Effect of Energy-related Occupants’ Interaction with The Control of Indoor Environment on Residential Energy Consumption:
Case Study on Energy Efficiency of Social Housing in Germany

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Abstract
Energy efficiency has been the core challenge and task of research in the building sector and strongly driven by real estate, resource management, energy policy and consumers with various socio-economic backgrounds. Existing building energy simulation tools have achieved a high dynamic dimension of energy consumption through accurate analysis of technical integration of building energy system. However, the impact of occupant interactions with the control of indoor environment on building energy performance is underestimated. Lack of real and comprehensive information and effective monitoring technologies for energy-related occupant behaviour (OB) could explain this overlooked impact. This study considered OB as an important influencing factor of controlling indoor environment quality and energy consumption, and introduced the process of OB data collection in Germany social housings, which worked as input for further simulation process. A method was proposed to integrate occupant behaviour into the conventional Retrofit-commissioning methodology to further research on improvement of energy efficiency in existing buildings.

Introduction
The average share of final energy for residential sector worldwide was reported nearly 12.6% in 2015 and is predicted by the U.S. Energy Information Administration (2017) that it would rise to 13.5% until 2050. In Germany, this share was much higher, i.e. residential energy accounted about 26% of total final energy consumption in 2015 and just followed the industry share (about 29%) and transport share (about 30%), according to statistical analysis of the German Federal Ministry of Economic Affairs and Energy (2017). From the environmental point of view, greenhouse gas emissions caused by building energy consumption have become one of focuses of environmental protection. Although European Union (EU) has focused on rising awareness on climate change and aims to achieve up to 90% cut of CO₂ emissions below 1990 levels from houses and office buildings until 2050, it indicate that the implementation of energy-saving measures is very hard to reach the expected CO₂ reduction.

Residential energy consumption varies with physical differences in the size of dwellings, type of properties, age of residential building and efficiency of building energy equipment, climate and energy prices, as well as occupant behaviour, in particular which are affected by individual socio-economic background (e.g., household income, family size and composition, educational levels, rented or owner-occupied). Schipper et al. (1989) have approved in their study on relationship between lifestyle and energy use that approximately 45-55% of energy use was affected by occupant activities. In the scope of the ongoing research and investigation on residential energy efficiency and its environmental impacts, we always focus on implementing technical facilities and energy management services with higher efficiency in building construction. Despite the analysis of occupant behaviour has attracted the attention in recent years, it must be investigated thoroughly, especially among the occupant group whose energy bills has no or little relevance or impact on their major household expenditure, for example, occupants living in German social housing.

A balance between reducing energy bills and without sacrifices of living comfort is pursued by all stakeholders related to residential energy use. Though building energy saving technologies, low-energy building concepts and building energy management system have reached to a mature degree, a gap between the designed and real residential energy consumption appears often. Building simulation tools are developed to predict energy consumption based on the designed parameters, but the engagement of occupants during the building operation phase leads to a degree of deviation from the expected energy consumption. Interactions between occupants and building energy systems could significantly affect the total final energy consumption and indoor environmental quality (IEQ). Andersen et al. (2007) found in their research that OB could affect the building energy performance by up to a factor of 330%. This paper outlines the energy-related OB in social housing and efforts to explore the reasons and possibility of improvement. A simulation process is conducted based on change of OB and indoor thermal preference to prove the synergic effects of objective and subjective energy saving measures.

Case study
EU has concerned energy efficiency in social housing as a special case of residential energy efficiency for a few years. It co-operates with social housing organizations of EU countries to develop and implement targeted energy-
saving measures. One of most important objectives of this action is to explore the weakness of energy-related behaviours of social housing residents and the challenges of improving process, thus to achieve a sustainable optimization of energy performance with necessary and effective technical interventions in European social housings. Social housings in most EU countries are provided for low-income households or ones with difficulties. For example in Germany, social housings are mainly for people with long-term diseases (physical or mental disability), or immigrants of low socio-economic status, or the older people living alone with low-income. The special social backgrounds strongly influence their attitudes and abilities toward energy conservation. As case study in this paper, social housing residents in Darmstadt (Germany) were investigated and the characteristics of their energy-related behaviours and the underlying causes were addressed in this section.

**Data collection**
Investigation on the attributes of energy-related OB relates principally to occupancy, activity on heating, and the acceptability of energy-saving measures. Before collecting the relevant information, occupant recruitment were conducted to obtain the valuable information for the following survey and solution formulation. Occupant recruitment was deployed by different ways, e.g., newsletter, brochures, published articles, workshop and local events. During the recruitment process, the potential problems hindering the implementation of energy-saving measures were revealed as follows:

- **Education-related**, e.g., occupants have difficulties to understand project’s goals due to immigration background, and most are not familiar with information and communication technologies (ICT);
- **Finance-related**, e.g., low-income occupants will not pay or cannot afford more expenditures for energy-efficient products and services;
- **Motivation-related**, e.g., occupants do not consider new energy-saving measures as profitable or beneficial.

