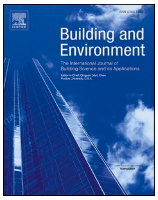
Building and Environment 245 (2023) 110911

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



How much is the indoor comfort of a residential building worth? A discrete choice experiment

Raul Berto *, Francesca Tintinaglia, Paolo Rosato

Department of Engineering and Architecture, University of Trieste, Trieste, Italy

ARTICLE INFO

Keywords:
Thermal comfort
Indoor air quality
Visual comfort
Acoustic comfort
Discrete choice experiment
Willingness to pay

ABSTRACT

Generally, people spend most of their time indoors, and the COVID-19 pandemic has further increased the amount of time people spent at home, owing to the widespread adoption of remote work. Consequently, there has been a heightened interest in indoor comfort, including thermal, visual, and acoustic comfort and indoor air quality. This interest has prompted a need to understand the economic value of each aspect of indoor comfort. To address this, a discrete choice experiment (DCE) was performed to estimate the willingness to pay (WTP) for advanced technological solutions that provide greater comfort than basic solutions in residential housing. The research showed a significant WTP for all aspects of comfort, with the greatest appreciation for thermal comfort. Additionally, the WTP for each aspect of comfort was greater than the additional costs required to implement advanced technological solutions to enable the desired comfort. The findings demonstrated that the sample population, mostly comprising people under the age of forty, was highly sensitive to comfort considerations and the related benefits derived from energy-efficient solutions. Specifically, comparing the WTP of the different aspect of comfort and the total one identified, the following relative importance was found: 51 % for thermal comfort (WTP = 377.94 EUR/m^2); 22 % for visual comfort (WTP = 166.83 EUR/m^2); 16 % for acoustic comfort (WTP = 119.60 EUR/m^2) and 11 % for indoor air quality (WTP = 79.21 EUR/m^2). These motivations can guide future decision-making and designers in the building market.

1. Introduction

People spend a significant amount of their time indoors in both commercial and residential buildings. Indoor comfort is a fundamental aspect of wellbeing and productivity. The pandemic has also spread to remote areas, highlighting the importance of this topic. Consequently, the economic evaluation of indoor comfort has become a subject of great interest to the scientific community and building market.

This study aims to evaluate people's willingness to pay (WTP) to obtain a high level of indoor comfort with respect to four aspects: thermal comfort, visual comfort, acoustic comfort, and air quality. The methodology used was a discrete choice experiment, an economic evaluation technique that assesses the relevance of each aspect and determines the value that individuals are willing to pay to obtain a high degree of comfort guaranteed by advanced technological solutions compared to what is offered by current solutions. This topic is already covered in literature, but used approaches, as we will highlight in section 3, are heterogeneous and often lead to inconsistent results. Moreover, the literature tends to focus only on certain aspects of comfort, neglecting a comprehensive evaluation.

The research results represent a preliminary examination of the value of indoor comfort in buildings and can be useful in guiding investment decisions in the construction sector and design. Furthermore, by considering indoor comfort as a co-benefit resulting from the adoption of energy-efficient technological solutions, this study highlights how economic evaluations of indoor comfort can contribute to promoting sustainable design and efficient use of resources, offering synergy in environmental and social benefits.

2. Indoor comfort in buildings

Indoor comfort is a concept that is often considered subjective and is therefore difficult to define objectively. Comfort in closed environments is determined by multiple factors and can be divided into four main categories: thermal comfort, visual comfort, acoustic comfort, and air quality.

---

* Corresponding author.
E-mail address: rberto@units.it (R. Berto).

https://doi.org/10.1016/j.buildenv.2023.110911
Received 4 July 2023; Received in revised form 6 September 2023; Accepted 6 October 2023

Abbreviation description

AC	Acoustic Comfort
COST	Cost
DCE	Discrete Choice Experiment
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
PMV	Predicted Mean Vote
PPD	Predicted Percentage of dissatisfied
RUM	Random Utility Model
TC	Thermal Comfort
VC	Visual Comfort
WTP	Willingness To Pay
EMF	Electric and Magnetic Field
AHP	Analytic Hierarchy Process
FCE	Fuzzy Comprehensive Evaluation
FAHP	Fuzzy Analytic Hierarchy Process
CVM	Contingent Valuation Method
LCC	Life Cycle Cost

2.1. Thermal comfort

The scientific literature has reported various definitions of thermal comfort. Hansen [1] defines it as “a state in which there are no driving impulses to correct the environment through behaviour.” The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has defined it as “the condition of the mind in which satisfaction with the thermal environment is expressed” [2]. Thermal comfort assessment is a cognitive process involving various inputs influenced by physical, physiological, and other factors [3].Macpherson [4] defined the following six factors that influence thermal perception: four physical variables (air temperature, relative humidity, air velocity, and mean radiant temperature) and two personal variables (clothing insulation and activity level, which are the metabolic rate).

Currently, there are three different approaches to defining thermal comfort:

- Rational or thermal balance approach: This method utilises data from studies conducted in climatic chambers, often associated with the work of Fanger, from whom the model takes its name. This also applies to air-conditioned spaces.
- Adaptive approach: This approach suggests a correlation between the comfort temperature for building occupants and outdoor air temperature. This relationship is defined by the standard EN 15251:2007 and is applicable to non-air-conditioned environments.
- Personal thermal comfort model: this method is able to predict an individual’s thermal comfort responses using the Internet of Things (IoT) and machine learning, rather than the responses of an “average person”. The primary benefit of these models lies in its ability of self-learning and updating to fit an individual with a data-driven approach, resulting in a greater predictive power [5].

With reference to the first approach, the indicators used to evaluate the thermal comfort were the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) occupants [6]. In the model proposed by Fanger [6], the PMV is associated with another index, PPD, which offers an estimate of how many occupants in a space would feel dissatisfied by the thermal conditions.

Notably, several studies on the relationship between internal thermal conditions and productivity have indicated that the objectively optimal predicted mean vote (PMV) is slightly lower than the subjectively assessed thermal comfort [7,8]. The adaptive model assumes that occupants in a non-air-conditioned environment tend to adapt if they have the freedom to control their microclimate according to their habits.

There are three types of adaptation:

1. Behavioural adaptation encompasses changes in which a person consciously or unconsciously modifies the parameters that regulate the body’s thermal balance. These can be classified as personal, technological, and cultural adaptations.
2. Physiological adaptation: Prolonged exposure to certain conditions reduces stress. In typical moderate environments, this type of adaptation has a negligible influence on the comfort perception.
3. Psychological adaptation: Past experiences and expectations modify the perception of and reactions to sensory stimuli.

Among the three mechanisms of adaptation, behavioural adaptation plays an active role in maintaining comfort because it is directly linked to the thermal balance of the human body.

2.2. Visual comfort

Visual comfort is defined by the European standard UNI EN 12665:2018 as a “subjective condition of visual well-being induced by the visual environment”. It depends on the physiology of the human eye, the physical quantities that describe the quantity and distribution of light in space, and the spectral emission of the light source.

Visual comfort was mainly studied through factors such as light quantity, light uniformity, light quality based on colour rendering, and the prediction of glare risk for occupants.

To ensure good visibility, it is necessary to have an adequate amount of light inside a space to allow users to perform their tasks effectively. Good light uniformity helps avoid visual stress caused by frequent eye adjustments from overly to poorly illuminated areas. Glare is a visual phenomenon resulting from excessive luminance within a visual field. In general, it can be defined as “the sensation produced by luminance within the visual field that is sufficiently higher than the luminance to which the eyes are adapted, causing discomfort or loss of visual performance and visibility” [9]. Another important aspect for ensuring visual comfort is achieving good colour rendering in the environment. The colour rendering index of a light source indicates the nature of the colours of the illuminated objects.

2.3. Acoustic comfort

Acoustic comfort refers to a psychophysical condition related to meeting the acoustic needs of the user. It is commonly associated with the prevention of discomfort and annoyance. Particularly for residential buildings, the underlying logic of acoustic design is to reduce the levels of noise to which occupants are exposed to prevent discomfort and other negative health outcomes [10]. The acoustic comfort indices reflect the efficacy of passive acoustic insulation. Passive acoustic insulation requirements are related to the reverberation time, apparent soundproofing power, standardised acoustic insulation of the façade, impact insulation, maximum sound pressure level, and equivalent sound pressure level are measures that quantify the average sound pressure level over a given time period. Reverberation is important for good listening conditions, as it makes the sound more intelligible and increases the energy density in the environment. The apparent sound insulation of the internal partitions between residential spaces belonging to different housing units represents the ability of a partition, whether horizontal or vertical, to reduce airborne noise. Normalised facade sound insulation characterizes the ability of a facade to reduce airborne noise from the external environment.

The impact sound insulation represents the insulation of horizontal partitions and characterizes the ability of a floor structure to reduce impact noise.

The maximum sound pressure level is the highest value that can be emitted into residential spaces by intermittent systems that do not serve the same housing units. The continuous equivalent sound pressure level represents the sound level that can be emitted into residential spaces by continuous operating systems.

