Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings

Andrea Invidiata[a,*], Monica Lavagna[b], Enedir Ghisi[a]

[a] Federal University of Santa Catarina, Department of Civil Engineering, Laboratory of Energy Efficiency in Buildings, Florianópolis, SC, 88040-900, Brazil
[b] Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Milan, 20133, Italy

The building sector is one of the largest consumers of natural resources and energy in the world. Design stra-tegies to improve the energy efficiency can decrease the negative impacts of a building. In order to evaluate and select the most appropriate design strategies for buildings, they should be analysed through a multidisciplinary approach based on sustainable development. The objective of this study is to propose a method that combines adaptive thermal comfort, climate change, life cycle assessment, life cycle cost analysis and multi-criteria de-cision making to help selecting the best design strategies to improve the sustainability of buildings. The method presented herein is based on a system of indicators that allows a comprehensive evaluation of design strategies. A multi-family social building, located in Milan, northern Italy, was used as a case study considering a 100-year lifespan. Six design strategies were evaluated. The EnergyPlus computer programme was used to estimate the annual energy demand for air-conditioning alone, with and without the design strategies. Three different da-tabases were used to perform the life cycle analysis. For the life cycle cost analysis, the cost of each strategy was estimated based on the pricelist of the Milan Chamber of Commerce (Camera di Commercio di Milano). The results show that there will be an average increase of 53% in the cooling energy demand and a decrease of 49% in the heating energy demand in 2080 compared to the consumption in 2017. The design strategy with the highest level of sustainability was a reinforced concrete frame with rectified bricks, followed by a reinforced concrete frame with cellular concrete blocks and by cross-laminated timber (X-Lam) and wood fibre. This research highlighted the need for the use of a multi-criteria method to ensure the right selection of design strategies to obtain more sustainable buildings.

Keywords: Energy efficiency, Life cycle assessment, Life cycle cost analysis, Multi-criteria decision, making Thermal comfort, Sustainable buildings

1. Introduction

The building construction sector is considered one of the largest consumers of natural resources and energy. Buildings consume 30–40% of all primary energy and natural resources over their lifespan (construction, operation, maintenance and demolition) and account for 30% of the global emission of greenhouse gases [1,2]. An appropriate choice of design strategy reduces the energy demand of buildings [3–5] and improves the indoor comfort conditions for the inhabitants [6,7]. Assaf and Nour [8] stated that through the correct use of energy efficiency strategies the energy demand can be reduced in 38% in new residential and commercial buildings. Perez et al. [6] studied passive design strategies in buildings through the adaptive thermal comfort model. The use of passive techniques, like natural ventilation and solar control systems, can decrease thermal discomfort. In these studies, the buildings were frequently analysed over their operational phase [8,9]. However, a greater amount of materials and resources are required in order to obtain better indoor conditions and a more energy-efficient building. As a consequence, the environmental impact of the building over its construction, maintenance and demolition phases is greatly increased [10–16]. Therefore, some authors have investigated a more holistic approach, which covers the period from the production of the materials used for the construction all the way to the demolition and recycling phases. Through a methodology based on the sustainable design of buildings, it is possible to reduce their environmental impact and improve the quality of life of the inhabitants. In recent years, different methods have been developed. One of these is life cycle assessment (LCA), which is used to analyse the environmental impacts during the life cycle of products and services [17]. By means of LCA it is possible to analyse different environmental impact categories associated with the construction, use, maintenance and demolition of a building. In recent studies, different approaches applying LCA to buildings have been described. Stazi et al. [18] studied 70 residential buildings in Italy; five case studies were monitored and one case

Received 15 November 2017;
Received in revised form 5 April 2018;
Accepted 29 April 2018
Available online 03 May 2018

* Corresponding author.
E-mail address: a.invidiata@gmail.com (A. Invidiata).

Published Journal Article available at: https://doi.org/10.1016/j.buildenv.2018.04.041

underwent an in-depth environmental evaluation. The authors considered the global warming potential, ozone layer depletion and acidification potential in the analysis of the buildings. Motuziene et al. [14] analysed the life cycle of a single-family house in Lithuania considering three impact categories: primary energy demand, global warming potential and ozone layer depletion. The goal of the study was to improve the energy efficiency of buildings, given the impact on the environment over the life cycle. Atmaca and Atmaca [19] studied the life cycle of two residential buildings in Turkey considering two impact categories: the primary energy demand and the carbon dioxide emissions. These studies demonstrate different ways of analysing buildings through the LCA method. The impact category most frequently used is the global warming potential and this is followed by the energy demand [14,18,19]. This is because the energy efficiency aspect is the most relevant parameter according to researchers who have assessed buildings through LCA. Often, the LCA method is associated with life-cycle cost analysis (LCCA) to evaluate the cost of the building over the life cycle [20–22]. Studies employing LCCA have been conducted to identify the best choice and determine which phase presents the highest cost [20–22]. However, frequently, the application of LCA and LCCA to buildings does not facilitate the selection of the best design strategy [14,23,24]. In this context, multi-criteria decision making (MCDM) appears to be a suitable tool to complement LCA or LCCA [14,24]. There are many ways to apply different multi-criteria analysis methods. One of the most commonly used is the analytic hierarchy process (AHP). AHP was first proposed by Saaty [25] as an MCDM tool, aimed at the determination of weighting factors for the criteria under consideration through pairwise comparisons. MCDM is an effective tool for the analysis of different parameters in the same case study. However, its application in LCA is not common. With the use of MCDM, LCA and LCCA, Motuziene et al. [14] analysed three different types of envelopes in a single-family house in Lithuania. The results show that the MCDM method is an important tool for the analysis of different parameters in buildings. The appropriate selection of design strategies for buildings needs to be based on the analysis of several factors rather than considering a single factor. Thus, the objective of this study was to propose a method that combines adaptive thermal comfort, climate change, life cycle assessment, life cycle cost analysis and multi-criteria decision making to help selecting the best design strategies to improve the sustainability of buildings. This paper shows a small part of an extensive research; therefore, it has some limitations that will be addressed in section 5.1.

2. Method

The method considered the three pillars of sustainable development (social, environmental and economic factors) to evaluate the design strategies for buildings. Four parameters were analysed: number of hours in which there is internal thermal comfort, primary energy demand over the life cycle, carbon dioxide emissions over the life cycle and cost over the life cycle. The method encompasses a combination of LCA, LCCA, indoor comfort conditions, future effects of climate change and MCDM to analyse the design strategies (Fig. 1).

The method is divided into five main parts: (i) evaluation of the thermal performance of the building through the adaptive comfort method; (ii) life cycle energy assessment (LCEA); (iii) life cycle carbon dioxide emissions assessment ($LCCO_2A$); (iv) evaluation of the design strategies through life cycle cost analysis (LCCA); and (v) multi-criteria decision making (MCDM).