These underlying hindering factors gave a direction for developing survey and solution in the following process. Survey with questionnaires and local events were carried out, which focused on investigation on daily energy-using behaviours at home and their attitude and motivation to energy conservation. Questionnaires were performed face-to-face three times between investigators and occupants, during the same period local events were held for providing energy-saving information to and inquiring feedback from occupants. All information of surveys was used for a combined analysis of measured consumption data and occupants’ self-reports, owing to the cognitive bias of occupants, i.e. many occupants identify themselves as energy-savers but the facts are proved not so. The energy provider provided also online service for occupants to check their energy consumption, thus to inspect if occupants cared about their energy consumption quietly based on their login-data on this service. The most notable characteristics of OB in German social housing in connection with this project Balanced European Conservation Approach (BECA) could be summarized as follows.

**High occupancy rate and weak energy-saving awareness**
According to the survey on more than 600 dwellings in Darmstadt (Germany) in 2013, about 50% households left their apartments unoccupied for less than two hours per day, and only 2% stayed outside for nearly ten hours daily (Figure. 1). This result could be attributable to the social background of the investigated households, because old or unemployed people occupy most of the investigated dwellings. They spent much time at home and were used to keep heating always on in cold weather.

![Figure 1: Average non-occupancy rate.](image)

Meanwhile, about 56% of occupants turned off heating when they left a room unused, and about 66% turned off heating when they lefted their apartments for a long time. Only one third of interviewees used cold water to wash hands. It could be recognized that heating energy was consumed even when it was unnecessary. Besides, only about 20% of households would give their compromise by lowering room temperature for energy saving. Although about 75% of occupants expressed their interest in measures of energy saving at home, only half of them thought they know how to do it. In addition, opening windows was the only way for fresh air owing to shortage of mechanical ventilation system.

In the advanced level of survey, it was inquired in-depth about the attitude and motivation towards energy conservation and environmental protection related to their purchase and usage behaviour. There were about half of occupants in this case expressed that energy consumption was considered indeed when they were purchasing new electrical appliances. About 70% of the respondents took both saving money and environmental protection as motivation to change their opinion and behaviour on residential energy use, but saving money seemed more important and economically beneficial than reducing CO₂ emissions. Providing a web-portal on energy use information and energy-saving tips, unfortunately did not attract interest of occupants; about 40% would unlikely use it regularly and thus gradually change their behaviours, and only about 20% would like to try this service. In view of the outcomes of the survey above, it is noteworthy that part of energy costs (for space heating and domestic hot water (DHW)) in German social housing are paid by local government or housing providers instead of occupants. It is thus hardly
surprising about the very weak energy-saving awareness and little interest in energy saving measures.

**Poor ability to conserve energy**

Energy use characteristics of social housing residents in Germany are influenced by many factors. In short, it is a lack of ability to residential energy conservation. Based on the survey results, it could be summarized as follows:

- Poor affordability to energy-saving technologies. Low-income households are the main part of social housing residents, whose socio-economic situation restricts their affordability to new energy-efficient appliances. In this case, about one quarter of households receive social benefits or welfare as the predominant source of income. About 33% households in this case live on 500-900 Euros per month (net income) for an average three-people family.

- Lack of energy-saving information. It reflects that on the one hand the shortage of energy conservation knowledge from public or government, particular the energy-saving tips customized for social housing residents taking their socio-economic background into account; on the other hand due to the invisible nature of energy use (Brandon and Lewis, 1999; Fischer, 2008; Boomsma et al., 2016). It would thus be difficult for occupants to understand the impact of residential energy use on environment, as well a series of understandable „know-how” is missing to a certain extent.

- Lack of substantial building renovation. The most investigated social housings in this case were built before 1970 with single-panel windows and there were no regular renovation over last thirty years. Technical deficiencies of building and energy equipment (e.g., thermal bridges, poor insulation of façade and windows, rusty and calcified hot water tank, old and inefficient boiler and thermostat). Factors affecting social housing energy efficiency and their interrelations are illustrated in Figure 2.

