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Life cycle evaluation of seismic retrofit alternatives for reinforced concrete columns.

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ABSTRACT

The critical earthquakes of the last few years highlight the urgent seismic retrofitting of existing buildings due to their aging or inadequate design. This paper aims to evaluate reinforced concrete column retrofit alternatives in a region of high seismic risk. Significant economic, environmental, and functional factors must be considered when deciding between various building retrofit options. The study uses a cradle-to-grave analysis to examine the economic and environmental impacts through life cycle assessments. Specifically, the life-cycle performance of three classic alternatives for rehabilitating columns lacking adequate confinement is compared: concrete jacketing, steel jacketing, and carbon fiber incorporation. The research adopts a holistic approach using multi-criteria decision-making methods, integrating economic, environmental, and functional criteria. A set of criteria and indicators is presented in a structured hierarchy that facilitates the orderly evaluation of alternatives. The results suggest that steel jacketing is preferred, as it presents a balanced performance in most criteria. The incorporation of carbon fiber is viable due to its low environmental and functional impact, although the high production costs of the raw materials limit it. In contrast, concrete jacketing has the highest environmental and functional impacts, making it the least favorable option. The results of this study will provide relevant information for engineers and decision-makers to select the most suitable options for building retrofit when considering several simultaneous perspectives.

1. Introduction

Reinforced concrete buildings that do not meet current seismic requirements pose a significant risk of poor performance during earthquakes. The main reasons are that these structures were built before the establishment of seismic-resistant standards, were designed or constructed errors, or were non-engineered constructions that did not have professional involvement at any stage. Seismic retrofitting of existing buildings is a pressing issue attracting the attention of several research studies and communities (Caterino et al., 2021). Considering the challenges of an urban environment, the world has adopted several landmark international agreements, including the Sustainable Development Goals (2015–2030), the Paris Agreement (2015), and the Sendai Framework for Disaster Risk Reduction (2015–2030), which calls for sustainable urban resilience, through substantially reducing the number of global disaster losses (Alam and Haque, 2022).

Among the most devastating earthquakes in recent years, the Pedernales earthquake in April 2016 on the northwest coast of Ecuador, with a moment magnitude MW of 7.8, resulted in around 700 deaths, and thousands of buildings and structures were damaged (Pinzon et al., 2021). The observed damage suffered by many low- and mid-rise reinforced concrete buildings suggests that a lack of adequate seismic detailing and quality control caused numerous buildings' total or partial collapse (Goretti et al., 2017). Among the deficiencies observed are stiff slabs with slender columns, insufficient transverse confinement in columns with excessive spacing between abutments, poor slab-column connections, limited use of shear walls, structural alterations such as soft floors and additional levels, inadequate concrete topping, corrosion of reinforcement, and the use of unconfined and unreinforced masonry infills (Kagermanov et al., 2017).

The fundamental goal of structural engineering has traditionally been to ensure maximum safety with minimal investment. However, due to the growing concern for sustainability, economic, environmental, and social aspects, pillars of sustainability have gained importance

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(Penadés-Plà et al., 2019). The construction industry is responsible for significant CO_2 emissions worldwide, of which concrete accounts for a considerable share. The current upward trend illustrates the urgency for sustainable building solutions and more efficient use of building materials (Stoiber et al., 2021). Considering the significant number of buildings requiring seismic retrofitting, the environmental footprint worldwide is expected to be negatively affected by environmental impacts from material production and construction processes (Salgado et al., 2020).

Life cycle assessments comprehensively evaluate a product or system's economic, environmental, and social impacts. The publication of studies in the construction industry in this domain has significantly increased in recent years (Dong et al., 2023). Environmental life cycle assessment (LCA) has become highly standardized methodologically and in terms of implementation. The existing methodology for assessment from an economic perspective, life cycle costing (LCC), also shows a relatively mature state (Navarro et al., 2018). Various studies have employed LCA to assess the environmental impacts of different reinforced concrete structure retrofitting alternatives. In a study by Pushkar et al. (2022), three alternatives were explored: shear wall reinforcement, column jacketing with reinforced concrete, and base isolation. The analysis considered LCA from cradle to gate, focusing on material production and transportation stages. Vitiello et al. (2016) explored four retrofit methods for a building in a cradle-to-gate analysis. Salgado et al. (2020) investigated reinforced concrete column jacketing, beam weakening, and shear wall addition, performing a cradle-to-grave analysis but omitting the use and maintenance stages.