In this method, only the design strategies are analysed through LCA and LCCA. Other materials that make up the building are not evaluated. The recycling phase is not considered in LCA and LCCA. The EnergyPlus computer programme was used to evaluate the energy demand and the indoor comfort conditions over the operational phase. The method was applied in a multi-family social building located in Milan.

2.1. Adaptive thermal comfort

The first parameter assessed was the indoor comfort in the building. By means of the adaptive comfort method [26], it was possible to determine the number of hours in which there is internal thermal comfort in the building in a one-year period, with and without design strategies. This was carried out using the EnergyPlus computer programme, version 8.4. The analysis consists of verifying if the use of the design strategies allows for an improvement in the internal thermal comfort. Eq. (1) shows how the upper limit of the comfort zone is obtained [26].

$$U_{lim} = 0.31 \times t_{pma} + 21.3 \tag{1}$$

where U_{lim} is the upper limit of the comfort zone (°C) and t_{pma} is the mean outdoor air temperature (°C).

Eq. (2) shows how the lower limit of the comfort zone is obtained.

$$L_{lim} = 0.31 \times t_{pma} + 14.3 \tag{2}$$

where L_{lim} is the lower limit of the comfort zone (°C) and t_{pma} is the mean outdoor air temperature (°C).

By considering the limits of the comfort zone, it is possible to determine if the design strategies can improve the thermal comfort conditions in the building. Eq. (3) shows how to determine the number of hours in which there is internal thermal comfort when using a design strategy.

$$H_{comfort} = H_a - H_b \tag{3}$$

where $H_{comfort}$ is the increment in the number of hours in which there is internal thermal comfort over one year when a design strategy is used (h), H_a is the number of hours in which there is internal thermal comfort over one year when using a design strategy (h), and H_b is the number of hours in which there is internal thermal comfort over one year without the use of a design strategy (h).

2.2. Life cycle energy assessment

The primary energy demand was analysed through the LCA. This enabled the energy balance to be identified, i.e., the energy saved over the building life cycle due to the use of the design strategies (Eq. (4)).

$$LCE_b = OE_s - (EE + ME + DE) \tag{4}$$

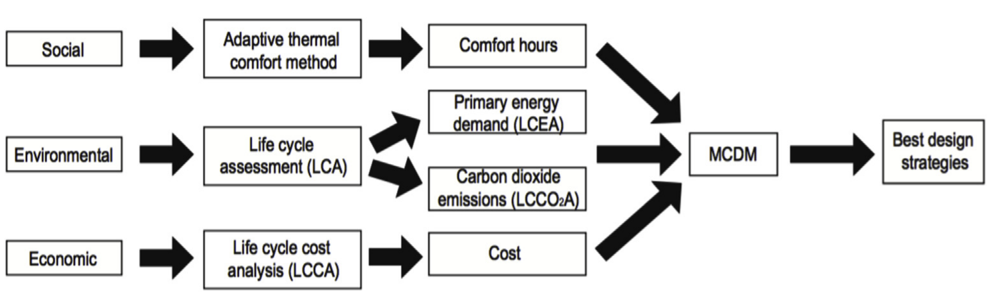

Fig. 1. Flowchart of the method.

where LCE_b is the life cycle energy balance (kWh); OE_s is the energy saved over the operational phase due to the use of the design strategy (kWh); EE is the energy embodied in the design strategy (kWh); ME is the energy associated with the design strategy over the maintenance phase (kWh); and DE is the energy associated with the design strategy over the demolition phase (kWh).

Over the operational phase only the consumption for air-conditioning was considered [27,28]. The heating and cooling energy demand represent more than 40% of the consumption in residential buildings in Europe [27,28]. Furthermore, the design strategies analysed in this study are design strategies typically used to reduce and improve the energy consumption for heating and cooling in residential buildings. For transportation of the design strategy from the manufacturer to the retailer, three distances were adopted in the primary energy demand and the carbon dioxide emissions parameters (50 km, 250 km and 1000 km) to analyse the impact of the transportation on the LCA. For transportation of the workers to the construction site, a distance of 50 km was adopted in the different LCA phases. In this case only one distance was adopted because workers generally live close to the construction site. For the transportation of the design strategy to the closest landfill site, a distance of 50 km was adopted. Also, in this case only one distance was adopted because the waste disposal site closest to the construction site is generally used. The re-use phase involves complex analysis in the LCA [29,30]. Therefore, the re-use phase of the design strategies was not considered.

2.3. Life cycle carbon dioxide assessment

Following the evaluation of the design strategies using the primary energy demand parameter, the design strategies were analysed considering their life cycle carbon emissions. Only the design strategies were analysed. The carbon emissions (CO_2e) balance is the CO_2e saved over the life cycle of the building due to the use of the design strategies (Eq. (5)).

$$LCO_2b = OCO_2s - (ECO_2 + MCO_2 + DCO_2) \tag{5}$$

where LCO_2b is the carbon emissions balance ($kgCO_2e$); OCO_2s is the carbon emissions saved over the operational phase due to the use of the design strategy ($kgCO_2e$); ECO_2 is the carbon emissions embodied in the design strategy ($kgCO_2e$); MCO_2 is the energy associated with the design strategy over the maintenance phase ($kgCO_2e$); and DCO_2 is the carbon emissions associated with the design strategy over the demolition phase ($kgCO_2e$).

2.4. Life cycle cost analysis

The cost of each design strategy was analysed applying LCCA. Through the economic balance it is possible to define the cost for the use of the design strategy during the life cycle of the building. The savings obtained by decreasing the energy demand during the lifespan of the building were subtracted from the initial costs, maintenance costs and final demolition costs (Eq. (6)).

$$LCCb = CS - (CI + CM + CD) \tag{6}$$

where LCCb is the economic balance (€); CS is the savings gained in relation to the electricity bill during the operational phase due to the use of the design strategy (€); CI is the initial cost of the design strategy (€); CM is the maintenance cost of the design strategy (€); and CD is the demolition cost of the design strategy (€).

2.5. Multi-criteria decision making

Multiple-criteria decision making (MCDM) can be applied for complex decisions involving many criteria. As mentioned above, there are a lot of MCDM used in international studies. Among them, the COPRAS method is acknowledged by scholars as one of the most reliable and accurate, and it is used to solve different engineering and management multi-attribute problems [31,32]. In order to find the best design strategy for the building, the AHP and multi-criteria decision-making method known as the complex proportional assessment (COPRAS) were applied [31]. The COPRAS method was first introduced in 1994 by Zavadskas and Kaklauskas [32]. This method assumes direct and proportional dependence of the significance and utility degree of investigated versions on a system of criteria adequately describing the alternatives and on values and weights of the criteria. The COPRAS method can be successfully applied for dealing with complex selection problems. In this study, by using COPRAS, it was possible to define the best design solutions giving to the four parameters used (indoor comfort hours, primary energy demand, CO_2 emissions and costs) a different weight in the construction sector.

