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Post-occupancy evaluation in residential buildings: A systematic literature review of current practices in the EU

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ABSTRACT

Post Occupancy Evaluation (POE) is a process that aims to assess buildings' performance after occupation. Assessments are conducted to create a better understanding of the actual performance of buildings, including energy efficiency, indoor environmental quality (IEQ), and occupant satisfaction. Despite POE potential benefits and practices in residential buildings in the EU, it has been marked by a lack of consistency in the methods, data collected, research approach, and analysis used, making comparability of the results and replicability of methods difficult. This study, through a systematic literature review of POE practices in residential buildings in the EU between 2011 and 2021, aims to provide a better understanding of most common methods applied in the POE studies. A total of seven POE identifiers are investigated, including the research objective, the case study investigated, data collection method, data collected, monitoring details, and the research approach and data analysis. Findings indicated the lack of consistency in reporting, the use of methods, tools, and data collected in POE studies. This research uncovers valuable insights that result in a roadmap recommendation for the successful implementation of POE practices in residential buildings for a more consistent POE approach.

1. Introduction

Existing poor housing conditions and inefficient residential buildings pose a big challenge to the EU, and there is great potential for improvement [1]. Renovation of inefficient buildings intends to reduce energy consumption, increase occupant satisfaction, and improve the indoor environment. It is, however, not sufficient to claim that renovated buildings will perform better post retrofit, and to reveal the actual performance an assessment protocol is required [2,3].) EU Member States are required to adopt the European Directive 2018/844, which focuses attention on evaluating the performance of existing buildings while providing higher comfort levels and wellbeing for their occupants [4]. Data from residential buildings can be obtained through monitoring and are necessary to identify solutions to improve buildings' overall performance and achieve economic, energy, and environmental benefits [5]. There are multiple co-benefits from monitoring a building's performance; e.g., monitoring results can reveal issues which then can be fixed, leading to improved indoor environmental quality (IEQ), comfort levels, housing conditions and overall quality of life [6] and reduced disease spread, and protecting people from expected future heat waves [7,8].

Typically, a building's performance evaluation involves theoretical guidelines, standards, and/or energy simulations using assumptions about fabric, occupant behaviour, and a building's expected performance, rather than using its actual performance [9]. Despite the rapid growth of building simulation software and its capacity to predict different aspects of a buildings' performance and IEQ conditions [10], its accuracy concerning actual building performance remains unclear, due to the complexity of the built environment and all the interrelated factors involved [11].

A building's performance evaluation spans a wide range of disciplines (e.g., architecture, services engineering, and facilities management) and it is multidisciplinary to a great extent (e.g., psychology, economics, planning, sociology, engineering, etc.). In addition, it is primarily based on empirical fieldwork, which includes visiting and studying buildings in use and speaking to people [12]. This can be done

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by conducting a post-occupancy evaluation (POE) [13].

POE is defined as "a general approach of obtaining feedback about a building's performance in use, including energy performance, IEQ, occupants' satisfaction, productivity, etc." [14], and it is used to perform rigorous audits and evaluations of "buildings in use", employing continuous evaluations throughout the building's lifespan. The retrieved information gives important feedback about the design assumptions and management strategies, and it ultimately leads to better solutions [15].

POE data collection methods can be subjective or objective. Subjective data collection methods include walkthroughs, interviews, and occupant surveys [14]. A walkthrough is an effective method for detecting defects in building systems or obvious faults in an early stage, and it is usually performed along with a design checklist, observation forms, and visual records [13]. Interviews with occupants and experts are appropriate methods for understanding the attitudes of occupants towards the investigated building [16]. Occupant surveys are considered the most effective method of measuring occupant satisfaction, thermal comfort, and visual comfort [14]. In addition, by administering customised surveys, occupants can provide explanations for phenomena that sensors cannot interpret or record, and fill the gaps in understanding the monitored data [17], or integrate information that objective methods are unable to reveal. There are other approaches to subjective research, such as open-ended interviews, participant observations, and photographic analysis that can be used to uncover implicit aspects of human life and comfort [16].

Objective data collection methods, on the other hand, include IEQ, energy, and water assessment parameters etc. that are measured. Advanced tools and sensors can capture thermal conditions like temperature, relative humidity (RH), air velocity, etc. [13]. Luminance and illuminance meters, as well as high dynamic range imaging cameras, can be used to measure lighting conditions, and acoustic performance can be assessed with sound level meters. Furthermore, carbon dioxide, total volatile organic compounds (VOCs), formaldehyde, carbon monoxide, and respirable particles could also be measured as indicators of indoor air quality [18]. Additionally, energy and water assessments can be undertaken through audits, sensors, meters, or bills [12].

Previous literature reviews have investigated POE in the construction sector (e.g. Refs. [14,19–25] [26], however the majority has focused on a wide variety of building types (e.g., commercial, public, educational, governmental, mixed-use, etc.), as well as on a broad geographical range of locations. Considering the unique characteristics, uses, and designs of different buildings, as well as the variety of users with varying needs [27], POE in residential buildings faces different challenges than non-residential buildings, such as gaining access, lack of dedicated facilities managers and fewer building users [28], as well as cultural, institutional and policy differences between countries [29]. Due to these factors, there is a lack of clear and comparable data regarding POE practices in residential buildings in the EU, which makes it difficult to make informed decisions [30]. In addition, there is no comprehensive, structured, or repeatable approach for conducting POEs, and most of them are carried out to the best knowledge of the researchers, based on experience, limited by the existing constraints (i.e., research objectives, monitoring technology available, duration of the study, access etc.) [31,32].

With these premises, Hence, this research extends previous POE studies highlighted above, by focuses uniquely focusing on EU residential buildings, thereby adding to the current research on POE. which constitute the place where people spend 80% of their time and undertake their subjective daily practices, needs, preferences and conveniences [33]. The main goal is to provide a comprehensive understanding of the most frequently used methods, limitations and barriers in residential POE studies in the EU. The objective is to develop a roadmap recommendation for effectively implementing POE practices in residential buildings, supporting a more consistent and standardized approach and implementation to residential POE. This paper focuses on the following research questions: what are the current practices of POE monitoring campaigns in residential buildings in the EU and what can we learn from this? The paper is structured as follows: Following the introduction (Section 1), section 2 outlines the research methods, including the systematic literature review method, eligibility criteria, information sources, search strategy, and the selection and data collection process. Section 3 presents a synthesis analysis, followed by a discussion of results in section 4, with final considerations and roadmap recommendations in Section 5. In Fig. 1, the research outline flowchart is presented.

2. Methods

For reporting the results of this review, the PRISMA 2020 statement was selected. PRISMA stands for "preferred reporting items for systematic review and meta-analysis". As part of the PRISMA statement, there is a checklist consisting of 27 items and a flowchart depicting four phases [34].

2.1. Data collection process and eligibility criteria

Research conducted in this study focused on mapping existing literature on the practice of ''post-occupancy evaluation'' for residential buildings in the EU in the last decade (2011–2021) (last updated in July 2022). This period was chosen because, within the last decade, monitoring instruments have become more affordable and accessible, which has had an impact on POE data collection [35,36]. This systematic review was conducted using five databases: Web of Science, Springer Link, Science Direct, ProQuest, Scopus, as well as google scholar search engine. The study was conducted using the following search terms: "Post-occupancy Evaluation", and/or its acronym "POE".