Given the complexity that characterizes the inclusion and integration of the often-contradictory criteria defining sustainability, multi-criteria decision-making (MCDM) methods have gained prominence in recent years. According to Zavadskas et al. (2018), the applications of MCDM have steadily expanded, underscoring the significant potential of these methods in making sustainable decisions within civil engineering, construction, and building technology. In pursuing optimal strengthening strategies, several authors have incorporated LCA into their studies employing MCDM. For instance, Formisano et al. (2017) assessed production energy, albeit focusing solely on pre-production and manufacturing processes. Clemett et al. (2022) determine the climate change potential measured in kilograms of carbon dioxide equivalent but do not consider the use stage. Meanwhile, Vázquez-Rowe et al. (2021) employed three metrics—greenhouse gas emissions, fine particulate formation, and the impact on human health—to evaluate environmental loads. However, this analysis only covered transportation processes, machinery, and raw materials.

Among the MCDM methods, TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) has been recognized by multiple authors as an appropriate choice for selecting the best building-retrofitting alternative. TOPSIS offers a comprehensive ranking of alternatives for each criterion, with minimal parameters to be defined by the decision maker (Gentile and Galasso, 2021). Caterino and Cosenza (2018) stated that TOPSIS is one of the most suitable methods for addressing problems related to seismic rehabilitation of structures. Furthermore, the combined use of AHP (Analytic Hierarchical Process) and TOPSIS has gained prominence in recent years in selecting optimal building retrofit alternatives. Authors like Santarsiero et al. (2021), Requena-Garcia-Cruz et al. (2022), Formisano et al. (2017), and Anelli et al. (2020), along with Gentile and Galasso (2021) and Caterino and Cosenza (2018), have employed this joint approach in their research endeavors.

The various retrofitting techniques applied in previous studies ensured equivalent compliance with structural requirements. The results facilitated a comprehensive analysis of the global retrofit strategies used in these structures. However, the applicability of these results to other buildings is limited. Therefore, it is crucial to investigate local retrofit alternatives for structural elements. This approach will broaden the knowledge base and enable and contribute to the emergence of general trends in this field. Palacios-Munoz et al. (2018) evaluated the LCA of four retrofit strategies to increase the flexural capacity of a reinforced concrete beam. The study assumed zero impact during the use stage and determined non-renewable energy consumption and kilograms of CO_2 equivalent emitted but did not include economic and functional aspects.

In response to the urgent demand for seismic retrofitting of buildings, this paper aims to fill a gap in research by providing a holistic evaluation of retrofit alternatives. Specifically, it focuses on a common structural deficiency reinforced concrete buildings exhibit during earthquakes: inadequate column confinement. The evaluation uses economic and environmental life cycle analyses (LCC and LCA). The article is structured as follows: Section 2 outlines the materials and methods utilized, encompassing the analysis of life cycle impacts from economic and environmental perspectives. It also elaborates on developing a methodology employing a system of economic, environmental, and functional indicators through MCDM. In Section 3, the study presents and discusses the results, while Section 4 provides the key conclusions drawn from this research.

2. Materials and methods

2.1. Problem definition

This paper compares three seismic retrofit alternatives for local strengthening of reinforced concrete structures through life cycle assessments with a cradle-to-grave approach. Alternatives are evaluated for a common structural deficiency in reinforced concrete buildings due to obsolete regulations or un-engineered construction: the lack of confinement in columns. Using MCDM, the optimal alternative is selected, considering a holistic approach.

Ecuador is among the countries considered to have a high seismic risk. This is due to the subduction process between the Nazca and South American plates and the Guayaquil-Caracas mega fault or cut that crosses the country by dividing the continental plates (Ballesteros-Salazar et al., 2022). Quito, the capital of Ecuador with a population of over 2.5 million, faces significant seismic risk due to its proximity to the Pacific subduction zone and active crustal faults, capable of generating significant earthquakes (Pacheco et al., 2022). The imperative to retrofit these concrete buildings is paramount.

