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A novel multicriteria methodology to assess the renovation of social buildings

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ABSTRACT

The current Energy Performance Certificates of buildings are mostly based on the expected energy consumption. Recently, some certification schemes are starting to incorporate Indoor Air Quality aspects, but it is still not usual. Another topic of interest, such as energy poverty, is not considered in current certification schemes either. This paper presents a novel multicriteria methodology to assess the renovation of social housing buildings: the ARCAS methodology. The novelty lies in its transversal approach, which considers three axes: Energy Efficiency, Energy Poverty, and Indoor Environment Quality. The indicators set for assessment are calculated based on actual on-site measurements. The methodology has been tested in six demonstrator buildings selected throughout the SUDOE territory (southwestern Europe). The results show that the ARCAS methodology allows a comprehensive assessment of the current situation of the building to be achieved and helps to propose the renovation measures in a specific direction. Advice and guidance for professionals who want to test the methodology are also given. Although the methodology has been developed for its application in social housing, according to the EU recommendations, it can be applied to any type of housing.

Abbreviations:

A	Acoustic comfort, regarding the TAIL Index acronyms
BEMS	Building Energy Management System
BIM	Building Information Modelling
DHW	Domestic Hot Water
EN	Energy Needs
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate

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ETICS	External Thermal Insulation Composite Systems
EU	European Union
GBC	Green Building Certification
GWP	Global Warming Potential
HLC	Heat Loss Coefficient
HP	Heat Pump
I	Indoor Air Quality, regarding the TAIL Index acronyms
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
IWI	Internal Wall Insulation
L	Visual Comfort, regarding the TAIL Index acronyms
LCA	Life Cycle Assessment
PEC	Primary Energy Consumption
PERC	Primary Energy Renewable Consumption
PERP	Primary Energy Renewable Production
PV	Photovoltaic
Radd	Additional Thermal Resistance
RREE	Renewable Energies
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
T	Thermal comfort, regarding the TAIL Index acronyms
U	Overall thermal coefficient

1. Introduction

Energy certification schemes for buildings began to appear at the end of the last century. Their first intention was to provide a common methodology for quantifying the energy consumption of buildings and to provide building stakeholders with strategies for improving energy efficiency and minimising energy consumption [1]. This was already stated in Article 2 of Directive 93/76/CEE [2], which indicated that this certification “shall consist of a description of their energy characteristics, must provide information for prospective users concerning a building’s energy efficiency’’ and additionally, “may also include options for the improvement of these energy characteristics”.

In the last 30 years, the use of different energy certification schemes has been spreading throughout the world. In some countries or regions, such as the European Union (EU), these certificates have become mandatory and are known as Energy Performance Certificates (EPC). Most EU countries had schemes running for certain types of buildings, but only seven countries had implemented the EPC scheme for all types of buildings by the beginning of 2009. By 2013, all Member States had implemented the Energy Performance of Buildings Directive (EPBD) [3] requirements into their national legislation. Several institutions have carried out different research regarding the status and implementation of the EPC in the EU. In 2014, the Buildings Performance Institute Europe (BPIE) carried out a study [4], in which the conclusions highlighted the fact that the transposition process of the EPBD in each country was significantly delayed and that the reasons for this vary from one country to another. Furthermore, one of the main recommendations of this study was that there is a need to strengthen the role of EPCs in the context of national legislation, especially for renovation policies and programmes. Another, more recent report carried out within the framework of the X-tendo project [5], outlined the importance of including new indicators to enhance the usefulness and attractiveness of the EPCs, and also that the EPCs are being undervalued regarding their usefulness for renovation assessment.

Within the scientific community, several studies have also been developed to assess the current status of EPCs within the EU countries. A study conducted in Portugal [6] analysed the changes within the certification scheme of the country in the past 10 years. Another study conducted in Spain [7], analysed a diverse sample of 146 EPCs, reinforcing the importance of external control in EPCs. The results of a survey conducted in over 2000 homes in the UK [8], outlined the fact that EPC had little impact on decision-making or price negotiation, and also that the use of EPCs to assess the results of building renovation are inconclusive. Another survey conducted in Denmark, in 743 dwellings [9], found that despite the fact that most homeowners regarded the EPC as a reliable and easy tool to understand, relatively few found it useful as a source of information for building renovation. All of the analyses mentioned above, both those carried out by institutions and researchers, have in common the fact that the perceived reliability of EPCs is low, which hampers many of the potential benefits of using this tool to assess building renovation.

The Green Building Certification (GBC) is a more comprehensive certification scheme, having introduced social and economic aspects in its scheme in order to look forward to more sustainable building projects. Common GBCs are LEED, BREAM, WELL, EDGE or EnerPHit. The scientific community is interested in these certification schemes and several studies have been carried out regarding their accuracy, perception by users and usefulness towards the assessment of building renovation. For instance, research carried out by Vosoughkhosravi et al. [10] analysed the impact of LEED in residential college buildings. Another research work used GBC to optimize the energy-saving potential of public hospitals [11]. Other studies are focused on analysing and comparing common GBCs with national certification schemes [12,13]. However, there are also studies which highlight the weaknesses of GBC. Research conducted in Beijing [14] analysed the results of 40 certified green buildings in the post-occupancy phase. The results showed aspects that made it difficult to motivate the owners to continuously implement, maintain and improve the designed green performance of the building in the operation stage. Another study, conducted by Wai Lam et al. [15], highlighted that some parameters, such as embodied energy and thermal insulation, are, but should not be, overlooked in GBC.