The initial search results were filtered and limited to engineering and architecture-related subject areas. Following that, the search was limited to original research papers, review papers, and conference proceedings that were conducted within the EU, and written in English - the shared language between the research team. Studies of non-residential buildings, literature reviews, studies not conducted within the EU, and papers not written in English, were excluded. Following this data collection, a duplicate check was conducted, and the eligible papers were further examined and tabulated in Microsoft Excel. By analysing titles and keywords, a total of 118 papers were then analysed in more detail following the PRISMA checklist. Papers that met the following criteria were kept for further investigation: (1) conducted in residential buildings (2) investigated one or more of the following parameters: energy consumption for heating and/or cooling, domestic hot water (DHW) consumption, occupant satisfaction, thermal comfort, indoor air quality, and indoor environmental quality. Papers that were based on laboratory or mock-up experiments were excluded. Until this stage, some papers' title nor keywords did not indicate the type of building, the scope of the research, nor the location, in such cases, these papers were included for further investigation in the next step.

As a result of applying all the criteria above for inclusion, 84 papers were selected for deeper analysis. The 84 papers were exported to an Excel spreadsheet, which included the title, abstract, methods, description of the case study, monitoring information, survey information and results. Each research paper was subsequently reviewed and evaluated carefully. An in-depth investigation of the selected papers resulted in the exclusion of 52 papers: a total of 21 papers were not relevant to the scope of the study (i.e., they did not undertake a POE study neither indoor monitoring), five papers investigated non-residential buildings; two papers were based on meta-studies; two papers were not conducted in the EU; one paper was based on a chamber study; 10 papers were based on simulation; three papers did not have relevant data for consideration such as no information about the POE process conducted for the research; seven papers were drawn from literature studies and archival data, and one paper was an extended version of other studies already included in other papers. Fig. 2

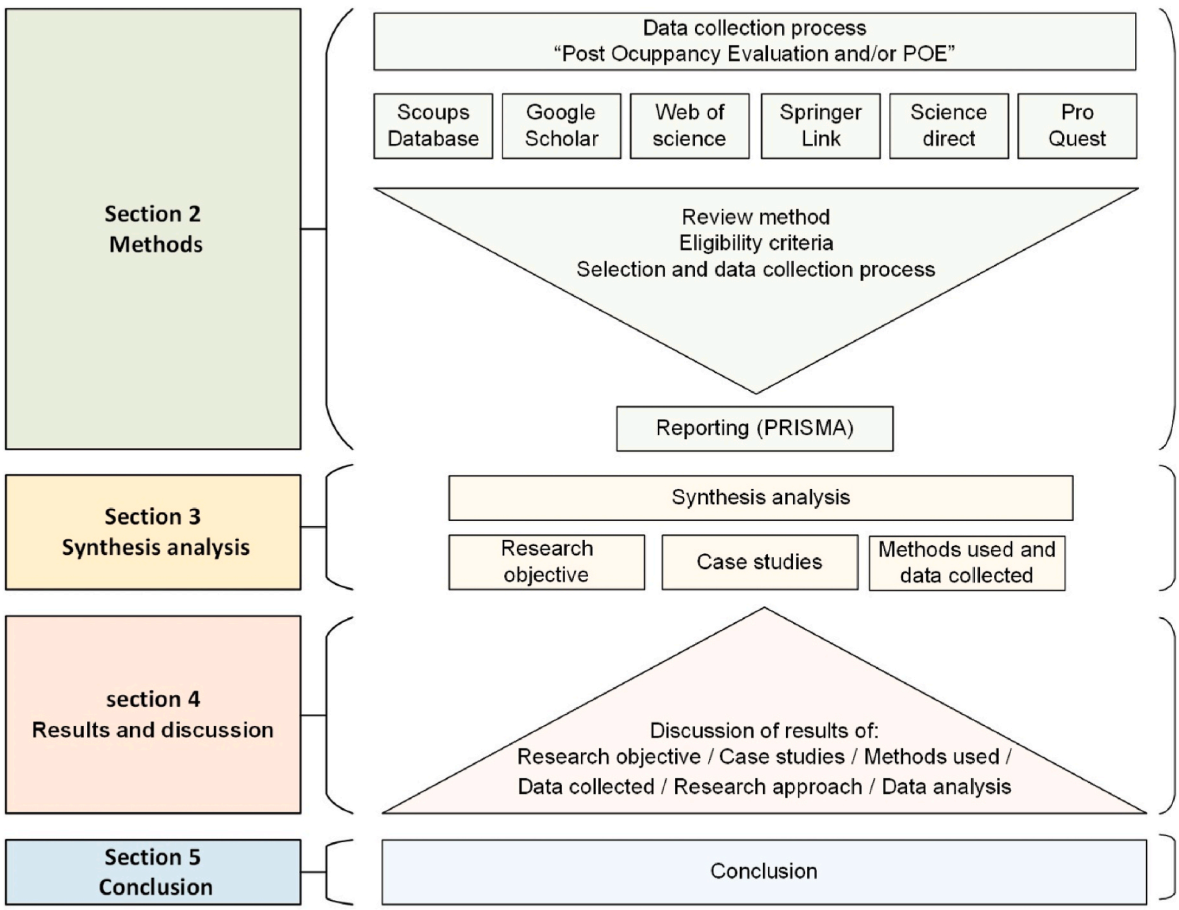

Fig. 1. Research outline flow chart.

illustrates the search process and results reported by the PRISMA flow chart.

In total, 32 papers were identified where POEs were conducted in residential buildings in the EU whose data could be used for this research and meet all the inclusion criteria mentioned above. Table 1 provides a list of papers included in the systematic literature review sorted by year, with the associated ID number, and country where the research was conducted.

3. Synthesis analysis

As part of this review, the primary identifiers in the reviewed papers were classified into three categories, namely: research objective, case studies, methods and data collected. Research objective in the reviewed papers was further divided into four subcategories: 1) investigating; 2) identifying; 3) comparing; and 4) contributing. These subcategories were based on the main research objective keywords extracted from each paper (see Appendix I - online supplemental material). The case studies were divided into three categories: typology, heating & cooling energy source/distribution systems, and materials. Methods and data collected were divided into subjective and objective data collection categories (see-Fig. 3).

For this research, the definition and scope of each main category were defined and analysed as follows.

4. Research objective

The first identifier is research objective. Reviewed papers tend to have different main objectives for conducting the POE research: investigating, identifying, comparing, and contributing with more focus on building performance such as 9, 16, 17, 21, 22, 24, and 29, energy efficiency (e.g., 8, and 11), electricity, and water consumption (16) occupant satisfaction, perception, behaviour, and comfort (3, 25), and IAQ (e.g., 1, 20, 26). Each of these objectives focus on studying: 1) buildings, which includes environmental parameters, energy consumption, and building fabric; 2) occupants, which includes occupant satisfaction, perception, comfort, behaviour, and health and wellbeing; and 3) the relationship between occupants and buildings. Table 2 presents the four different categories of the main objectives derived from the research statement, along with the aspects investigated.

4.1. Case studies

In this review, the case studies as described in each paper were divided into seven categories: nearly zero energy, certified PH, apartment, low carbon energy house, terraced semidetached, and detached. There was a wide variation between the residential case studies that were the subject of the reviewed papers concerning their heating and cooling systems, other systems such as solar panels, and the materials used in their construction. A broad range of heating & cooling energy source/distribution systems were investigated in the reviewed papers and were divided into nine categories: district heating (DH), cooling devices, ground heating, solar thermal panels, individual boiler, heat pump, mechanical ventilation (MV), natural ventilation, radiators, and photovoltaic (PV) cells. Building materials were divided into five categories: concrete, timber, steel, brick, and masonry.