To analyse the four parameters used in this study, 30 experts from three different areas (design, research, administrative/technical) of the construction sector from the region of Lombardia, Italy, were selected. The experts participated in the survey by setting the weightings for the criteria and determining their priority. Following the Saaty comparison scale of nine levels [25], they filled in the pairwise comparison matrix with the following parameters and their corresponding weights (w): indoor comfort hours (x1), primary energy demand (x2), CO_2 emissions (x3) and cost (x4) (Table 1).

The scale of the relative importance ranged from 1 to 9. The preference scale for the pairwise comparison of two parameters ranged from the maximum value of 9 to 1/9. In order to ensure the consistence of the comparison matrix, the consistency ratio (CR) must be determined and the condition $CR < 0.1$ must be satisfied.

The first step to obtain the final decision using the COPRAS method is the formation of the normalised decision-making matrix, where the goal is to obtain the non-dimensional weighted values from the comparative parameters (Eq. (7))

$$dij = \frac{xij \cdot qi}{\Sigma xij} \quad i = \overline{1, m}; \quad j = \overline{1, n} \tag{7}$$

where d_{ij} is the non-dimensional weighted values; x_{ij} is the value *j* of criterion *i* in the decision value; m is the number of criteria; n is the number of compared evaluations; and q_i is the significance of criterion *i*.

Eq. (8) shows how the sums of minimising S_+ and maximising S_- normalised indicators are obtained.

$$S_+ = \sum\nolimits_{j=1}^{n} S_{+j} = \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{m} d_{+ij} \quad S_- = \sum\nolimits_{j=1}^{n} S_{+j} = \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{m} d_{-ij} \tag{8}$$

where d_{+ij} and d_{-ij} are the non-dimensional weighted values; x_{ij} is the value *j* of criterion *i* in the decision value; m is the number of criteria; n is the number of compared evaluations; and q_i is the significance of criterion *i*.

The relative importance Qj of each alternative aj is evaluated using Eq. (9).

$$Q_j = S_{+j} + \frac{S_{-\min} \cdot \sum_{j=1}^{m} S_{-j}}{S_{-j} \cdot \sum_{j=1}^{m} \frac{S_{-\min}}{S_{-j}}} \quad j = 1,2,3, \ldots m \tag{9}$$

where S-min is the minimum value of S-j.

Table 1
Comparison matrix of the four parameters.

Parameters	weight	x1	x2	x3	x4
x1	w1	1			
x2	w2		1		
x3	w3			1	
x4	w4				1

Fig. 2. Multi-family social complex of buildings: *"Cenni di Cambiamento"*.

The final step is to calculate the ranking (utility degree) of each design strategy (Eq. (10)).

$$N_j = \frac{Q_j}{Q_{\max}} \cdot 100\% \tag{10}$$

where Q_j is the relative importance; Q_{max} is the maximum relative significance value. The index value Nj is used to obtain the ranking of the different design strategies.

Through the normalisation of the four parameters used in the study, it is possible to obtain the relative importance Qj of each design strategy and the utility degree Nj of each alternative.

3. Case study

The method was applied to a multi-family social building located in Milan (Fig. 2). A lifespan of 100 years was considered for the case study [33]. The *Cenni di Cambiamento* complex was designed by *Studio Rossi Prodi Associati* in 2013 to be highly energy efficient and obtained level A on the Italian energy certification scale [34]. The complex is comprised of four buildings. In this study, only one building was evaluated. The building has nine stories and a basement floor. The basement was not evaluated. On each floor there are four flats of different sizes. The internal and external walls are made of cross-laminated timber (X-Lam). Rock wool was used in the envelope of the building. Aluminium window frames with triple glass windows and argon gas, with a thermal transmittance of 0.60 W/m^{2}K, are installed. Aluminium shading devices are in place to reduce the solar radiation on the building. Table 2 shows the thermal characteristics of the envelope of the building.

3.1. Design strategies

To apply the proposed method to the case study, five design strategies were analysed and compared with the actual design of the building. Recent projects of multi-family social housing in Italy were analysed to identify the design strategies [35–41]. Three different structures of the building were evaluated: X-Lam, reinforced concrete frame and steel frame. A simplified method to calculate the dimensions of the structures was used. The three structures were analysed with different insulations or envelope materials. A total of six design strategies (cases) for the building were evaluated: X-Lam and rock wool (actual case), X-Lam and wood fibre, reinforced concrete frame with cellular concrete blocks, reinforced concrete frame with rectified bricks, steel frame and drywall with rock wool, and steel frame and drywall with wood fibre. With regard to the roof of the building, only the insulation was analysed. In the different design strategies the same thermal transmittance as the actual envelope was maintained. As mentioned above, only the design strategies were evaluated using the LCA and LCCA. Table 3 shows the characteristics of the six design strategies evaluated.

Table 4 shows the database used in the case study. The embodied energy of the design strategies was obtained from three different databases: ICE database [42], Ecoinvent 3 and the EPD certification of building materials. The average value and the standard deviation were used to analyse the design strategies.

Table 5 shows the lifespan of the design strategies based on a literature review [19,20,44–49].

In the cost parameter, the cost of each strategy was obtained through the pricelist of the Milan Chamber of Commerce [50]. The cost of maintenance and replacement of material took into account the average inflation in the last ten years in Italy, which was 1.34% a year [51].

3.2. Computer simulation

In order to assess the energy demand and the indoor comfort conditions, the EnergyPlus computer programme, version 8.4, was used. The building was evaluated disregarding the influence of other buildings in the area and considering constant use and occupation by the users. Details on the occupation, thermal load and use pattern were obtained based on the Italian regulation for energy efficiency in buildings [52]. The equipment and lighting system were operated with 100% load over the working hours. The building was evaluated under two different conditions: (i) while naturally ventilated to get the comfort hours; and (ii) operating with an air-conditioning system to get the energy demand of the building. The naturally-ventilated flats were analysed considering 20 °C as the indoor temperature controlling the opening or closing of the windows. When the flats were operating with air-conditioning, the operation period of the air-conditioning system was established according to the indoor occupation of the flat (bedrooms and living room). It was considered that when users are not at home, the rooms are naturally ventilated and the indoor temperature adopted to control the opening or closing of windows was 20 °C. In order to obtain the energy demand for air-conditioning, the set-point temperatures were taken as 20 °C for heating and 26 °C for cooling [52]. The air-conditioning system was defined based on a Baseline HVAC System Types from ANSI/ASHRAE Standard 90.1. The air-conditioning system considered for this study refers to System 2—PTHP (Packaged Terminal Heat Pump). The air-conditioning coefficient of performance was defined according to Section 6 of ANSI/ASHRAE Standard 90.1, i.e., 3.52 W/W.

Table 2
Thermal characteristics for each component of the building.