2.4. Indoor air quality

Wesolowski [11] defined indoor air quality as “the totality of indoor air attributes that affect a person’s health and well-being”. In 2001, the International Energy Agency defined air quality as “the characteristics of the indoor climate in a building, including the gaseous composition, temperature, relative humidity, and atmospheric contaminant levels. In 2003, the National Health and Medical Research Council (NHMRC) defined indoor air as “the air inside a building occupied for at least 1 h by individuals with varying health statuses”. In 2016, the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) provided the following definition: “air in which harmful contaminants are not present at concentrations determined by competent authorities to pose a significant risk of adverse health effects, and with which a substantial majority of the exposed population (80 % or more) is not dissatisfied”.

Indoor air quality has a significant impact on human health and thermal comfort [12]. Indoor ventilation systems play an important role in guaranteeing the quality of air and reducing occupants’ discomfort. The primary purpose of ventilation systems is to remove air pollutants and/or dilute their concentrations to acceptable levels [13]. Therefore, to evaluate air quality, reference is made to internal concentrations of pollutant. The concentration of a pollutant inside a room depends on the relationship between the volume of air contained in the space considered, the speed of production or release of the pollutant, the speed of pollutant removal from the air by reaction or sedimentation, the speed of air exchange with the external atmosphere, and the concentration of external pollutants [14]. Actual human exposure is often difficult to quantify largely because individual activities can strongly influence human exposure levels. The Environmental Protection Agency (EPA) conducted numerous studies in the 1980s, demonstrating that personal exposure to many pollutants can significantly exceed that predicted by ambient air concentrations [15].

The consequences of an unhealthy indoor environment can manifest as a well-defined set of symptoms known as the sick building syndrome (SBS). Discomfort resulting from exposure to indoor pollutants, often of chemical and biological origin, has also been identified, and is often characterised by an advanced stage of SBS. These discomforts, also known as building-related illnesses (BRI), are manifested as cough, chest tightness, fever, chills, and muscle aches and generally require extended recovery time or may become chronic issues [16].

3. Literature review

Numerous studies have been conducted on the indoor comfort in buildings but there was heterogeneity in the methodological approaches and inconsistent study reporting. In a review paper, Chinazzo et al. [17], which involved a considerable number of studies, highlighted significant heterogeneity among approaches, particularly regarding the choice of dependent and independent variables, as well as the statistical analysis methods used (identifying as many as 44 different methods). The same authors emphasised inconsistent study reporting, pointing out that key aspects of the research were not reported. Specifically, they referred to research hypotheses, setting features (building location, type, space layout, and building elements), exposure features (e.g., time and length of exposure), data collection and processing, experimental design quality, information about participants, reporting of results (e.g., some results not reported, missing graphical representations, and use of different terminology), and contents of the study discussion and conclusion.

An important background for the proposed work relates to studies that have investigated the relative importance of different aspects of comfort. Among these, Chiang and Lai [18] have proposed a comprehensive indicator for the evaluation of indoor environmental quality. Each aspect of comfort that comprises the indicator is characterized by a weight that quantifies its relative importance. The weights, determined through the Analytic Hierarchy Process (AHP) method, are 29 % for IAQ, 21 % for thermal comfort, 20 % for acoustic comfort, 16 % for visual comfort, and 14 % for the aspect related to electric and magnetic field (EMF). Another study [19], through continuous monitoring of the IEQ carried out with a IEQ logger, validated with large-scale surveys in Hong Kong, developed a composite IEQ index by determining the following weights for the various aspects of comfort: 53 % thermal, 36 % acoustic and 11 % IAQ. Wong et al. [20], proposing an empirical expression for the IEQ of office environments in Hong Kong, through the subjective assessments of the occupants determined the following weights of the different aspects of comfort: thermal 31 %, IAQ 25 %, visual 19 % and 25 % acoustic. A study similar to the previous one but relating to residential environments [21], also contextualised in Hong Kong, found the following weights: 38 % thermal, 38 % acoustic, 21 % visual and 3 % IAQ. A more recent study [22], which also had the objective of proposing a comprehensive index of comfort, with reference to university classroom environments, found the following weights: 35 % thermal, 35 % acoustic and 30 % visual. Again, Yang and Mak [23], using a fuzzy comprehensive evaluation (FCE) and AHP method, developed a model for evaluating IEQ considering the importance of the four aspects of comfort. Referring to the university classroom environment in Hong Kong, they found the following weights to the different aspects: 32 % thermal comfort, 28 % acoustic comfort, 24 % visual comfort and 16 % IAQ. Miao and Ding [24]conducted a study to evaluate the IEQ in existing public buildings with different intended uses in China, through nationwide questionnaire and physical measurements. The results show that the relative importance of the different aspects of comfort varies according to the intended use. For example, in meeting rooms the most important aspect is acoustic comfort, while in offices it is IAQ. Finally, a very recent work [25] has proposed an IEQ effectiveness index to evaluate the cost-effectiveness of improving specific IEQ parameters for Australian office buildings. Using the fuzzy analytic hierarchy process (FAHP) method, the weights of the aspects of comfort diversified for the categories of experts involved in the analysis were obtained. For example, for engineers and assessors thermal comfort is the most important aspect of the four considered, while for architects it is the visual one. Table 1 provides a summary of the relative importance of IEQ aspects as derived from some of the previously reported studies.

It is noted that studies investigating the relative importance of the different aspects of indoor comfort have produced heterogeneous results. Although in most studies thermal comfort can be the most important, the same consistency of results cannot be found for other aspects of comfort. The rankings of importance of acoustic comfort, visual comfort, and indoor air quality are inconsistent across different studies. Zhao and Li explained this inconsistency as being caused by the variability of research designs (e.g., sample size and number of environmental factors) [26].

From the economic point of view, an important line of research investigates the impact of comfort on the productivity of people in buildings to estimate the economic value of indoor comfort.[1] Generally, the quality of indoor climate has been correlated with two productivity indicators: sick leave and work performance.

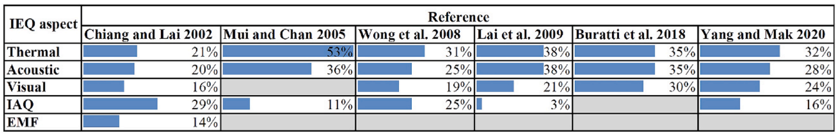
Regarding the sick leave indicator, for example, Milton et al. [27]

---

[1] Below, the economic values of some indoor comfort aspects will be reported, based on the results of various studies. These will be expressed in EUR, by converting the original currencies used in each study at the exchange rate in effect on March 30, 2023. The original currencies vary, including USD, DKK, HK $, RMB.

Table 1

IEQ relative importance in some of the previously reported studies.



IEQ aspect	Reference					
	Chiang and Lai 2002	Mui and Chan 2005	Wong et al. 2008	Lai et al. 2009	Buratti et al. 2018	Yang and Mak 2020
Thermal	21%	53%	31%	38%	35%	32%
Acoustic	20%	36%	25%	38%	35%	28%
Visual	16%		19%	21%	30%	24%
IAQ	29%	11%	25%	3%		16%
EMF	14%					

analysed sick leave data from 1994 for 3720 hourly employees of a large Massachusetts manufacturer in 40 buildings with 115 independently ventilated work areas, using Poisson regression. They found consistent associations among increased sick leave, low levels of outdoor air ventilation, and a high number of complaints regarding indoor air quality. This study estimates the sick leave cost attributable to low air exchange rates to be 442 EUR per employee per year. These findings suggest that net savings of 368 EUR per employee per year can be obtained with increased ventilation. Extending this estimate to the national scale in US results in a value exceeding 21 billion EUR per year.

However, most studies have considered the relationship between level of comfort and work performance indicators [28].

Petersen and Knudsen [29] proposed a method to include the economic aspects of indoor climate as a design criterion to optimise the design of a building intended for office use. Using the proposed approach, they calculated, in monetary terms, the loss of productivity resulting from variations in the indoor climate compared to the situation of optimal occupant performance, with reference to thermal comfort and air quality, using predicted mean vote (PMV) and perceived air quality (PAQ) indices, respectively. From the results of this study, it can be inferred that indoor comfort (in terms of thermal comfort and air quality alone) had a net present value over a period of 30 years equal to 545 EUR/m^2.

Valancius et al. [30] focused on the relationship between the investment costs for the renovation of a heating, ventilation, and air conditioning (HVAC) system and the resulting benefits in terms of energy savings and increased productivity of occupants in a commercial building. They implemented the EP-OP (energy performance and occupant productivity (EP–OP) method [31] using the technique for order preference by similarity to ideal solution (TOPSIS) approach [32]. From the obtained results, it can be inferred that increased productivity can vary, depending on the hypothetical scenario, between 0.14 and 5.11 EUR/m^2/year.

Another approach found in the literature is the estimation of the WTP for different components of indoor comfort. This approach is used for various evaluations, from the estimation of "green" buildings to energy saving measures and indoor comfort, which are of specific interest in this paper, as well as in other areas, such as Buso et al. [33], who investigated the WTP of hotel guests for particularly comfortable rooms. An average 14 % increase in the baseline room rate, quantified in 11.47 EUR/night, was obtained as the marginal WTP *procapite*.

Chau et al. [34], by applying discrete choice experiments (DCE), showed a higher WTP for energy savings compared to the WTP for the improvement of indoor comfort given by better indoor air quality and noise reduction. The results show the same monthly WTP for the two samples (green residents and conventional residents), which is equal to 1.98 EUR (low income) and 2.18 EUR (high income) for the aspect related to air quality and is equal to 1.32 EUR (low income) and 1.45 EUR (high income) for noise reduction.