Thus, considering the previously mentioned research and studies, it is evident that significant changes are needed in both energy certification schemes to improve the user experience and the renovation's usefulness. In this sense, recent studies have focused on analysing gaps within the current certification schemes and identifying opportunities for the improvement of the next generation of EPC. Among the aspects that stand out in these studies, some of the most repeated are the inclusion of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) in the certification schemes to boost the renovation of buildings [16–19]. Also, the accuracy of the measurements and the perception of the majority of building stakeholders is that EPC is mainly a bureaucratic formality, which means they are not perceived as key factors to boost the renovation of buildings [20,21]. Other studies focus on analysing which alternatives are viable in addition to EPCs to boost renovation, such as the Building Renovation Passport [22].

A systematic literature review carried out by Annie M.Y [23]. focused on the identification of appropriate key performance indicators (KPIs) for the holistic evaluation of building renovations. The results show that the selected KPIs fall into four aspects: economic, environmental, users' perspective, and health and safety; their distribution by quantity are as follows: 37%, 26%, 26% and 11%, respectively. Some of these groups of KPIs, as explained before, are already considered in EPC and GBC, such as the economic, environmental and health and safety aspects. For instance, such studies as [24,25] highlight the importance of IAQ in GBC. However, these key factors are still not considered within the same certification scheme.

Apart from climate change and the renovation wave, energy poverty is also becoming one of the main issues within the EU. As an example, in 2020, about 35 million inhabitants of the EU were unable to keep their homes adequately warm [26]. Thus, tackling energy poverty is also becoming one of the main objectives of the EU, as reflected in the *Clean Energy for all Europeans* package [27]. Indeed, the European Commission has provided several recommendations regarding the need to prioritize the renovation of buildings to tackle energy poverty [28,29]. Consequently, it would be interesting to consider energy poverty features in the renovation assessment tools. Some studies use EPC data to analyse energy poverty, but the application of energy poverty in certification schemes is still almost non-existent [30,31].

The ARCAS methodology has been developed to respond to the aforementioned needs. This methodology is a novel multicriteria procedure to assess the renovation of buildings. The novelty lies in its transversal approach, focusing on three different axes: *Energy Efficiency*, *Energy Poverty*, and *Indoor Environment Quality*. With this, the ARCAS methodology tries to assess the main aspects found within the literature that are of interest in the renovation of buildings. That is to say, it not only assesses the energy efficiency of the buildings, but also considers such aspects as the health conditions of the tenants and evaluates energy poverty, within the same certification scheme. Another strength of the ARCAS methodology is that its parameters are based on actual on-site measurements, which improves the accuracy and confidence in the results. With this, the proposed certification scheme aims to be a powerful market tool to create demand for building renovation and to encourage stakeholders to use these certification schemes, rather than being viewed as an administrative obligation.

In this work, the ARCAS methodology is introduced. Later, the results obtained after applying the methodology in six demonstrator buildings throughout the SUDOE territory are shown. The process for assessing each axis of the ARCAS methodology and the measurement protocol of the proposed indicators are explained in detail. In addition, the difficulties found when carrying out the measurements, as well as the advantages and disadvantages of the proposed methodology, are discussed. Finally, we analyse the possibility of extrapolating the ARCAS methodology to other buildings and the future implications of this novel scheme.

2. Material and methods

This section first describes the approach followed for the definition of the methodology, indicating the steps and criteria taken into account. Subsequently, the proposed methodology is detailed, describing the indicators selected, the reasons for their selection and the thresholds of the different categories.

2.1. Research method

A new multi-criteria methodology is proposed for the evaluation of different retrofitting solutions in social housing. The elaboration of this methodology has included the usual steps to define a multicriteria methodology [32], but with some particularities, as explained below.

Step 1: Objective of the methodology.

The proposed methodology can be applied in three situations:

- To assess the behaviour of the building in its current situation.
- To predict the effect that certain retrofitting actions would have on the performance of the building, thus facilitating decision making.
- Finally, to evaluate the performance of the building under retrofit and to check the effectiveness of the measures selected in the previous point.

Step 2. Criteria to be considered

As previously mentioned, the methodology developed aims to assess buildings in a more comprehensive way, including the following aspects:

- Energy efficiency;
- Sustainability, from the point of view of using renewable energy sources and the environmental impact assessment;
- Indoor air quality;
- Comfort;
- And energy poverty. The incorporation of the Energy Poverty axis is one of the most novel aspects of the proposed methodology.

Step 3: Target group

The methodology is designed for different stakeholders. On the one hand, it aims to facilitate decision-making by users, building designers, or social housing managers on which refurbishment measure is the most appropriate. On the other hand, it also aims to provide public administrations with a tool to evaluate projects and support policy makers when defining financial aid for refurbishment.

Step 4: Indicator selection

The indicators have been selected under the following principles:

- To be useable and understandable by all potential users, giving priority to those indicators that already exist and are well known in the building sector. For this reason, the first search for possible indicators has been carried out in existing regulations, research papers or projects, such as LEVELS [33], EXCEED [34] or ALDREN [35].
- The indicator should be quantitative and directly measurable from real measurements in the building, or indirectly by calculation from other variables measured in situ. Such measurements, if possible, should be of limited cost and technical complexity.
- Notwithstanding the above, taking into account the particularities of social housing (e.g., common situations of discomfort or absence of thermal equipment), it would also be advisable to be able to obtain the value of the indicator by alternative means, such as simulation or from statistical values.
- Be flexible and applicable to different types of housing.
- The complete set of indicators has to be able to reliably show and explain the situation of that dwelling or building. For example, it should be able to explain whether a discomfort situation is due to poor insulation of the envelope, inefficient equipment, low incomes or misuse by the user.

Step 5: Indicator categories

Four categories have been established, ranging from Category I (the best) to Category IV (the worst). The number of categories chosen is not such a high number that it could make the ranking confusing, but high enough to appreciate different aspects when assessing a renovation proposal.

The intermediate limits have been established in an attempt to get homogeneous ranges among the different classes. The upper or lower limits have been defined according to existing regulations or recommendations in such aspects as pollutant concentration, thermal discomfort or primary energy consumption. In the case of energy poverty, Category I has been chosen as the only class that does not imply a risk of energy poverty.