This study analyzed the reinforced concrete columns of three different buildings. The buildings are reinforced concrete buildings consisting of moment-resisting portal frames. The buildings, 4, 7, and 10 stories high, each have a 3.0 m mezzanine. The buildings are assumed to be symmetrical in plan and elevation and are located in the northern center of Quito. Table 1 shows the general geometric details of the buildings, the number of axes, and the distance between axes in both directions. The buildings are assumed to be located on type D soil with a maximum ground acceleration (PGA) of 0.4 gravity. Information on the total basal shear stress applied to each building, calculated from seismic parameters derived from the current Ecuadorian national building standard NEC (MIDUVI Norma Ecuatoriana de la Construcción, 2015), is included. This study analyzes a central column on the first floor of each building.

The characteristics of the columns considered lessons learned from reinforced concrete buildings damaged or collapsed during the Pedernales earthquake. The lack of confinement in the columns results from obsolete regulations or undesigned constructions. For example, Aguiar and Mieles Bravo (2016)strated the case of the Mutualista Pichincha building, which was demolished after the earthquake. This 9-story building had square columns of 0.60 m × 0.60 m, with 10 mm diameter stirrups spaced every 15 cm on a fifth level. Excessive stirrup spacings, lack of confinement, and seismic hooks due to construction oversights or non-application of the standard were the probable causes of several column failures (Castañeda and Mieles Bravo, 2017). Table 1 shows the main structural characteristics of the columns under study. The transverse reinforcement of each column consisted of 10 mm

Table 1
General information on the columns to be retrofitted..

Building	V[a]	Nx,y[b]	d (m)[c]	a (m)[d]	b (m)[d]	D_L (mm)[e]	#[f]
4 stories	0,149W	4	5,00	0,50	0,50	18	12
7 stories	0,099W	6	6,00	0,60	0,60	20	16
10 stories	0,072W	6	6,00	0,70	0,70	22	16
c = 0,04 m[g]	D_T = 10 mm[h]		s = 0,15 m[i]		f'c = 28 MPa[j]	fy = 412 MPa[k]	

[a] Base Shear, where W is the effective seismic weight.

[b] Number of axles in both directions.

[c] Axle distance.

[d] Dimensions of the column.

[e] Diameter of longitudinal reinforcement.

[f] Number of Longitudinal Bars.

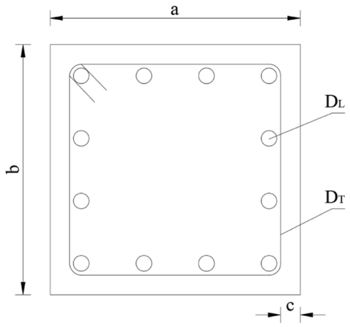
[g] Thickness of concrete cover.

[h] Diameter of transverse reinforcement.

[i] Spacing of ties.

[j] Compressive strength of concrete.

[k] Yield stress of reinforcing steel.



diameter steel bars. The spacing of the transverse reinforcement throughout the column was 150 mm.

Current regulations stipulate that the spacing of supplementary hooks or branches with rectilinear confining stirrups within a section of the element should not exceed 350 mm in the center. On the other hand, the spacing of transverse reinforcement along the longitudinal axis of the element must be at least six times the diameter of the longitudinal reinforcing bar or at least 100 mm in confining zones 150 mm outside these zones. Three different retrofit alternatives were evaluated in this study to improve column confinement, concrete jacketing (CR), steel jacketing (ST), and incorporation of carbon fiber-reinforced polymers (CFRP).

1. Concrete Jacketing (RC), reinforced with a 75 mm thick concrete jacket, compressive strength of 32 MPa, longitudinal bars of 12 φ 12 mm for the 4-story structure, and 12 φ 16 mm for 7 and 10 stories. The stirrups are 10 mm with 75 mm spacing for the 4-story building and 100 mm for 7 and 10 stories. A structural adhesive was considered for proper bonding between fresh and hardened concrete.
2. Steel Jacketing (ST) along the entire column length with hot rolled steel A572 Gr50 thickness 4 mm welded in place, filled with structural epoxy adhesive.
3. Fiber-reinforced polymer (CFRP), with a wrap over the entire length of the column with the application of carbon woven fabric sewn unidirectionally in two layers, with wet application processes, 0.333 mm thick, tensile strength 3800 MPa, ultimate elongation of 1.55% and weight of 610 g/m^2.

