for the first, the reasoning is that as the house is used as an exhibition space, the user behaviour cannot be taken as uniform as in residential use, even if the monitoring system can detect user presence. Also, periods of malfunctioning sensors in the main rooms of the house are also excluded. This filtering results in 15 testing periods, each of which had at least 12 hours of continuous measuring.

These periods are then simulated with the EnergyPlus software (Energyplus, 2013) and relevant weather conditions per period, derived from hourly measured data from KNMI, the royal meteorological institute of Netherlands. The filtering allows the use of a "free-running" simulation to study only the reaction of the house to the fluctuation of external temperatures. It is noted that the model is "pre-conditioned" through a custom developed process in EnergyPlus, in order to reach the initial conditions of each measured period. In total, the model forms an accurate representation of the actual geometry of the house, where each room is simulated as a separate zone; while its material properties are assumed from the design and the weather data from the wider Delft area as monitored by KNMI. On the other hand, the whole building simulation approach of EnergyPlus, including heat balance-based zones and multi-zone air-flows, allows for a physical modelling of heat flows that is deemed sufficient for this typology.

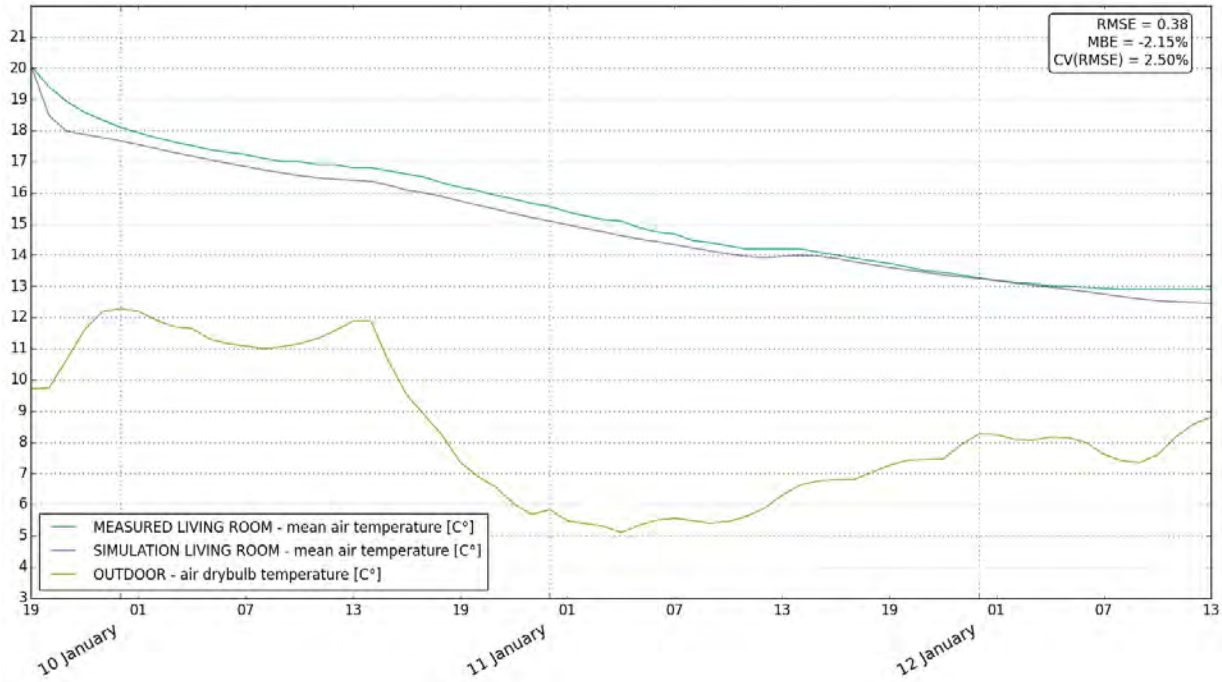

FIg. 2. Living room temperature convergence.

The plot shown in Fig. 2 refers to the living room, which represents more than 50% of the total house volume. From a visual observation it can be derived that the convergence achieved is significant, as for a representative period in January, the simulation temperature profile fits closely the one from measured data, with 2.5% of error. The error is around 2-7% below the measured data in the other zones and the rest of examined periods. This suggests that the design assumptions used were possibly over-conservative, or that there are more parameters favourable for the real building, which were not taken into account. If the house is modelled as single-zone, the error stays at the same level, but its position varies per period, found below and mostly above the measured curve. Opposite from before that may mean that the building properties are slightly worse than designed. This can be explained due to the multiple assembly (first as a test house, then at the competition in Versailles, finally at the TU Delft campus), creating cracks and slits lowering the efficiency of the building envelope.

Although convergence criteria exist for energy calibrations, e.g. from ASHRAE (ASHRAE, 2002), for the temperature case no apparent indication can be found in literature. Nevertheless, it can be suggested that since the temperature root mean square error is less than 1°C in most of the cases, there is no appreciable difference for the user or for the HVAC control system. Therefore it can be assumed that the physical behaviour of the house is simulated to a satisfying level.

Comparison with a user week

To further explore the actual behaviour of the house, an experimentation week was performed from 6th to 12th of April 2015 (spring, heating season for Delft). In this period, the premises were not used as an exhibition space but solely as housing for one person. The behaviour was kept as close to reality as possible, following a daily protocol that resembled the intended housing occupation with a regular activity pattern such as sleeping, office working, cooking and eating. These included normal appliance use and configuration of the climate system to address the comfort experience e.g. use heating when felt cold or turn on ventilation in cases of low air quality. Different residential user behaviour patterns were tested and the actions involved were logged and subsequently used to explain the data from the monitoring system. Two days with the most influential behaviour for energy are presented in Fig 3.