Step 6: Criteria weighting

One of the most important aspects of multi-criteria methodologies, and perhaps the most difficult, is the assignment of weights to each category or even to each indicator within a category. Generally, this step is intended to establish a ranking between different alternatives. There are numerous weighting techniques such as the analytic hierarchy process (AHP) [36], simple additive weighting (SAW) [37,38], the Technique for order of preference by similarity to ideal solution (TOPSIS) [39], (PROMETHEE) [40,41] or Elimination Et Choix Traduisant la Realité (ELECTRE) [42].

Table 1
Description of each axis and indicator, comments about the measurement process and categories of the ARCAS methodology.

Axis	Acronym	Indicator	Unit	Comments about the measurement process	Categories of the ARCAS methodology			
					I	II	III	IV
Energy Efficiency	PE_C	Primary energy consumption	kWh/m^2·y	Direct measurement, through monitoring or energy bills, or estimation of the PE_C of the building used for heating, cooling, DHW, ventilation and lighting	<85	[85, 125)	[125,165)	[165,205)
	EN	Energy Needs	kWh/m^2·y	Heat to be delivered to or extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period, obtained using the EPC of the building	<18	[18, 50)	[50, 85)	[85, 115)
	PER_C/PE_C	Renewable energy self-sufficiency ratio	%	Measures the ratio between RREE consumption and total PE_C	≥60	[40, 60)	[20, 40)	[0, 20)
	PER_C/PER_P	Renewable energy self-consumption ratio	%	Measures the ratio between the RREE consumption and RREE production	<40	[40, 60)	[60, 80)	[80, 100)
	HLC	Heat Loss Coefficient	W/m^2·K	Measures, through a monitoring process or estimate, the total thermal losses of the building through the envelope, including thermal bridges and total air change	<1.4	[1.4, 2.4)	[2.4, 3.4)	≥3.4
	GWP	Reduction of the Global Warming Potential	%	Measures the potential of reduction of the carbon footprint of the building after the renovation process	≥30	[20, 30)	[10, 20)	[0, 10)
Energy Poverty	10% Indicator	10% Indicator	%	Measures the relation between the energy expenditure, when reaching comfort conditions, and the net income of the dwelling	≤10	(10, 15]	(15, 20]	>20
Indoor Environment Quality	Thermal comfort, T	Temperature [a]	°C	During warm season	[21,23]	≥20 & ≤24	≥19 & ≤25	Others
				During cold season (mech. cooling) *Use of standardised thermohygrometer is needed.*	[23.5, 25.5]	≥23 & ≤26	≥22 & ≤27	Others
	Acoustic comfort, A	Acoustic Comfort [b]	dB(A)	Living-room	≤25	≤30	≤35	Others
				Main bedroom *Measures the Sound Pressure Level, according to standard EN 16798.*	≤30	≤35	≤40	Others
	Indoor Air Quality, I	CO_2 (above outdoors) [b]	ppm	Living-room	≤550	≤800	≤1350	Others
				Main bedroom *Use of standardised acoustic meter is needed.*	≤380	≤550	≤950	Others
		Relative Humidity	%	*Use of standardised thermohygrometer is needed.*	[30,50]	≥25 & ≤60	≥20 & ≤60	Others
		Ventilation Flow Rate [d]	h^{-1}	*Use of standardised thermoanemometer is needed.*	ACH ≥0.7	ACH ≥0.6	ACH ≥0.5	Others
		Mold [a]	cm^2	*Visual inspection is needed*	0	<400	<2500	Others
		Particulate matter PM2.5 [c]	μg/m^3	*Use of standardised particles' meter is needed.*	<10	≥10	–	≥25
		VOC Formaldehyde [b]	μg/m^3	*Use of standardised Formaldehyde concentration meter is needed.*	<30	≥30 & <100	–	≥100
		VOC Benzene [b]	μg/m^3	*Use of standardised Benzene concentration meter is needed.*	<2	≥2 & <5	–	≥5
		Radon [b]	Bq/m^3	*Standardised procedure to measure Radon concentration is needed.*	<100	≥100 & <300	–	≥300
	Visual Comfort, L	Illuminance [c]	%	% of the day with 300–500 lux	[100, 60]	(60, 40]	(40, 10]	<10
				% of the night with 100 lux *Use of standardised luxometer is needed.*	0	≤50 & >0	≤90 & >50	>90
		Daylight factor [a]	%	Daylight factor during daytime *Simulations and calculations are needed.*	≥5.0	≥3.3	≥2.0	Others

[a] Measurements in living-room and main bedroom are mandatory.

[b] Measurements are optional in living-room and mandatory in main bedroom.

[c] Measurements are mandatory in living-room and optional in main bedroom.

[d] At all air inlets if presence of a mechanical ventilation system.

Numerous examples of its application in the building sector for building design [43], retrofitting strategies [44] or design of HVAC systems [45] can be found in the literature.

There are even examples in the field of some of the criteria chosen for the proposed methodology in Step 2, such as energy performance [46], sustainability [47,48], indoor air quality [49], comfort [50] and energy poverty [51,52].

However, in the methodology developed, it has been decided not to establish a ranking or classification, so none of the methods described above have been used. The main reason is that the tool aims to provide a global view so that each user (owners, managers, public administrations or policy makers) can choose the best solution, prioritising according to their needs or specific particularities. In this way, for example, if energy poverty is not a problem in that building, neighbourhood, city, etcetera., the results will not be conditioned by the weight that indicators related to this category would have in a hypothetical overall weighting.

