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In-situ monitoring of occupant behavior in residential buildings – a timely review

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Abstract

Occupant behavior has a significant impact on building energy consumption and sustainable development of the community. In-situ monitoring of occupant behavior is one of the most effective and widely used research methods. It collects data of occupant behavior using smart sensors in the natural environment and, if appropriately designed and applied, can effectively avoid bias in the results. However, previous studies have rarely discussed how to design and apply in-situ monitoring activities in residential buildings. This paper, through a comprehensive and critical literature review, aims to close the knowledge gap on in-situ monitoring of occupant behavior in residential buildings. Multiple review techniques were used. First, a conceptual framework of monitoring activities was proposed based on a narrative appraisal of related publications. Second, the body of literature was established

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through an exhaustive search of papers by Web of Science and Scopus, two popular search engines. In total, 68 monitoring activities from 74 journal papers were selected according to the inclusion criteria. Third, meta-analysis and meta-synthesis were applied to this body of literature under the conceptual framework to reflect the achievements of previous studies and to explore the challenges facing future research. Results show that previous studies had limited consideration of sampling methods, setting of time interval and monitoring duration, installation of sensors, and the impact of microclimate. Ignoring these issues would reduce the productivity of data collected from in-situ monitoring activities and thus bring bias into the results. To address such limitations, recommendations are given for the design procedure of in-situ monitoring activities. In addition, an empirical rule is proposed with regard to setting the time interval and monitoring duration. Possible areas of future research are also discussed, e.g. occupant behavior in high-rise residential buildings in hot humid zone. The findings of this paper should facilitate the application of in-situ monitoring in building energy research and familiarize future studies with regard to occupant behavior in residential buildings.

Keywords

Occupant behavior, in-situ monitoring, residential buildings

1. Introduction

Occupant behavior is the interaction between occupants and various building systems and built environments through their presence and activities [1]. Occupant behavior can be categorized as adaptive actions and non-adaptive actions: adaptive actions are occupant actions taken to adapt the indoor environment to their requirements, whereas non-adaptive actions are more extensive, including occupancy, movement, and the operation of plug-ins and electrical appliances [2].

Building energy consumption is influenced by both building-related factors and occupant-related factors, and the latter can exert as much as or even more impact than the former [3]. In other words, "Technology alone does not guarantee low energy use in buildings", and human dimensions act as significantly as technological advances in maximizing the energy performance of buildings[4]. Improperly assumed behavioral patterns can mislead the estimation of potential energy saving, especially for non-extreme behaviors [5]. However, the significance of occupant behavior should be neither overestimated nor underestimated. Another study reported that occupant behavior had limited influence on the technology-driven measures but had significant influence on occupant-involved measures that needed strong interaction with occupants. The energy savings of technology-driven measures and those of occupant-involved measures can differ by up to 20% [6]. In addition, sophisticated models are not necessarily more accurate or more reliable. As for building-level energy simulation, the stochastic or non-stochastic presence patterns are less important than a reliable estimation of actual occupancy [7]. Thus, more research on occupant behavior is necessary in order to explore this important and complicated issue.

Primary occupant behavior research approaches include in-situ monitoring, laboratory experiments and survey methods [8]. This paper focuses on in-situ monitoring activities, which refers to the monitoring of energy-related occupant behaviors in a natural environment, e.g. an occupied house, using data loggers to record the parameters of thermal environment and behaviors, rather than using laboratory studies or literal surveys. The precisely controlled indoor conditions make laboratory studies advantageous against in-situ monitoring [9]. However, participants always feel observed in an artificial environment [10] which can affect participant's behavior (the Hawthorne effect) [11, 12]. In-situ monitoring in a natural environment is more convenient and economical than laboratory studies. With the development of new technologies, more parameters and more functions are available in data loggers, such as long-term running and real-time data reporting [13]. Using non-invasive monitoring, it is then possible to reduce the Hawthorne effect [14] [15]. In-situ monitoring is also supplemented with other research methods, such as mixed-method studies, that help improve result accuracy [15]. Interviews, daily journals, logbooks and questionnaire surveys are common methods combined with sensor-based monitoring activities in existing studies to collect behavioral data.

Though in-situ monitoring is widely used, research gaps remain in its application within residential buildings. Constructive and comprehensive reviews on behavior monitoring in office buildings are easily accessible to researchers [16, 17], but compared to office buildings, less discussion is available with regard to behavior monitoring in residential buildings [15]. In addition, existing experiences in office buildings may fail to adequately reflect field measurements required in residential buildings. Under the Theory of Planned Behavior [18, 19], occupant behavior in office buildings and residential buildings differ in several respects. First, occupants in residential buildings pay for the energy bills themselves, so this close link between their own actions and energy bills somehow shapes their "attitude" to energy-related behaviors. Second, occupants in residential buildings and office buildings have different "subjective norms". The former have social pressure from neighbors, but the latter have social pressure from their workplace [20]. Third, occupants in residential buildings generally have greater freedom over controlling the energy system, thus being more motivated in "perceived behavior control". Fourth, occupant behavior is more dynamic in residential buildings than in office buildings. Occupants in residential buildings have timely feedback of their behaviors, whereas it is difficult to get such frequent feedback in office buildings with a large workspace and centralized energy systems. Moreover, a spillover effect has not been found between environmental behavior in the workplace and at home [21]. In other words, an individual can behave differently in office buildings compared to residential buildings. For example, occupants can tolerate wider temperature variations in their homes compared to that in the office. In a Sydney residential buildings, for instance, the comfort zone widths for 80% acceptability were 2℃ wider than in office buildings [22]. Thus, the results of monitoring activities in homes can be questionable if directly applying experience from previous studies in office buildings.

This paper aims to close the knowledge gap on designing and applying in-situ monitoring activities for occupant behavior research in residential buildings. To achieve the research aim, in Section 2 the paper first of all identifies key issues that determine the performance of in-situ monitoring activity. Next, in Section 3, it summarizes the achievements and limitations of existing monitoring activities, and finally, in Sections 4 and 5, it proposes recommendations for improving the design of monitoring activities in building energy research.

2. Methodology

2.1 Review methods

Multiple review techniques and analysis methods are employed to achieve different research objectives, as shown in Figure 1. The methodology of this paper has been designed with reference to the seven-step model of literature review [23] and is examined under the Search-Appraisal-Synthesis-Analysis (SALSA) [24] framework.

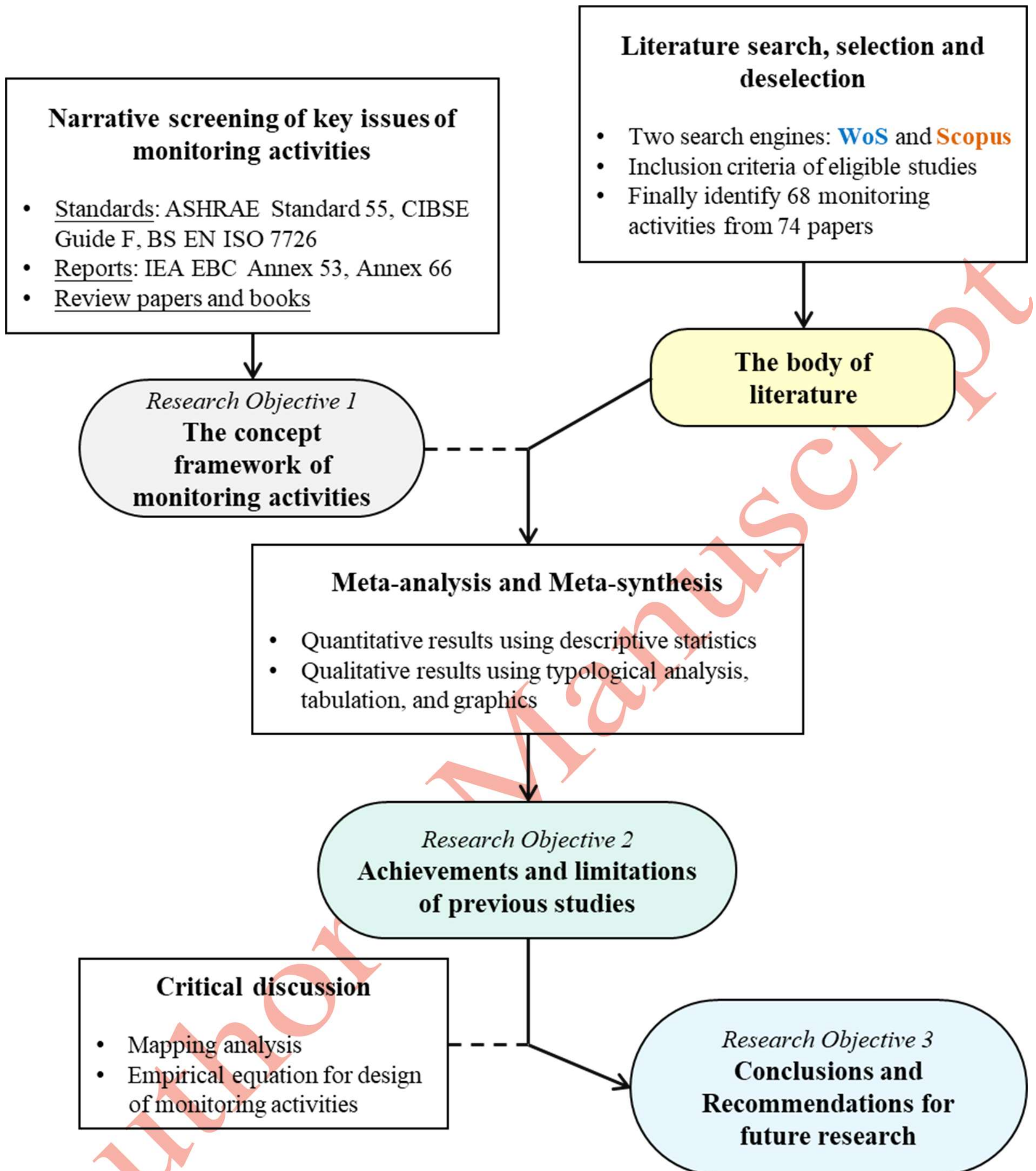

Figure 1: Methodology of this paper

First, the key issues relating to monitoring activities were summarized from a narrative appraisal of international standards, representative reports, highly relevant review papers and books. These key issues constructed a conceptual framework for in-situ monitoring activities of occupant behavior in residential buildings (Research Objective 1). Second, an exhaustive search was conducted of all available publications, using Web of Science and Scopus, two popular search engines, along with carefully chosen and precise keywords. The body of literature was made up of carefully selected eligible papers according to the inclusion criteria. Third, both meta-analysis and meta-synthesis were applied to evaluate monitoring activities in previous studies (Research Objective 2) using the conceptual framework. Quantitative methods, e.g. descriptive analysis, were used to generate statistical results; and qualitative methods, such as typological analysis, were used to generate unquantifiable results. Finally, this paper discusses the opportunities and challenges involved in applying in-situ monitoring activities for the research of occupant behavior in residential buildings. Recommendations for future study are then proposed, based on a critical discussion (Research Objective 3).