Component of the building	Materials	Thermal transmittance (W/m^2K)	Thermal capacity (kJ/m^2K)	Solar absorptance (%)
Roof	Waterproofing (0.1 cm) Concrete (7.0 cm) Rock Wool (11 cm) X-Lam Panel (20 cm) Plasterboard (1.5 cm)	0.20	354	0.30
External wall	Fibre Cement Panel (1.5 cm) Cavity (> 5.0 cm) Rock Wool (11 cm) X-Lam Panel (16.0 cm) Plasterboard (1.5 cm)	0.21	203	0.30
Floor	Ceramic Floor (0.75 cm) Under Floor (2.0 cm) Concrete (7.0 cm) X-Lam Panel (20 cm) Plasterboard (1.5 cm)	0.55	345	–
Windows	Glass Cavity with Argon gas Glass Cavity with Argon gas Glass	0.60	–	0.56 (solar factor)

Table 3
Design strategies analysed.

Structure	Case	External walls	Roof	Internal walls
X-Lam	1 - Actual	X-Lam (20 cm) – Rock wool (11 cm)	Rock wool (12 cm)	X-Lam (12 cm)
	2	X-Lam (20 cm) – Wood fibre (12 cm)	Wood fibre (14 cm)	X-Lam (12 cm)
Reinforced concrete frame	3	Cellular concrete block (30 cm)	Rock wool (12 cm)	Perforated bricks (8 cm)
	4	Rectified bricks (45 cm)	Rock wool (12 cm)	Perforated bricks (8 cm)
Steel Frame	5	Drywall - Rock wool (15 cm)	Rock wool (12 cm)	Drywall (10 cm)
	6	Drywall - Wood fibre (17 cm)	Wood fibre (14 cm)	Drywall (10 cm)

3.3. Climatic data and tool to assess climate change

The effect of climate change was investigated in the case study. Recent studies show the importance of evaluating the effect of climate change on buildings [7,53,55]. For this reason, to analyse the design strategies considering the four parameters, the effects of climate change on the building were studied. The tool Climate Change World Weather File Generator [54,55] was used for the A2 (medium high) emissions scenario for three future time slices, the 2020s, 2050s and 2080s [56]. The building was evaluated based on the current climate data (2017) and the three sets of future climate data generated for the city of Milan, using the weather data file in the Italian climatic data collection *"Gianni De Giorgio"* (IGDG) [57]. Recent publications provide further details on the operation of this tool [7,55].

4. Results and discussion

4.1. Climatic data analysis

Fig. 3 shows the annual outdoor air temperature, relative humidity and global horizontal radiation in Milan given in the four climate data files: 2017, 2020, 2050 and 2080.

The outdoor air temperature is predicted to increase over the next few decades in Milan. Thus, by 2080, the annual average outdoor air temperature is expected to increase by 3.6 °C compared to the current temperature. On the other hand, the annual average relative humidity

Table 4
Embodied energy and CO_2 emissions in the three databases used.

Material	Embodied Energy (MJ/kg)					Embodied Emissions ($kgCO_2/kg$)				
	ICE	EPD	Eco-inv.	Average	Std. Deviation	ICE	EPD	Eco-inv.	Average	Std. Deviation
Rock wool	16.8	27.1	16.6	20.2	6.0	1.12	1.30	1.36	1.26	0.12
EPS	88.6	92.0	106.4	95.7	9.4	3.29	3.32	4.61	3.74	0.75
XPS	–	88.4	91.0	89.7	1.8	–	2.9	3.51	3.21	0.43
Wood fibre	20.0	36.4	23.9	26.8	8.6	0.98	−0.93	1.93	0.66	1.46
Concrete frame	1.9	–	–	1.9	–	0.19	–	–	0.19	–
Brick	3.0	4.2	2.9	3.4	0.7	0.24	0.3	0.25	0.26	0.03
Concrete block	0.7	3.6	0.9	1.8	1.6	0.09	0.41	0.11	0.20	0.18
X-Lam	16.0	27.5	29.6	25.8	8.6	1.09	−1.5	0.75	0.21	1.24
Aluminium	155.0	146.0	129.0	143.3	13.2	9.16	7.7	9.96	8.94	1.15
Fibreboard	10.4	8.8	8.5	9.2	1.0	0.9	0.5	0.61	0.67	0.21
Mortar	1.1	0.8	1.5	1.1	0.4	0.18	0.09	0.19	0.15	0.06
Plasterboard	6.7	5.06	1.7	4.5	2.5	0.39	0.25	0.22	0.29	0.09
Concrete	1.0	1.7	1.4	1.4	0.4	0.16	0.23	0.22	0.20	0.04
Steel	20.1	11.19	22.4	17.9	5.9	1.46	0.76	2.04	1.42	0.64

Over the operational phase, the average generation factor used to convert the electricity consumption into carbon emissions was 0.3524 $kgCO_2e/kWh$ [43].

Table 5
Lifespan of materials.

Material/Component	Lifespan (Years)								
	SBSA [44]	Takano et al. [45]	Atmaca and Atmaca [19]	Rauf and Crowford [46]	Lewan-dowska et al. [47]	Mithra-ratne and Vale [20]	Inter NACHI [48]	Sche-uer [49]	Average
Reinforced concrete frame	60	–	–	150	–	100	100	–	**102**
Steel frame	–	–	–	150	–	100	100	75	**131**
Wood frame	60	–	–	150	100	100	100	–	**102**
Thermal insulation	–	–	–	–	50	100	100	75	**81**
Brick	–	50	25	150	100	100	–	–	**85**
Fibre cement panel	–	50	–	–	–	50	100	–	**67**
Ceramic floor	–	–	15	–	20	30	–	30	**24**
Wood panel	–		–	–	–	30	–	75	**52**
Plaster	–	50	–	–	50	100	–	–	**67**