**Methodology**

Meeting the energy efficiency requirements in social housings means that on the one hand occupants benefit from better indoor environmental quality, i.e. warm homes with the possibility and ability to manage their energy consumption efficiently. One the other hand, real estate company or corporation in view of leasing as the main form of social housing in Germany benefit from the higher building energy efficiency due to technical renovation to improve their reputation in the real estate market, as well optimise the relationship with tenants owing to the increasing tenants’ satisfaction. This has been identified as one of the objectives of conventional Retro-commissioning (PECI, 2001). However, the increasing impacts of OB on residential energy use are regarded as a very important factor for developing building energy-saving measures. This study aims to integrate the influencing factor of occupants into traditional technical improvement, namely Integrated Retro-commissioning, to make energy-saving measures be acceptable by and beneficial for all stakeholders. Based on social housing in this case study, the integrated Retro-commissioning needs to identify:

- Technical requirements: renovation of building construction and energy equipment, update of energy management system;
- Non-functional occupant requirements: social context, preference of indoor climate, cognitive and performing ability toward home energy conservation;
- Legal requirements: permissibility of implementing new energy-saving measures considering occupant privacy and data security.

Two systems were developed to analyse requirements mentioned above and provide solutions for real estate company with energy management system (EMS) and for occupants with energy use awareness system (EUAS):

- EUAS works as an online service to provide occupants timely and comprehensible information of their monthly and annual energy consumption. Implementing this service is enabled under the condition of agreement and authorization of occupants with their signatures regarding energy data collection and control by energy provider, meanwhile occupants have access to go through their data online; in this respect the specific equipment (e.g., smart meters and data loggers) is installed in individual households, illustrated in Figure 3.

- EMS works as a service that includes energy management applications to reduce peak consumption, optimize the timing of energy consumption in line with supplier requirements and tariffs, control the efficient operation of systems, manage the production and distribution of renewable energy, as well enable occupants

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**Figure 2: Influencing factors of energy efficiency in social housings**

![Figure 2: Influencing factors of energy efficiency in social housings](image-url)
to report malfunction of energy system in time, as Figure 4 illustrated.

The two systems form the key concept of integrated Retro-commissioning. EUAS enables occupants to read energy consumption data monthly, bi-monthly or annually, depending on the technical feasibility of service provider and occupant agreement. Data presented in forms of tables and figures provides a simple and clear overview of energy consumption and trends, which contribute to getting a better understanding of the impact of individual behaviour on home energy efficiency.

EMS provides a capability for professionals to monitor and control technical factors (e.g., indoor temperature, heating demand and supply, hot water temperature, automatic alarm message on web portal in case of malfunction or deficiencies). Based on the real energy demand of occupants, energy provider allows adapting heating energy supply through regulating heating curve of the central heating system, in case of overheating.

Modelling

In this study IDA Indoor Climate and Energy (IDA ICE) is used as the simulation tool, which is dynamic building energy simulation software for heating, cooling, hot water and other resource simulation using the equation-based language Neutral Model Format. In view of the energy-related OB in this case study, two main features are observed: the high room temperature setting and the relatively long occupancy due to weak façade insulation and older people as the main occupants in social housing. Aiming to explore the impacts of occupancy rate and thermal set-point on energy consumption, two dwellings with same architectural characteristics were modelled. Each dwelling has with a floor/heat area of 99m² (a length in east-west direction of 11m and a width in north-south direction of 9m), 3m room height, north-facing door and windows in the kitchen and bathroom, south-facing windows in bedrooms; dwelling 1 with west facing windows in the living room, while dwelling 2 with east facing windows in the living room (Figure 5).
absorption, lighting, occupants and electrical appliances. Due to data protection and privacy, more details on occupant behaviour at home were not allowed to be collected, therefore some schedules on behaviours at home were assumed for simulation, for example,

- activities of window shading depends on sun radiation, i.e. shading is drawn if the incident solar radiation exceeds 100 W/m² on the outside of glazing;
- relative window opening extent is 30%;
- average thermal bridge coefficient of total envelope is 0.1 W/(K·m²);
- average dwelling infiltration is 0.5 ACH;
- both dwellings are installed with same household appliances in quantity and power, and gas as energy carrier for heating and DHW, and electricity for lighting and appliances.

Requirement on cooling and room ventilation is achieved only through occupant interaction with windows and doors, which depends significantly on the occupancy rate, temperature difference between indoor and outdoor, and the individual personal factors (e.g., metabolic rate and clothing level). Occupancy rate has major impact on fuel energy consumption for space heating and cooling, and while operating/use schedules of appliances significantly influence the electricity consumption. Therefore, these two situations were modelled in both dwellings for comparison: 1) different occupant schedules and occupancy but the same thermal set-point; 2) same schedules and occupancy but different thermal set-point.

**Dwelling 1:** both occupants are retirees with an approximate activity level of 2.2 METs (Jette, et al., 1990) and spend average 22 hours/day at home as shown in Fig.6 illustrated. Their average daily schedules of equipment use (i.e. different household appliances) are investigated and results shown in Fig.7-17.
Results and discussion

Except input of occupancy and schedules, there is some other information as input for energy simulation:

- thermal attributes of building construction (e.g., U-values, thermal bridges), building location and orientation according to project data;
- local climate (e.g., monthly average temperature, wind profile) from International Weather for Energy Calculations (IWEC) and ASHRAE 1993;
- energy-related parameters of occupants (e.g., number of occupants in each dwelling, behaviour schedules) and set-point of energy controller for heating, cooling, relative humidity from project investigation.