2.2 Conceptual framework of monitoring activities

The conceptual framework of monitoring activities contains important issues that can determine the performance of monitoring activities and should thus be considered carefully at the design stage. Eleven issues were identified via a narrative appraisal of highly cited publications. The issues were classified into three groups (Figure 2), namely, objectives and methods, sampling process, and monitoring process. The definition and scope of each issue was defined as follows.

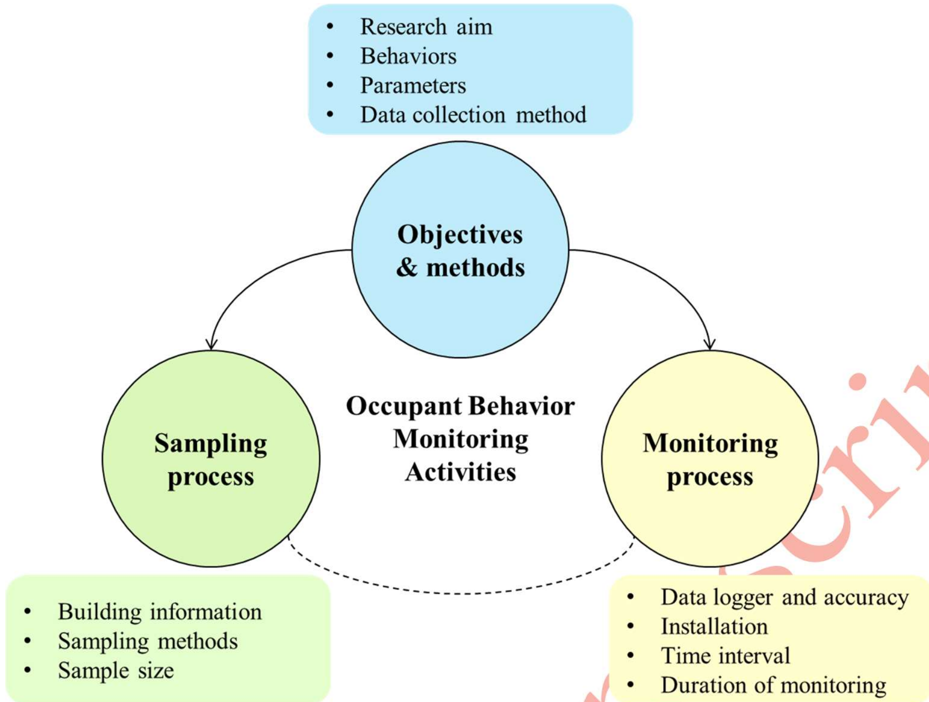

Figure 2: The conceptual framework of monitoring activities

(1) Research aim: This refers to the motivation of the reviewed paper and monitoring activity, such as to validate building energy models, to study certain occupant behavior, to evaluate indoor air quality or thermal comfort, or to study behavior-related energy conservation technologies.

(2) Behaviors: Behaviors refer to occupant behaviors monitored and studied in the reviewed paper, including occupancy, lighting, shading, window operation, use of the cooling system (thermostat setting and motivations behind operation), the heating system, cooking, showering, use of domestic hot water and other appliances etc [15, 16, 25-27].

(3) Parameters: These are the observed parameters of a behavior, usually the ontology of a behavior, i.e. the driver(s), the need(s), the action, and the system involved in performing such a behavior [28], for example, adjusting the indoor or outdoor environment quality, the actions of an occupant, and other related data.

(4) Data collection methods: This refers to the method(s) used by researchers to get quantitative or

qualitative behavioral data. In particular, this paper discusses if mixed methods are used in previous studies, such as using both in-situ monitoring and face-to-face interviews for both quantitative and qualitative results [29, 30].

(5) Building information: Building information here refers to building type and location of the target building. The building type includes single-family buildings and multi-family buildings. The former is occupied by one family and stands separate from other buildings, such as a dwelling that is a detached house, while the latter accommodates more than one family in one building, such as an apartment block.

(6) Sampling methods: This refers to the sampling of or selection criteria for residential buildings or households.

(7) Sample size: This refers to the number of households involved in the monitoring activity.

(8) Data logger and accuracy: This refers to the information produced by data loggers and whether the product meets the accuracy requirements of international standards [31, 32].

(9) Installation: This refers to where and how to install sensors, such as where on the floor plan and the height above the floor.

(10) Time interval: This refers to the temporal granularity of data collection. Other arguments involved in this issue include frequency of data logging, temporal granularity, and the data acquisition step.

(11) Duration of monitoring: This refers to the duration of data collection activities or the operation time of data loggers.

2.3 Literature search, selection and deselection

The literature search was launched using two citation databases, namely, the Web of Science by

Clarivate Analytics and Scopus by Elsevier. These two online search engines were selected because of their popularity and effectiveness. Based on the research objectives, the keywords were set as "residential building energy behavior monitor" and "residential building energy behavior measurement". Research papers published since 2009 were recorded (accessed in April 2019). The year 2009 was chosen because from then on researchers paid increasing attention to occupant behavior [27, 33], and an increasing number of data collection activities were undertaken after 2009 [34]. In the end, 177 and 89 papers respectively were found to be available from Web of Science and Scopus.

The selection of eligible papers was based on the following criteria: First, conference papers were excluded because, in general, monitoring activities in conference papers are mentioned again in journal papers published later. Second, unrelated papers were excluded; related papers must include both a discussion on occupant behavior and the application of monitoring activities. Third, six duplicate papers from Web of Science and Scopus were excluded. In total, from this systematic review 74 papers were included as the body of literature. The eligible papers contained 68 different in-situ monitoring activities and the results of this paper are given based on these monitoring activities.

Studies on occupant behavior using in-situ monitoring activities have been increasing over the last ten years, as shown in Figure 3, and the ten most cited papers are listed below in Table 1. Energy and Buildings and Building and Environment comprise nearly half of the body of literature for this paper, as shown in Figure 4, where the space represents the number of papers.

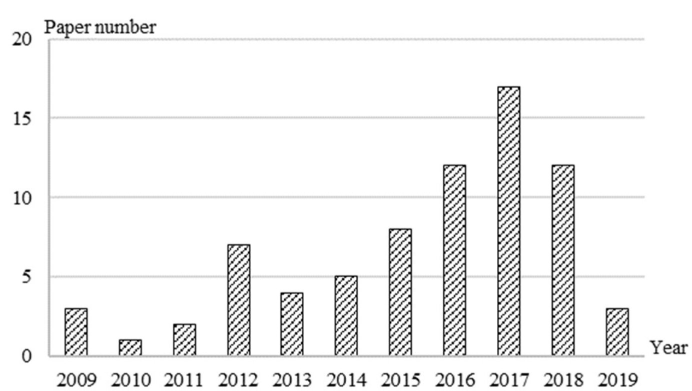

Figure 3: Year of publication

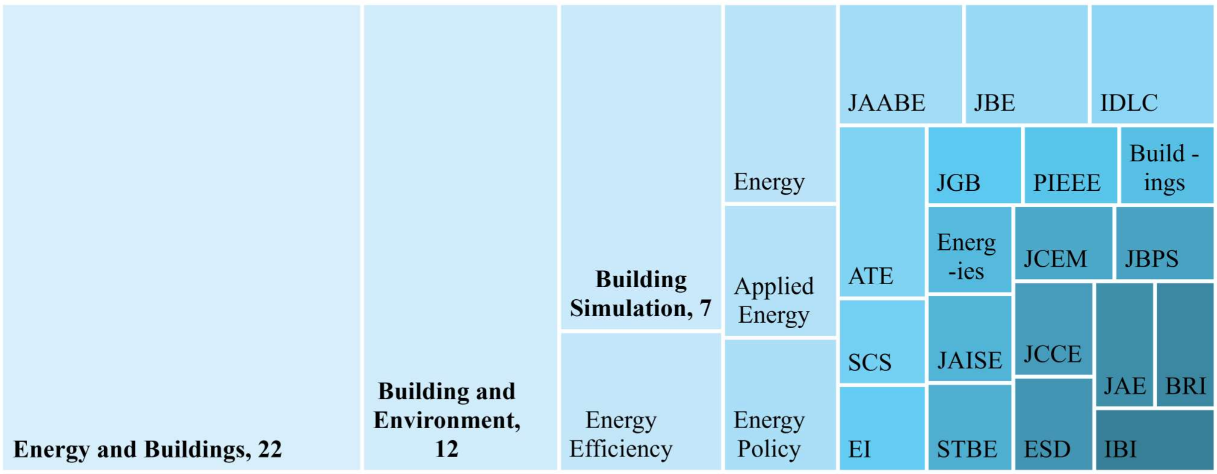

Figure 4: Sources of the body of literature (Abbreviations of journals are listed in Appendix I, Table A)