Apartments were the most frequently examined case study type in 15 papers, followed semi-detached houses in 7 papers, detached houses in 6 papers, and nearly zero energy houses in five papers (see papers in columns C, D, F, G, and A respectively – Fig. 4). Mechanical ventilation

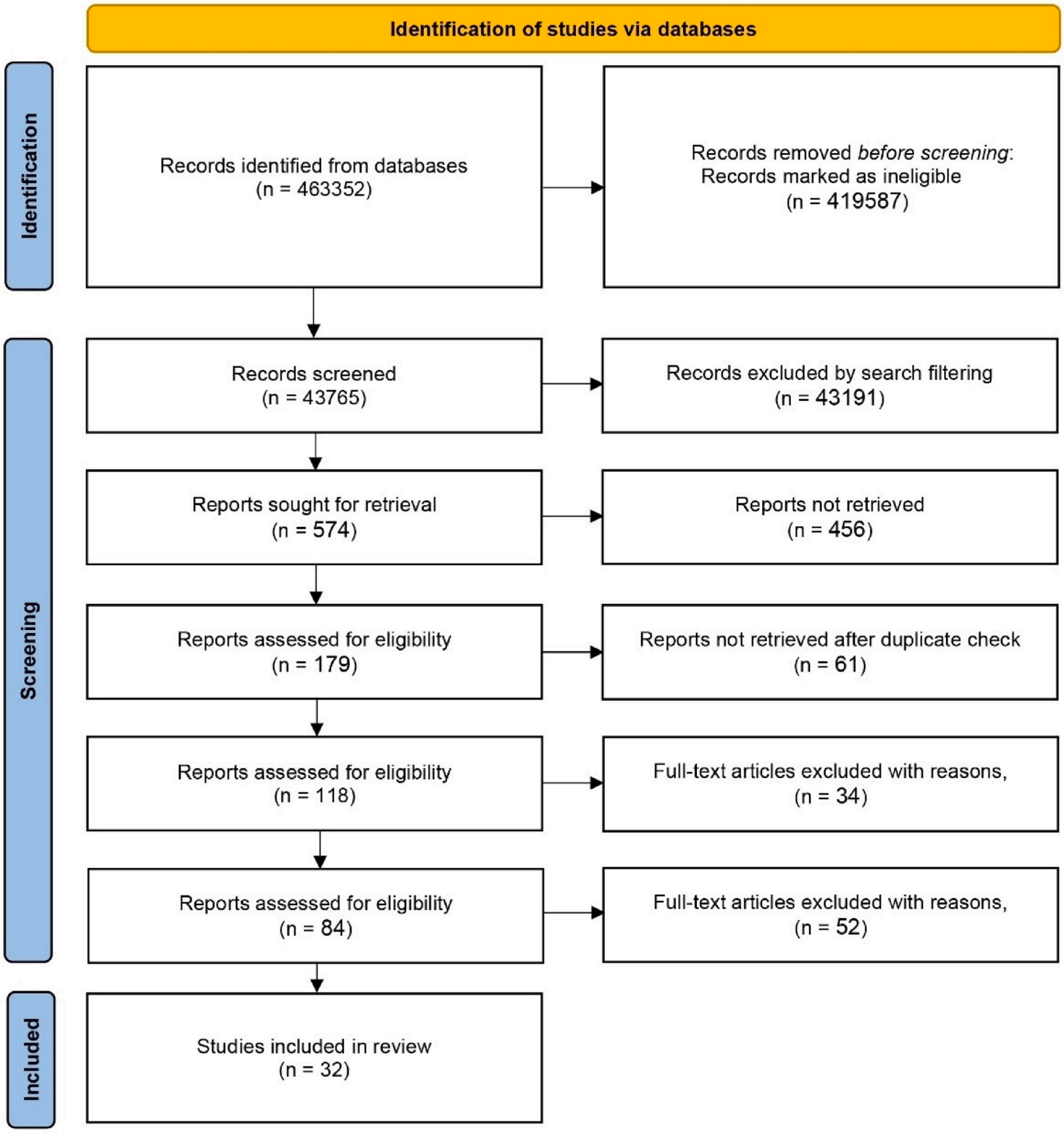

Fig. 2. PRISMA flow diagram.

Table 1
Paper included in the review with their respective ID.

ID	Source	Country	Obtained from	ID	Source	Country	Obtained from
1	[37]	NL	Web of science	**17**	[38]	UK	Scopus
2	[39]	UK	Web of science	**18**	[40]	Sweden	Google scholar
3	[41]	UK	Science direct	**19**	[42]	UK	SpringerLink
4	Erwin [43]	Belgium	ProQuest	**20**	[44]	Luxembourg	Scopus
5	[45]	Sweden	Scopus	**21**	[46]	UK	Science direct
6	[47]	UK	Web of science	**22**	[48]	Ireland	Scopus
7	[49]	UK	Scopus	**23**	[50]	Estonia	ProQuest
8	[51]	UK	Scopus	**24**	[52]	NL&Sweden&France	Web of science
9	[53]	UK	Science direct	**25**	[54]	UK	Web of science
10	[55]	UK	Science direct	**26**	[56]	Spain	Scopus
11	[57]	Latvia	Science direct	**27**	[58]	Italy	Science direct
12	[59]	UK	Google scholar	**28**	[60]	UK	Scopus
13	[61]	Spain/NL	Scopus	**29**	[62]	Portugal	Science direct
14	[7]	Norway	Web of science	**30**	[63]	Spain	Scopus
15	[64]	UK	Scopus	**31**	[65]	Belgium	Scopus
16	[66]	UK	Scopus	**32**	[67]	Italy	Science direct