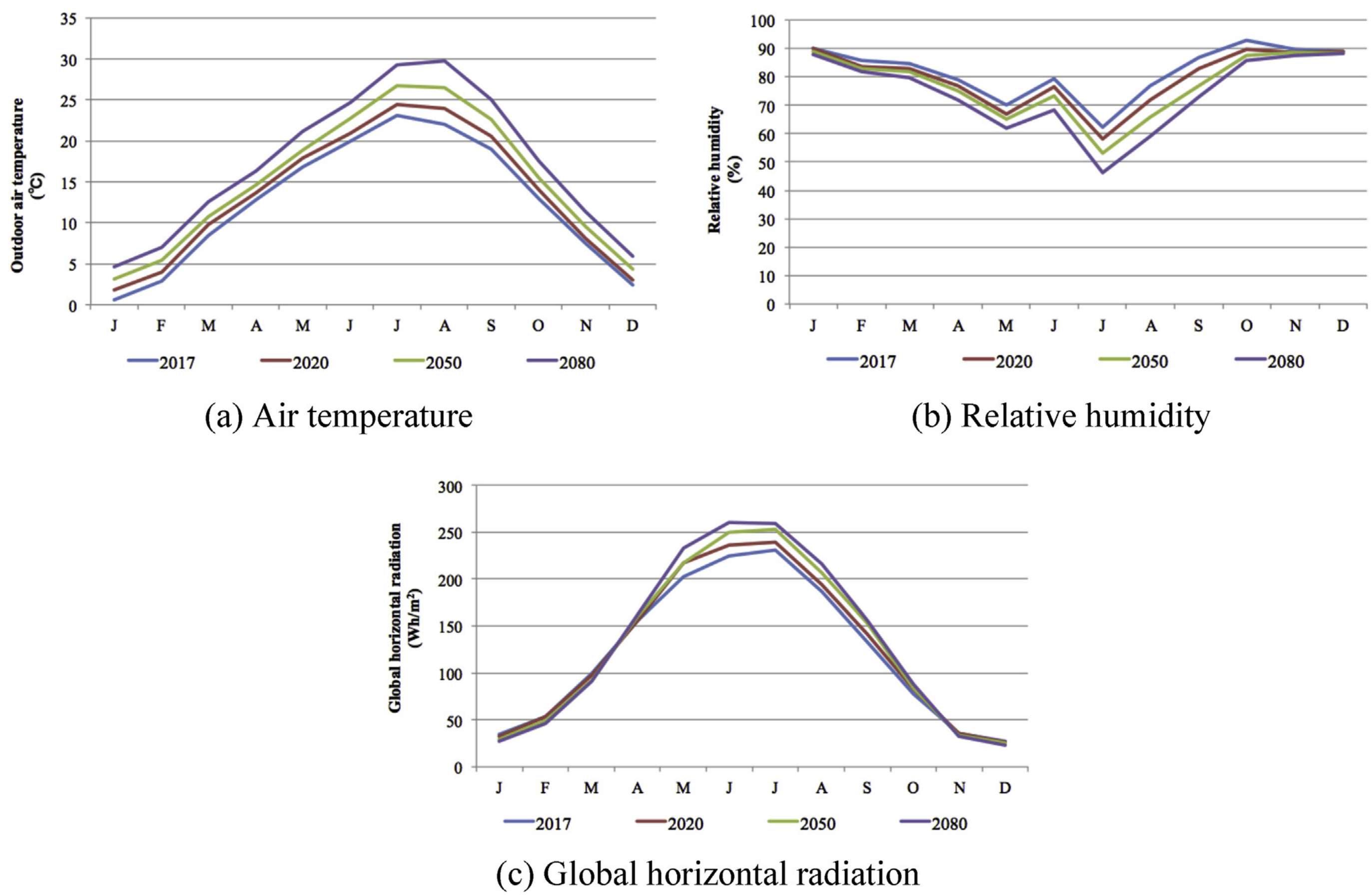

Fig. 3. Climate data for Milan over four different periods.

is predicted to decrease in this period and by 2080 it is expected to be 5.7% lower compared to the current levels. Finally, by 2080 the average global horizontal radiation is expected to increase by 7.2 Wh/m^2 compared to the current levels. The analysis of the future climate conditions in Milan highlights the future effects of climate change and these directly affect the energy and thermal performance of buildings, as demonstrated by recent international studies [7,54,55]. For this reason, it is important to consider the climate change effects when analysing the life cycle of buildings.

4.2. Effect of climate change on the building

Considering that climate change directly affects the energy and thermal behaviour of the building, Fig. 4 shows the comfort hours in the building, considering the six design strategies, currently and over the next few decades. In all cases, by comparing 2080 to the current year, the internal heat discomfort hours will increase 185% on average. The increase in the heat discomfort will cause an average reduction of 7% in comfort hours, however, simultaneously, the internal cold discomfort hours will decrease 47% on average. The best design strategy in terms of comfort hours was case 4, i.e., reinforced concrete frame with rectified bricks.

Fig. 5 shows the heating and cooling energy demand of the building with the six design strategies, currently and over the next few decades. In all cases, comparing 2080 to the current year, the energy demand will increase 13% on average. This increase is due to the considerable growth in the cooling energy demand due to the warmer conditions in the future. On the other hand, climate warming has a direct positive effect on the heating energy demand, which will decrease by 50% on average. Case 4 was again the best design strategy in terms of comfort

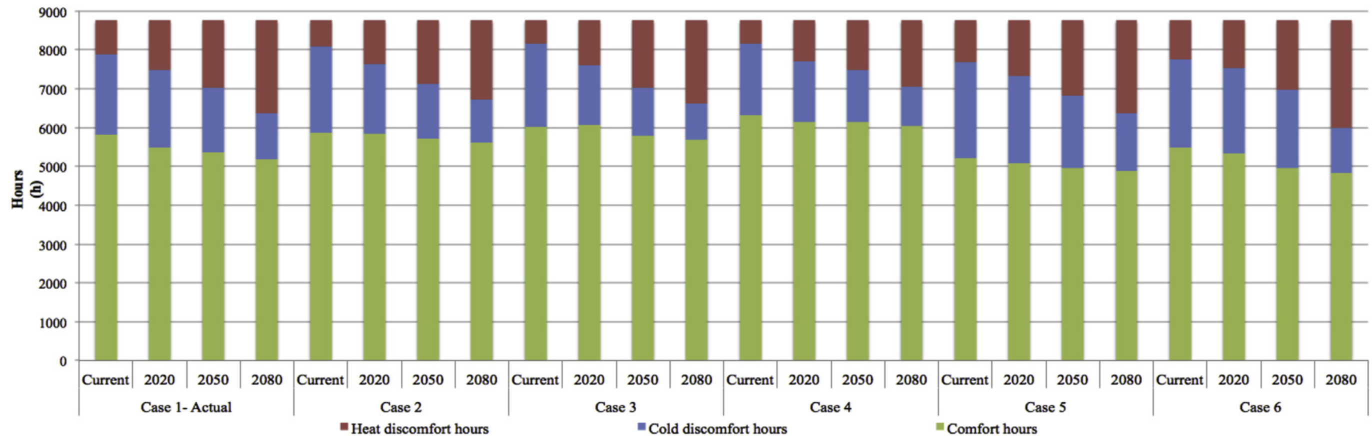

Fig. 4. Annual comfort hours for each design strategy and climate data.

hours.