Table 1: Ten most cited papers

Author	**Year**	**Title**	**Journal**	**Times cited**
Yu et al.	2011	A systematic procedure to study the influence of occupant behavior on building energy consumption	Energy and Buildings	220
Kavousian et al.	2013	Determinants of residential electricity consumption: Using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior	Energy	148
Jain et al.	2014	Forecasting energy consumption of multi-family residential buildings using support vector regression: Investigating the impact of temporal and spatial monitoring granularity on performance accuracy	Applied Energy	139
Peschiera et al.	2010	Response-relapse patterns of building occupant electricity consumption following exposure to personal, contextualized and occupant peer network utilization data	Energy and Buildings	111
Schweiker and Shukuya	2009	Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions	Building and Environment	67
Becker and Paciuk	2009	Thermal comfort in residential buildings - Failure to predict by Standard model	Building and Environment	60
Vassileva et al.	2012	Analytical comparison between electricity consumption and behavioral characteristics of Swedish households in rented apartments	Applied Energy	47
Jain et al.	2013	Investigating the impact eco-feedback information representation has on building occupant energy consumption behavior and savings	Energy and Buildings	45
D'Oca et al.	2014	Effect of thermostat and window opening occupant behavior models on energy use in homes	Building Simulation	45
Peng et al.	2012	Quantitative description and simulation of human behavior in residential buildings	Building Simulation	40

In general, previous papers have insufficient documentation of the sampling and monitoring processes. Some issues are not mentioned or have oversimplified description, such as selection criteria of target flats. Some issues have largely differing monitoring activities, such as setting of the time intervals.

3. Results and analyses

3.1 Objectives and methods

3.1.1 Research aims of reviewed papers

Most reviewed papers employed in-situ monitoring activities to study certain occupant behaviors (51% of reviewed papers) or to validate building energy models (19%). The research aim is the most important issue because it determines other key issues. For example, data collection methods should be consistent with the research aim. Some researchers adopted mixed methods to explore the drivers of behavior, while others used long-term measurements for model calibration. As another example, the time intervals between data collection should also be decided in accordance with the research aims. Sometimes, meteorological data has been recorded every half an hour as an input of the building energy model [35]; whereas in other cases, in order to reflect the factors influencing window operation behavior, the meteorological data was recorded with a much shorter time interval of 10 minutes [36]. Thus a standardized monitoring activity that fits all the various research aims is unavailable. The design of monitoring activities should carefully consider the research aim and ensure the reliability and validity of data.

3.1.2 Target behaviors of reviewed papers

Window opening and the use of cooling and heating systems are the three most frequently discussed behaviors in reviewed papers among ten energy-related occupant behaviors under the conceptual framework (Figure 5). However, the most frequently discussed behaviors are not necessarily the largest energy end users. For example, cooking habits and use of domestic hot water are discussed much less than cooling and heating, even though in the residential buildings they are the two greatest consumers of energy [37].

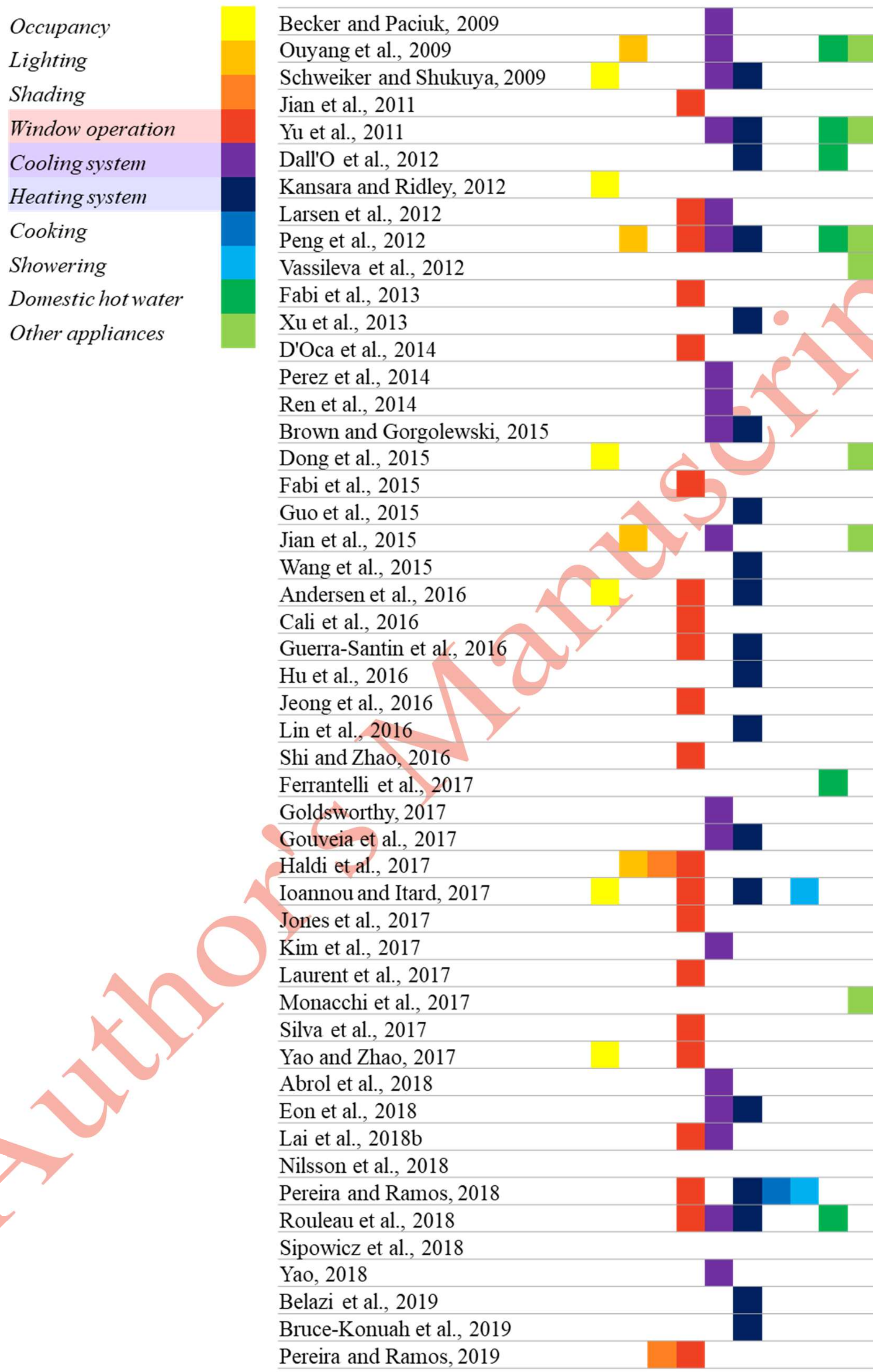

Figure 5: Target behaviors in reviewed monitoring activities (Top down from 2009 to 2019)

In addition, certain behaviors can be studied either independently or alongside other behaviors. Occupancy was frequently mentioned in multiple behavior research [38]. Dong et al. predicted energy usage with occupancy [39]; and Yao and Zhao introduced occupancy into the window operation model [40]. Except for occupancy, interaction between other behaviors also started to draw attention. For example, window opening could increase the heating load and cause noticeable energy variance [41].

3.1.3 Observed parameters of behaviors

Parameters observed in monitoring activities contain three categories: behavioral parameters, indoor environmental parameters and outdoor environmental parameters (i.e., meteorological parameters), as shown in Table 2. Behaviors can be described directly by the status of the system or by actions upon the system, such as occupancy, windows being open or not, and the power of electric appliances. Behaviors can also be described indirectly using environmental parameters. Indoor air CO_2 concentration has been used as an indicator of occupancy status in previous research [36, 42, 43]. Temperature has been used to model on/off actions of the air conditioner [44]. The indoor air temperature, relative humidity and CO_2 have been used as signals for showering actions [45].

Table 2: Observed parameters in reviewed monitoring activities

Behaviors	Parameters
Occupancy	Occupancy, CO_2
Lighting	Power or electricity use
Window operation	Window open or not, indoor air temperature and relative humidity, CO_2, VOC, and PM2.5; outdoor air temperature and relative humidity, solar radiation, wind speed, wind direction, PM 2.5
Cooling system	Power or electricity use, cooling load, temperature of air supply, temperature of extracted air, thermostat settings, indoor air temperature and relative humidity, outdoor air temperature and relative humidity, solar radiation, wind speed, wind direction
Heating system	Power or electricity use, heating load; indoor air temperature and relative humidity; outdoor air temperature and relative humidity; solar radiation, wind speed, wind direction
Cooking	Power or electricity use
Showering	Indoor air temperature and relative humidity, CO_2
Domestic hot water	Water floor, water temperature, supply heat
Other appliances	Power or electricity use

3.1.4 Data collection methods

Both qualitative and quantitative data are necessary in occupant behavior research to satisfy the multi-disciplinary needs. Quantitative data is good at recording "what" happens, e.g. the actions taken by occupants. On the other hand, qualitative data, e.g. occupant stories, enables researchers to understand why and how occupants use buildings [46]. Thus, mixed-methods research, collecting both qualitative and quantitative data, are advantageous to answer the "why" and "how" questions in addition to the "what" questions about occupant behavior [30]. Also, in some studies mixed methods can improve the accuracy of monitoring results [15].