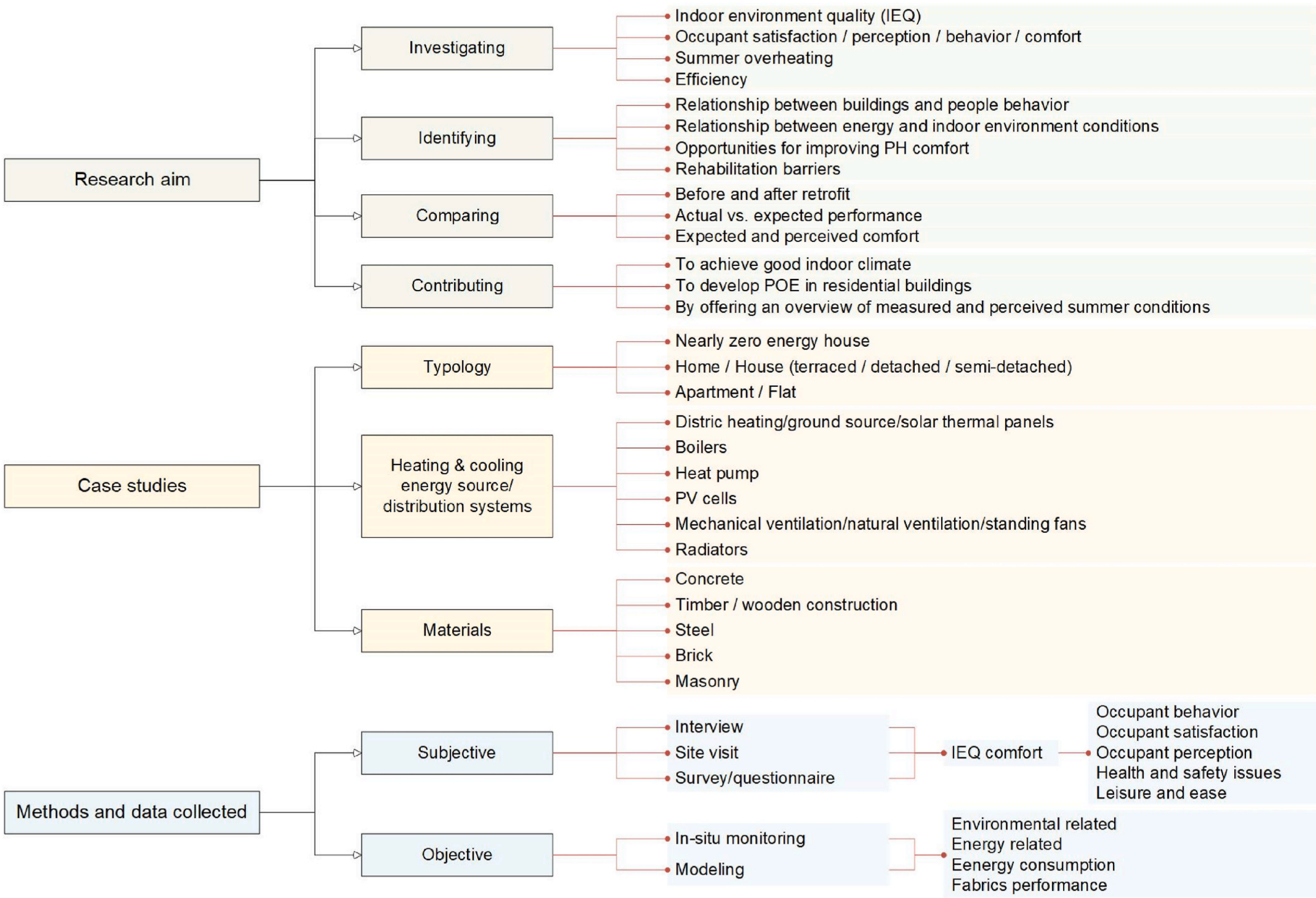

Fig. 3. A mapping of the papers' main categories and subcategories.

Table 2
Main categories of the research objective of the reviewed papers.

Main category	Aspects investigated	Article ID
Investigate	Building performance	17, 21, and 22
	User (satisfaction-comfort)	1, and 26
	User (perception & satisfaction & behaviour)	3, and 25
	IAQ and overheating risk	12, 15, and 20
	Energy retrofitting effectiveness	6, 8, and 18
	Mechanical ventilation system efficiency	11
Identify	Relationship between energy and IEQ	5, and 13
	Relationship between building and occupant's behaviour	7
	Relationship between occupants and aspects of IEQ	2, and 32
	Performance gap reasons	27, and 32
	Opportunities for improving Passive house comfort	4
	Opportunities to engaging in-home use learning	19
	Rehabilitation barriers	30
Compare	Before and after retrofit	23
	Actual vs. expected performance	9, 16, 24, and 29
	Expected and perceived comfort	10
Contribute	Having a good indoor climate	14
	Development POE in residential buildings	20
	Achieving energy savings	28
	In understanding summer thermal conditions	31

was the most common ventilation system investigated in 23 papers, radiators were the most common indoor heating distribution system in 12 papers, cooling systems, and cooling energy consumption was investigated in four papers (see papers in columns N, P, and I respectively – Fig. 4).

Although not all papers presented full details of the case study, construction materials were only mentioned in 19 papers out of 32. Among this group of papers, timber was the most common construction material in 11 papers, followed by concrete in 10 papers, brick in five papers, masonry in three papers, and steel in one paper (see columns T, S, V, W, and U respectively – Fig. 4). Fig. 4 provides a summary of the building typology investigated in each paper, the installed systems, and building materials.

4.2. Methods and data collected

Both subjective and objective data collection methods were employed in the reviewed papers. This classification was developed according to most common methods used for building performance evaluation studies around the world [13]. The use of mixed methods was utilised in papers examining energy, IAQ, occupant behaviour, thermal comfort, energy consumption, and/or rehabilitation barriers such as social barriers, and the use of building systems. The data collected primarily concerned IEQ, energy, and fabric related. Both subjective and objective methods and data collected are explained in the following section. Fig. 5 provides a summary of the methods applied and data collected in each reviewed paper.

		Building type							Heating & cooling energy source and distribution systems											Materials				
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
ID	Source	Nearly Zero energy house	Certified PH	Apartment	Low carbon energy house	Terraced house	Semidetached house	Detached house	District heating	Cooling devices	Ground heating	Solar thermal panels	Gas / electric / oil boiler	Heat pumps	Mechanical ventilation	Natural ventilation	Radiators	Underfloor heating distribution	PV	Concrete	Timber/wooden	Steel	Brick	Masonry
1	Mlecnik et al., (2012)	A						G							N				R					
2	Altan et al., (2013)	A														O								
3	Nooraei et al., (2013)			C									L		N	O					T			
4	Erwin Mlecnik (2013)		B							I		K			N				R					
5	Rohdin et al., (2014b)		B														P			S				
6	Gupta et al., (2014)				D							K	L		N				R					
7	Chiu et al., (2014b)					E	F								N	O	P							
8	Behar (2014)			C						I					N			Q		S				
9	Littlewood et al., (2014)					E	F							M		O			R		T		V	
10	Zhao & Carter (2015)						F	G											R					
11	Kamendere et al., (2015)					E									N	O	P							
12	Gupta & Kapsali (2016)					E		G				K			N			Q	R		T	U	V	
13	Guerra-Santin et al., (2016)			C			F									O	P							
14	Berge & Mathisen (2016)			C								K			N		P			S				
15	Adekunle & Nikolopoulou (2016)			C																	T			W
16	Sodagar & Starkey (2016)						F								N				R	S	T		V	
17	Pretlove & Kade (2016)						F					K			N	O	P		R		T			W
18	Hilliaho et al. (2016)							G							N		P						V	
19	Baborska-Narozny et al., (2017)			C		E						K	L		N		P			S	T			
20	Silva et al., (2017)			C											N								V	
21	Jones et al., (2017)			C	D										N				R					
22	Colclough et al., (2018)						F	G				K	L	M	N	O	P		R	S	T			
23	Hamburg & Kalamees (2018)			C									L		N	O	P							
24	van der Grijp et al., (2019b)	A		C					H	I	J	K			N				R					
25	Adekunle & Nikolopoulou (2020)			C											N	O				S	T			
26	Vidal et al., (2020)			C												O				S				
27	Aste et al., (2020)			C						I	J			M	N						T			
28	Bourikas et al., (2020)															O	P							
29	P. F. Pereira et al., (2020)			C											N					S				
30	Arriazu-Ramos et al., (2021)			C									L			O	P			S				
31	Dartevelle et al., (2021)	A						G							N						T			W
32	Mavrigiannaki et al., (2021)	A									J			M	N				R					

Fig. 4. Building typology investigated.