In contrast, He et al. [35] promoted green housing purchases and estimated the WTP using the DCE for various aspects of green buildings, including thermal comfort and air quality. The study showed that for ideal thermal comfort, WTP ranged from 7.43 EUR/m^2 (lower-middle class) to 17.89 EUR/m^2 (upper-middle class), while for ideal air quality, it ranged from 9.31 EUR/m^2 (lower-middle class) to 28.08 EUR/m^2 (upper-middle class).

Another study [36] conducted a DCE to estimate the WTP for various aspects characterising green residential buildings in Shanghai. The results revealed that respondents valued indoor comfort and health. The WTP, expressed in m^2/month, of 77.98 EUR value was quantified for acoustic comfort and 18.73 EUR value was quantified for air quality.

Table 2 summarises the analysed studies and reports their main economic results. Studies that have investigated the economic value of indoor comfort have primarily focused on residential and office use. This is most likely because these uses involve longer occupancy periods for people in indoor environments, making comfort a topic of greater research interest. The main aspects of comfort that have been evaluated economically are thermal comfort and air quality. To a lesser extent, acoustic comfort has also been assessed; however, no study has specifically addressed the economic value of visual comfort.

Methodological approaches used to estimate indoor comfort are heterogeneous. The most commonly used methodology is a DCE. Second, statistical analysis approaches were employed to establish the relationship between sick building syndrome symptoms and one or more aspects of indoor comfort, thereby deducing the economic value based on the reduction of these symptoms (and the associated expenses) following the improvement of comfort conditions.

The results obtained in terms of the economic value are highly disparate. They are presented as net savings per employee per year, total national benefits, an increase in the market value per unit of building area, or an increase per unit of monthly rental prices. The different modes of presenting results depend primarily on the methodological approach adopted. However, the heterogeneity of the measurement units makes it challenging to compare results across different studies. Table 2 summarises the publications reported investigating comfort from the economic point of view.

4. Methodology

In this study, a DCE was conducted to estimate the economic value of indoor comfort by estimating the WTP for adopting more advanced technological solutions than those commonly available in the market for new construction that can provide a higher level of indoor comfort. DCE involves creating hypothetical scenarios for the respondent's preference judgment. However, because these are stated preferences that may not fully represent individuals' actual intentions, the methodology requires controls, such as including the respondent's current choices among the alternatives, ensuring the plausibility of hypothetical alternatives, and explicitly stating income constraints to minimise unrealistic economic distortion. Moreover, the scenarios must consist of at least two alternatives that represent the most significant characteristics of the object of study (i.e., indoor comfort technologies).

DCE is grounded in a well-established and extensively validated theory of decision-making behaviour that can consider interconnected behaviours, unlike traditional conjoint analysis that relies on conjoint measurement, which is not a behavioural theory [38]. DCE finds its theoretical basis in Lancaster's theory [39] in which the utility of a particular good is determined by the utility of the various characteristics, is designed to jointly evaluate the characteristics by hypothesising different combinations to evaluate the relevant advantages and

Table 2
Summary of the reported publications investigating the economic aspect of indoor comfort.

Year of publication	Title	Ref.	Building use	Evaluated aspect	Evaluation method	Main finding
2000	Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints	[27]	Varies	IAQ	Poisson regression	Consistent associations of increased sick leave with lower levels of outdoor air supply and IEQ complaints, which suggest that net savings of 368 EUR per employee per year may be obtained with increased ventilation.
2010	A choice experiment to estimate the effect of green experience on preferences and WTP for green building attributes	[34]	Residential	IAQ, AC	DCE	Monthly WTP is equal to 1.98 EUR (low income) and 2.18 EUR (high income) for the aspect related to air quality and is equal to 1.32 EUR (low income) and 1.45 EUR (high income) for noise reduction.
2012	Changing ventilation rates in U.S. offices: implications for health, work performance, energy, and associated economics	[37]	Office	IAQ	Statistical analysis, which relates sick building syndrome symptoms and ventilation rate	The study reports the yearly economic benefit of 12 billion EUR by increasing minimum ventilation rates from 8 to 10 l/s per person and 35 billion EUR by increasing ventilation rates from 8 to 15 l/s per person on a U.S wide scale.
2013	Method for cost-benefit analysis of improved indoor climate conditions and reduced energy consumption in office buildings	[30]	Office	TC, IAQ	EP-OP with TOPSIS	The increased productivity after renovation of renovation of an HVAC (heating, ventilation and air conditioning) system can vary between 0.14 and 5.11 EUR/m^2/year.
2017	Method for including the economic value of indoor climate as design criterion in optimisation of office building design	[29]	Office	TC, IAQ	LCC, Capitalising the relation between indoor climate and productivity	Thermal comfort and air quality have a net present value over a period of 30 years equal to 545 EUR/m^2.
2017	Of comfort and cost: examining indoor comfort conditions and guests' valuations in Italian hotel rooms	[33]	Hotel	TC	CVM	An average 14 % increase in the baseline room rate, quantified in 11.47 EUR/night, was obtained as the marginal WTP *procapite.*
2019	How to attract customers to buy green housing? Their heterogeneous WTP for different attributes	[35]	Residential	TC, IAQ	DCE	For ideal thermal comfort, WTP ranged from 7.43 EUR/m^2 (lower-middle class) to 17.89 EUR/m^2 (upper-middle class), while for ideal air quality, it ranged from 9.31 EUR/m^2 (lower-middle class) to 28.08 EUR/m^2 (upper-middle class).
2022	WTP for green office: evidence from Shanghai	[36]	Office	IAQ, AC	DCE	A WTP of 77.98 EUR/m^2/month value was quantified for acoustic comfort and 18.73 EUR/m^2/month value was quantified for air quality.

disadvantages. Among the various versions of the method [40], a DCE was used in which the respondent chose between two different alternatives each time (without assigning a score or ranking). The alternatives must meet the following requirements [41]: a) the number of alternatives in the set is finite, b) the alternatives are mutually exclusive, and c) the set defined by the alternatives is exhaustive (i.e., it includes all possible combinations). DCE and, in general, stated-preference methods offer the advantage of excellent control over the experiment. However, this approach has a potential disadvantage that the results may not be consistent with those that would occur in reality due to possible differences between "stated" and "real" preferences. For this reason and for all consequences, this methodology is occasionally viewed with scepticism [42]. Therefore, it is essential to carry out a precise and careful identification of attributes and levels, analysis (focus group), and preliminary calibration of the questionnaire.

The method is structured into several phases. The first phase involved a description of the features to be evaluated. This must be accurate and detailed to allow the interviewee to evaluate the variations in utility derived from different combinations of attributes. The second phase defines the hypothetical market. This clarifies from the outset that the DCE seeks a WTP for improvement in comfort. In the third phase, the attributes of interest were defined. This phase does not follow a specific standard but refers to some considerations. It is important that the attributes are relevant to the analysis being conducted and that they are significant and relevant to the sample of respondents [43]. Qualitative research was conducted through interviews or focus groups to identify relevant attributes. The fourth phase involved assigning levels to the identified attributes. The choice of levels is made with reference to Ryan [44]; in particular, it takes into account that they must be plausible and useable for the interviewees and must be constructed in such a way that interviewees are willing to make trade-offs between the combinations of attributes presented. After determining the attributes and levels, the fifth phase of the experiment was conducted. The number of alternatives to be presented in each choice set must be determined depending on the type of value measured and/or context of the study [42]. In the next phase, a questionnaire was constructed, and data were collected. The questionnaire contained the following parts: a detailed description of the feature to be evaluated and the hypothetical market; questions aimed at identifying the interviewees' WTP for the evaluated feature; and a collection of information relating to the characteristics of the interviewee, concerning age, income, educational qualification, profession, and others. The data collection procedure can take place in various manners, such as by phone, mail, personal interviews, the web, or a combination of methodologies. The last phase concerns the analysis of the collected data, particularly the organisation and standardisation of the data, calibration of the model, and a critical discussion of the results obtained and their reliability.

The stated-preference data were analysed using the random utility model (RUM) developed from Thurstone's concept of random utility [45]. The model assumes that individual i associates a perceived utility U_{ij} with each alternative j in their choice set I and chooses the alternative that maximises its perceived utility. The utility associated with each alternative depends on its characteristic x_{ij} and marginal utility assigned to each characteristic. The perceived utility of individual i for alternative j is unknown; therefore, it is represented as being composed of a deterministic part V_{ij} that is conditioned on observable characteristics observed by the researcher and a stochastic part ε_{ij} that tracks the effect of all choice-relevant characteristics that are unobserved or unobservable by the researcher and any observation errors. Therefore,

$$U_{ij} = V_{ij} + \varepsilon_{ij}, \tag{1}$$

where U_{ij} is the utility perceived by individual i with respect to alternative *j*, V_{ij} is the deterministic component of utility (i.e., the directly observable component), and ε_{ij} is a random component of utility (i.e., the indirectly explainable component).