In the first graph, the exterior conditions include mostly cloudy weather, light precipitation and temperatures of around 5 to 12°C. It can be observed that the temperature in the glasshouse reached almost 17°C, minimising the losses from the south-east side. However, it has to be noted that although the air temperature in the living room-kitchen was between 19 and 21°C, the comfort level experienced was not ideal, leading to an almost constant use of heating. It is suspected that the difference between air and operative temperature is the culprit, as the small thermal mass of the wall possibly leads to low radiant temperature. The small mass results from the timber frame construction of the house, used in order to facilitate transportation and fast assembly during the competition. The real house has lime stone blocks and brick masonry, creating greater mass. Another possible reason was the experienced draft, which is presumed to be created from the direct staircase connection of the living room with the first floor. The hot water requirement from the radiators led to a constantly operating heat pump (nominal power around 0.6-1.5 kW) and subsequently to the largest energy use of the house.

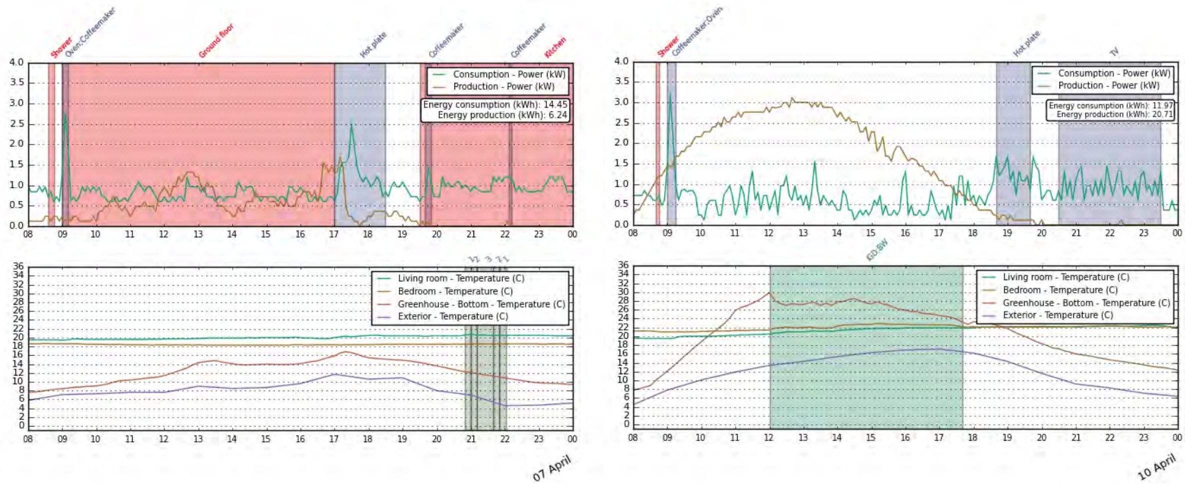

FIg. 3. Parallel diagrams of energy and temperature along with appliance use (blue), heating/hot water use (red) and ventilation information (green – first day mechanical, second natural from glasshouse).

In contrast, the second day was sunny with a maximum exterior temperature of 17°C. The temperature in the glasshouse reached almost 30 degrees, enabling passive heating of the house, by opening the interior glasshouse doors and the bedroom windows. The overheating was controlled by adjusting the operable windows on top and bottom, bringing in fresh air and creating thus a pleasant working environment in the glasshouse between 12:00-17:00 h. Active heating or ventilation was not used and the compressor of the heat pump was in less frequent operation and with higher efficiency to keep the water at 55°C. Due to the high solar irradiance, a power production of 20.71 kWh surpassed the total consumption of 11.8 kWh, however without covering all the peaks, which are attributed to the specific use schedule. For reference with the above, the energy consumption from the simulations for similar residential use resulted to around 10 kWh on an average day.

Finally, it has to be noted, that the power diagrams offer insight on the energy consumption characteristics of the house, especially on the use of appliances, Nevertheless, the problem remains to estimate the significant and continuous consumption of the heat pump, in relation with the space heating requirements and the external temperature fluctuation. For this, further research will be conducted using the specific case-study.

Conclusion, discussion and recommendations

The results of the study discussed above can offer some possible indications about what might affect the real behaviour of the dwelling. It appears that for the building envelope characteristics, there is no significant difference between the model and reality for the available data. The project's high-quality control, where it was assured that panel components were constructed as designed in the factory, might pose a possible explanation for it. Nevertheless, efficiency could still have been reduced by assembly errors, resulting in thermal bridges between elements. Although this is the expected scenario, it is only validated if the house is simulated as single-zone, suggesting that the modelling technique is also a significant factor and should be researched further.

A higher variation in the energy predicted can be seemingly accounted to the user behaviour, specifically to experienced comfort and user actions or schedule. For the first, experienced comfort, it can be assumed that the difference in comfort conditions might stem from the lower quality control of the assembly and finishing of the building, in contrast to the panel manufacturing. Also, the design target of optimal comfort conditions can often become secondary in front of architectural, construction or even policy issues, as shown here with the open staircase and the low thermal mass. For the second, user actions or schedule, it can been suggested that the knowledge and use of passive strategies, such as ventilating from the pre-heated glasshouse, can help reduce the energy use, along with support from active control and advice from the monitoring system.

Finally, a future continuation of research in the prototype house can include detailed user comfort in zero-energy designs. Another subject can be the effect of HVAC configuration and home automation systems, deemed here as influential to energy consumption.

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