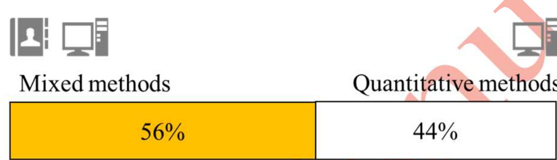

Figure 6: Mixed methods research applied in residential buildings

In the reviewed 68 monitoring activities, more than half adopted mixed methods, as shown in Figure 6. Survey methods, e.g. daily journal, logbook, questionnaire and interview, are frequently used to supplement in-situ monitoring activities. For example, an unstructured interview with residents is often applied in order to understand the observed behaviors [47].

3.2 Sampling process

3.2.1 Building information

Building information that must be documented during monitoring activities include the location of the target building and the building type.

All papers clearly stated the location of their samples. The countries mentioned include: Argentina, Austria, Australia, Canada, China, Denmark, Egypt, Finland, France, Germany, Israel, Italy, Japan, Korea, Lithuania, Luxembourg, Morocco, Netherlands, Portugal, Romania, Spain, Sweden, United Arab Emirates and United States. More details are presented in the Appendix II (Table). China, United States and Australia are the three most enthusiastic areas of behavior monitoring in residential buildings. Most monitoring activities were conducted with buildings located in the same country or area, whereas four monitoring activities, out of sixty-eight, were carried out with buildings located in more than one country [48-51]. Kavousian et al. (2013) even collected data from buildings in twenty-six countries.

Out of a total 68 monitoring activities, 44 studied multi-family buildings, 15 studied single-family buildings, six studied both types, and three papers did not mention building types. In addition to ordinary low-rise and mid-rise residential buildings, a monitoring activity was targeted at four high-rise residential buildings in Canada [52]. Besides domestic residential buildings, four studies focused on university student residential halls in United Arab Emirates [53], Japan [54] and the United States [55, 56].

3.2.2 Sampling methods

About half of the reviewed monitoring activities somehow ignored sampling methods. Only thirty-two out of sixty-eight (47%) monitoring activities mentioned the recruitment process. Even less stated the sampling criteria. Participants were accessed by radio broadcast, email, mail-boxes and on-site recruitment. Most sampling processes considered no more than two items in their eligibility criteria. Sampling criteria included items relating to residents, buildings and research. Sampling criteria relating to residents were mostly comprised of the social demographics of residents, e.g. family size, income and age [57-59]. Examples of building related criteria are floor number, orientation, construction, energy systems [60], energy efficiency design [61] and energy-saving renovations [48]. Research feasibility was another frequently used sampling criterion. Two kinds of buildings were favorable under this criterion, including new buildings built for research purposes [39, 62-64] and existing buildings equipped with data loggers or with available datasets [55, 65-69]. In addition, voluntary participation was more common than compensation participation, there being only one paper that mentioned compensation participation. Thus, it is predictable that "a convenience sample" has been widely adopted.

3.2.3 Sample size

Sample size of reviewed monitoring activities ranged from one to over one thousand, except for one paper that did not state the sample size (Figure 7).

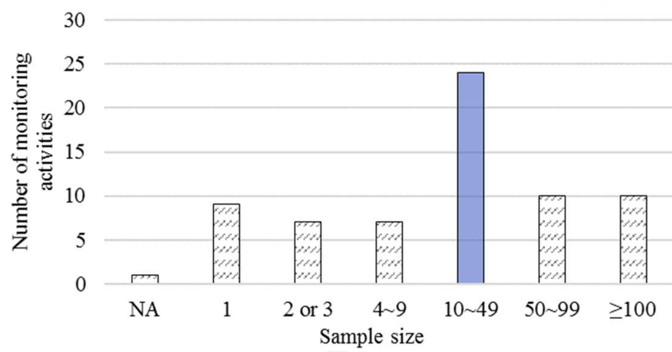

Figure 7: Sample size of reviewed monitoring activities

Half of the monitoring activities achieved a sample size of between ten and a hundred. The largest sample size (1638 participants) was achieved by recruiting through a workplace social network in an international technical company [51]. Since participants were from different regions and countries, they were required to install the electricity meters by themselves. Electricity bills during the monitoring period were paid as a reward for their participation. The second largest sample size (725 participants) was achieved in a residential community that installed thermal meters and electricity meters in advance [52]. The third largest sample size (310 participants) was also available in buildings with pre-installed data loggers [70]. A relatively high participation rate was achieved in a campus monitoring. Nearly 45% of the students actively participating in the feedback experiment in a university student dormitory were recruited via multiple message channels, such as emails and on-site recruitment [55].

Generally, the sample size of monitoring activities may not support statistical analysis and would not reach so-called universal or representative conclusions. Zhou and Yang (2016) reviewed previous studies on household energy consumption behavior with big data analytics [71]. Results showed that, sample sizes of most studies were less than 1000, which was not big enough. Also, surveys were used more frequently to collect extensive data. Thus, it is necessary to use mixed methods to examine the conclusions on a large scale.

3.3 Monitoring process

3.3.1 Data logger and accuracy

International standard ISO 7726 [32] and ASHRAE handbook [31] are highly-cited references which state the expected accuracy of data loggers in field measurement. The available accuracy of existing data loggers was summarized in one review paper [13]. Indoor air temperature, relative humidity and air velocity are the three most frequently measured parameters. Expected accuracy and available accuracy of the three parameters in thermal comfort evaluation are shown in Table 3.

Table 3: Expected accuracy and available accuracy of data loggers

Parameter	*Information source*	*Measurement range*	*Accuracy*
Temperature	ASHRAE 55	10~40℃	±0.2℃
	ISO 7726	(Class C) 10~40℃	±0.2~0.5℃
	Ahmad et al., 2016	(Thermistor) -50~180℃	±0.1~0.5℃
Relative humidity	ASHRAE 55	25%~95%	±5%
	ISO 7726	/	/
	Ahmad et al., 2016	(Capacitive polymer) 0~100%	±2%~4.5%
Air velocity	ASHRAE 55	0.05~2m/s	±0.02m/s
	ISO 7726	(Class C) 0.05~1m/s	±0.02~0.05m/s
	Ahmad et al., 2016	(hotwire) 0.05~20m/s	±2%~5% of reading

In total, 57% of the monitoring activities stated the data logger product information, whereas less than half provided the accuracy of the data loggers. Few monitoring activities were able to meet the requirements in ASHRAE handbook (2017), but most of them met the requirements in ISO 7726 (2001). For example, the accuracy of temperature was often said to be ±0.3℃ or ±0.5℃. Also, with the development of sensing technology, data loggers were able to record new parameters in addition to electricity use, such as occupancy and thermal graphs. In addition, a single box with collective sensors to measure different parameters, e.g. temperature, relative humidity and CO_2, was also used in monitoring activities [68].

Preliminary processing of the raw data is necessary for quality assurance before applying more complex data analysis [72]. Accuracy and completeness are two most important aspects of the data quality. Different techniques have been proposed to deal with errors in raw data such as moving average and distance analysis [73]. Shi and Zhao (2016) used the former value to set the missing hourly data within two hours and the other missing periods were removed from further analysis [74].

3.3.2 Installation

In total, 45 out of 68 monitoring activities showed how to install data loggers, using photos, floor plan drawings or a literal description. Indoor installation was usually made in the living room and bedroom. Several papers set the floor plan and the height above floor to install sensors, according to standards, e.g. ASHRAE 55, ISO 7726 [75]. However, most studies preferred to go by previous experience rather than standards. There exist numerous good practices in reviewed papers. For example, in one monitoring activity, the sensor box was put in the most used room at a sitting level height on a central location, away from windows [49]. Similarly, the sensors were installed both in the living room and bedroom, on the internal walls at 1.5m height, at least 0.5m from the ceiling, the partition angles and other blind zones, as far away as possible from direct radiation and air streams, heat sources and occupant proximity [69]. In a more exhaustive filed measurement, the sensors were put in eight zones as set in the building simulation model, hanging from the ceiling at 1.5m above the floor in the middle of each zone [76].

Other than on-site measurement, meteorological data were often downloaded from official observatories within several kilometers. The climatic differences between observed buildings and the official observatories were seldom discussed. Andersen et al. (2016) used outdoor air temperature as an indicator to calibrate meteorological data. The weather station was 11.2 km from the observed building. Temperature data from the official station was compared with data obtained from a sensor just outside the observed building. Results showed that 95% of the data was within 0.5℃ difference [77]. However, the difference in other climatic parameters, such as wind speed and wind direction, remains unclear.

Both technological faults and improper use of sensors can lead to errors and uncertainties in an in-situ monitoring activity. Previous studies have reported comprehensive reviews of common monitoring sensors with respect to technological aspects [13, 73, 78]. Readers can refer to these papers for more details. Compared to technological faults, this paper focuses more on uncertainties brought by improper use of sensors. Generally, one set of data loggers was installed in one room. However, more than one set of data loggers were sometimes used for data reliability and validity. For example, paired sensors were used to record indoor temperature and relative humidity for data reliability [79]. Two sets of temperature and relative humidity sensors were placed separately in both the cold area and warm area of a room for data validity [48]. Two temperature and relative humidity sensors were places respectively on the south and north facades to collect outdoor environmental data for two opposite rooms [75]. In addition, researchers also applied various measures to make sure that the sensors were installed correctly and worked well. For example, all the interviewees were trained to use the sensors before the monitoring activity [80]. Participants were informed of the indicator light on the sensor which showed its work status [81]. Once the sensor went wrong, participants would notice and contact researchers.