Therefore, the probabilistic model of choice predicts that the probability of choosing alternative *j* is greater if its perceived utility is higher than that of the available alternatives, as described by

$$P_i(j|I_i) = P\left[U_{ij} > U_{ik} \forall k \neq j, k \in I_i\right]. \tag{2}$$

From which it can be stated that

$$P_i(j|I_i) = P\left[V_{ij} + \varepsilon_{ij} > V_{ik} + \varepsilon_{ik} \forall k \neq j, k \in I_i\right]. \tag{3}$$

The hypotheses formulated for the joint distribution of the stochastic components of utility functions determine the characteristics and properties of the random utility model. Assuming that the difference in the stochastic components of each pair of alternatives follows a logistic distribution or that the stochastic components of the utility function of each alternative are independent and identically distributed as a Gumbel function, the logit model is derived (binary in the case where the comparisons involve no more than two alternatives at a time) as

$$P_i(j|I_i) = \frac{1}{\left[1 + e^{-\mu\beta'\left(x_{ij} - x_{ik}\right)}\right]}, \tag{4}$$

where μ is conventionally set equal to 1 and linked to the variance of the stochastic components of utility functions, and β represents the perceived marginal utility for each characteristic under consideration.

The economic valuation of the perceived marginal utility for each feature under consideration (marginal willingness to pay) is the ratio between the estimated β coefficient for each feature and the estimated β coefficient for the price or cost features used to describe the choice alternatives.

4.1. The discrete choice experiment

A DCE was conducted to estimate the WTP for technological solutions capable of improving indoor comfort within residential buildings, specifically for a housing unit of approximately 100 m^2 composed of a living room, kitchen, two bedrooms, and two bathrooms.[2] After defining the features to be evaluated, information on basic technological solutions (reference utility levels) was provided to the respondents, who indicated whether changes in the characteristics of the features were improvements or detractions compared with the current building state. Additional information on the usability of the features was provided. The following flowchart (Fig. 1) illustrates the phases of the method with reference to the applications of this study.

An evaluation was conducted with respect to different aspects of indoor comfort and cost.

Cost attributes play important and distinct roles in DCE. Its inclusion allows this methodology to indicate WTP and estimate the expected utility of adopting different technological solutions in monetary terms. Determining the WTP for an alternative or given attribute is possible by determining the marginal WTP for various levels of each attribute [46].

For each of these attributes, two levels were identified (level 0 and level 1), represented by different technological solutions concerning aspects of comfort, as reported in Table 3. When it comes to the attribute of thermal comfort, level 1 enables a better management of internal thermal conditions, with a temperature controller available for each room within the accommodation. The ability to customize and manage the temperature of different rooms is associated with an improved comfort condition [47] due to the full control on the users preferred thermal conditions. The automatic management of shading systems, allowing for continuous adjustment, is linked to higher visual comfort [48]. On the other hand, manual management, leads to suboptimal visual comfort conditions between adjustments. The definition of the two levels of the attribute related to acoustic comfort is based on a probabilistic approach. Adhering to the predicted acoustic requirements outlined by regulations allows for achieving good levels of acoustic comfort within the building's indoor spaces. However, in order for design performance to be confirmed in practice, particular attention must be paid to the technological and construction aspects during the implementation phase. Hence, a building whose acoustic performance is verified in practice ensures an adequate level of acoustic comfort, as mandated by the law. Conversely, a building lacking verification of acoustic performance in practice will have a higher probability of experiencing poorer acoustic comfort. Regarding technologies related to indoor air quality, the solution that ensures better ventilation rate is the "decentralized mechanical ventilation with coupled machines" type. As several studies have pointed out, as reported in the review of Al Horr et al. [48], the ventilation rate parameter is associated with better indoor air quality.

For cost attribute three levels were identified:0 EUR, 15,000 EUR, and 30,000 EUR.

Therefore, in this study, five product attributes were defined, four of which were expressed in two levels and the remaining one in three levels, for 48 different combinations. Considering the impracticality of presenting interviewees with a number of alternative profiles, a fractional factorial design was used that considered a subset of the profiles generated in the full factorial design. To better determine the experimental design, a pre-test phase was conducted involving a small group of expert interviewees in the research field. Then, they were asked to rank the technologies under investigation. Thus, based on the preferences revealed by this small group regarding the investigative attributes, econometric analysis, and literature review, it was possible to define the weights of the experimental design attributes. From these analyses, greater perceived importance emerged for the cost and thermal comfort attributes than for other characteristics.

Despite the small size of the interviewee group, we consider these results as a basis for building the experimental design, as the interviewed sample is representative of the preferences of the sample involved in the subsequent phase. The experimental design was modified using an efficiency choice design [49,50] by assigning a weight to each comfort attribute, as reported in Table 4 (see Table 5).

We prepared 12 choice exercises per individual, each consisting of two attribute combinations, to which the respondent was asked to assign a preference and to develop an experimental design that meets the requirements of orthogonality, minimal overlap, and balance of levels and utilities. In the choice set determination phase, we decided to force a response and eliminate the possibility for respondents to not choose among the proposed alternatives and therefore select the "no-choice" option. Appendix A reports all choice exercises proposed to the respondents.

A questionnaire was prepared and administered to the selected sample through a specific web application. For a better understanding, the choice alternatives were reported both graphically and in tabular mode within the questionnaire (see Fig. 2).

At the end of the twelve choice exercises, the final section of the questionnaire captured the sociodemographic characteristics of the interviewees and included questions regarding gender, age, education level, occupation, income bracket, and characteristics of the municipality of residence.

---

[2] This housing size represents the average size of residences in Italy in according with 2023 Real Estate Market Report by the Italian Revenue Agency [52].

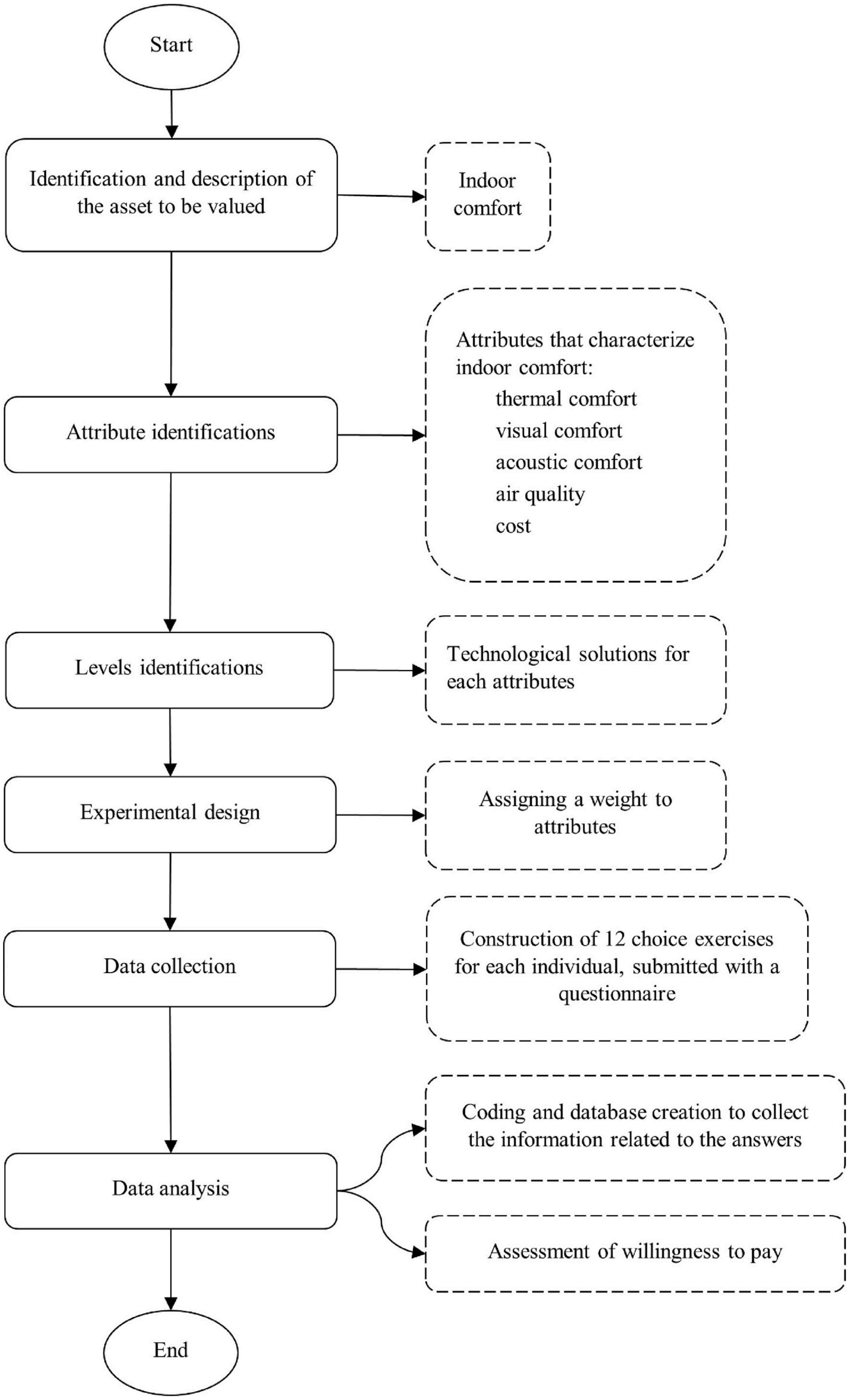


Fig. 1. Flow chart of the method.

Table 3
Attributes, levels, and performance.