2.2. Description of the ARCAS methodology

The ARCAS project [53] started in 2019 with a consortium formed by six partners located in the Atlantic Arc of the SUDOE territory, which includes the northern region of Portugal, the northern coast of Spain and the southwest coast of France. Thus, the acronym of the project comes from the Spanish: *ARCo Atlántico Sur*. The climatology of this area appears to be similar, and there are cultural and organisational synergies. Thus, the ARCAS project aims to develop a methodology to assess the renovation of social housing buildings, focusing on tackling energy poverty and promoting sustainable rehabilitation, energy efficiency and health in the SUDOE territory. Focusing on social rental housing is due to the fact that, as previously explained, the EU has recently emphasized that the renovation wave should prioritize this type of housing. For this reason, one of the objectives of the ARCAS project has been, from the beginning, to provide a methodology adapted to the said casuistry.

The main novelty of the ARCAS methodology is that it is a holistic methodology which combines three aspects usually assessed separately: namely, *Energy Efficiency*, *Energy Poverty*, and *Indoor Environment Quality*. As explained above, energy efficiency and IEQ are considered in most building certification schemes, but the inclusion of the energy poverty assessment is an important innovation.

The set of proposed indicators used to assess each of these axes have been obtained through debate and the experience of each member of the consortium in each of the fields that make up the ARCAS methodology. With this, after an extensive analysis of the indicators used in other projects, such as LEVELS or ALDREN [33,35]; it was decided to use the indicators shown in Table 1, which provides general information about each axis and shows the indicators proposed for each one. For more in-depth information regarding the development and the procedure to measure each indicator, several guides can be found on the official website of the project [54]. Regarding the *Energy Efficiency* axis, six indicators have been selected: primary energy consumption (PE_C), energy needs (EN), renewable energy self-sufficiency ratio (PER_C/PE_C), renewable energy self-consumption ratio (PER_C/PER_P), Heat Loss Coefficient (HLC) and Global Warming Potential (GWP). The proposed indicators provide a comprehensive overview of the energy performance of the building, considering the quality of the external envelope (EN and HLC), the energy consumption and energy efficiency of the systems (PE_C), the integration of RREE installations (PER_C/PE_C and PER_C/PER_P), and the global warming impact associated with the life-cycle of the renovated building (GWP). The EN indicator considers the energy needed to achieve comfort conditions in the dwelling, and using the value provided by the official EPC is suggested. On the other hand, the HLC indicator is measured on-site [55,56], and it takes into account the total thermal losses of the building through the envelope, including thermal bridges and air leakages. If there is no heating equipment in the dwelling, the HLC may be estimated according to nationally established procedures. The inclusion of the HLC, together with the EN indicator, allows the complete definition of the quality of the thermal envelope. The PE_C is obtained by measuring the final energy consumption for heating, cooling, DHW, ventilation, lighting and appliances, with energy meters that use the BEMS of the building or energy bills. Then, the Primary Energy Consumption is obtained by considering the conversion factor for each energy vector used, depending on the country. The self-sufficiency ratio (PER_C/PE_C) measures the amount of PE_C which comes from on-site renewable sources; while the self-consumption ratio (PER_C/PER_P) measures the amount of on-site RREE production energy consumed within the building, and thus, not exported to the grid. Both indicators are based on real measurements, using the BEMS data whenever possible, or estimated according to established national methods. Finally, the Global Warming Potential (GWP) indicator is used to assess the sustainability of the renovation, calculating the amount of CO_2 emissions not emitted due to the, supposedly lower, energy consumption of the renovated building. This calculation of this indicator is proposed as the relation between the GWP of the building in its current situation, before renovation, and the building after renovation, 30 years later. The baseline is established in the building in its current situation. That is to say, the GWP of the building before renovation considers only the operational impact of the use stage (B1–B7) in the upcoming 30 years. On the other hand, the GWP of the renovated building considers the impact of the use stage of the renovated building in the coming 30 years. In addition, it considers the embodied impact (A1-A5) of the new materials and equipment needed for the renovation.

In order to measure energy poverty, the scientific community suggests a long list of indicators, such as the *inability to keep the home adequately warm*, the 2 M, and the M/2, among others [57]. For the ARCAS methodology, the 10% Indicator has been chosen to evaluate how the building's performance can support energy poverty alleviation. This indicator measures the ratio between the total energy expenditure of the dwelling and the household's net income. This indicator has been chosen for several reasons. Firstly, it is a consistent, flexible, and relatively easy-to-measure indicator. Secondly, it is related to the PE_C indicator of the *Energy Efficiency* axis through the final energy consumption parameter, uniting the methodology. Lastly, the choice of an expenditure-based indicator has been considered appropriate, since the project focuses on social housing buildings, which means that economic availability to pay for energy services is valued in the chosen approach.

Finally, in the scientific community, there is no clear consensus regarding which method should be used to rate the overall level of IEQ in dwellings. In this sense, within the framework of the EU ALDREN project [58], a new classification rating scheme, the TAIL Index was developed to assess IEQ in offices and hotels undergoing deep energy renovation, and it has been adapted to the reality of the dwellings by some of its authors [59]. This methodology combines the Thermal Environment, the Acoustic Environment, the Indoor Air Quality, and the Visual Environment. Thus, the TAIL Index indicator has been chosen as a comprehensive methodology to assess the *Indoor Environment Quality* axis and is also based on real on-site measurements.

Concerning the advantages of the proposed methodology, the second main strength of the ARCAS methodology is that it is mostly based on direct measurements; whereas most of the certification schemes are only based on simulations, i.e., to derive the majority of the indicators for each axis, direct measurements or monitoring processes within the building need to be carried out. Also, the calculations needed to develop each indicator are not excessively difficult and may be performed using a spreadsheet or similar. Nevertheless, as will be explained later, there are some exceptions in which it is not possible to carry out the on-site measurements. In these situations, the use of energy bills, consistent energy simulations according to national regulations, or estimations based on energy audits are suggested for calculating the indicators.