4.3. Design strategies based on the four parameters

Fig. 6 shows the results for each design strategy according to each parameter. Case 1 represents the actual building design. The results show a different behaviour for each design strategy. The influence of the three different databases on the design strategies (indicated by a vertical line) showing the highest and lowest values in Fig. 6 was analysed for the parameters energy demand and CO_2 emissions. The comfort parameter in case 4 (reinforced concrete frame with rectified bricks) obtained the best result, with more than 6000 indoor comfort hours per year, while case 5 (steel frame and drywall with rock wool) obtained less than 5000 h per year. For the energy demand parameter, the best design strategy was found to be case 3 (reinforced concrete frame with cellular concrete blocks) with 1500 MWh, while case 2 (X-Lam and wood fibre) was the least attractive option (3400 MWh over the life cycle). Among all design strategies, the embodied energy represents the largest part of the energy consumed over the life cycle. In case 4 the embodied energy represents 91% of the total energy. Maintenance is also a relevant phase in the energy life cycle of the design strategies, accounting for 30% of the total energy demand in case 5. In all design strategies, the demolition phase represents less than 2% of the energy consumed over the life cycle. Fig. 6 shows that the use of different databases may impact the results of the life cycle by 30%. Thus, it is clear that the selection of the correct database is one of the main issues in a LCA, as shown in international studies [11,13]. The results for the carbon dioxide emissions show that the two design strategies using an X-Lam frame are the best choices, with just over 230 tCO_2e. Case 4 (reinforced concrete frame with rectified bricks), obtained the highest emissions (630 tCO_2e) over the life cycle. The embodied emissions represent the main part of the total emissions. The maintenance phase accounts for 34% of the life cycle emissions in the case of X-Lam structures, between 20% and 23% for the steel frame design strategies and only 8% for the reinforced concrete frame. The demolition phase represents around 3% of the life cycle of the design strategies. For the emission parameter, the variation due to the three databases is significant; for instance, over the entire life cycle of the X-Lam design strategies the results may vary by 200%. As for the cost parameter, the best design strategy was case 4 (reinforced concrete frame with rectified bricks), with a cost of € 2,500,000, while case 2 (X-Lam and wood fibre) was associated with the highest cost of € 2,927,000 over the life cycle. In relation to the final cost, considering all the design strategies, the initial phase represents 43–49%, the maintenance phase 46–54% and the demolition phase 1–5%. An interesting finding is that labour accounts for 40% of the life cycle costs, which is a high contribution compared to the energy and emission parameters.

4.4. Design strategies applied to the building

After analysing the design strategies according to the four parameters, the application of the design strategies to the building was

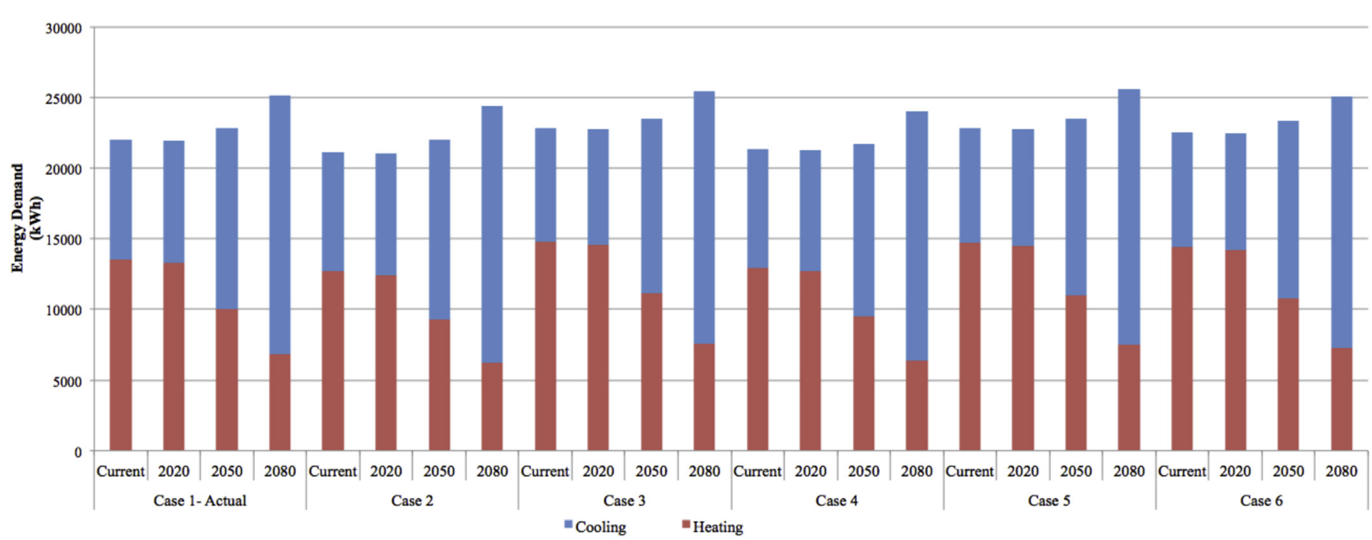

Fig. 5. Cooling and heating energy demand for each design strategy and climate data.