		Subjective methods&data collected											Objective methods & data collected																
		Methods					Data collected						Methods			Data collected													
		Subjective					IEQ related						Objective			Environmental					Energy related							Fabric	
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	1	2
ID	Source	Semi-structured interview	Structured interview / focus group	Site visits	Walk through procedure	Survey / Questionnaire	Comfort (thermal/acoustics/visual)	Occupant behaviour	Occupant satisfaction	Occupant perception	Overheating	Health and safty / Leisure	In-situ monitoring	Modelling / Simulation	Consumption bills	Air temperature	Relative humidity	CO2 levels	Daylight	Acoustics level	Occupancy presence	Window opening	Electricity consumption	Gas consumption	Heating energy	DHW	Operational/Energy use	Thermographic images	Building fabric performance
1	Mlecnik et al., (2012)					E			H																				
2	Altan et al., (2013)												L			O	P	Q					V	W					
3	Nooraei et al., (2013)		B			E	F	G	H	I		K	L			O	P	Q	R	S									2
4	Erwin Mlecnik (2013)		B	C	D	E	F						L			O	P	Q											
5	Rohdin et al., (2014b)		B			E	F			I			L	M		O				S							Z		
6	Gupta et al., (2014)					E		G					L		N	O	P	Q					V	W					2
7	Chiu et al., (2014b)	A			D				H				L			O							V	W					
8	Behar (2014)					E	F	G	H														V		X				
9	Littlewood et al., (2014)			C									L			O	P	Q				U	V		X	Y	Z		
10	Zhao & Carter (2015)	A				E	F	G		I		K																	
11	Kamendere et al., (2015)												L			O	P	Q											
12	Gupta & Kapsali (2016)	A			D	E	F		H		J		L		N	O	P	Q										1	2
13	Guerra-Santin et al., (2016)		B			E	F	G					L			O	P	Q	R	S	T		V	W					
14	Berge & Mathisen (2016)					E	F	G	H				L			O	P	Q				U							
15	Adekunle & Nikolopoulou (2016)					E	F	G	H		J		L	M		O	P												
16	Sodagar & Starkey (2016)		B		D	E		G					L			O	P	Q					V	W		Y		1	2
17	Pretlove & Kade (2016)		B			E	F						L			O	P						V	W		Y			
18	Hilliaho et al., (2016)												L	M		O	P								X				2
19	Baborska-Narozny et al., (2017)	A		C	D	E		G				K				O	P	Q								Y	Z		2
20	Silva et al., (2017)					E	F			I			L			O	P	Q		S									2
21	Jones et al., (2017)							G					L			O							V	W					
22	Colclough et al., (2018)					E	F		H				L			O	P	Q		S			V		X	Y			2
23	Hamburg & Kalamees (2018)					E		G		I			L		N	O	P						V		X	Y			2
24	van der Grijp et al., (2019b)					E			H						N	O											Z		
25	Adekunle & Nikolopoulou (2020)			C		E	F			I																			
26	Vidal et al., (2020)					E	F				J		L			O	P	Q											
27	Aste et al., (2020)					E							L	M									V		X	Y	Z		
28	Bourikas et al., (2020)		B		D	E							L			O											Z	1	
29	P. F. Pereira et al., (2020)					E										O	P	Q				U							2
30	Arriazu-Ramos et al., (2021)												L		N	O	P							W	X				
31	Dartevelle et al., (2021)	A				E	F				J		L			O													
32	Mavrigiannaki et al., (2021)					E			H				L	M		O	P	Q			T	U	V		X	Y	Z		2

Fig. 5. Methods, and data collected within the reviewed papers sorted by publication year.

4.2.1. Subjective methods and data collected

The subjective data collection methods refer to the methods that use subjective data to explain a phenomenon, e.g., interviews, site visits, walkthroughs, and questionnaires/surveys. In the reviewed papers, subjective data were collected on IEQ, i.e., thermal, acoustic, and visual comfort, occupant behaviour, satisfaction, perception, overheating, health and safety issues, and leisure and ease (i.e., how many occupants feel relaxed or how easily they handle everyday domestic matters).

Interviews were conducted in 12 out of the 32 papers. Within these 12 papers, it was coupled with a walk-through procedure in six papers (4, 7, 12, 16, 19, and 28). In the other 3 papers (5, 13, and 17) the interview was coupled with a survey, and with a questionnaire in papers 3, and 10. Site visits and/or walk-throughs were conducted in a total of eight papers (4, 7, 9, 12, 16, 19, 25, and 28).

The survey and/or questionnaire was a common method used to get feedback from occupants regarding their thermal comfort, perception, satisfaction, behaviour, and to evaluate indoor air quality or building and systems performance [68,69]. The survey/questionnaire was used in 25 papers; in most of the papers, survey questions were designed according to the case study to investigate more specific issues such as satisfaction with the newly installed technology such as in paper 28, reasons for choosing a home in paper 24, interaction with windows and home management and maintenance in paper 3, with a focus on specific features such as satisfaction with the installed heating system in papers 13 and 17, and design aspects, materials, building services, layout, furnishing, leisure and ease, etc.

The survey was collected either from all adults living in the dwelling or from a single respondent from each household to maintain consistency in responses such as in paper 6. For all papers that used bespoke questionnaires, three papers (17, 21, and 20) included the survey questions as an appendix, which may help in the development of other POE surveys. Appendix II (online supplemental material) summarizes the subjective methods used in each case study, as well as the main issues examined.

4.2.2. Objective methods and data collected

Objective methods in this paper are those that utilise data collected by monitoring or recording building performance or by monitoring people's behaviour with sensors. Such data is collected in quantities that could be compared with building standards, guidelines, energy performance certificates, etc. Objective data collected were categorized into three categories: 1) environmental parameters, 2) parameters related to and influencing energy consumption, and 3) building fabric performance parameters describing how the building fabric performs compared to building code requirements and standards (e.g., U-values and airflow rates for mechanically ventilated buildings)- (see Fig. 5).

Among the most widely used methods of obtaining environmental, energy-related, or building fabric efficiency parameters are in-situ monitoring and energy bills. Among the 32 reviewed papers, 24 used in-situ monitoring. While research based on modelling only was omitted from this review, five papers utilised performance modelling/simulation in addition to in situ monitoring due to a lack of data and calibration purposes (paper 5), to investigate the aspects of thermal comfort and local discomfort (paper 5), overheating risks in prefabricated timber buildings (paper 15), validation of IDA-ICE modelling behaviour in a qualitatively realistic way (paper 18), use of building simulation software in the early decision-making and project phases (paper 27), and finally comparing the expected performance with real monitoring (paper 32).

For environmental parameters, most of the papers used stand-alone sensors, while in some cases wireless technology and remote sensing were employed. (e.g., 12, 16, 31 and 32). Moreover, when sensors were used by the research team, few standard protocols were followed, and based on the best knowledge of the researchers. Sensor placement was not explained in all cases (6, 7, 21, 22, and 32), however, when reported, it was noted that sensors were placed away from openable windows (2, 13, and 31), typically in bedrooms, living rooms, and kitchens, at heights ranging from 1.1 m to 1.7 m, which is in accordance with ISO 7726 [70]. Sensors were placed on the inner walls (e.g., 14, 15, and 23), or in the middle of the room (13). Only one paper (16) emphasized the use of thermography according to the requirements of BS EN 13187:1998 standard and use of thermal as recommended by ISO 6781:1983. All the available information about the tools used for the in-situ monitoring, their classifications, and their characteristics are presented in Appendix III - online supplemental material.

According to some papers (e.g., 15), access to dwellings was easy and sensors could be placed easily. In other papers, however, researchers faced difficulties in obtaining data due to privacy concerns, and non-accessibility to dwellings (e.g., 16). There were some cases in which the metering system was not available for a particular case study, and therefore an average consumption was calculated, such as in papers 8, 20, and 23. The monitoring process, including placement of sensors and sensors' technical details were missing in many papers such as in 5, 6, 7, 11, 21, and 22. Calibration of sensors was not mentioned, or known to be undertaken except for paper 14 which uses a self-calibrated CO_2 sensor, whereas paper 31 conducted preliminary calibration tests before the measurement campaign and verified compliance with the manufacturer's maximum error limits.

As for energy and building fabric-related performance parameters, it was possible to obtain energy consumption from energy bills such as in papers 6, 12, and 30; in other situations, pulse sensors were used such as in 21; in other papers, energy meters were used for obtaining energy consumption (e.g., 2, 8, 13, 16, 17, and 22). Window opening and occupancy presence were obtained by using sensors such as in 32 and 21 or self-reported such as in paper 12. U-values, air flow, thermal bridges, and barometric pressure were evaluated with in-situ data collection measurements (e.g., 9, 12, 16, 20 and 22). For the papers that use simulations, an IDA Indoor Climate and Energy (ICE) building energy simulation model was used in papers 5, and 18, DesignBuilder software in paper 15, and EnergyPlus software in papers 27 and 32. Appendix IV (online supplemental material) summarizes all papers that were able to gather energy and fabric performance-related parameters, with an explanation of how it was measured and collected.

5. Results and discussion

POE is a recognised method for gathering feedback about a building's overall performance once occupied. The review and classification of the reviewed papers allows us to summarise the main identifiers of the investigated POE studies as follows: the research objective, case study, data collection methods, data collected, monitoring, research approach, and data analysis (Fig. 6).