A 50-year service life is considered, considering that the chosen retrofitting option will allow a new helpful life in compliance with seismic regulations. The service life of these retrofit options is calculated from the moment they are implemented in the building until the building is demolished, or removing the retrofit due to earthquake-induced damage is necessary. This service life assessment was feasible because all retrofits were designed to meet identical requirements, ensuring similar structural performance. Consequently, this assessment rules out the possibility of one alternative having a longer service life than the others (Salgado et al., 2020). Insufficient investment or inefficient maintenance strategies lead to high economic costs in the long term (Torres-Machí et al., 2014). Each retrofit alternative incorporates preventive maintenance measures to ensure this service life. Maintenance included the application of protection for carbonation in RC, the use of anti-corrosion paint for ST, and fireproof mortar in the case of ST and CFRP.

2.2. Environmental life cycle analysis

The study followed a systematic process comprising four distinct steps to conduct the environmental life cycle analysis. Firstly, while defining the objective and scope, the retrofit alternatives under assessment, the functional unit, and the four phases encompassed within this LCA were precisely outlined. The second step involved conducting an inventory analysis for each case. The third step defined the specific method for assessing the environmental impacts. Finally, the results were interpreted using midpoint and endpoint approaches in the fourth step. This thorough process ensured a comprehensive assessment of the environmental implications of the different life cycle stages.

2.2.1. Definition of objectives and scope

This study aims to conduct an LCA of three distinct retrofit alternatives for a column: RC concrete jacketing, ST metal jacketing, and the integration of CFRP fibers. The aim is to compare the results obtained for each case comprehensively. The LCA methodology was applied, adopting a "cradle to grave" approach. The assessment included the production of raw materials, transport to the site, the construction process, preventive maintenance at the use stage, and the disassembly of the retrofit column and its transport to landfill or recycling facilities. A standard functional unit was defined to facilitate an accurate comparison and interpretation of the results. This functional unit precisely outlines the properties and functionalities of the product in question. In this context, the chosen functional unit was a reinforced concrete column retrofitted to ensure the structural safety of buildings over a service life of 50 years.

The LCA process was divided into four distinct stages, as illustrated in Fig. 1. The manufacturing stage covered all processes of producing the necessary materials and their transportation to the construction site. It is assumed that the buildings are situated in the north-central sector of Quito. The transport distances are 9.3 km for concrete and 43.4 km for steel fabrication. The distances for CFRP and epoxy resin include 3800 km for air transport and an additional 36.8 km for land transport. Structural adhesives and materials used in maintenance processes are considered a distance of 39.7 km. These distances were used based on the industry maintained by Ecuador, where fiber-reinforced polymer composite materials must be imported. The construction stage covered the machinery operations and activities conducted for column retrofitting. The utilization stage included the production processes of materials