3.3.3 Time interval

The temporal granularity of the monitoring process determines the productivity of the data [13]. There are no standards on the time interval of data recording, except for literal discussion in publications. As for energy modelling, the five-minute time interval is suggested for behaviors which are expected to be acted out frequently by occupants, 15 minutes to 1 hour is acceptable for a whole year simulation, whereas event-based data loggers are preferred for recording infrequent behaviors [33, 82]. A notable experiment by Jain et al. explored the impact of temporal and spatial granularity on the accuracy of the predicted energy consumption through regression models [83]. The experiment was conducted via building simulation, and the simulation model was calibrated by field measurement data. Results indicated that the most effective models were built with hourly energy consumption at the floor level. More than half of the reviewed monitoring activities would set a time interval within 15-min, as shown in Figure 8. The observed parameters usually have the same time interval, except for the meteorological data from an official observatory, the electricity consumption from a building energy management system, and event-based data loggers. In summary, the setting of time intervals should be based on the research aim and the capacity of data loggers.

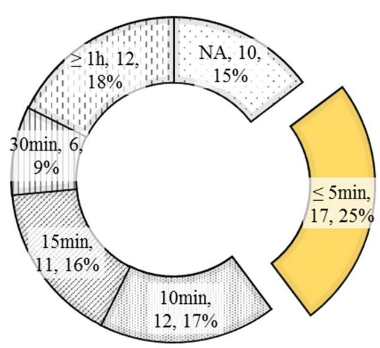

Figure 8: Distribution of time interval in 68 reviewed monitoring activities

3.3.4 Duration of monitoring

How long does it take to collect enough data for analysis? The duration of the reviewed monitoring activities ranges from less than one week to more than one year, as shown in Figure 9. In addition to the duration of monitoring, the sample size and the time interval will also affect the number of observed actions. Table 4 illustrates the number of observed actions and the related settings of some monitoring activities. In most cases, behavior monitoring lasts for more than one month, in order to collect enough actions for process analysis, such as thirty actions of turning on air conditioners.

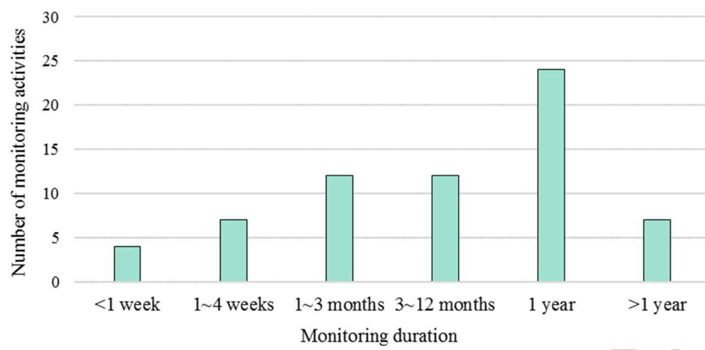

Figure 9: Monitoring duration of reviewed monitoring activities

Table 4: Number of observed actions in 10 monitoring activities

Paper	**Sample size**	**Time interval**	**Duration of monitoring**	**Number of observed actions**
Larsen et al., 2012	1	15min	28 days	About 10 turning on and 10 turning off of air conditioners, and about 10 opening and closing of windows in a room in 10 days
Fabi et al., 2015	10	10min	3 months	About 0~80 opening or closing of windows per room in 3 months
Guo et al., 2015	48	10min	6 months	More than 100 heating activities with air conditioners per household in 3 months
Jian et al., 2015	44	10min	1 year	At least 1 lighting activity per day per room
Cali et al., 2016	60	1min	2 year	More than 8000 window opening activities by 10 households in 1 year
Guerra-Santin et al., 2016	5	16s	3 year	7 window opening and 5 heating activities in a household in 7 days
Kim et al., 2017	42	15min	2 years	More than 1000 cooling, more than 1000 heating, and more than 1000 fan opening activities by 42 households in 2 years
Laurent et al., 2017	91	5min	2 months	About 10 window openings in 8 days
Yao, 2018	1	10min	52 days	31 turnings on of air conditioner in a bedroom in 52 days
Belazi et al., 2019	11	1h	1 year	About 10~200 thermostat changes by 1 household in 1 year

Seasons should also be carefully considered to set a proper monitoring duration. For example, behavior modes can change in line with seasons. The frequency of window openings was found to be different between the non-heating and heating periods of a year [58]. In another example, a monitoring activity of temperature regulation behaviors was set to be in summer in New York, because at that time of year occupants had full control of the thermostat settings [70].

4. Discussion

4.1 Research gaps in in-situ monitoring activities

4.1.1 Insufficient consideration of building height

Microclimate changes with the building height because, for example, at higher floors the outdoor air temperature is lower and the wind speed is faster. This cooler and airier environment makes it easier to achieve thermal comfort in rooms on higher floors than rooms on lower floors. Thus, high-rise and low-rise buildings can have considerably different thermal environments and energy performance. A study in the UK found that office buildings of 21 floors or more consumed 137% more electricity and 42% more fossil fuel than those of five floors or less [84]. Different thermal comfort and energy performance caused by building height exist even in the same building, e.g. high-rise buildings. For example, the outdoor dry bulb temperature is estimated to change by about 8℃/km, according to the Dry Adiabatic Lapse Rate (DALR) [85]; the difference is quite small in low-rise or mid-rise buildings, whereas in a twenty-floor building the difference can be 0.5℃. A field measurement in Malaysia reported that both indoor air temperature and wind speed were significantly different between living rooms on Floor 3 and Floor 13 [86]. Different environmental factors can thus shape different behavior modes. A case study in Hong Kong reported different behavior patterns of using air conditioners, as residents living on higher floors used air conditioners in the bedroom less frequently than those living on lower floors of a residential building [87].

To accommodate the increasing population within a limited land area, high-rise buildings have become an irreversible trend [88]. Thus, building height should be taken into consideration during the sampling process. However, a review of the sampling methods indicates insufficient consideration of building height. Only four monitoring activities considered building height when selecting participants. Dall'O et al. (2012) chose flats on the ground, middle, and upper floors, namely floors 0, 4 and 7 of 8-storey buildings [89]. Xu et al. (2013) selected three apartments on floors 1, 4 and 9, choosing bottom, middle, and top floors [90]. Laurent et al. (2017) randomly recruited rooms based on their bedroom location and orientation on each floor [42]. Rouleau et al. (2018) chose four apartments on the ground floor and another four on the top floor [41]. However, none of these involved high-rise buildings. Thus, it is strongly suggested to consider the building height carefully in future practice.

4.1.2 Limited monitoring activities located in hot humid zone

The reviewed monitoring activities are marked on the world map colored according to climate zones, with reference to the ASHRAE Standard 169-2013 [91], as shown in Figure 10. One monitoring activity can contain more than one samples from different climate zones even different countries. One paper [51] was excluded in Figure 10, which was based on monitoring activities in 26 countries but not specified the locations of the samples.