5.1. Research objective evaluation

The objective of research in the studied papers is the guiding principle for determining the methods, data collection, research methodology, and data analysis used in POE studies. By focusing on the data collection methods, most papers used a combination of subjective and objective methods, and there was no consistency in their data collection and analysis. For example, using only objective methods to evaluate thermal comfort, such as monitoring indoor environmental conditions, without assessing occupants' satisfaction levels, is inadequate for determining user satisfaction and comfort. On the other hand, investigating indoor environment conditions without considering energy consumption would fail to identify the relationship between energy use and indoor environmental quality. Researchers tend to rely on objective methods when comparing actual and expected performance, as numerical values can be easily compared. However, this approach is typically used in laboratory settings and simulation software, and may not be suitable for residential buildings, where there is constant interaction between users and the building and its systems. Therefore, using a mixed

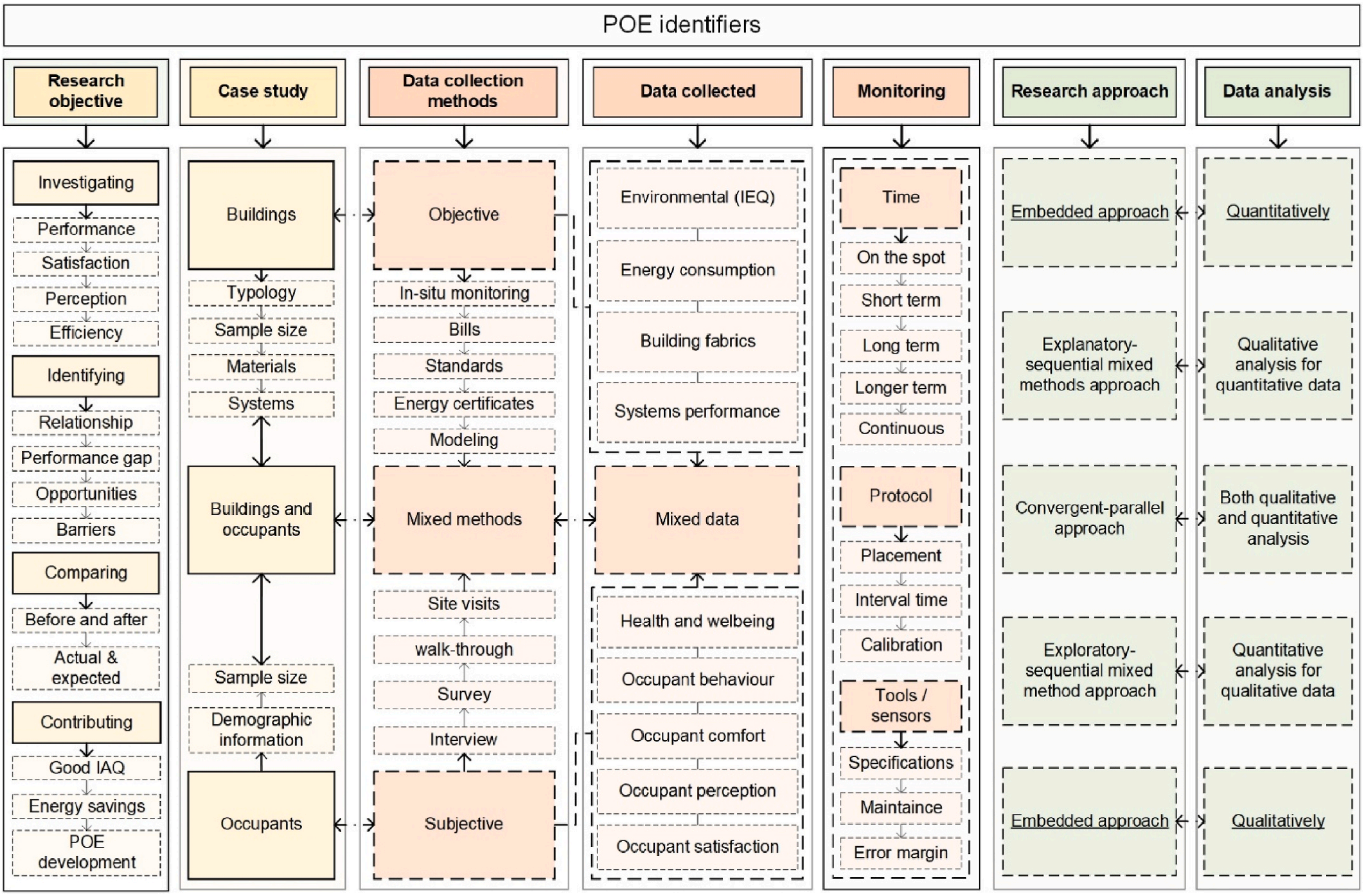

Fig. 6. Post-occupancy evaluation identifiers.

methods of methods for the four categories presented would be more informative and reliable than using only one method.

5.2. Evaluation according to case study

The reviewed papers indicate that generally, researchers tend to focus on specific building typologies, installed systems, or construction materials when focusing on a case study. This approach has the drawback of not being able to generalize results to a larger population. For example, studying a successful passive house in a specific country during a specific season, such as winter, does not mean the same results would be achieved with different populations, in different locations, or during different seasons, such as summer. Similarly, studying a specific system, such as a heating system, in isolation from other systems, such as a cooling system, may not consider unintended consequences that could result from the same set-up, such as more insulation or a higher temperature set-point. It is possible however, to focus on specific building elements if the study's main focus is on the characteristics of that element, such as the actual U-value of an entire wall. However, this type of study would be limited in its ability to generalize results to other building elements or overall building performance.

Providing a detailed description of the case study being investigated and highlighting all its limitations is crucial for conducting a best practice POE study. This includes information such as the location, building type, population, and any other relevant factors that may impact the results. By including this information, researchers can ensure that their findings can be accurately replicated and applied to other similar cases in the future. In the reviewed papers, however, the descriptions of the case study were inadequate, e.g., lack of descriptive information about the case study building, number of people, and building materials were lacking (e.g., 1, 2, and 11), while in other papers there was detailed information regarding construction materials, building description, number of occupants, heating and cooling systems used, etc. (e.g., 3, 6, 7, 9, 10, and 18). Despite the aforementioned descriptive classifications for the investigated papers, there was a lack of consistency between descriptive terms used with same research objectives. For example, the terms 'house', 'home', and 'dwelling', were used interchangeably without noting the research tradition differences. However, the term "house/dwelling" refers to physical and quantitative features, while "home" includes interpretations of social and cultural expectations and norms, as well as emotions and relationships within the household [71].

5.3. Evaluation according to the data collection methods

Both subjective and objective data collection methods were applied in the reviewed papers. Some papers, use only objective methods such as paper 11 to investigate the mechanical ventilation system efficiency, paper 18 to investigate the efficiency of the energy retrofit interventions, paper 2, to evaluate the indoor environment and energy consumption compared to standard criteria, and in paper 32 the focus is on monitoring energy and environmental parameters to identify the performance gap reasons. In the papers mentioned above, the use of only objective methods approach was utilised when investigating technical issues related to buildings, their performance, and related issues.

On the other hand, papers use only subjective methods when focusing mainly on the human aspect. For example, investigating occupants' perceived comfort expectations, perception, and behaviour such as in paper 25, and investigating perception, satisfaction, behaviour, and comfort in paper 10. Following the EU directive [72], which aim for sustainable communities and the assurance of good health and wellbeing, POE studies ought to focus on occupants, their health, well-being and satisfaction, and not just on buildings and energy performance issues. However, the majority of studies utilise more objective methods than subjective methods, not providing sufficient information about the impact of occupant behaviour or interaction with buildings that affects overall energy consumption, comfort, and wellbeing [73]. To fully understand whether buildings are performing as intended, and whether occupants are satisfied with their performance, it is important to use a combination of both subjective and objective methods. This approach allows to have a comprehensive view of the effects that buildings have on the built environment, while also considering the perceptions and feedback of building users.