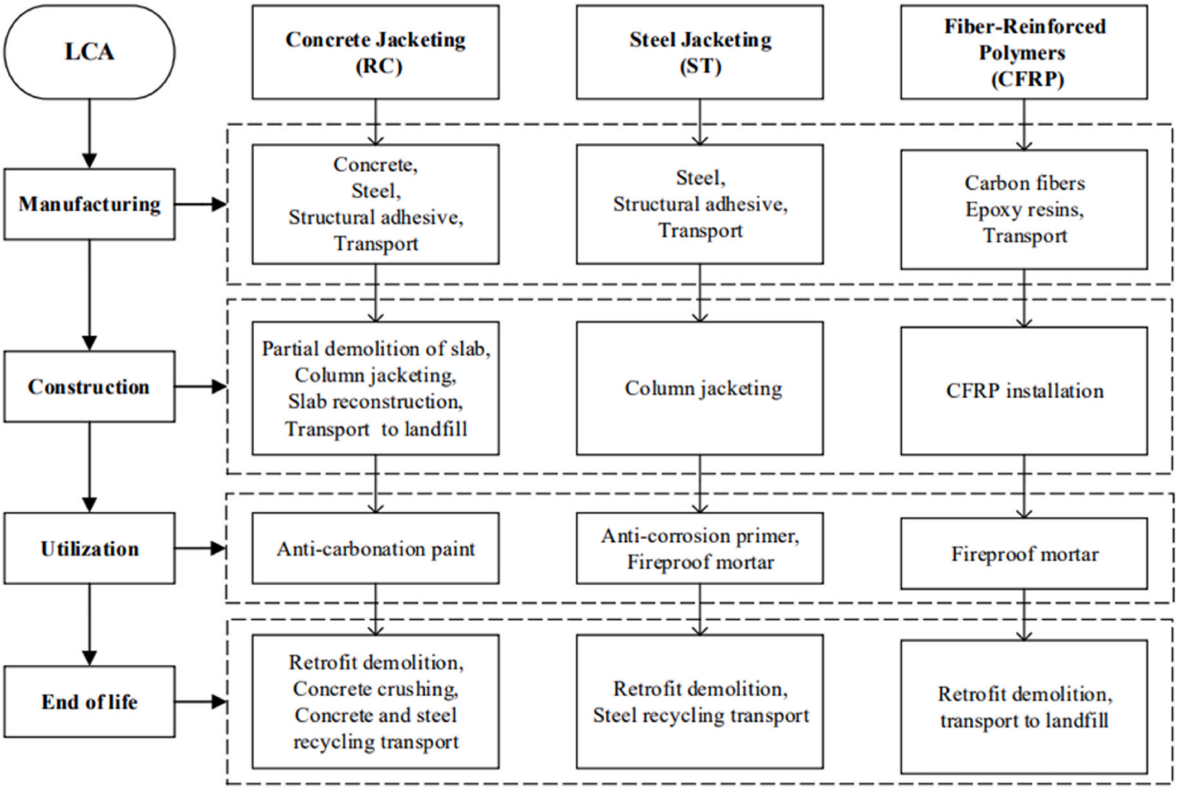


Fig. 1. Stages of environmental life cycle analysis.

used in preventive maintenance. The materials used are acrylic resin dispersion-based anti-carbonation paint for RC, two-component epoxy resin-based anti-corrosion paint for ST, and cement-based fireproof mortar for ST and CFRP.

Lastly, the end-of-life stage (EoL) encompasses the operations involved in dismantling the column retrofit and transportation to either landfill or recycling facilities. Recycling distances are the same for concrete and steel plants, as material production plants usually integrate recycling processes. Landfill distance stands at 13.2 km. For RC, the process includes concrete crushing before recycling and recycling steel. For ST, steel recycling was also considered. In the case of CFRP, the literature indicates several waste management routes, including landfill without recycling, thermal incineration, co-incineration with material recovery, mechanical recycling, pyrolysis, and fluidized bed (Sbahieh et al., 2022). However, most CFRP waste ends up in landfills because, among other things, composite recycling is inherently difficult due to its complex composition and the thermosetting resins used that cannot be remolded (Palacios-Munoz et al., 2018). Hence, the end-of-life scenario for FRP adopted here assumes landfill disposal, aligning with prevalent real-world practices. Lueddeckens et al. (2020) reports that distortions in the assessment are described if discounting over time horizons of more than 100 years is not considered. This study considers a zero-discount rate, considering future emissions from the EoL stage in 50 years.

2.2.2. *Inventory analysis*

In this study, the life cycle inventory has been developed using the Ecoinvent database. This database was used due to its wide acceptance in LCA research, consistent development, transparent and reliable data, and various products, processes, and construction material categories (Valencia-Barba et al., 2021). The quantities of materials for the functional unit were quantified by analyzing each alternative's structural characteristics and construction details. For the operation processes of the machinery used in the construction stage, the energy of the necessary processes associated with using the machinery was estimated from the BEDEC database (Catalonia Institute of Construction Technology). Some adjustments were made for specific cases. The CFRP material was modeled according to the guidelines Xie et al. (2023), incorporating recommended environmental impact values for carbon fibers and epoxy resin that closely align with the medians derived from various published sources. This particular study conducts a cradle-to-gate environmental assessment of fiber-reinforced polymers, explicitly focusing on the performance of short FRP-confined concrete columns.