Attribute	Level	Technology	Performance	Icon
Thermal comfort	1	Underfloor heating with zone control: multiple thermostats inside the housing.	Customizable temperature in each zone.	
	0	Underfloor heating with a single thermostat inside the housing.	Single temperature set point for the housing.	
Visual comfort	1	Automatic shutter with integrated sensors.	Optimal use of daylighting: great use of natural light throughout the day.	
	0	Manual shutter.	Manual control of brightness: usage left to the user.	
Acoustic comfort	1	Correct design and on-site verification of passive acoustic requirements.	Verified acoustic performance.	
	0	Correct design of passive acoustic requirements.	Correct design with uncertainty in performance	
Indoor air quality	1	Decentralized mechanical ventilation with coupled machines.	Airflow control in individual zones	
	0	Centralized mechanical ventilation.	One machine managing the air exchange throughout the entire housing	

Table 4
Weights assigned to each attribute following the pretest evaluations.

	Thermal comfort	Visual comfort	Acoustic comfort	Air quality
Weight	1.8	0.3	0.4	0.3

5. Results

A questionnaire was administered to the selected sample, and it was possible to trace the profile of the resulting sample based on socio-demographic information from the 83 complete responses obtained. The sample comprised mostly young people under the age of 40 years (80.7 %), with only a minority over the age of 40 years (19.3 %). This selected sample allows for the estimation of the WTP for indoor comfort among the population group that is most pertinent in present and future choices related to housing and should exhibit the greatest influence on investment and design choices.

After completing the questionnaire administration phase, the data were encoded and a database was created. The model specification (utility function) used in this study is linear and is described as follows:

$$U = \beta_{COST} \times (COS\,T_1 - COS\,T_2) + \beta_{TC} \times (TC_1 - TC_2) + \beta_{VC} \times (VC_1 - VC_2) + \beta_{AC} \times (AC_1 - AC_2) + \beta_{AQ} \times (IAQ_1 - IAQ_2). \tag{5}$$

In other words:

$$U = \beta_{COST} \times D_{Cost} + \beta_{TC} \times D_{TC} + \beta_{VC} \times D_{VC} + \beta_{AC} \times D_{AC} + \beta_{IAQ} \times D_{IAQ}, \tag{6}$$

where subscripts 1 and 2 represent the options for choices 1 and 2, respectively, as previously defined.

Table 6 reports the coding of the main independent variables used in the model, while the others are reported in Appendix B.

The dependent variable was the choice:1 for the chosen alternative and 0 for the discarded alternative.

Table 5
Characteristics of the analysed sample.

Variable	Level	Absolute Frequency	Relative Frequency (%)
Gender	Woman	28	33.7
	Man	54	65.1
	Other	1	1.2
	I do not answer	0	0
Age	18–30	48	57.8
	31–40	19	22.9
	41–50	4	4.8
	51–60	11	13.3
	61–70	1	1.2
Education level	Secondary school	1	1.2
	High school	19	22.9
	Bachelor's degree	45	54.2
	PhD	18	21.7
Occupation	Public employee	2	2.4
	Entrepreneur	2	2.4
	Employee	13	15.7
	Freelancer	11	13.2
	Researcher	16	19.3
	Student	37	44.6
	Retiree	0	0
	Other	2	2.4
Income	0-15,000 EUR	31	37.3
	15,001–28,000 EUR	18	21.8
	28,001–55,000 EUR	30	36.1
	55,001–75,000 EUR	2	2.4
	75,001 or more	2	2.4
Altitude of place of residence	Mountainous	4	4.8
	Hilly	14	16.9
	Plain	65	78.3
Population size of place of residence	Up to 5000	18	21.7
	5000–20,000	27	32.5
	20,000–50,000	11	13.3
	50,000–100,000	7	8.4
	100,000–200,000	5	6.0
	Over 200,000	15	18.1

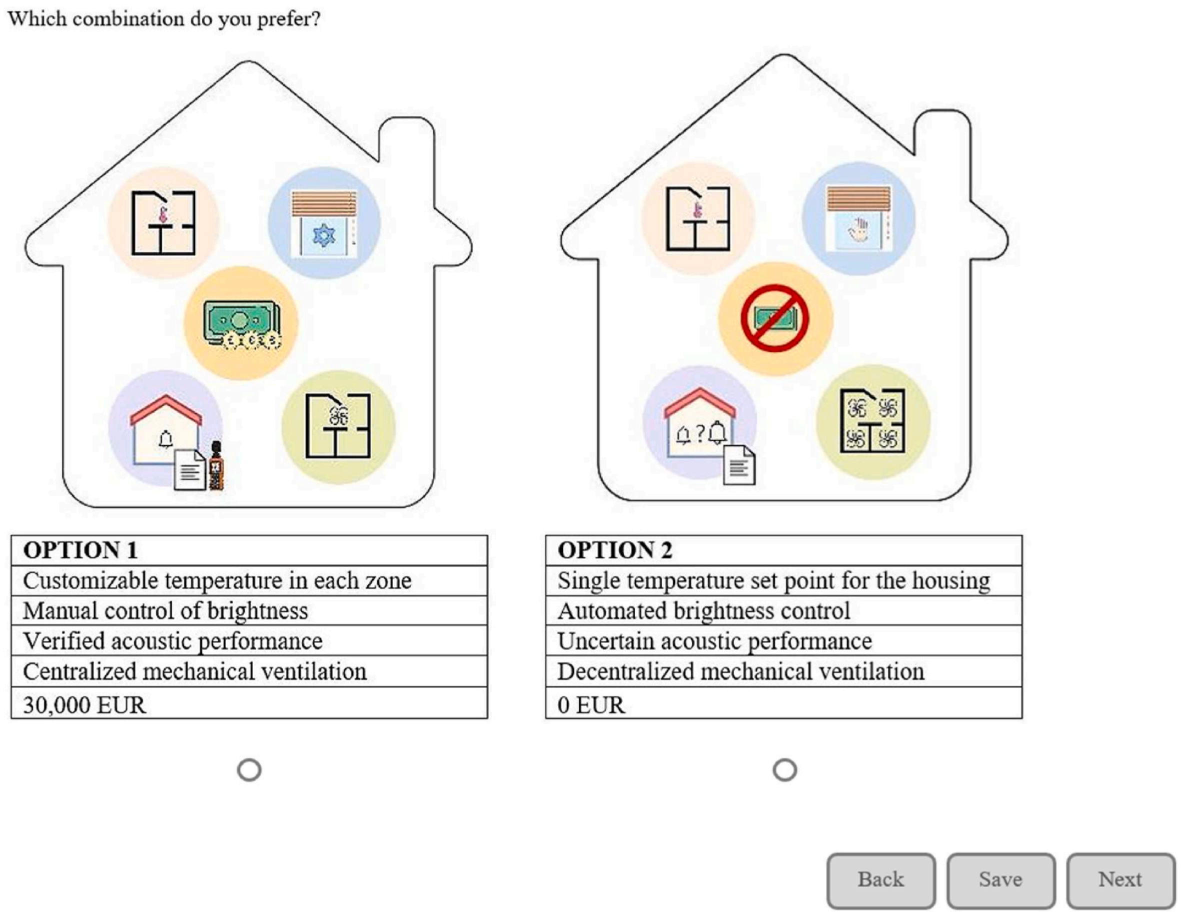
The coefficients of the model were estimated using binary logistic regression. The positive coefficients of the model indicate a preference for the considered mode. As is typical in DCE, the value of the coefficients incorporates a scale factor, and the corresponding value cannot be directly interpreted. Rather, by calculating the ratio between the two coefficients, the scale factor is eliminated, and the obtained contribution assumes a precise economic meaning. Particularly, the ratio between the coefficient associated with a certain attribute state and that associated with the cost expresses the marginal WTP for that specific state. Table 7 presents the results of the regression analyses.

The general validity of the model is confirmed by the likelihood ratio test (probability of the calculated χ^2 lower than 0 %).

The model shows that all four aspects of comfort have positive and significant coefficients. Furthermore, for incomes greater than 28,000 EUR, the coefficient is negative and significant. This counterintuitive result can be explained by the sample characteristics, mostly comprising of young people with low incomes, but with greater sensitivity to aspects of comfort. Generally, this group expressed interest in high-quality buildings in terms of energy and environmental performance.

Table 8 summarises the β coefficients and the WTP obtained for each comfort technology. It represents the WTP for a technology that provides a higher level of comfort (attributes at level 1) than the base technology (attributes at level 0).

The sum of all values results in a total WTP, corresponding to the WTP that would be obtained if all four technologies were implemented at level 1 and the solutions that provide the highest level of comfort. This total value is equal to 74,358.09 EUR assuming a reference housing area



Which combination do you prefer?

OPTION 1	OPTION 2
Customizable temperature in each zone	Single temperature set point for the housing
Manual control of brightness	Automated brightness control
Verified acoustic performance	Uncertain acoustic performance
Centralized mechanical ventilation	Decentralized mechanical ventilation
30,000 EUR	0 EUR
○	○

Fig. 2. Example of a choice question within the questionnaire.

Table 6
Encoding of the main independent variables.