Figure 30 shows the average occupancy rate of two dwellings. Energy consumption for occupants, household appliances and lighting, and indoor air quality were calculated in the simulation process to compare the influence of occupancy rate, as shown Fig.31-34.
Based on the simulation results, it found out that a higher occupancy rate in dwelling 1 (average 1,833) results in a relative higher energy for heating and cooling, electricity consumption for household appliances and lighting, also a higher CO₂ concentration of spaces, than those of dwelling 2 with an average occupancy rate 1,441. Both dwellings have the same heating set-point 21°C and cooling set-point 27°C. However, if the heating and cooling set-point are changed to 18°C and 25°C, respectively, a remarkable change only appeared in the local heating and cooling energy supply (see Table 1).

| Figure 30: Average dwelling occupancy |
| Figure 31: Energy for occupants of two dwellings |
| Figure 32: Electricity consumption for appliances |
| Figure 33: Electricity consumption for lighting |
| Figure 34: average CO₂ concentration of dwellings |

Based on the holistic literature review and the practical work experience with energy efficiency in social housings, some limitations are summarized as follows:

- Lack of adequate data for analysis. Due to strict privacy protection in Germany, it is hard to collect data on daily routines of occupants at home through monitoring with sensors. Particular for residents in social housing, comprehensive and long-term introduction must be conducted to gain the trust of occupants and thus to attract them into the project. It is not a technical barrier anymore, but an effective support from government with relevant regulation and laws is necessary.

- Lack of complete and real data for simulation. IDA ICE version 4.7, as a building simulation tool, takes the intervention of occupants during energy simulation process into account. Andersen et al. (2011) and Fabi et al. (2012) and D’Oca et al. (2014) analysed the impact of window opening behaviour and use of thermostatic radiator valves on Danish home energy consumption by IDA ICE respectively, according to OB probabilities developed in logic regression, which based on high volume of OB data by observing and measuring. Hong et al. (2016) developed with his team in LBNL an advanced simulation tool option, i.e. OB Functional Mock-up (obFMU), which would be further developed as a plug-in for IDA ICE to achieve more OB possibilities (e.g., occupants movement from one room to another), therefore

| Table 1: Impact of thermal set-point on energy consumption and indoor air quality |
| Dwelling 1 | Dwelling 2 |
| 18°C-25°C | 21°C-27°C | 18°C-25°C | 21°C-27°C |
| Heating supply/a | 5403.5 kWh | 7951.0 kWh | 6515.7 kWh | 9272.2 kWh |
| Cooling supply/a | 1045.1 kWh | 552.3 kWh | 767.1 kWh | 386.5 kWh |
| Electricity appliances | 5662.4 kWh | 5661.9 kWh | 3443.8 kWh | 3445.1 kWh |
| Electricity lighting | 154.6 kWh | 154.9 kWh | 116.8 kWh | 116.8 kWh |
| Average CO₂ concentration | 1032.7 ppm, vol. | 1041.9 ppm, vol. | 917.3 ppm, vol. | 918.4 ppm, vol. |
to strengthen stochastic simulation of OB by IDA-ICE.

- Weak motivation of social housing residents. Some of dwellings in this project have installed smart meters by building owners, which aims to help occupants control their indoor air quality in energy-efficient way. However, it did not work as expected. Most households reject to use technical ancillary since they have to change their living habits for energy benefits that are hard to achieve in a short term.

Conclusion and outlook

Building energy efficiency cannot be achieved without addressing the human factor, which is one of the key factors for design optimization, energy diagnosis and performance evaluation, and building energy simulation (Yan et al., 2017). Occupant behaviour is not in a mode of „if-then” (Jia et al.), especially residential buildings where OB has higher randomness and diversity. A comprehensive analysis of reasons behind energy-related OB is essential for developing effective and targeted solutions for better energy efficiency and IEQ. This paper aims to introduce the measures and limitations of data collection in German social housing that are significantly affected by social background of occupants and local regulations, and also to reveal the impacts of occupancy rate on energy consumption, in particular for social housing group, as occupancy rate directly influences the frequency of occupant interaction with energy-consuming equipment.

OB modeling is an effective way to improve the prediction of building energy performance, but various researches show that it needs to be improved constantly. Meanwhile, an effective instrument for data collection must be established or optimized to provide complete, authentic information for effective OB simulation. In summary, energy saving in social housings is an interdisciplinary study that needs support from all involved stakeholders, that is to say technical improvement should consider the household characteristics (e.g., social-economic backgrounds, educational levels), meanwhile policy instrument should address special needs of occupants in social housing.

References


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