Table 2 presents the inventory utilized for each retrofit alternative and its equivalence in the Ecoinvent processes. In the case of RC, the concrete used includes the jacketing and the restoration of the partially demolished slab, poured with a pump. Due to the limitations of the Ecoinvent database in terms of the specific construction materials used in this study, the structural adhesives and anti-corrosion primer considered the impacts associated with the production of epoxy resin. For its part, the fireproof mortar is considered a cement composite. The energy consumption values of the machinery required for construction operations, adjusted for this study, were also included. Table 3 shows the BEDEC processes used for this purpose. Furthermore, all transportation processes necessary for the respective stages were also modeled.

2.2.3. *Impact evaluation*

The OpenLCA software (GreenDelta, GmbH, Berlin, Germany) was employed to implement the data and analyze the results. This open-source tool enables the scientific community to conduct various environmental studies at different levels of detail, tailored to their specific needs and scopes. In treating uncertainty related to using an existing database, the geographical location is one of the largest sources of uncertainty (Hong et al., 2017), as well as the date of data collection and the technology used. The Ecoinvent database allowed the implementation of semiquantitative pedigree approaches to characterize

Table 2
Amount of materials per functional unit.

Process	4 stories	7 stories	10 stories	Unit	Ecoinvent process
Concrete Jacketing (RC)					
Concrete	0.75	0.85	0.94	m^3	Concrete, 30–32 MPa
Reinforcement steel	101.80	124.80	132.58	kg	Reinforcing steel
Structural adhesive	9.45	11.34	13.23	kg	Epoxy resin
Partial demolition of slab	128.45	128.45	128.45	MJ	Diesel, burned in building machine[a]
Column jacketing	748.45	889.46	1030.47	MJ	
Slab reconstruction	23.89	23.89	23.89	MJ	
Anti-carbonation paint	3.28	3.78	4.28	kg	Epoxy resin
Retrofit demolition	145.26	170.52	195.79	MJ	Diesel, burned in building machine[a]
Concrete crushing	1218.97	1430.97	1642.97	kg	Rock crushing
Steel Jacketing (ST)					
Structural steel	197.82	237.38	276.95	kg	Hot rolling, steel
Structural adhesive	12.60	15.12	17.64	kg	Epoxy resin
Column jacketing	626.22	751.46	876.71	MJ	Diesel, burned in building machine[a]
Anti-corrosion primer	3.15	3.78	4.41	kg	Epoxy resin
Fireproof mortar	127.20	152.64	178.08	kg	Cement mortar
Fiber-Reinforced Polymers (CFRP)					
Carbon Fibers	7.69	9.22	10.76	kg	Xie et al. (2023)
Epoxy Resins	14.18	17.01	19.85	kg	
CFRP installation	288.77	346.53	404.28	MJ	Diesel, burned in building machine[a]
Fireproof mortar	127.20	152.64	178.08	kg	Cement mortar

[a] BEDEC database.

Table 3
Processes associated with the use of machinery.

Process	BEDEC process
Concrete Jacketing (RC)	
Partial demolition of slab	Demolition of reinforced concrete floor slab, by hand and with compressor and manual loading of rubble on truck or container.
Column jacketing	Retrofit of reinforced concrete columns
Slab reconstruction	Reinforced concrete slab
Retrofit demolition	Demolition of reinforced concrete structures, with mechanical means and manual and mechanical loading of debris.
Steel Jacketing (ST)	
Column jacketing	Reinforcement of concrete elements by means of rolled steel strips
Fiber-Reinforced Polymers (CFRP)	
CFRP installation	Carbon fiber sheet structural element reinforcement

uncertainty in the form of probability distributions (Marsh et al., 2023). This pedigree matrix introduced an uncertainty factor based on five indicators: reliability, completeness, temporal correlation, geographical correlation, and technological correlation. A basic factor was combined with the pedigree matrix to determine the total uncertainty, which provides the standard deviation of the lognormal distribution (Pons et al., 2020).