Variable	Type	Meaning	Coding
Cost	Quantitative	Additional cost for the proposed technologies.	Additional cost for the technologies of the alternative to which the utility function refers.
TC	Dummy	Thermal Comfort	1: Zone-controlled underfloor heating 0: Single thermostat underfloor heating
VC	Dummy	Visual Comfort	1: Automatic brightness control 0: Manual brightness control
AC	Dummy	Acoustic Comfort	1: On-site verification of acoustic requirements 0: No on-site verification of acoustic requirements
IAQ	Dummy	Indoor Air Quality	1: Decentralized ventilation 0: Centralized ventilation

of approximately 100 m^2, resulting in a WTP of 743.58 EUR/m^2.

To evaluate the benefit-to-cost ratio, the WTP values were compared with the difference between the cost of the solution that provided a higher level of comfort and the cost of the basic technological solution. These costs were estimated using surveys conducted in the construction market. Table 9 presents the results. Notably, the WTP greatly exceeds the additional cost of technology.

The proposed technology for improving thermal comfort has relatively low installation costs. In fact, a room-by-room temperature control system requires the implementation of a greater number of temperature sensors (one for each heated room), actuators, and control units capable of managing the operational logic than a system with a single regulation for the entire accommodation. However, there were no significant burdens from the perspective of the installed hydraulic system. Therefore, considering the relatively low additional installation cost and significant WTP, the adoption of the level 1 technological solution for thermal comfort presents the highest benefit-to-cost ratio.

The additional cost of installing level 1 technology for visual comfort is significant. The implementation of an automatic shutter control system, which is necessary to ensure the optimal use of daylighting, requires the installation of several components that are not present in the solution with a manual shutter. These devices include brightness sensors, motors for shutter movement, actuators, electrical power supply systems, and control units. Nevertheless, even with a significant additional cost, the results show a more significant WTP, ensuring a favourable benefit-to-cost ratio.

From the perspective of acoustic comfort, the major cost compared to the base solution is represented by the expenses required to perform *in situ* instrumental verification of the acoustic performance. Compared to the standard solution, in which acoustic performance checks are limited to the design phase, the level 1 solution is certified during construction. For this aspect of comfort, the WTP is more than five times greater than the additional cost of adopting the level 1 solution compared with the base solution.

Finally, the additional installation cost of a decentralized mechanical ventilation system with coupled machines compared to a centralised mechanical ventilation system can be attributed to both higher labour costs (more electrical supply points and a greater number of wall openings for the installation of individual units) and higher product supply costs. In this case, the WTP is 2.48 times greater than the additional cost, thus resulting in a significant advantage of adopting an

Table 7
The results of the logit model.

Variable	Coefficient	Standard Error	P value	
Constant	0.587146	0.515152	0.2544	
Interest in housing [INT]	0.338312	0.292909	0.2481	
Housing where one resides similar to the housing described in the experiment [HOUS]	−0.0880497	0.174518	0.6139	
Gender [GEND]	0.0877950	0.159454	0.5819	
Age [AGE]	−0.194828	0.243720	0.4241	
Educational level [ED_LEV]	−0.122647	0.180224	0.4962	
Occupation [OCC]	−0.278322	0.163360	0.0884	*
Participation in the pretest [PART]	−0.105203	0.197322	0.5939	
Income over 28,000 EUR [R_28]	−0.404475	0.171498	0.0183	**
Population of the place of residence under 5000 people [P_M_5]	0.0333550	0.234879	0.8871	
Population of the place of residence between 5000 and 20,000 people [P_520]	0.00130168	0.0756149	0.9863	
Population of the place of residence between 20,000 and 50,000 people [P_2050]	0.0403532	0.244204	0.8688	
Population of the place of residence between 50,000 and 100,000 people [P_50100]	0.146286	0.305754	0.6323	
Population of the place of residence between 100,000 and 200,000 people [P_100200]	0.235977	0.382256	0.5370	
Population of the place of residence over 200,000 people [P_P_200]	0.198257	0.270939	0.4643	
Altitude of the place of residence [ALT]	−0.268876	0.212866	0.2065	
Thermal Comfort differential [D_TC]	1.05039	0.138907	<0.0001	***
Visual Comfort differential [D_VC]	0.463659	0.0733329	<0.0001	***
Acoustic Comfort differential [D_AC]	0.332394	0.0726357	<0.0001	***
Indoor Air Quality differential [D_IAQ]	0.220132	0.0708345	0.0019	***
Cost differential [D_Cost]	−2.77922e-05	5.18825e-06	<0.0001	***

* The correlation is significant at the 0.1 level (2-tailed).
**The correlation is significant at the 0.05 level (2-tailed).
***The correlation is significant at the 0.01 level (2-tailed).
Number of observations: 996.
Likelihood ratio test: Chi-square(20) = 107.416 [0.0000].
Number of cases ‘predicted correctly’ = 621 (62.3 %).

improved technological solution compared to the proposed standard solution.

Table 8
Calculation of WTP and relative importance of comfort aspects.

Comfort aspect and technology	Coefficient β of the technology	Coefficient β of the cost	Willingness to pay	Relative importance
Thermal Comfort - Underfloor heating with zone control	1.05039	−2.77922e-05	377.94 EUR/m^2	51 %
Visual Comfort - Automatic shutter with integrated sensors	0.463659		166.83 EUR/m^2	22 %
Acoustic Comfort - Correct design and on-site verification of passive acoustic requirements.	0.332394		119.60 EUR/m^2	16 %
Indoor Air Quality - Decentralized mechanical ventilation with coupled machines.	0.220132		79.21 EUR/m^2	11 %
Total willingness to pay			**743.58 EUR**/m^2	

Table 9
Comparison between WTP and the additional cost for each aspect of comfort.

Comfort aspect and technology	WTP	Additional installation cost	Benefit-to-cost ratio
Thermal Comfort - Underfloor heating with zone control	377.94 EUR/m^2	26.00 EUR/m^2	14.54
Visual Comfort - Automatic shutter with integrated sensors	166.83 EUR/m^2	65.00 EUR/m^2	2.57
Acoustic Comfort - Correct design and on-site verification of passive acoustic requirements.	119.60 EUR/m^2	22.00 EUR/m^2	5.44
Indoor Air Quality - Decentralized mechanical ventilation with coupled machines.	79.21 EUR/m^2	32.00 EUR/m^2	2.48

6. Discussion

The selected sample for the DCE presented some population skew. Specifically, it mostly comprises young people who show a notable sensitivity towards sustainability and comfort in the building sector, with the latter often being understood as a co-benefit derived from the adoption of more efficient technological solutions. This characteristic emerged from the regression analysis results, which showed a negative coefficient for the income variable. Young people who showed the greatest sensitivity to different aspects of comfort had the lowest income. Despite the skewed age distribution, representing one of the main limitations of the study, the general sample remains valid because it is representative of the population segment that is most likely to be involved in short-term dwelling choices and will therefore express its appreciation for the features investigated herein.

The results of this study can be useful in the early stages of real estate investments, favouring the implementation of technological solutions that guarantee greater indoor comfort, as favoured by the market. This trend has already been confirmed by evidence from the real estate market in recent years, where new homes equipped with all the aforementioned technological solutions obtain high valuations and are easily sold. In contrast, homes equipped with standard solutions have become increasingly difficult to sell in the market despite significant price discounts that exceed the cost of upgrading to the advanced technologies described above.

Given the significant heterogeneity in studies exploring indoor comfort, particularly regarding sample size, building types, technological characteristics of buildings, and environmental conditions, it is essential to contextualise the results (WTP) of this study from a relative rather than an absolute standpoint. Moreover, the higher value of a property and the increased rental price should always be interpreted within the specific real estate market to which they pertain. These findings cannot be universally generalised and cannot be used as a benchmark to compare results across other studies. Further support for the findings in existing literature, which indicate that thermal comfort holds the highest relative importance in most cases, is provided by examining the results of this study in relative terms [19–23,51]. The lower relative importance of indoor air quality as an aspect of comfort is another result that confirms the findings of other studies [19,21,23,51], indicating that indoor air quality is less significant compared to thermal, visual, and acoustic comfort aspects.

7. Conclusions

In the first part of this paper, we report the different definitions proposed in the literature for thermal, visual, and acoustic comfort and indoor air quality. In summary, the aspects of comfort refer to the subjective perception of occupants in an indoor environment, and also on objective factors, like physical environment. Different approaches to comfort evaluation have been presented, such as the predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) for thermal comfort; light quantity, light uniformity, light quality based on colour rendering, and prediction of glare risk for visual comfort; reverberation time, apparent soundproofing power, standardised acoustic insulation of the façade, impact insulation, maximum sound pressure level, and equivalent sound pressure level for acoustic comfort; and internal concentrations of pollutants for indoor air quality.

After outlining the topic of indoor comfort evaluation, a literature review was conducted. It focuses on published works that deal with the relative importance of the different aspects of IEQ and its economic evaluation. For these works, we can succinctly state that a certain heterogeneity of the methodological approaches used; therefore, the presentation of results has been observed, resulting in greater difficulty in comparing the results of different studies. In this study, through a DCE, the WTP of a selected sample for the adoption of technological solutions to be implemented in a residential dwelling that guarantees better comfort from a thermal, visual, acoustic, and air quality standpoint was obtained. The results showed a significant WTP for all four aspects of comfort, with the highest value attributed to thermal comfort. There is significant convenience in adopting more efficient technological solutions in all cases based on the comparison of the WTP for different aspects of comfort with the marginal costs for the implementation of level 1 technological solutions compared to level 0 for each aspect. The highest convenience was achieved in terms of thermal comfort. Then, the potential limitations of the study have been discussed. These primarily pertain to the selected sample, which is predominantly composed of young individuals, and the heterogeneity among various studies on the same topic (in terms of sample sizes, building types, technological characteristics, etc.), making result validation through comparison challenging.