The ultimate aim of the ARCAS Methodology introduced here is to assess a specific building, with a multicriteria and transversal scope, by measuring and calculating the selected indicators previously described. Thus, for each indicator, four different categories have been established, depending on their results. The ranks for each of them have been obtained using the reference standards of each participant country of the ARCAS project. Table 1 also summarises the ranks for each category, the best category shown in green (I) and the worst in red (IV). The ranking categories for the Renewable Energy Self-Consumption Ratio (PER_C/PER_P) are clarified here. This indicator, as explained above, measures the amount of produced RREE energy consumed within the building and thus, not exported to the grid. In the ARCAS methodology, positive energy buildings are willed, meaning that the lower the value of the PER_C/PER_P indicator, the more RREE is being exported to the grid. Thus, the best category for this indicator is when its value is lower than 40%.

Fig. 1 shows a schematic example of the use of the ARCAS methodology to assess the renovation of a building. As depicted in this figure, the building is certified in three different stages. Firstly, the building is certified in its *Current Situation*. For this, it is necessary to gather information and carry out the measurements needed to calculate each indicator. Once the ARCAS certification has been obtained, different renovation measures may be proposed to improve the energy efficiency, IEQ and energy poverty of the tenants. In this stage, the *Design Phase*, calculations and estimations are performed to obtain the ARCAS Certification. Finally, once the renovation proposal is decided, the renovation works are developed. After the renovation has finished, the measurements to calculate each indicator are performed again, so as to obtain the ARCAS Certification in the *After Renovation* stage.

To summarize, the transversality of the ARCAS methodology helps, when evaluating an existing building, to get a comprehensive overview of the actual conditions of the building; is not only because of the three-axis focus, but also because most of the indicators proposed are based on actual on-site measurements. Basing the methodology not only on software simulations, but also on real measurements provides the strength and security of evaluating the performance of the building, and the energy poverty and indoor conditions of the users with a high level of accuracy and confidence.

2.3. Description of the sample

To test the ARCAS methodology, six demonstrator buildings were selected in the SUDOE territory; chosen by each of the partners of the ARCAS consortium to analyse a representative sample of the Sudoe territory. Other aspects, such as the year of construction,

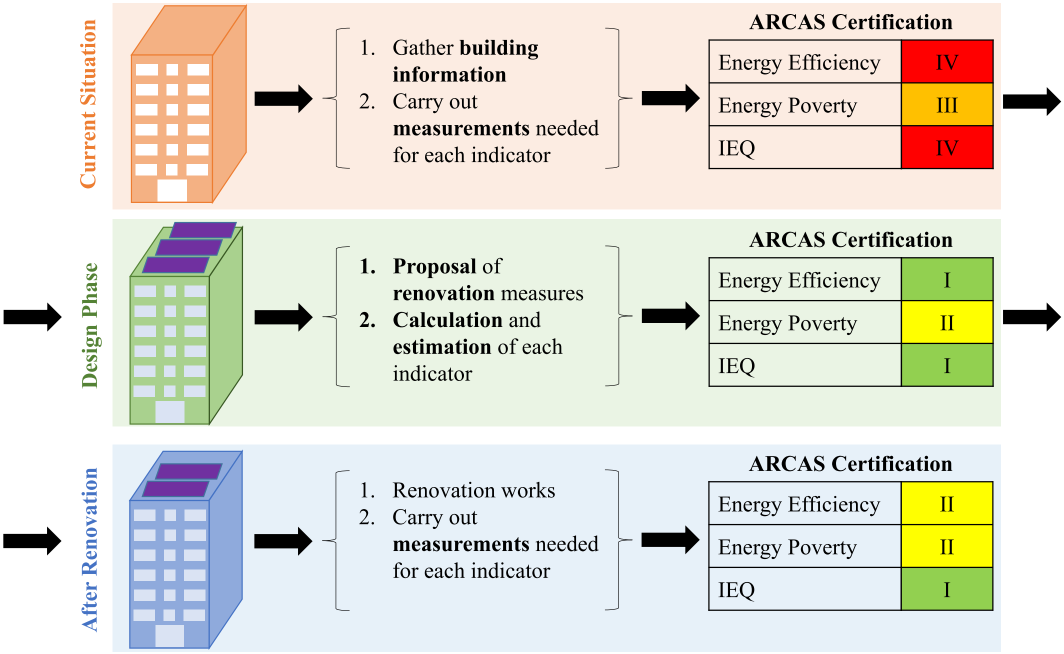

Fig. 1. General scheme of the ARCAS certification methodology.

Table 2
General characteristics of the demonstrator buildings for the ARCAS Methodology.