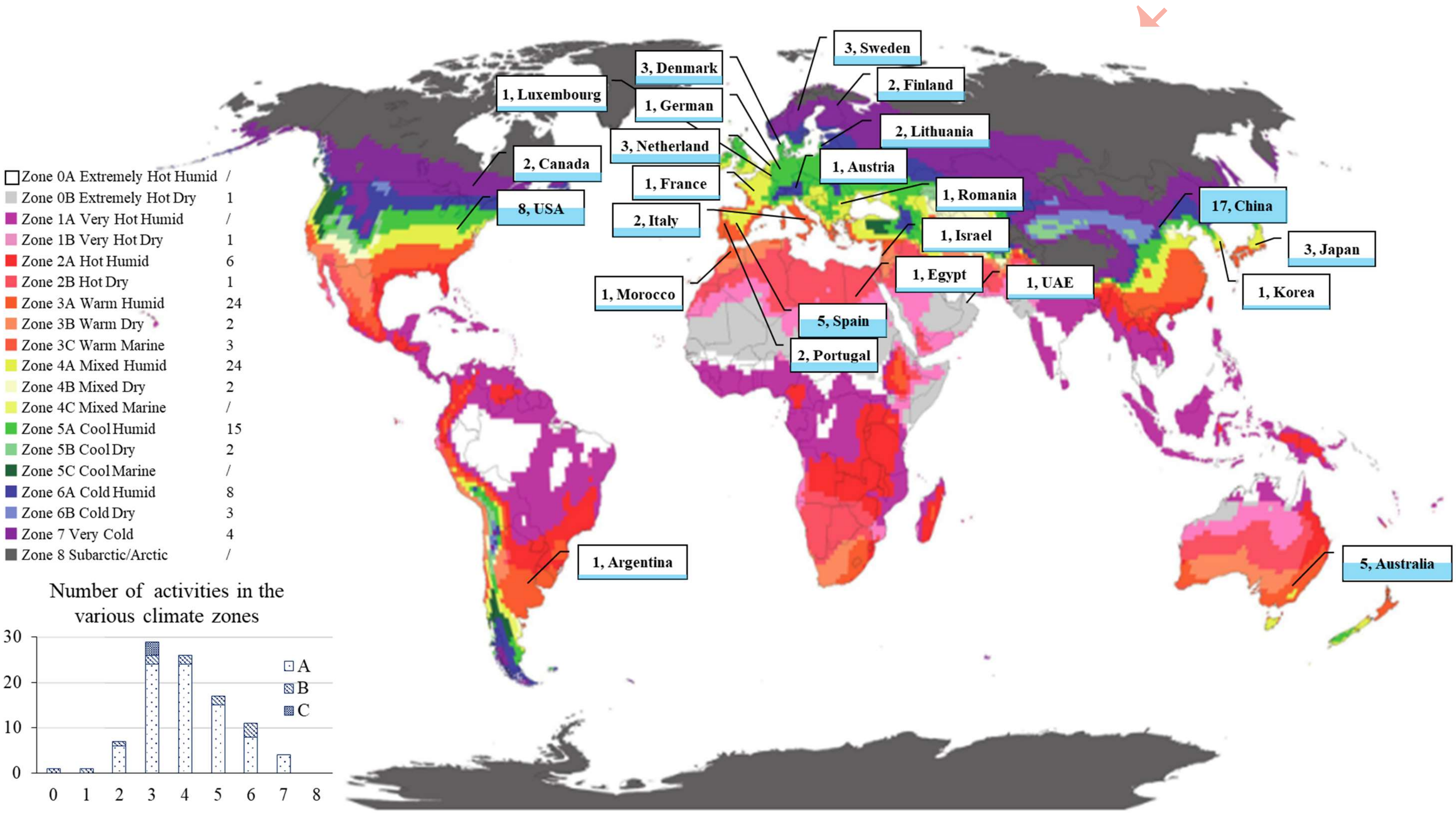

Figure 10: Locations of monitoring activities in the various climate zones

Previous studies have covered most climate zones, but limited data is available for the hot humid zone (Zone 2A in Figure 10) compared to other human residential areas [92]. Occupants in the tropics were shown to prefer a warmer temperature and elevated air speed [93]. The hot humid zone has a hot summer and long transitional seasons. Although natural ventilation was able to increase the thermal comfort zone and improve the comfort experience, buildings in the hot humid zone cannot rely completely on passive solutions to deal with the cooling load [94]. Thus, artificial cooling is necessary in summer, and natural ventilation can sometimes replace artificial cooling to cool down rooms during the transitional seasons, i.e. adaptive behaviors in the hot humid zone can change with the seasons. Monitoring the changes in behavior modes between summer and transitional seasons enables a theoretical explanation of how environmental factors can shape occupant behavior. The interaction among multiple behaviors, e.g. use of air conditioner and window opening, is another meaningful topic in the hot humid zone. All this increased knowledge will in turn facilitate human-in-the-loop energy saving management.

4.2 Recommendations on design of monitoring activities

Procedures involved in designing a monitoring activity are elaborated on in Figure 11. Overall, the sampling process and monitoring process should be designed with reference to the research aim, and the whole data collection plan should be thoroughly reviewed prior to its application. Going through the procedure will evaluate all the key issues of in-situ monitoring activities in an organized way.

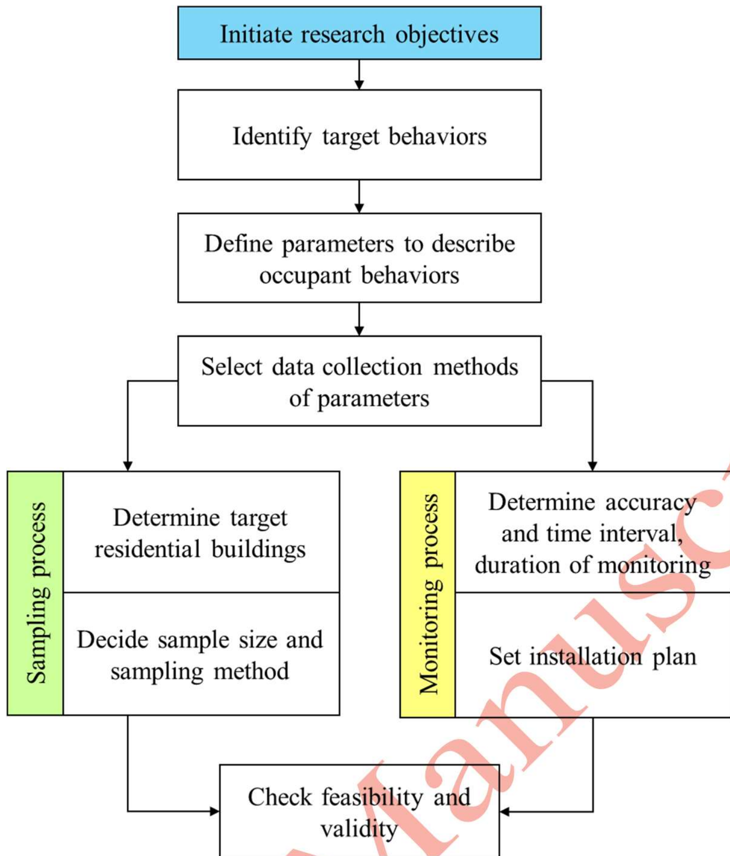

Figure 11: Procedures involved in designing monitoring activities

With regard to the design of monitoring processes, one key problem is how to set the appropriate monitoring duration and time interval. There is an empirical rule on deciding the monitoring duration and time interval by calculating data magnitude. The magnitude of collected data is the amount of data points for one particular parameter. In Equation 1, θ is the magnitude of data, μ is the duration (unit: day) and τ is the time interval (unit: minute). Lower limits on μ and τ are set as one minute and one month, and the upper limit on τ is set as one hour, based on previous experience.

$$\theta = 1440 \times \mu \times \tau^{-1} \qquad \text{Equation 1}$$

In total, 76% of the monitoring activities have a data magnitude ranging from 10^3 to 10^5, as highlighted by the green and yellow areas in Figure 12. Logarithmic transformation of μ and τ are used in the figure for linear expression. Each point represents a monitoring activity. A deeper color of the same icon means it represents more than one monitoring activity. Data labels in dark grey are used to show time intervals. The data magnitude of in-situ monitoring activities indicates the productivity of the collected data. Data productivity can be improved by appropriately extending the duration or narrowing down the time interval. Considering the magnitude simply ensures a shortest monitoring duration or widest time interval to achieve qualified raw data with the least effort.

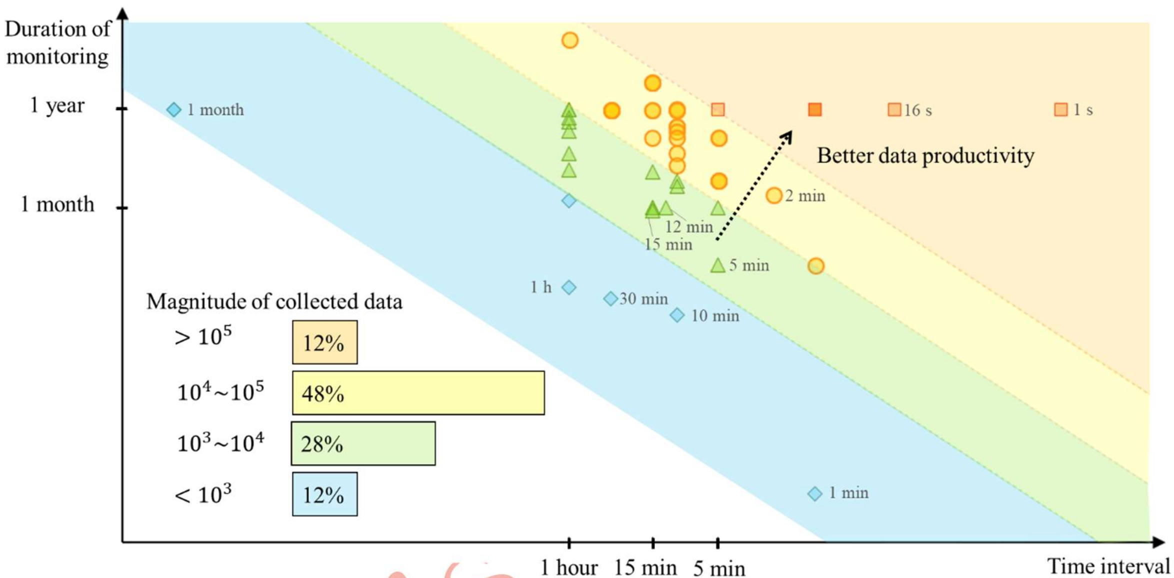

Figure 12: Distribution of monitoring duration and time interval

Other recommendations include:

- Employ a mixed research method to comprehend behaviors, such as conducting a questionnaire survey to supplement in-situ monitoring activities.
- Define the target behavior with proper parameters. First consider the following: Does this behavior interact with other behaviors? Can the parameter(s) reflect the target behavior?
- Consider the sampling criteria and recruitment method carefully. Are floor number and orientation of the apartment important in this research? Will this recruitment method bring bias into the results?

- Set monitoring duration and time interval according to the requirements of data productivity. Is hourly data effective enough to calibrate the building energy model? Does data collected within one week contain enough window operation actions for regression analysis?

- Prior to putting it into application, check if the monitoring activity can satisfy the research objectives, and maintain good documentation of the eleven key issues mentioned in Section 2.

In occupant behavior research, privacy issues are important and should be carefully considered. Data collection of occupant behavior research is a challenging task due to privacy protection [95]. Smart sensors and advanced data analytics enable researchers to gather more complex occupant behavior data. Dziedzic et al. (2019) managed to identify particular individuals from the video data while ensuring privacy of participants by introducing enhanced registration techniques [96]. In addition, ethical review and approval are necessary before conducting monitoring activities. More details are available in the book chapter by Chen et al. (2018) [97] and the paper by Sharpe (2019) [98].

5. Conclusions

This paper has presented a systematical review of previous studies that applied in-situ monitoring activities to studying occupant behavior in residential buildings. Since 2009, there has been an increasing number of in-situ monitoring activities in residential buildings. Various behaviors have been studied, including occupancy, lighting, shading, window operation, cooling, heating, cooking, showering, use of domestic hot water and use of other appliances. The monitoring activities have been performed in more than twenty-six countries, covering most climate zones. In addition, mixed-methods research, which combines both sensor-based monitoring and a story-telling survey, has been developed to address a better comprehension of occupant behavior.