5.3.1. Evaluation according to subjective methods data collected

The use of occupant interviews and surveys was a common method for capturing occupants' comfort, satisfaction, and perception with the IEQ, as was also reported by Ref. [74]. The concept of comfort is highly related to cultural and societal aspects, shaped and constantly evolving through time and history [75]. However, social practice theorists perceive comfort in the home as the result of household practices ('doing' and 'saying'), such as cooking, washing, and cleaning, which vary in culture, place, and time [76], while in literature four main IEQ comfort areas are evaluated, i.e., thermal comfort, visual comfort, acoustics, and indoor air quality [77].

Although questionnaires and interviews were commonly used in 27 papers out of 32, occasionally researchers mention only the results of a survey or questionnaire but do not explain how it was introduced to occupants, evaluated, or analysed such as in paper 13. Furthermore, it is important to provide the residents with a brief explanation about the aim of the survey/questionnaire as well as how to fill it in, and explain how this is achieved, as people might have different perceptions of the questions asked, especially if they do not have a chance to ask researchers [78,79], which is common with the online survey in which participants may have to respond to all questions even if there is a non-relevant answer [80].

Occupant's perception, satisfaction, and comfort feedback was obtained by responding to rating scales (e.g., a 5-points; a 7-points, and a 10-points scale). In previous research, it was identified that the various grading points could lead to biased results [81,82] due to people subjective inner capacity to process the information on simultaneous different elements, with reliable and robust accuracy and validity [83]. The evaluation of human comfort and satisfaction (subjective data) in the reviewed papers were mostly based on perception and satisfaction scales taken at a particular point in time, instead of comprehensive synthesis of perceptions and judgments over a period of time. For example, a new situation, or a situation that is of particular concern to users, may prompt short-term judgments that do not reflect the long-term operation of the building [15,84], which in this context, makes it difficult to define the best practices for IEQ comfort, perception, and occupants' satisfaction. On the other hand, it is easier to define energy efficiency in a building based on technical, operational, and financial factors [85].

5.3.2. Evaluation according to objective methods data collected

In terms of data collected from objective methods, necessary heterogeneity exists regarding the sensors used, their placement and monitoring duration but is often insufficiently declared for comparison purposes. The most widely used objective method for measuring environmental, energy and fabric performance parameters was the use of in-situ monitoring data collection. In theory, such practice should be achieved in an organised and high-quality manner [86], however, in the majority of the reviewed papers, this was not possible due to the case study constraints; a common issue in residential buildings [87].

For the environmental parameters, across all reviewed papers, air temperature measurements were taken in different ways, e.g., on the spot (i.e., one measurement and not logging over time); over a period of one to two weeks; from a month and up to one year, and one year or more. In one paper (4) there was no information about the monitoring duration. In some papers, the same technology/sensor was used to monitor all the case studies, such as in, other papers utilised different technologies/sensors for the different case studies investigated. There were, however, papers in which the monitoring technology or tools were not described (e.g., 4, 5, 6, and 7).

Among the environmental data collected objectively were air temperature, relative humidity, CO_2 levels, daylight, and acoustics. Occasionally, occupants would be asked their opinion regarding natural lighting, air quality, etc. (i.e., subjective data collection) without measuring the actual daylight value, or CO_2 levels in the case of air quality such as in papers 8, 10, 17, 25, and 31. However, when the parameters were monitored, there was no standard monitoring protocol applied, and most of the papers displayed no consistency. For example, temperature and humidity may have been monitored for long periods (e.g., 17, 18, 26, and 31), whereas noise level and light intensity were usually measured on the spot as in paper 3, sensor placement and logging time intervals were not consistent even in some cases within the same research, which was also reported by Ref. [80]. This discrepancy, often caused by the pragmatic realities of real-world data collection, makes it more difficult to compare findings between dwellings and may reduce the reliability of findings.

Agreed monitoring protocols and transparency are especially important for residential buildings [88], where gaining access to data and occupants is not as evident as in public buildings where facilities managers can assist and often have Building Management Systems data that can support POE [89]. In residential buildings, occupants also have more control over their environment (e.g., opening windows, switching the heating on and off), making the comparison of, for example, energy consumption as an indicator of fabric performance between dwellings (even in the same building) harder.

As for energy and building fabric-related performance parameters, there is no consistency in how energy consumption is reported and there is a variety of energy sources, metering systems, and energy costs, especially when the investigated case studies were proposed for different countries such as in paper 13. Different energy sources were reported for the different investigated buildings such as in paper 10, in which some of the investigated buildings used electricity as the main source of energy; other cases used gas for heating and DHW (e.g., 2, 10, and 12). Energy consumption was reported in kWh in papers such as 16 and 20, while in others it was presented as energy cost (3).

Considering the many factors that might affect building energy consumption (e.g., microclimate, building design, orientation, occupant behaviour etc.) [90], the un consistency in investigating energy and building fabric-related performance parameters is a shortcoming and makes it difficult to compare the energy efficiency of houses nationally, and internationally [91]. In addition, the non-detailed reporting of energy source/consumption highlights the risk of insufficient data for calculating potential energy savings and carbon footprint minimization.

5.4. Evaluation according to the research approach and data analysis

POE studies typically follow one of the following four methods approaches (see Fig. 6): (1) embedded approach, which is used when the researcher utilizes only one type of data analysis, such as quantitative or qualitative analysis, (2) explanatory-sequential mixed methods approach, which seeks to follow up quantitative results with qualitative analysis, (3) convergent-parallel approach, which seeks to integrate the results of both quantitative and qualitative data simultaneously, and (4) exploratory-sequential mixed method approach, which seeks to follow up qualitative data with quantitative analysis [92]. All reviewed papers use at least one of the research approaches above; however, the used approach was only explicitly described in paper 13 (i.e., embedded approach), and paper 14 (i.e., explanatory approach).

Approach selection impacts the methods employed and data obtained, each with its own obstacles. For example, with paper 8 (with a sample size of 395 people living in different units located in different buildings with different configurations regarding systems, windows, etc.), a satisfaction survey is used to obtain comfort and satisfaction levels with the indoor environment which is analysed qualitatively for each unit. However, a 7-points scale is used to quantify the subjective responses and to correlate the results between all the different cases studied. While this approach may not accurately evaluate individual comfort and satisfaction, it is adopted due to the challenges of qualitatively analysing data from a large sample, such as limited time and resources for interviews and participant involvement.

In paper 19, however (with a sample size of six dwellings), questionnaires and surveys (subjective methods) are used to elicit both quantitative and qualitative data [93]. But in-situ observations and interviews have been conducted to examine how occupants are using their homes and understand the reasons behind their responses. In this case, each case study was investigated separately, and only similar findings were correlated and highlighted such as complains about controlling integrated systems such as the new installed mechanical ventilation with heat recovery units (MVHR).

Despite POE practices use rating scales to quantify the subjective data, their use is questionable in small sample sizes and not only concerning the number of buildings in the case studies but also the number of people using those buildings. In a house, for example, one person might represent 100% of the residents, so the rating scale might not be the best method to evaluate the building's performance. More useful is to understand why and how residents perceive a situation the way it is. The same method (i.e., rating scales) may be more appropriate for public buildings such as university buildings with more people available for interviews or responses to surveys in a short timeframe [94].

It is noticed that when studying a larger sample, the approach might be different depending on the resource used. For example, paper 28 received 298 responses, the results of which were categorized and analysed to represent the level of occupant satisfaction in the studied building. Analysing performance and satisfaction of a single unit or household in large samples can be difficult as there may not be enough resources for qualitative analysis using subjective methods like interviews or sufficient objective data like temperatures for each unit.