Building	F-1	F-2	P-1	P-2	P-3	S-1
General information						
Renovation status	Renovated during 2019–2020.	Renovated during 2019–2020.	No renovation	No renovation	No renovation	No renovation
Location	La Rochelle, France	La Rochelle, France	Braga, Portugal	Braga, Portugal	Braga, Portugal	Vitoria-Gasteiz, Spain
Year of construction	1954	1974	1983	1976	1976	2010
Number of dwellings	16	64	246	171	171	126
Monitored dwellings	2	2	1	1	1	4
General description and number of floors	1 building block with 4 floors of dwellings	2 blocks with 5 floors and 1 block with 6 floors of dwellings	32 building blocks with 4 floors of dwellings each	Several blocks with 4 floors of dwellings each	Several blocks with 4 floors of dwellings each	1 block with 8 floors and 1 block with 6 floors of dwellings
U walls [W/m^2·K]	1.75	0.73	0.60	0.71–1.46	0.71–1.46	0.31
U windows [W/m^2·K]	1.6–4.5	2.9–4.95	4.1–5.05	1.98	3.4–5.1	3.3
Heating and DHW	Gas-fired condensing boiler	District Heating	Individual Electric Heater and Gas water heater for DHW	Individual Electric Heater and Gas water heater for DHW	Individual Electric Heater and Gas water heater for DHW	Collective gas fired boiler
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural
Stages in which each building has been assessed with the ARCAS methodology						
Before Renovation	X	X	X	X	X	X
Design Phase			X	X	X	X
After Renovation	X	X				
	Buildings After Renovation		**Buildings in the Design Stage**			
Renovation details	External walls - IWI (Radd > 4–5 m^2 K/W). Insulation floor (Radd >4 m^2 K/W) and roof (Radd >7.1 m^2 K/W) Double-glazing (4–16/4 with Argon filling). Mechanical ventilation with humidity control. Collective DHW production system.	External walls 20 + 9.5 cm (U = 0.12 W/m^2·K). Insulation floor (14 cm) and roof (20 cm). Double-glazing (U = 1.3 W/m^2·K) Assisted natural ventilation. Change of emission systems. Solar collectors (34 vacuum tube solar collectors). PV panels (36 kWp).	70 mm EPS insulation wall apartment -stairwell. 80 mm EPS insulation slab basement-dwelling. ETICS 100 mm EPS. Replacement of the exterior door with a wooden door without glazing. Replacement of all windows with standard double-glazed PVC windows U = 1.95 W/m^2·K. HP for AC, SCOP = 4.0 and SEER = 6.1. Solar collectors for DHW.	70 mm EPS insulation wall apartment -stairwell. ETICS 60 mm EPS. 100 mm EPS above the horizontal slab of the unoccupied pitched roof. HP for AC, with SCOP = 4.0 and SEER = 6.1. Solar collectors for DHW.	70 mm EPS insulation wall apartment -stairwell. ETICS 60 mm EPS Replacement of all windows with standard double-glazed PVC windows U = 1.97 W/m^2·K. HP for AC, with SCOP = 4.0 and SEER = 6.1. Solar collectors for DHW.	ETICS 100 mm EPS. 16 cm of XPS in the roof. 8 cm of MW to the lower floor of dwellings. Renovation of all the windows transmission of U = 1.45 W/m^2·K. HP for heating and DHW of SCOP = 2.5 or higher. PV panels with 4.1 kWp.

F-1 F-2 P-1

P-2 P-3 S-1

Fig. 2. Pictures of the demonstrator buildings.

quality of the external envelope, and last but most important, the availability of data and tenants to allow access to the dwellings to carry out the needed measurements. An attempt was also made to include demonstrator buildings already renovated, in order to carry out the certification in the *After Renovation* stage. With these main criteria, each partner chose suitable buildings to apply the ARCAS methodology.

Thus, Table 2 includes general information on the demonstrator buildings, such as the year of construction or the size of the dwellings. Fig. 2 shows pictures of the selected demonstrator buildings. Regarding the size of the buildings, the demonstrator buildings comprise a wide range of configurations: from small buildings of 16 dwellings to high developments of 171 dwellings. The reluctance of the tenants to access the dwellings is also reflected in the number of dwellings analysed in each building. For instance, in building S-1, the partners were able to measure 4 different dwellings; whereas in the French buildings, partners were only able to analyse 2 dwellings.

Furthermore, the quality of the external envelope and the type of energy system is shown in Table 2. Although the overall coefficient of transmission of the opaque envelope is not significantly bad, there is room for improvement considering the quality of the windows. Regarding the energy systems, there is a high variety, with buildings using district heating for heating and DHW, buildings using collective gas boilers, or even buildings with individual gas heaters for DHW and portable electric heaters.

As depicted in Table 2, most of the buildings are quite old, with over 40 years since construction, except for the building S-1, located in Spain, which was constructed in 2010. However, the buildings located in France have undergone a renovation process in 2019–2020, affecting both the external envelope and the energy systems. Thus, the ARCAS methodology has been tested in different scenarios, with buildings which have not been renovated yet, and buildings which have already been renovated. What is more, for the non-renovated buildings, a proposal for renovation measures is assessed using the ARCAS methodology. The buildings that have been tested in each scenario are also shown in Table 2, which shows the main characteristics of the renovation packages considered in each of the demonstrator buildings, for both the *After Renovation* scenario and the *Design Stage* scenario. It can be seen that all the renovation

Table 3
Results of the ARCAS methodology for the demonstrator buildings, in the *Before Renovation*, *Design Stage* and *After Renovation* scenarios.

			Energy Efficiency						Energy Poverty	Indoor Environment Quality				
Country	Location	Building	PE$_C$ [kWh/m^2·y]	EN [kWh/m^2·y]	PER$_C$/PE$_C$ [%]	PER$_C$/PER$_P$ [%]	HLC [W/m^2·K]	GWP [%]	10% Ind. [%]	T [-]	A [-]	I [-]	L [-]	TAIL [-]
							Before Renovation							
France	La Rochelle	F-1	187.0	130.0	0.0	-	3.88	-	16.9	II	IV	IV	IV	IV
	La Rochelle	F-2	198.0	137.0	6.7	100.0	3.01	-	17.2	II	IV	IV	IV	IV
Portugal	Braga	P-1	387.7	141.1	0	-	4.91	-	17.9	IV	IV	IV	IV	IV
	Braga	P-2	449.3	164.6	0	-	5.29	-	16.8	IV	IV	IV	II	IV
	Braga	P-3	220.5	75.9	0	-	2.96	-	15.3	IV	IV	IV	I	IV
Spain	Vitoria-Gast.	S-1	140.6	55.1	0	-	2.10	-	21.0	IV	II	IV	IV	IV
							Design Stage							
Portugal	Braga	P-1	42.5	20.0	73.0	100.0	1.22	88.0	1.02			-		
	Braga	P-2	49.7	26.0	65.8	100.0	1.31	88.1	0.97					
	Braga	P-3	38.8	20.2	67.5	100.0	1.15	80.3	1.35					
Spain	Vitoria-Gast.	S-1	70.9	16.5	27.0	100.0	0.6	54.0	14.0					
							After Renovation							
France	La Rochelle	F-1	64.0	25.0	0.0	-	1.37	45.0	8.3	NA [1]	NA [1]	NA [1]	NA [1]	NA [1]
	La Rochelle	F-2	72.0	25.0	44.0	100.0	0.92	62.0	8.1	II	I	IV	IV	IV

[1] NA: Not Available

packages involve deep renovations, affecting the external envelope, the improvement of the energy systems and the installation of RREE systems.