However, previous studies show limitations in several respects. First, previous researchers paid little attention to the sampling criteria and the recruitment of participants. In most cases, “a convenience sample" was adopted. There is little control over the potential incentives behind energy-related behaviors, such as the floor number and the social demographics of participants. Second, although there have been some actual discussions about it, it remains largely unclear how to set the monitoring duration and the time interval. Third, the installation of data loggers depends largely on a researcher's personal experience. General instructions are not available and it is almost impossible to compare results from different monitoring activities. Fourth, very few monitoring activities reflect a consideration of the microclimate. Meteorological data used in previous studies were mainly downloaded from official observatories several kilometers away, only a small amount of downloaded data being calibrated using locally measured data.

Future research should carefully address the issues above, and suggestions are given as follows. First, take careful consideration of the building height when high-rise buildings are involved. Compared to low-rise and middle-rise buildings, the differences in microclimate are more obvious in high-rise buildings and can thus inject bias into the results. Second, it would be beneficial to explore occupant behavior in the hot humid zone. Occupants in the hot humid zone prefer a warmer environment and elevated air speed, and their behavior modes may also change with the seasons. In-situ monitoring of occupant behavior in the hot humid zone will facilitate research into behavior change, and will help researchers appreciate the contribution that environmental factors have on behavior change. Third, careful design of in-situ monitoring activities is necessary. It is recommended to follow certain established design procedures so as to appraise the key issues in an organized way. This paper has also proposed an empirical rule with regard to setting the duration and time interval of monitoring activities.

The findings of this review paper will contribute to a better understanding of the data collection methodology for research on occupant behavior in residential buildings, and will expedite the design and practice of in-situ monitoring of occupant behavior in future efforts.

Appendix I

Table A: Abbreviations of Journals

Abbreviation	Full name of the journal
JBE	Journal of Building Engineering
IDLC	Informes De La Construccion
ATE	Applied Thermal Engineering
SCS	Sustainable Cities and Society
EI	Environment International
JGB	Journal of Green Building
PIEEE	Proceedings of the IEEE
JAABE	Journal of Asian Architecture and Building Engineering
JAISE	Journal of Ambient Intelligence and Smart Environments
STBE	Science and Technology for the Built Environment
JCEM	Journal of Civil Engineering and Management
JBPS	Journal of Building Performance Simulation
JCCE	Journal of Computing in Civil Engineering
ESD	Energy for Sustainable Development
JAE	Journal of Architectural Engineering
BRI	Building Research and Information
IBI	Intelligent Buildings International

Appendix II

Table B: Summary of monitoring activities in previous studies

No	Ref.	Parameters	Sample size	Building info	Time interval	Duration of monitoring
	Template The studies are arranged in chronological order.	O: occupancy OB: occupant behavior (L: lux; W: window open or not; AC/H-thermostat/power; Cooking, Showering, DHW-temperature/flow/schedule, A-product/quantity/power) IEQ: T-Temperature, RH-relative humidity, CO_2, VOC, ... OEQ: T, RH, WS-wind speed, WD-wind direction, SR-solar radiation, … The monitoring can be from BAS, official meteorological station or measured by the researchers	Qty. of households involved in monitoring activity	SF: single-family building, the building is occupied by one family and stand along from other construction; e.g. detached, dwelling MF: multi-family building, the building are divided into different houses, accommodating different families; e.g. host more than 1 family in 1 building, e.g. apartment HR: high-rise building;	Temporal granularity of data collection, 1min, 5min, 10min, …, 30min, 1h, 2h, >2h	Duration of the monitoring activity, containing operation time only of data loggers: 1 week, 2 weeks, 20 days, 1 month, 1 year, ...; Seasons: Spr-spring, Sum-summer, Aut-autumn, Win-winter
1	Becker and Paciuk, 2009 [99]	IEQ: T, RH, global T, WS	Win: 189, Sum: 205	MF, in Israel	1min	30 min, Sum, Win, 2002
2	Ouyang et al., 2009 [100]	NA	71	MF, 3 buildings in China	1month	1 year, 2007-2008
3	Schweiker and Shukuya, 2009 [54]	IEQ: T, RH, W; OEQ: T, RH, SR, WS	39	MF, international student dormitory, Japan	2min	2 weeks Sum, 2007; 1month Win, 2008
4	Peschiera et al., 2010 [55]	Electricity use	83	MF, student dormitory, in USA	5min	3 days, 1 week, 2 weeks, 2009
5	Jian et al., 2011 [57]	IEQ: T, RH, CO2, CO; OEQ: CO2, T, RH, SR (official station)	5	MF, in China	10min	2 days/3 days, Spr, 2010
6	Yu et al., 2011 [101]	Electricity use, gas use	67	Either SF or MF in 6 districts of Japan	Electricity use: 1min; Gas use: 5min; IEQ: T: 15min	2 years, 2002-2004
7	Dall'O' et al., 2012 [89]	OB: H, DHW: heat meters, flow meters for DHW (BAS); IEQ: T, RH; OEQ (official station)	196, 3 with super-monitoring	MF, 2 buildings, in Italy	15min	2.5 months, Win, 2011
8	Dziugaite-Tumeniene et al., 2012 [35]	IEQ: T, RH, air pollution; AC: supply/ extracted air T; OEQ: T, RH, SR; Air change rate of house	1	SF, a low energy house in Lithuania	Sub-hourly, the simulation time step is 1h	7 months, Win, Spr, 2010-2011
9	Hiller, 2012 [60]	Electricity use; IEQ: T	57	SF, in Sweden	1h	4 days, Win, 2005. 2 weekdays + 1 weekend.
10	Kansara and Ridley, 2012 [53]	IEQ: T, RH; Energy use	Not clear, 100 residences, 250 T/RH sensors	Student residence, in United Arab Emirates	NA	2 years, 2010-2011

No	Ref.	Parameters	Sample size	Building info	Time interval	Duration of monitoring
11	Larsen et al., 2012 [102]	Electricity use, gas use; IEQ: T; OEQ: T; HVAC: use schedule	1	SF, a two-floor house in Argentina	IEQ: 15min EU: 2months	EU: 5 years, 2006-2010 H, V, AC: 2 weeks, Sum, 2010; 2 weeks Win, 2010 IEQ: 7 months, Sum, Aut, Win, 2010
12	Peng et al., 2012 [103]	IEQ: T, OB: power of AC, TV;	1	MF, China	NA	10 days, Sum, 2010; 1 month, Win, 2010
13	Vassileva et al., 2012 [65]	Electricity use	24	MF, Two buildings, in Sweden	1h	6 years: electricity use, 2004-2009
14	Fabi et al., 2013 [104]	IEQ: T, RH, CO_2; OEQ: T, RH, WS, SR (from official stations); W open or not	15	10 MF and 5 SF houses in Denmark	10min	8 months, Win, Spr, Sum, Aut, 2008
15	Jain et al., 2013 [56]	Electricity use	39	MF, a student residence, in USA	EU: 5min	1 month, Spr, 2012; EU: 10 months, 2011-2012
16	Kavousian and Rajagopal, 2014 [51]	Electricity use	1638	OD: selected households are from 26 countries, 6 climate zones	EU: 10min	238 days, 2010
17	Xu et al., 2013 [90]	IEQ: T; Electricity use; OEQ: TMY2 (from official station)	3	MF, in China	1h	4 months, Win, 2008
18	D'Oca et al., 2014 [105]	The same data source as paper No. 14				
19	Jain et al., 2014 [83]	Electricity use; OEQ: T, (official station)	21	MF, a building, in USA	OEQ: T: 1h; EU: 10min	4 months, Aut, Win, 2012
20	Kavousian et al., 2014 [106]	The same data source as paper No. 16				
21	Perez et al., 2014 [61]	Electricity use; AC-power	E-EU: 88; AC-power: 19	SF, in USA	1min	1 year, 2012-2013
22	Ren et al., 2014 [107]	IEQ: T, CO_2; AC-Power	34	MF, buildings from 3 climate zones, in China	IEQ: 10min; Power: 1min	2 months, Sum
23	Blazquez et al., 2015 [108]	IEQ: T, RH; OEQ: T, RH, WS, WD (official station); Air tightness; Thermal bridges: , thermography	2	MF, in Spain	30min	1 year: 2013-2014
24	Brown and Gorgolewski, 2015 [52]	AC, H load: flow rate and T-change; Acoustic: sound-level meter; IEQ: CO_2, T, RH, PM, VOC	725	High-rise residential towers in Toronto, Canada	AC, H thermal meter: 1month	Thermal meter: since tenancy in 2010 IEQ: spot measurements
25	Dong et al., 2015 [39]	O; IEQ: T; Electricity use	4	SF, in USA	O: 5min; EU: 1min	2months
26	Du et al., 2015 [48]	IEQ: T, RH, CO_2, VOCs, PM, NO_2, radon, microbial content in settled dust; Air tightness and leak (spot measurement); OEQ: PM	94+96	MF, 16 buildings in Finland and 20 buildings in Lithuania	CO_2, PM: 1min	CO_2, PM: 24 hours; NO_2, VOC: 7 days; Dust: 2 months; 2011-2013
27	Fabi et al., 2015 [36]	IEQ: T, RH, CO_2 (occupancy); OEQ: T, RH, WS, SR; W open or not	10	MF, in Denmark	10min; W: activity-based	3 months, Spr, 2010