Future research developments should aim to address the limitations related to the sample by improving the size and enhancing its characteristics. Another significant effort should be directed towards homogenize methodological approaches and ensuring consistency in study reporting.

Ethical approval

The authors declare no conflicts of interest. This article does not contain any studies involving human participants and/or animals performed by any of the authors.

8. Consent to participate

Not applicable.

9. Consent to publish

Not applicable.

Funding

This study was supported by the Eurac Research, Bolzano (South Tyrol), Italy, where Francesca Tintinaglia conducted internships under the supervision of Paolo Rosato and Francesco Babich.

Availability of data and materials

The data supporting the findings of this study are available from the corresponding author, RB, upon reasonable request.

CRediT authorship contribution statement

Raul Berto: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Francesca Tintinaglia:** Writing – original draft, Validation, Resources, Data curation. **Paolo Rosato:** Validation, Supervision, Methodology, Conceptualization.

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

Data will be made available on request.

Acknowledgments

The authors especially thank Francesco Babich for encouraging the deepening of indoor comfort in residential buildings and Lucia Rotaris for their valuable suggestions for setting up the discrete choice experiment.

APPENDIX A

Table A.1
Experimental design.

Choice exercise	Option 1	Option 2
1	Customizable temperature in each zone Manual control of brightness Verified acoustic performance Centralized mechanical ventilation 30,000 EUR	Single temperature set point for the housing Automated brightness control Uncertain acoustic performance Decentralized mechanical ventilation 0 EUR
2	Single temperature set point for the housing Automated brightness control Uncertain acoustic performance Centralized mechanical ventilation	Customizable temperature in each zone Manual control of brightness Verified acoustic performance Decentralized mechanical ventilation

(*continued on next page*)

Table A.1 (*continued*)

Choice exercise	Option 1	Option 2
	0 EUR	30,000 EUR
3	Single temperature set point for the housing Automated brightness control Verified acoustic performance Decentralized mechanical ventilation 30,000 EUR	Customizable temperature in each zone Manual control of brightness Uncertain acoustic performance Centralized mechanical ventilation 0 EUR
4	Single temperature set point for the housing Manual control of brightness Uncertain acoustic performance Decentralized mechanical ventilation 0 EUR	Customizable temperature in each zone Automated brightness control Uncertain acoustic performance Centralized mechanical ventilation 30,000 EUR
5	Customizable temperature in each zone Manual control of brightness Verified acoustic performance Centralized mechanical ventilation 15,000 EUR	Single temperature set point for the housing Automated brightness control Uncertain acoustic performance Decentralized mechanical ventilation 15,000 EUR
6	Single temperature set point for the housing Manual control of brightness Uncertain acoustic performance Centralized mechanical ventilation 0 EUR	Customizable temperature in each zone Automated brightness control Verified acoustic performance Decentralized mechanical ventilation 30,000 EUR
7	Customizable temperature in each zone Automated brightness control Uncertain acoustic performance Centralized mechanical ventilation 15,000 EUR	Single temperature set point for the housing Manual control of brightness Verified acoustic performance Decentralized mechanical ventilation 15,000 EUR
8	Single temperature set point for the housing Automated brightness control Verified acoustic performance Centralized mechanical ventilation 15,000 EUR	Customizable temperature in each zone Manual control of brightness Uncertain acoustic performance Decentralized mechanical ventilation 15,000 EUR
9	Customizable temperature in each zone Automated brightness control Uncertain acoustic performance Decentralized mechanical ventilation 0 EUR	Single temperature set point for the housing Manual control of brightness Verified acoustic performance Centralized mechanical ventilation 0 EUR
10	Single temperature set point for the housing Automated brightness control Verified acoustic performance Decentralized mechanical ventilation 0 EUR	Customizable temperature in each zone Manual control of brightness Uncertain acoustic performance Centralized mechanical ventilation 30,000 EUR
11	Customizable temperature in each zone Manual control of brightness Uncertain acoustic performance Decentralized mechanical ventilation 30,000 EUR	Single temperature set point for the housing Automated brightness control Verified acoustic performance Centralized mechanical ventilation 0 EUR
12	Customizable temperature in each zone Manual control of brightness Verified acoustic performance Decentralized mechanical ventilation 15,000 EUR	Single temperature set point for the housing Automated brightness control Uncertain acoustic performance Centralized mechanical ventilation 15,000 EUR

APPENDIX B. 12

Table B.1
Encoding of independent variables.

Variable	Meaning	Coding
INT	Interest in housing	1: Yes 0: No 0: I do not answer
HOUS	Housing where one resides similar to the housing described in the experiment	1: Yes 0: No 0: I do not answer
GEND	Gender	1: Womano 0: Man 0: Other 0: I do not answer
AGE	Age	1:18–30 years 1: 31–40 years 1: 41–50 years 0: 51–60 years 0: 61–70 years

(*continued on next page*)

Table B.1 (*continued*)

Variable	Meaning	Coding
		0: 71 or more
ED_LEV	Education level	0: Elementary school 0: Secondary school 0: High school 1: Bachelor's degree 1: PhD
OCC	Occupation	0: Merchant 0: Public employee 0: Entrepreneur 0: Employee 0: Freelancer 1: Researcher 1: Student 0: Retiree 0: Other
PART	Participation in the pretest	1: Yes 0: No
R_28	Income over 28,000 EUR	1: Yes 0: No
P_M_5	Population of the place of residence under 5000 people	1: Yes 0: No
P_520	Population of the place of residence between 5000 and 20,000 people	1: Yes 0: No
P_2050	Population of the place of residence between 20,000 and 50,000 people	1: Yes 0: No
P_50100	Population of the place of residence between 50,000 and 100,000 people	1: Yes 0: No
P_100200	Population of the place of residence between 100,000 and 200,000 people	1: Yes 0: No
P_P_200	Population of the place of residence over 200,000 people	1: Yes 0: No
ALT	Altitude of the place of residence	1: Plain 0: Hilly 0: Mountainous

References

[1] J.L.M. Hensen, On the Thermal Interaction of Building Structure and Heating and Ventilating System of Building Structure and Heating and Ventilating System, 1991.

[2] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy Build. 34 (2002) 549–561, https://doi.org/10.1016/S0378-7788(02)00005-1.

[3] Z. Lin, S. Deng, A study on the thermal comfort in sleeping environments in the subtropics-Developing a thermal comfort model for sleeping environments, Build. Environ. 43 (2008) 70–81, https://doi.org/10.1016/j.buildenv.2006.11.026.

[4] R.K. Macpherson, The assessment of the thermal environment. A review, Occup. Environ. Med. 19 (1962) 151–164, https://doi.org/10.1136/OEM.19.3.151.

[5] S. Liu, S. Schiavon, H.P. Das, M. Jin, C.J. Spanos, Personal thermal comfort models with wearable sensors, Build. Environ. 162 (2019), 106281, https://doi.org/10.1016/J.BUILDENV.2019.106281.

[6] P.O. Fanger, Assessment of thermal comfort, Build. Eng. 84 (1973) 1–6.

[7] O. Seppänen, W.J. Fisk, Q. Lei-Gomez, Q. Lei, Effect of temperature on task performance in office environment, in: 5th International Conference on Cold Climate Heating, Ventilating and Air Conditioning, 2006. https://escholarship.org/content/qt45g4n3rv/qt45g4n3rv.pdf.

[8] L. Lan, P. Wargocki, Z. Lian, Quantitative measurement of productivity loss due to thermal discomfort, Energy Build. 43 (2011) 1057–1062, https://doi.org/10.1016/J.ENBUILD.2010.09.001.

[9] W.K.E. Osterhaus, Discomfort glare assessment and prevention for daylight applications in office environments, Sol. Energy 79 (2005) 140–158, https://doi.org/10.1016/j.solener.2004.11.011.

[10] S. Torresin, R. Albatici, F. Aletta, F. Babich, T. Oberman, S. Siboni, J. Kang, Indoor soundscape assessment: a principal components model of acoustic perception in residential buildings, Build. Environ. 182 (2020), 107152, https://doi.org/10.1016/J.BUILDENV.2020.107152.

[11] J.J. Wesolowski, An overview of indoor air quality, J. Environ. Health 46 (1984) 311–316.

[12] J. Sundell, On the history of indoor air quality and health, Indoor Air 14 (2004) 51–58.

[13] B. Chenari, J. Dias Carrilho, M. Gameiro Da Silva, Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review, Renew. Sustain. Energy Rev. 59 (2016) 1426–1447, https://doi.org/10.1016/j.rser.2016.01.074.

[14] M. Maroni, B. Seifert, T. Lindvall, Indoor Air Quality: a Comprehensive Reference Book, Elsevier Science, 1995. https://books.google.it/books?hl=it&lr=&id=qsyLaKnn-nYC&oi=fnd&pg=PP1&dq=Indoor+Air+Quality:+A+Comprehensive+Reference+Book&ots=mFysMPx4jS&sig=f6X7O2SuiqYxioadjFGFDcbXgyw (accessed March 21, 2023).