3. Results

The results obtained when using the ARCAS methodology to assess the different scenarios of the demonstrator buildings are shown in Table 3. The result for each indicator is highlighted with the corresponding colour for its category, as indicated in Table 1. Thus, not only the numerical results for each indicator may be analysed, but also the ARCAS category may be compared at a glance when analysing Table 3.

Regarding the *Before Renovation* scenario, it is clearly depicted that the overall results for the housing stock analysed are poor in the three axes of the ARCAS methodology. The indicators of the energy efficiency axis show that both the energy demand and the primary energy consumption of the buildings are considerably high, implying a poor energy efficiency category. Regarding the RREE indicators, as there are no RREE installations in most of the buildings, both the self-consumption and self-sufficient indicators are really bad. The HLC indicator is in line with the EN of the building. In some cases, the result for the HLC indicator is slightly better than the result for the EN indicator. This is because the HLC indicator is derived from real measurements carried out in real operation conditions with the occupied dwellings during a specific period; whereas the EN indicator is based on the standardised conditions of the EPC of the building.

All of these poor results derived from the energy efficiency indicators are reflected in the indicators of the Energy Poverty and IEQ axes. Together with the user profile of these dwellings, the results for the Energy Poverty axis are significantly bad. Five of the six demonstrator buildings have category III and one has category IV in terms of energy poverty. As far as IEQ is concerned, the results of the TAIL Index also show bad conditions in the dwellings, with a generalised result for the IV category. There are a few exceptions in some buildings where Temperature, Acoustic and Luminance are not category IV.

Thus, considering the results of the ARCAS methodology for the analysed buildings in the *Before Renovation* scenario, it is clear that there is room for improvement in the demonstrator buildings. This will be assessed using the ARCAS methodology for the *Design Stage* scenario and for the *After Renovation* scenario. Comparing, at a glance, the results shown in Tables 3 and it is clear that there is a significant improvement in the ARCAS indicators for the renovation scenarios. Regarding the energy efficiency indicators, it can be seen that the PE_C, EN and HLC indicators achieve really high categories, meaning that the renovation proposals are useful for decreasing the energy consumption of the buildings. With the installation of RREE facilities, the self-sufficiency indicator (PER_C/PE_C) shows different results. In some cases (P-1, P-2, and P-3), the improvement of the (PER_C/PE_C) is clear. In the rest of the demonstrator buildings, the proposed installation of the RREE is not enough to achieve a high category for this indicator. Regarding the self-consumption ratio (PER_C/PER_P), none of the buildings, even those with important RREE installations, achieve a good category. This is because the RREE production is mostly self-consumed in the building and is not exported to the grid.

In addition, since the energy expenditure is expected to decrease with increasing energy efficiency due to the renovation of the buildings, the previous results presented for the energy efficiency indicators are directly reflected in the energy poverty indicator, where improvements of two categories (from category III to category I, and from category IV to II) are achieved. With this, the importance of analysing social aspects is proved. When facing the renovation of a building, not only the reduction of energy consumption should be expected, but also the improvement of the living conditions of the households.

Finally, regarding the IEQ, it is not possible to calculate the TAIL Index in the Design Stage scenario. In the *After Renovation* scenarios, it has only been possible to measure the TAIL Index in the demonstrator building F-2. Comparing the TAIL Index for this demonstrator building before and after renovation, it can be depicted that the renovation has not significantly affected the indoor environment of the dwellings. There is an improvement in the Acoustic sub-parameter, but the rest remain the same. In this sense, the utility of the ARCAS methodology is to notice that further renovation measures need to be applied if a significant improvement in the IEQ conditions is to be achieved.

4. Discussion

The previous section showed the results when applying the ARCAS methodology to the demonstrator buildings, and compared the outcomes depending on whether the building was certified in its Current Situation, in the *Design Stage* or *After Renovation*. In this section, we discuss the advantages and disadvantages of using the ARCAS methodology to assess the renovation of buildings rather than using conventional EPCs or GBCs. Also, at the end, we discuss several aspects that hinder the applicability of the method, or problems that have been detected while carrying out the measurements.

As explained throughout this document, the multicriteria and transversal focus of the ARCAS methodology provides an overall and comprehensive picture of the *Current Situation* of the building, not only focusing on energy efficiency, as most of the certification schemes do, but also considering possible energy poverty situations of the users and the indoor environment quality of the dwellings. For instance, if we focus on the results found in building P-1, it can be seen that the current situation of the building is considerably worrying in all of the axes. The current state of the building is bad in energy efficiency, energy poverty, and IEQ. Thus, the ARCAS certification suggests that a comprehensive renovation should be performed in this building, together with social initiatives to tackle energy poverty. On the other hand, the results for the IEQ in buildings F-1 and F-2 show that the thermal comfort (T) is not entirely bad (category II). This could suggest that, despite the fact that the quality of the envelope is not good (as the results for the EN and HLC are bad), the renovation measures would not have to be very deep to achieve good thermal comfort among users. If a conventional certification scheme had been considered, without analysing the IEQ, it would possibly consider greatly increasing the level of insulation, which could cause overheating situations in the future. Another case, in which the advantages of the ARCAS methodology can be observed, is the S-1 building. In this case, the results for energy poverty and IEQ are bad. Furthermore, most of the indicators of the energy efficiency axis are bad, except the HLC indicator (category II). This suggests that when proposing renovation measures, the quality of the thermal envelope should not be the priority, rather it should be improving the efficiency of the HVAC systems or installing RREE systems.