As mentioned, the research approach impacts the research process and data analysis, but it is also chosen subjectively by researchers based on their primary objective and expertise. To ensure reliable identification of POE best practices, it is crucial to report the research approach for credibility in results.

5.5. Implications of findings in theory and practice: a roadmap recommendation for future residential POE studies

The reviewed articles reveal that residential POE studies are frequently carried out using diverse methods and suffer from a lack of consistency. The objectives of the chosen papers primarily fall under two categories: either solely focusing on occupants or buildings and their systems or examining the relationship between both users and buildings. As a result, POE studies can only offer limited information about the functioning of residential buildings and the satisfaction of their inhabitants, making it hard to compare between different studies and to

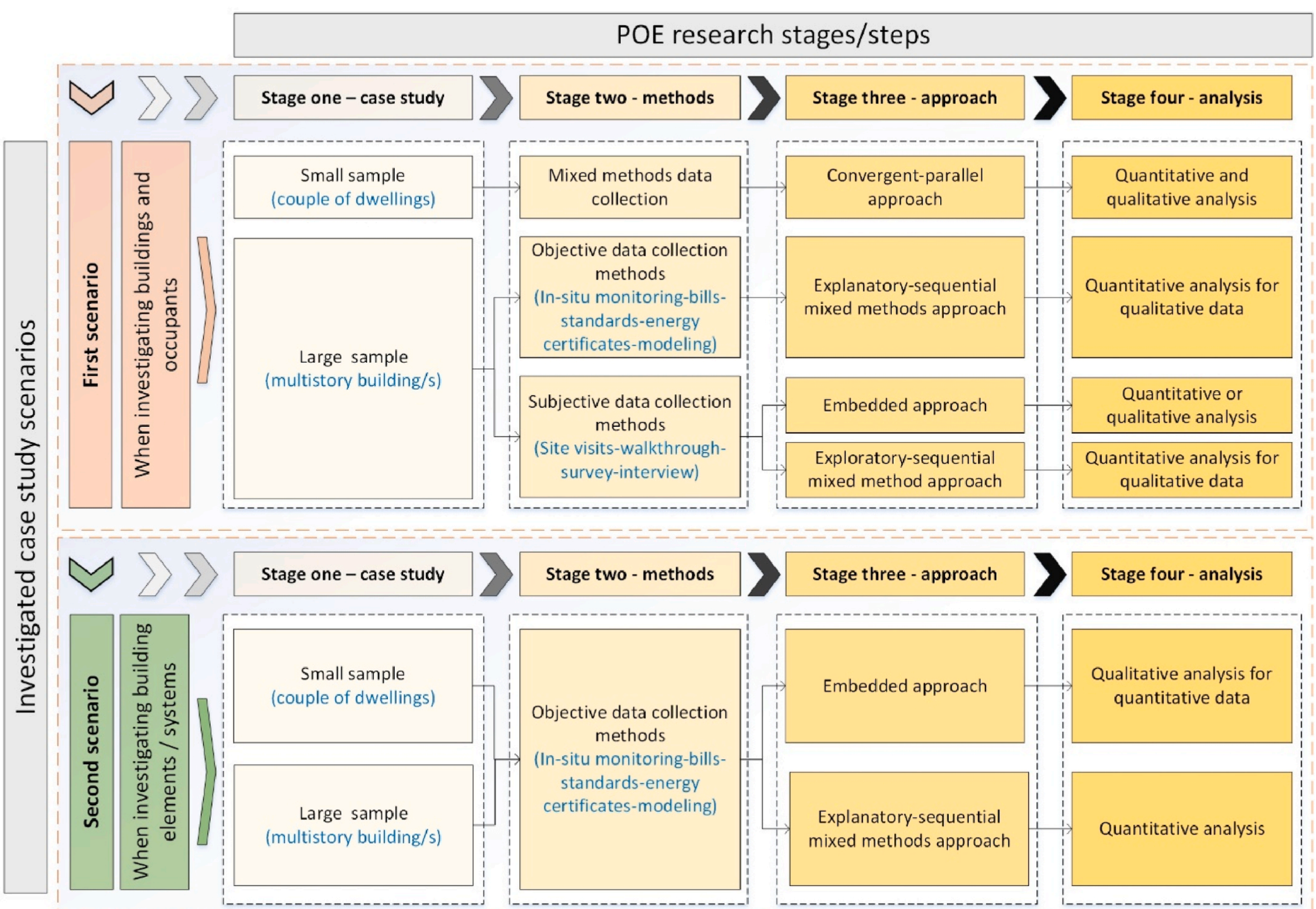

Fig. 7. Recommended roadmap for POE studies in residential buildings depending on sample size, data collection and analysis methods.

transfer findings beyond the case investigated. There are several factors contributing to the uncertain results, such as a shortage of information regarding the investigations and the varied use of techniques by different researchers. To ensure the effective implementation of POE practices in residential buildings, it is recommended that future POE studies take into account the specific context and identifying factors presented in Fig. 6, and adopt one of the two scenarios outlined in Fig. 7. Seven recommended identifiers (see Fig. 6) should be considered as part of any POE study, and should be explicitly shared in publications to enable the contextualisation and comparison of the findings and transferability of methods. These seven considerations are: (1) research objective; (2) case study details; (3) data collection methods (4) data collected and parameters investigated; (5) monitoring details; (6) research approach, and (7) data analysis. This suggested approach would result in a more consistent approach to POE studies and enable more robust comparison between cases and generalisation of findings. The undertaking of future studies using the roadmap will test the suggested recommendations in Figs. 6 and 7.

6. Conclusion

This paper presents a systematic literature review of studies that use POE to evaluate the actual performance of residential buildings in the EU. The review is limited to published scientific papers and conference papers in the last decade (2011–2021). Following the PRISMA checklist, 84 papers were analysed, and 32 were included for screening after applying the selection criteria. Although the analysed papers share several similarities in the parameters investigated regarding building performance and occupant satisfaction, heterogeneity in methodologies and approaches persists. This results in limitations to an overall univocal application of POE in residential buildings.

Several significant shortcomings were identified in the reviewed POE practices, which can be summarized as follows:

- Although occupant surveys and interviews are commonly used as subjective data collection techniques, there is a lack of information available on the specific questions posed to participants, delivery methods, and relevant details related to response times and rates. Consequently, a complete understanding of the research context (including participants' engagement) may be difficult to attain, impeding the ability to replicate or enhance future POE research planning and implementation.
- For objective data collection, in-situ monitoring is the main method. However, the reviewed literature shows inconsistency in the methods used for monitoring, analysing and reporting the collected data. These present difficulties when attempting to compare results between various studies and buildings.
- The reviewed POE studies utilise both qualitative and quantitative analysis. While qualitative analysis provides a more comprehensive understanding of the building's performance and occupants' feedback, it is limited by the number of case studies that can be investigated, research resources, and time available. On the other hand, relying solely on quantitative analysis of small sample sizes, such as one building, led to results that cannot be generalised and only represent a specific case study.

Uniquely, this research proposed a roadmap with seven aspects to be considered and to be transparently reported (see Fig. 6) as part of any POE study to enable the contextualisation and comparison of the findings and transferability of methods.

This study, like all research, has certain limitations, including the limited time frame of the papers analysed (2011–2021) and the possibility that the inclusion and exclusion criteria outlined may not be exhaustive. Nevertheless, these findings contribute to the existing research gap in identifying best practices for undertaking POE studies in residential buildings in the European Union.

CRediT authorship contribution statement

Mohamed Elsayed: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Data curation, Conceptualization. **Sofie Pelsmakers:** Writing – review & editing, Supervision. **Lorenza Pistore:** Writing – review & editing, Investigation. **Raúl Castaño-Rosa:** Writing – review & editing. **Piercarlo Romagnoni:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110307.

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