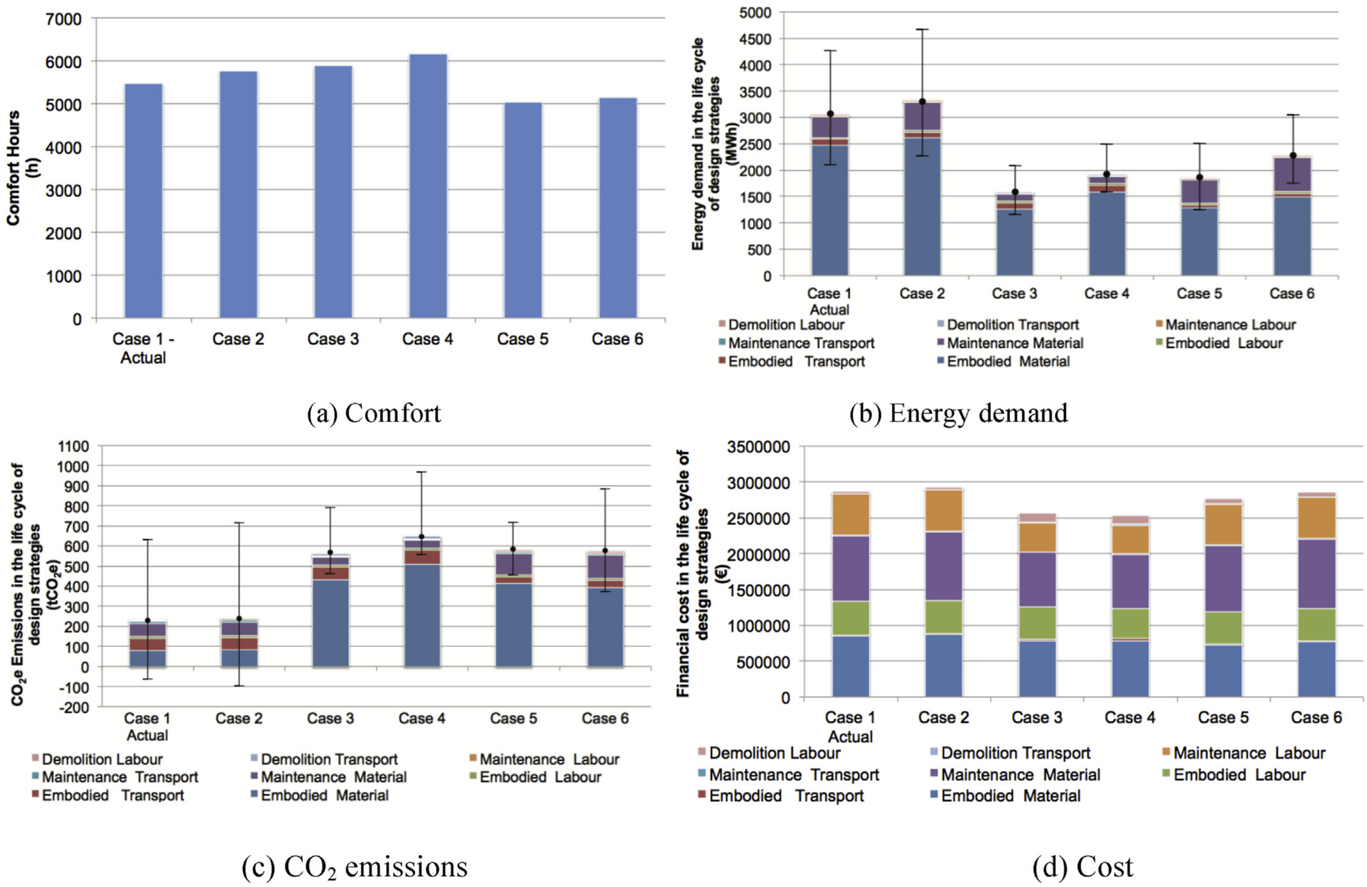

Fig. 6. Comfort, energy demand, CO_2 emissions and costs for the design strategies over the life cycle.

investigated. The results for the energy simulation of the building with different design strategies show a similar behaviour due to the constant thermal transmittance of the envelope. Fig. 7 shows the results of the design strategies compared to the actual building design. The results represent the entire lifespan of the building (100 years). For the comfort parameter, only the two design strategies with a steel frame obtained negative comfort hours compared to the actual building design, due to the low thermal capacity of the steel frame. Case 4 (reinforced concrete frame with rectified bricks) provided the best result, increasing the number of hours in the life cycle of the building in which there is internal thermal comfort by up to 69,000 h (11%), around 700 h per year, in comparison to the actual design. The greater thermal mass ensures a better thermal performance, increasing the comfort hours. For the energy demand parameter, case 2 obtained a negative energy balance, while case 3 resulted in the greatest reduction in the energy demand compared to the actual building design. Case 3 (reinforced concrete frame with cellular concrete blocks) allowed energy savings of approximately 1300 MWh over the life cycle. The actual design and case 2 obtained the worst performances due to the highest embodied energy of the wood structure in X-Lam. With regard to the carbon emissions balance, only case 2 improved the performance of the building. The other design strategies obtained a negative CO_2e balance compared the actual design. The X-Lam uses natural materials in the envelope of the building which reduces the carbon emissions. The databases used for the analyses of CO_2 emissions and embodied energy of the X-Lam material show significant differences, which leads to contrasting results for both parameters. Finally, for the economic balance, all design strategies applied to the building obtained a positive balance and the best design strategy was the reinforced concrete frame with rectified bricks, with cost savings of over € 290,000. This result shows that the use of consolidated construction solutions, such as reinforced concrete structures and walls in brick blocks, is still the best economic solution compared to more recent construction solutions.

4.5. Multi-criteria decision making

In order to find the best design strategy for the building, the AHP and multi-criteria decision making method COPRAS were applied. Firstly, the results of the survey were analysed. Through a survey it is possible to understand which of the parameters used is the most relevant among professionals. Table 6 shows the weighting and priority for each parameter. The 30 experts were divided into three groups according to their activities. The results show that among the three groups of professionals there are different perceptions regarding the importance of the four sustainability parameters. This is due to the fact that the 30 experts come from three distinct construction sectors and have a different approach. Despite this, all three groups of professionals participate in the implementation and development of the construction sector. For this reason, the average of the results was used. For the researchers, comfort is considered the most important parameter, followed by CO_2 emissions, cost and energy demand. The cost parameter is the most relevant for the administrative and technical professional, followed by energy, CO_2 emissions and comfort. For the designers, cost is also considered the most important parameter, followed by energy demand, comfort and CO_2 emissions. Finally, among the 30 experts the cost parameter was the most relevant, followed by energy, emissions and comfort. To ensure the consistency of the comparison matrix, the consistency ratio (CR) was determined and the condition CR < 0.1 was satisfied. The results show that the average priorities of the criteria (and weightings) are as follows: cost (0.306), energy demand (0.258), comfort (0.233), and carbon dioxide emissions (0.204).