Having certified a building in the *Current Situation*, decisions can be made with the certification of the Design Stage in order to prioritize which aspect of the building may be improved. For instance, with the renovation proposal for building S-1, it can be seen that the RREE proposed may not be sufficient to achieve a good category for the RREE indicators, and perhaps more photovoltaic panels are needed. Another aspect to highlight is that, for buildings P-1, P-2 and P-3, with the renovation proposals, the energy poverty improves from category III to category I. The GWP indicator also shows that the sustainability of the proposed renovations is considerably improved when compared to the sustainability of the building without renovation. These latter aspects could not be depicted if conventional EPCs or GBCs had been used instead of the ARCAS methodology.

Finally, when certifying the building in the After Renovation scenario, the actual effect of the renovation measures may be assessed. For building F-2, it can be seen that the energy efficiency indicators have improved with the renovation. However, more RREE would be needed to improve the renewable energy self-consumption ratio. Furthermore, the energy poverty has been effectively tackled. Regarding the IEQ axis, the Acoustic (A) conditions have significantly improved (from category IV to category I), but other renovation measures are needed if the Indoor Air Quality (I) or the Luminance (L) are to be improved. Again, this overall picture of the renovation measures could not have been obtained if a conventional certification scheme had been used instead of the ARCAS methodology.

However, several difficulties have also been found during the ARCAS monitoring processes needed to measure and calculate the different indicators. For instance, some of the analysed dwellings did not have heating systems; hence, the monitoring process for the HLC indicator could not be carried out. Likewise, if the users of a specific dwelling do not use the heating, the energy poverty indicator needs to be calculated using the theoretical heating consumption provided by the EPC. In addition, it may be that households do not allow access to the dwelling or the installation of the monitoring equipment. Another possible eventuality is that the certification needs to be performed, for instance during the summer, due to availability or agenda issues, so several parameters cannot be assessed.

In all of these scenarios, indicators may be estimated according to the official EPC, or using data from previous energy audits, but the on-site measurements should always be prioritised. All of these aspects and drawbacks have to be considered by anyone who wants to apply the ARCAS methodology to any building. A properly arranged and scheduled monitoring campaign, considering dates, period, possible assistance from external agents, etc., is needed to achieve success with the ARCAS methodology.

Finally, one important step for the future of the ARCAS methodology would be to involve local agencies and governments in using the ARCAS methodology to assess the renovation wave. In this work, it has been shown that the ARCAS methodology is a multicriteria tool, thus allowing local agencies to assess the renovation of buildings, not only in the energy consumption aspect, but also in social and indoor environment quality aspects.

5. Conclusions

In this work, a novel multicriteria methodology to assess the renovation of social housing buildings is presented. This transversal methodology evaluates the building in three axes, namely, Energy Efficiency, Energy Poverty, and Indoor Environment Quality. In order to test the methodology, six demonstrator buildings were selected in the SUDOE territory, and the ARCAS methodology was used to assess the current situation, the renovation proposal, and the rehabilitated scenario for those buildings.

The results for the *Before Renovation* scenario show that there is a lot of room for improvement in all three axes of the ARCAS methodology. The poor quality of the external envelope, together with the low-efficiency energy installations, implies a high energy consumption. Considering the user profile of these buildings, and the high energy consumption, the results for the Energy Poverty indicator show a worrying situation. Finally, the TAIL Index for the IEQ axis also depicts existing poor conditions of the indoor environment.

When using the ARCAS methodology for the *Design Stage* and the *After Renovation* scenarios, the effects of the renovation proposals towards the three axes may be assessed. The influence of the renovation proposals on the energy efficiency of the buildings is clear, since most of the indicators improve considerably. The quality of the external envelope and the efficiency of the installations improve, and so does the energy consumption. The bad results for the self-consumption ratio (PER_C/PER_P) indicate that more RREE exported to the grid is suggested. In addition, the renovation proposals are also effective to alleviate energy poverty in social housing, where improvements in two categories (from category III to category I, and from category IV to II) are achieved for the energy poverty indicator. The incorporation of the Energy Poverty axis provides a social assessment of the renovation, which is not considered by other certification schemes. Finally, the results for the TAIL Index in the renovated building indicate that other types of renovation packages are needed to improve the indoor environment of the dwellings. This overall picture of the effect of the renovation measures could not have been obtained if a conventional certification scheme had been used instead of the ARCAS methodology.

Evidently, some difficulties have also been found during the development of the ARCAS methodology, mostly related to the measurements needed to calculate the indicators. For instance, the availability of the tenants to access the dwellings, the climate conditions to calculate the HLC indicator, or the lack of data. However, these disadvantages can be avoided with good certification planning and are offset once the transversal picture of the certified building is obtained.

With this, the ARCAS methodology has been presented, as well as its utility to assess the renovation of social buildings with a multicriteria focus. Further steps are needed to reinforce this methodology, considering the difficulties of measuring some of the proposed indicators; while further actions are being developed to involve local agencies in the use of this methodology.

Author contributions

Ivan Flores-Abascal, Pablo Hernandez-Cruz, Moises Odriozola-Maritorena: Term, Conceptualisation, Methodology, Data Curation, Writing - Original Draft, Writing - Review. Manuela Almeida, Bruna Onety, Jérôme Nicolle, Francis Allard, Jérôme Le Dréau, Emilio Suárez: Conceptualisation, Methodology, Data Curation, Writing - Review. All authors have read and agreed to the published version of the manuscript.

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

The data that has been used is confidential.

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