The environmental impacts were systematically classified and evaluated to translate them into specific indicators or themes. The ReCiPe methodology was selected for this purpose because of its numerous advantages over other methods. It employs a dual approach, allowing for the presentation of environmental impacts at a detailed level through the midpoint approach and on an easier-to-understand level with the endpoint approach (Pons et al., 2018). Over the past five years, this methodology has been applied across diverse areas of civil engineering, including material studies (Sampaio et al., 2022; Goh et al., 2022; Tanhadoust et al., 2023), bridges (Navarro et al., 2019) and buildings (Pujadas-Gispert et al., 2018; Pushkar et al., 2022; Sánchez-Garrido et al., 2022b).

The midpoint approach offered a comprehensive perspective on the particular impacts associated with each retrofit alternative, encompassing 18 impact categories. These categories include agricultural land occupation ((ALO), global warming potential (GWP), fossil depletion (FD), freshwater ecotoxicity (FEPT), freshwater eutrophication (FEP), human toxicity (HTP), ionising radiation (IRP), marine ecotoxicity (MEPT), marine eutrophication (MEP), metal depletion (MD), natural land transformation (NLT), ozone depletion (ODP), particulate matter formation (PMF), photochemical oxidant formation (POFP), terrestrial acidification (TAP), terrestrial ecotoxicity (TEPT), urban land occupation (ULO), and water depletion (WD). These impact categories provide highly detailed and accurate results, although they may require more complex interpretation.

The endpoint approach encompasses various impact categories grouped into three distinct damage aspects. Firstly, ecosystems were evaluated in terms of species per year. Secondly, human health impacts were measured using disability-adjusted life years. Lastly, resource availability was quantified in terms of US dollars. While this approach is easier to interpret, it introduces higher uncertainty due to its extensive integration. The hierarchical (H) perspective was adopted to incorporate a long-term scenario. The damage categories were normalized using the World ReCiPe characterization, hierarchies/hierarchies H/H [person/year]. This methodology calculates the total environmental impact score induced by the retrofitting alternative throughout the life cycle. The normalized score is expressed in points, enabling a comprehensive evaluation and comparison of each case. Characterization hierarchies/average H/A were included to compare the results.

2.3. *Economic life cycle analysis*

A comprehensive life cycle analysis evaluated all the activities essential to retrofit a column through several stages: studies and testing, construction, service life stage, and end-of-life. Ecuador-specific costs, extracted from the construction cost database developed by CYPE Ingenieros, were used for the analysis, as they contain specific information for the location of the case study. In the initial survey and testing phase, costs included semi-destructive testing pachometers to locate and determine the diameter and spacing of longitudinal and transverse reinforcement. In addition, sclerometry and ultrasonic tests were used to characterize the strength properties of the concrete. Testing drilled cores were considered to calibrate the results. Quality control measures included compressive strength of cylindrical concrete specimens for RC, penetrant dyes for inspection of welds in ST, and pull-out tests to ensure proper bonding of the CFRP. The costs also covered the completion of a complete final report. All costs related to this phase were distributed for one column of each building and included in the analysis.

The construction stage included costs for material procurement, equipment, machinery, labor costs, and minor tools, with quantities adjusted according to the required materials. In the case of CFRP, data from local factories were incorporated, with epoxy resin yields adjusted accordingly. Service life stage costs were divided into two components. Firstly, preventive activities were factored in, such as using acrylic resin-based anticorrosive paint for RC, the anticorrosive primer for ST, and passive fire protection involving sprayed fireproof mortar for ST and CFRP. Secondly, the ten-year maintenance accounted for decennial expenses over the initial ten years. The end-of-life costs included demolition, waste sorting, and transportation, in the case of RC, and crushing the concrete. Future costs associated with the ten-year maintenance and end-of-life were adjusted to current costs using Equation (1). In sustainability-oriented decision-making, minimizing burdens for future generations is crucial. Therefore, the study utilized a low discount rate, often called the social discount rate in the literature (Sánchez-Garrido et al., 2022b). A social discount rate (d = 2%) was employed, as suggested by Allacker (2012), aligning with the objective of long-term sustainability.

$$LCC = \sum_{t=t_0}^{t_{SL}} C_i \times 1/(1+d)^{t-t_0} \tag{1}$$

where LCC is the Life Cycle Cost of the structure, C_i is the economic costs linked to time t, t_0 is the time corresponding to the beginning of the evaluation period, t_{SL} is the expected number of years, and d is the value of the discount rate.