No	Ref.	Parameters	Sample size	Building info	Time interval	Duration of monitoring
28	Guo et al., 2015 [109]	IEQ spot measurement: Thermograph, CO2; IEQ long term: T, RH, CO2, Power	Spot measurement: 371; Long term: 48	MF, HSCW climate zone, China	CO2: 10min; Power: 1min	Heating season from 2012-2014
29	Jian et al., 2015 [110]	E-EU, AC, L; A-power; IEQ: T, RH;	44	MF, a 17-storey building, China	TEU: 3-4days; Power: 10min; T, RH: 10min	T, RH, EU-TEU/AC/L: 1 year, 2008-2009; Power: 1 week;
30	Wang et al., 2015 [111]	IEQ: T; H-duration, energy; OEQ (official station)	27	MF, in China	NA	NA
31	Andersen et al., 2016 [77]	IEQ: T, RH, CO2; OEQ: T, RH, WS, SR, sunshine hours (from official stations)	5	MF, a building in Denmark	5min; OEQ: 2min	2 months, Spr, 2014
32	Barry et al., 2016 [66]	Electricity use, gas use (from community record)	92	Not clear, in USA	NA	36 months
33	Cali et al., 2016 [112]	IEQ: T, RH, CO2, VOC; L: Light on the ceiling, visible light ratio; W open or not; OEQ: T, RH, WS	60 households, 300 windows	MF, three refurbished buildings in German	1min	1 year, 2012
34	Dan et al., 2016 [62]	IEQ: T, RH, SR, CO2; OB: A, L, H, V, power	1	SF, in Romania	NA	2 years, 2013-2015
35	Guerra-Santin et al., 2016 [49]	O; IEQ: T, RH, CO2; OEQ: T, RH, SR, WS, WD; OB: use of radiator(C), use of thermostat (C), use of small power, L, H	5	2 MF in Spain; 3 SF houses in Netherlands	16s but use as 15min or 30min	1 year, 2014 in Spain; Win, 2014-2015 in Netherland
36	Hu et al., 2016 [113]	IEQ: T, RH, CO2, power, W open or not; H on-off	31	MF, 6 cities in China	NA	Win 2012-2013
37	Jeong et al., 2016 [58]	IEQ: T, RH, CO2, PM; OEQ: T, RH; W open or not; OEQ:SR, WS, PM, rainfall (official station)	20	MF, three complexes in Korean	10min; PM:1h	4 months, Spr 2015; 3 months, Win, 2014-2015
38	Lin et al., 2016 [114]	The same data source as paper No. 30				
39	Shi and Zhao, 2016 [74]	W open or not; OEQ: PM2.5, meteorological data (official station)	8	MF, 5 in Beijing, 3 in Nanjing, China	W: activity-based; OEQ: 1h	>20 days for each season, during 14 months of 2014-2015
40	Yan et al., 2016 [115]	IEQ: T, RH; OEQ: T, RH	176	MF, in 3 cities in China	OEQ: 30min IEQ: at least manually record at morning, noon, evening each day.	1 or 3 days
41	Zhang et al., 2016 [59]	E-EU-Wi-Fi-shown on website; Check frequency of the website	131	MF, in China	15min; Check frequency: 5min	1 month, Win, 2013
42	Berry et al., 2017 [63]	A-Electricity use of up to 11 separate electrical services; Water use, Gas use, GHG use; IEQ: T	10	SF, in south Australia	NA	1 year
43	Cuerda et al., 2017 [116]	Air tightness; A-electricity use: total and selected appliances	2	MF, a complex in Spain	NA	E-EU: 1 year, 2014-2015
44	Blázquez et al., 2016 [117]	IEQ: T, RH; OEQ: T, RH, WS; Airtightness; Thermography	2	MF, a block in Spain	30min	1 year: 20132014

No	Ref.	Parameters	Sample size	Building info	Time interval	Duration of monitoring
45	Escandon et al., 2017 [118]	Power and electricity use division; IEQ: T, RH, CO2; Airtightness; Thermography; OEQ: T, RH, SR, WS, WD, precipitation (official station)	3	MF, 3 cities in Spain	IEQ: 30min; Power: 15min; OEQ: 30min	1 year
46	Ferrantelli et al., 2017 [119]	DHW use	86	MF, a building in Finland	1h	10 months, Sum, Atu, Win, 2014-2015
47	Goldsworthy, 2017 [120]	Electricity use: total and up to 8 sub-circuits; IEQ: T; OEQ: Cooling degree days CDD, Heating degree days HDD (official station)	140	In Australia	30min	12 months
48	Gouveia et al., 2017 [67]	Electricity use; OEQ: average daily min/max T (official station)	19	Not clear. In Portugal	15min	1 year, 2014
49	Haldi et al., 2017 [121]	The same data source as paper No. 14, No. 33 as database of residential buildings				
50	Ioannou and Itard, 2017 [68]	O; IEQ: CO2, RH, T	32	SF, in Netherland	5min	6 months, Win, Spr, 2014-2015
51	Jones et al., 2017 [122]	IEQ: T, RH; OEQ: T, RH, WS, SR, rainfall; W open or not; O	10	Mixed type, in UK	10min	370 days, 2013-2014
52	Kim et al., 2017 [123]	IEQ: T; OEQ (official station)	42	Majority SF, Two cities in Australia	15min; OEQ: 1h	2 years, 2012-2014
53	Kindaichi et al., 2017 [124]	Power: total, up to 10 appliances; AC-power	87	SF, in Japan	30min	1 year, 2008-2009
54	Laurent et al., 2017 [42]	IEQ: black-bulb T, dry-bulb T, RH, CO2 (also indicate occupancy); OEQ (official station); Sleeping and L; Electricity use: total and A	91	MF, three natural ventilated Univ. residential halls, USA	5min; OEQ: 1h; EU: 1h	5* 10~15 days, 2012-2014; Sleeping and L: 2 weeks
55	Monacchi et al., 2017 [50]	Power	8	Mixed type in Italy and Austria	1s (1Hz)	1 year
56	Pan et al., 2017 [125]	Total EU,	138	MF, in China	15min	>2 years
57	Silva et al., 2017 [126]	IEQ: CO2, T, RH; Ventilation: Airflow; OEQ (website)	15	MF, 2 buildings with ventilation renovation in Luxembourg	15min; OEQ: 1day	1 month, Spr, 2015
58	Sobhy et al., 2017 [76]	IEQ: T, RH; OEQ: T, RH, SR, WS, WD;	1	SF, in Morocco	12min	10 days, Win, 2014; 2 months, Sum, 2013
59	Yao et al., 2017 [40]	W open or not; IEQ: T, RH, CO2; OEQ: T, RH, WS, WD, PM2.5 (official station)	19	MF, in China	5min; OEQ: 1h	1year
60	Abrol et al., 2018 [70]	O; AC-Thermostats; IEQ: T; Room/floor/building level management record; OEQ (official station)	310	MF, 2 buildings in USA	15min	3+3 months, 2 Sum, 2015 and 2016
61	Beckett et al., 2018 [79]	IEQ T, RH; OEQ: WS, WD, precipitation, T, RH;	2	SF, in Australia.	1h	9 months, Spr, Sum, Atu, 2014
62	Dabaieh and Johansson, 2018 [127]	IEQ: T, RH, CO2; OEQ: T, RH, CO2	1	SF, an off-grid low carbon building in Egypt.	1h	1 year: 2014-2015
63	Eon et al., 2018 [64]	IEQ: T; Electricity use, gas use, PV electricity	10	SF, in Australia	15min	1 year, 2015

No	Ref.		Parameters	Sample size	Building info	Time interval	Duration of monitoring
			generation; OEQ (official station)				
64	Ioannou et al., 2018	[128]	O; IEQ: T, RH, CO2; The data source is expanded from paper [49]	17	SF, in Netherland	5min	6 months, Win, Spr, 2015
65	Lai et al., 2018	[43]	W open or not; IEQ: CO2 (occupancy signal); OEQ (official station)	58	MF, 14 cities in China	OEQ: 2h; IEQ: CO2: 1min	1 year, 2016-2017
66	Lai et al., 2018	[129]	Mechanical ventilation operation status; W open or not; IEQ: T, RH, CO2, PM2.5, TVOC; OEQ: T, RH, WS, WD (website), PM.5 (official station)	46	MF, cross climate zones in China	1min; OEQ: 2h	1 year, 2016-2017
67	Nilsson et al., 2018	[130]	E-EU; DHW (records of HEMS: a smart home management system)	154	MF, in Sweden	NA	1 year, 2017
68	Pereira and Ramos, 2018	[45]	IEQ: T, RH, CO2; W open or not; OEQ (official station), but 2 exterior sensors of T/RH for redundant information.	1	MF, in Portugal	NA	1 year; Daily journal: 1 month in Sum and 0.5 month in Win
69	Rouleau et al., 2018	[41]	E-EU; DWH: water T, water flow; Super monitoring: IEQ: T, RH, mechanical ventilation on or off, W open or not; OEQ: T, RH, WS, WD, SR, precipitation	40 E-Eu, DWH; 8 super monitoring	MF, in Canada	10min	1 year, 2016
70	Sipowicz et al., 2018	[47]	IEQ: T, RH; OEQ: T, RH, SR	1	SF, in Argentina	1h	13 days, Win, 2010 23 days, Sum, 2011
71	Yao, 2018	[44]	AC-electricity use; IEQ: T (to indicate the AC on-off); OEQ: T, RH, SR	1	MF, in China	10min; OEQ: 1h	Total 52 days, Sum, 2016 and 2018
72	Belazi et al., 2019	[69]	IEQ: T, RH, CO2; OEQ: T, RH; M data: T, RH, SR, WS, CO2	11	MF, a building with total 18 apartments in France	1h	1 year, 2011-2012
73	Bruce-Konuah et al., 2019	[131]	The same data source as paper No. 51				
74	Pereira and Ramos, 2019	[75]	The same data source as paper No. 68				

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