[15] L. Wallace, E. Pellizzari, C. Wendel, Total volatile organic concentrations in 2700 personal, indoor; and outdoor air samples collected in the US EPA team studies, Indoor Air 1 (1991) 465–477, https://doi.org/10.1111/J.1600-0668.1991.00011.X.

[16] K. Andersson, G. Stridh, The Use of Standardized Questionnaires in Building Related Illness (BRI) and Sick Building Syndrome (SBS) Surveys, NATO/OCCM Pilot Study on Indoor Air Quality. Oslo, National Institute of Occupational Health, 1992, pp. 47–64.

[17] G. Chinazzo, R.K. Andersen, E. Azar, V.M. Barthelmes, C. Becchio, L. Belussi, C. Berger, S. Carlucci, S.P. Corgnati, S. Crosby, L. Danza, L. de Castro, M. Favero, S. Gauthier, R.T. Hellwig, Q. Jin, J. Kim, M. Sarey Khanie, D. Khovalyg, C. Lingua, A. Luna-Navarro, A. Mahdavi, C. Miller, I. Mino-Rodriguez, I. Pigliautile, A. L. Pisello, R.F. Rupp, A.M. Sadick, F. Salamone, M. Schweiker, M. Syndicus, G. Spigliantini, N.G. Vasquez, D. Vakalis, M. Vellei, S. Wei, Quality criteria for multi-domain studies in the indoor environment: critical review towards research guidelines and recommendations, Build. Environ. 226 (2022), 109719, https://doi.org/10.1016/J.BUILDENV.2022.109719.

[18] C.M. Chiang, C.M. Lai, A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan, Build. Environ. 37 (2002) 387–392, https://doi.org/10.1016/S0360-1323(01)00034-8.

[19] K.W. Mui, W.T. Chan, A new indoor environmental quality equation for air-conditioned buildings, Architect. Sci. Rev. 48 (2005) 41–46, https://doi.org/10.3763/ASRE.2005.4806.

[20] L.T. Wong, K.W. Mui, P.S. Hui, A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices, Build. Environ. 43 (2008) 1–6, https://doi.org/10.1016/J.BUILDENV.2007.01.001.

[21] A.C.K. Lai, K.W. Mui, L.T. Wong, L.Y. Law, An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings, Energy Build. 41 (2009) 930–936, https://doi.org/10.1016/J.ENBUILD.2009.03.016.

[22] C. Buratti, E. Belloni, F. Merli, P. Ricciardi, A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates, Build. Environ. 139 (2018) 27–37, https://doi.org/10.1016/J.BUILDENV.2018.04.038.

[23] D. Yang, C.M. Mak, Relationships between indoor environmental quality and environmental factors in university classrooms, Build. Environ. 186 (2020), 107331, https://doi.org/10.1016/J.BUILDENV.2020.107331.

[24] Y. Miao, Y. Ding, Indoor environmental quality in existing public buildings in China: measurement results and retrofitting priorities, Build. Environ. 185 (2020), 107216, https://doi.org/10.1016/J.BUILDENV.2020.107216.

[25] S. Roumi, F. Zhang, R.A. Stewart, M. Santamouris, Weighting of indoor environment quality parameters for occupant satisfaction and energy efficiency, Build. Environ. 228 (2023), 109898, https://doi.org/10.1016/J.BUILDENV.2022.109898.

[26] Y. Zhao, D. Li, Multi-domain indoor environmental quality in buildings: a review of their interaction and combined effects on occupant satisfaction, Build. Environ. 228 (2023), https://doi.org/10.1016/J.BUILDENV.2022.109844.

[27] D.K. Milton, P.M. Glencorss, M.D. Walters, Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints, Indoor Air 10 (2000) 212–221, https://doi.org/10.1034/J.1600-0668.2000.010004212.X.

[28] J.A. Porras-Salazar, S. Schiavon, P. Wargocki, T. Cheung, K.W. Tham, Meta-analysis of 35 studies examining the effect of indoor temperature on office work performance, Build. Environ. 203 (2021), https://doi.org/10.1016/J.BUILDENV.2021.108037.

[29] S. Petersen, M.D. Knudsen, Method for including the economic value of indoor climate as design criterion in optimisation of office building design, Build. Environ. 122 (2017) 15–22, https://doi.org/10.1016/J.BUILDENV.2017.05.036.

[30] R. Valancius, A. Jurelionis, V. Dorosevas, Method for cost-benefit analysis of improved indoor climate conditions and reduced energy consumption in office buildings, Energies 6 (2013) 4591–4606, https://doi.org/10.3390/EN6094591.

[31] R. Valancius, A. Jurelionis, V. Dorosevas, Method for cost-benefit analysis of improved indoor climate conditions and reduced energy consumption in office buildings, Energies 6 (2013) 4591–4606, https://doi.org/10.3390/en6094591.

[32] T.C. Wang, H. Da Lee, Developing a fuzzy TOPSIS approach based on subjective weights and objective weights, Expert Syst. Appl. 36 (2009) 8980–8985, https://doi.org/10.1016/j.eswa.2008.11.035.

[33] T. Buso, F. Dell'Anna, C. Becchio, M.C. Bottero, S.P. Corgnati, Of comfort and cost: examining indoor comfort conditions and guests' valuations in Italian hotel rooms, Energy Res. Social Sci. 32 (2017) 94–111, https://doi.org/10.1016/J.ERSS.2017.01.006.

[34] C.K. Chau, M.S. Tse, K.Y. Chung, A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes, Build. Environ. 45 (2010) 2553–2561, https://doi.org/10.1016/J.BUILDENV.2010.05.017.

[35] C. He, S. Yu, Q. Han, B. de Vries, How to attract customers to buy green housing? Their heterogeneous willingness to pay for different attributes, J. Clean. Prod. 230 (2019) 709–719, https://doi.org/10.1016/J.JCLEPRO.2019.05.160.

[36] Y. Zhang, H. Yin, Willingness to pay for green office: evidence from shanghai, Environ. Sci. Pollut. Control Ser. 29 (2022) 84345–84356, https://doi.org/10.1007/S11356-022-21555-6.

[37] W.J. Fisk, D. Black, G. Brunner, Changing ventilation rates in U.S. offices: implications for health, work performance, energy, and associated economics, Build. Environ. 47 (2012) 368–372, https://doi.org/10.1016/J.BUILDENV.2011.07.001.

[38] J.J. Louviere, T.N. Flynn, R.T. Carson, Discrete choice experiments are not conjoint analysis, Journal of Choice Modelling 3 (2010) 57–72, https://doi.org/10.1016/S1755-5345(13)70014-9.

[39] K.J. Lancaster, A new approach to consumer theory, J. Polit. Econ. 74 (1966) 132–157.

[40] A.S. Choi, B.W. Ritchie, F. Papandrea, J. Bennett, Economic valuation of cultural heritage sites: a choice modeling approach, Tourism Manag. 31 (2010) 213–220.

[41] K.E. Train, Discrete Choice Methods with Simulation, second ed., Cambridge University Press, Cambridge, 2009 https://doi.org/10.1017/CBO9780511805271.

[42] T.P. Holmes, W.L. Adamowicz, F. Carlsson, Choice Experiments, 2017, https://doi.org/10.1007/978-94-007-7104-8_5.

[43] T. Kjær, A Review of the Discrete Choice Experiment - with Emphasis on its Application in Health Care, Syddansk Universitet, 2005.

[44] M. Ryan, Using conjoint analysis to take account of patient preferences and go beyond health outcomes: an application to in vitro fertilization, Soc. Sci. Med. 48 (1999) 535–546, https://doi.org/10.1016/S0277-9536(98)00374-8.

[45] L.L. Thurstone, A law of comparative judgment, Psychol. Rev. 34 (1927), https://doi.org/10.1037/h0070288.

[46] R.K. Blamey, J.W. Bennett, J.J. Louviere, M.D. Morrison, J.C. Rolfe, Attribute causality in environmental choice modelling, Environ. Resour. Econ. 23 (2002), https://doi.org/10.1023/A:1021202425295.

[47] N. Aqilah, H.B. Rijal, S.A. Zaki, A review of thermal comfort in residential buildings: comfort threads and energy saving potential, Energies 15 (2022), https://doi.org/10.3390/EN15239012.

[48] Y. Al Horr, M. Arif, A. Kaushik, A. Mazroei, M. Katafygiotou, E. Elsarrag, Occupant productivity and office indoor environment quality: a review of the literature, Build. Environ. 105 (2016) 369–389, https://doi.org/10.1016/J.BUILDENV.2016.06.001.

[49] W. Kuhfeld, Experimental design, efficiency, coding, and choice designs, in: Marketing Research Methods in Sas: Experimental Design, Choice, Conjoint, and Graphical Techniques, vols. 47–97, 2005.

[50] J.M. Rose, M.C.J. Bliemer, Constructing efficient stated choice experimental designs, Transp Rev 29 (2009) 587–617, https://doi.org/10.1080/01441640902827623.

[51] B. Cao, Q. Ouyang, Y. Zhu, L. Huang, H. Hu, G. Deng, Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai, Build. Environ. 47 (2012) 394–399, https://doi.org/10.1016/J.BUILDENV.2011.06.022.

[52] Osservatorio del Mercato Immobiliare (OMI) dell'Agenzia delle Entrate, RAPPORTO IMMOBILIARE 2023 - Il Settore Residenziale, 2023.