Table 7 shows the results for the five design strategies compared to

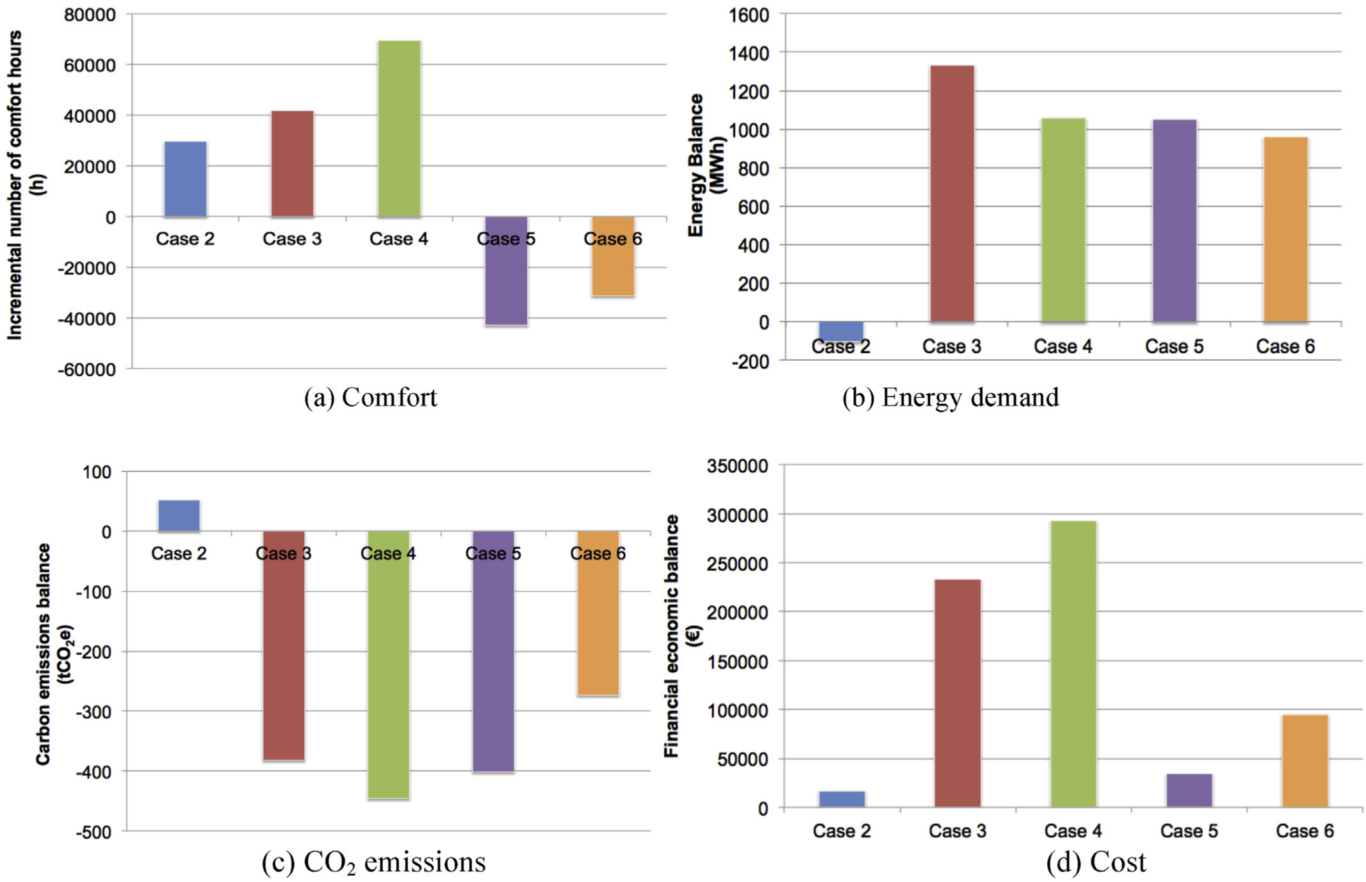

Fig. 7. Comfort, energy demand, CO_2 emissions and costs for the design strategies over the life cycle compared to the actual design strategy.

the actual building design. Through the relative importance *Qj* the ranking of the six case studies can be obtained, where the design strategy that obtained the best *Qj* will have a utility degree of 100%. The best design strategy was case 4 (reinforced concrete frame with rectified bricks, 100%), followed by case 3 (reinforced concrete frame with cellular concrete blocks, 75.4%), and case 2 (X-Lam and wood fibre, 20.8%). For cases 6 and 5 the results obtained were similar to those for the actual design strategy of the building, despite a positive result in the cost parameter (most influent parameter). Case 5 obtained a negative utility degree (−7.1) despite having a positive cost.

The results obtained are strongly influenced by the survey. In order to apply this method on a large-scale, it is necessary to apply the questionnaire to a greater number of professionals and not only from the Milan region. In this way, the method may be used in different regions and just considering the data from a single group of professionals based on the specific objective of the study.

5. Conclusions

The results reported in this paper demonstrate the importance of evaluating the application of design strategies to buildings, not exclusively over the operational phase but during the entire life cycle considering different parameters. The purpose of the method is to analyse design strategies for buildings with a sustainable approach. This article presents a new approach based on a complex system of criteria that allows the comprehensive evaluation of the design strategies for buildings combining the indoor comfort conditions, life cycle assessment (LCA), life cycle cost analysis (LCCA) and the multi-criteria decision making (MCDM). Using the proposed method, it was possible to identify the design strategies that reduce the environmental impact, improve the indoor comfort conditions and reduce costs. On applying the design strategies to a multi-family social building, different levels of performance were observed for the four parameters. In the case of comfort and financial cost, the best strategies were those using the traditional reinforced concrete frame. Since reinforced concrete has

Table 6
Priorities for the four parameters according to the experts.

Parameters	Thirty experts						TOTAL	
	Designer		Researcher/Professor		Administrative and technical			
	Weighting	Priority	Weighting	Priority	Weighting	Priority	Weighting	Priority
Comfort	0.254	3	0.306	1	0.213	4	0.258	2
Energy demand	0.280	2	0.189	4	0.229	2	0.233	3
CO_2e emissions	0.101	4	0.292	2	0.218	3	0.204	4
Cost	0.364	1	0.213	3	0.340	1	0.306	1
	$CR_a = 0.061 < 0.1$		$CR_a = 0.061 < 0.1$		$CR_a = 0.035 < 0.1$			

Table 7
Results of the multi-criteria analysis for the design strategies applied to the building.

Parameters	Unit	Weightings	Case 2	Case 3	Case 4	Case 5	Case 6
Comfort	hour	0.258	29602	41847	69525	− 42928	− 31350
Energy demand	MWh	0.233	− 104	1333	1058	1051	961
CO_2e emissions	tCO_2e	0.204	52	− 382	− 446	− 401	− 274
Cost	€	0.306	16,554	232,887	293,125	34,489	94,822
Relative importance *Qj*	0.108	0.393	0.522	− 0.037	0.014		
Utility degree *Nj*	20.8%	75.4%	100.0%	− 7.1%	2.6%		
Priority order	**3**	**2**	**1**	**5**	**4**		

been in constant use for a hundred years in civil engineering, it allows for a significant cost reduction compared to more advanced techniques. With regard to energy demand, the concrete and steel frame strategies provided better behaviour compared to the actual design project. In contrast, the X-Lam design strategies showed better results for the carbon dioxide emissions. The study shows that significant emission savings can be achieved with the use of wood products in buildings. Based on an initial analysis of the results, it is not clear which are the best design strategies for application to the building studied. However, by means of the MCDM, it was possible to identify that the best strategy for the case study was the reinforced concrete frame with rectified bricks.

The three databases used can completely change the behaviour of a design strategy in terms of energy demand and CO_2 emissions over the life cycle. This is one of the problems associated with international studies in the field of LCA. Climate change directly affects the future thermal and energy performance of a building and thus this is another important aspect to investigate in life cycle analysis. Only two impact categories of the LCA were evaluated. Previous studies have shown that the energy demand and the global warming potential are not the categories with the greatest impact and the selection of other impact categories can ensure a more comprehensive and accurate assessment. Thus, the selection of the most significant impact categories can be made by identifying the impact categories most used in studies reported in the literature or through normalisation or considering the categories highlighted by experts in a survey.

Selecting design strategies to be used in buildings should take different aspects into account. The approach presented herein is based on a complex system of criteria that enables a comprehensive evaluation of the design strategies. The method used can be applied to different types of buildings, locations and building sector. The method described could be a useful tool to aid designers, researchers and builders in selecting the most suitable design strategies, which would decrease the environmental impact and increase the quality of life of the users considering the economic aspects.

5.1. Future work

The research reported in this paper represents a small part of a larger study. For this reason, it has some limitations, which will be addressed in future work:

- In the demolition phase, the re-use of the design strategies material was not considered. Through recycling, the performance of the design strategy in terms of energy and emissions could be improved;
- In the energy demand only the consumption for air-conditioning was considered;
- Only one of the six emission scenarios published by the IPCC [2] was considered. Other emission scenarios will be analysed in future studies;
- Only two impact categories of the LCA method were analysed. Through the study of other impact categories it should be possible to improve the analysis of the environmental impact of the building;
- Future improvements in the energy efficiency of air-conditioning systems were not considered;
- Only 30 experts participated in the survey to determine the parameters of greatest priority.

Acknowledgements

The authors would like to thank CAPES, a Brazilian Government agency for post-graduation education, for the Ph.D. scholarship granted to Andrea Invidiata for the development of this research project.

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