2.4. Multi-criteria decision making

To achieve a holistic evaluation of retrofit alternatives, MCDM was employed, using a combination of AHP and TOPSIS. A total of 8 criteria were meticulously analyzed, enabling the integration of economic, environmental, and functional perspectives, measured through 20 specific indicators.

2.4.1. AHP

The Analytic Hierarchy Process is a widely adopted technique in decision-making, aiding in selecting alternatives based on specific criteria. AHP's popularity stems from its ability to translate the decision maker's perspective (DM) into numerical values, allowing tangible, intangible, objective, subjective, rational, and emotional factors. This method is particularly suited for problems that can decompose a hierarchical structure. It is an easy-to-use procedure applicable to numerous real-life scenarios requiring a choice between alternatives. The model allows individual and group decisions to be combined, although it is sometimes difficult to reach a consensual agreement (Sánchez-Garrido et al., 2022a). In this approach, comparison matrices are constructed using the fundamental scale proposed by Saaty (1990). These matrices derive weights based on the subjective importance of each element relative to others. The semantic scale gauges the significance of a criterion or alternative *"i"* concerning another *"j"*, ranging from 1, denoting *"equally important"* to 9, signifying *"i is extremely more important than j"*. The resulting decision matrix $A = \{a_{ij}\}$ meets the properties: reciprocity (if $a_{ij} = x$, then $a_{ji} = 1/x \; \forall i,j \in \{1,\dots,n\}$, where n represents the number of criteria or alternatives to compare) and homogeneity (if i and j are of equal importance, $a_{ij} = a_{ji} = 1$, also, $a_{ii} = 1 \; \forall_i \in \{1,\dots,n\}$). The consistency index (CI) is computed to ensure that the matrix does not contain contradictions, defined as follows:

$$CI = (\lambda_{max} - n) / (n-1) \tag{2}$$

where λ_{max} is the greatest eigenvalue and n is the dimension of the decision matrix. The consistency radius *(CR)* is obtained by:

$$CR = CI/RI \tag{3}$$

where RI is the random index, indicating the consistency of a random matrix determined according to Table 4, generally, pairwise comparisons can be considered consistent if CR does not exceed 5% if $n = 3$, 9% if $n = 4$, and 10% if $n \geq 5$.

Aggregating individual judgments (AIJ) based on the geometric mean to aggregate judgments was used in this study. Individual pairwise comparison matrices (PCM) are transformed into a group PCM from which group priorities are derived, where the resulting eigenvector is normalized. If the individual matrices exhibit acceptable consistency, the group matrix also tends to be acceptable; the geometric mean satisfies the conditions of unanimity and homogeneity (Dong and Saaty, 2014). Three professionals from civil engineering and architecture were selected to form the group of experts to ensure different points of view and a variety of approaches, according to Clemen and Winkler (1985), who suggest several experts between three and five. DMs have between 17 and 35 years of academic and professional experience in areas related to structural engineering, construction, and sustainability.

2.4.2. TOPSIS

This method, defined for the first time by Hwang and Yoon (1981), selects the best alternative by considering the distance to the positive ideal solution (PIS) and the negative ideal solution (NIS) simultaneously. Firstly, the scores r_{ij} of each alternative i and for each criterion j are normalized by the equation:

$$r'_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^{n} r_{ij}^2}} \tag{4}$$

where n is the number of criteria. The normalized scores r'_{ij} are subsequently multiplied by the corresponding weights of each criterion w_i to obtain the standardized weighted score v_{ij}. The distance to the positive ideal solution (d_i^+) and the negative ideal solution (d_i^-) is obtained by calculating the Euclidean distances as follows:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \tag{5}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \tag{6}$$

where v_j^+ and v_j^- are the best and worst scores for criterion j of each alternative i. Finally, the index C_i^* represents the final score of each alternative, considering simultaneously the position relative to the positive and negative ideal solutions.

$$C_i^* = \frac{d_i^-}{\left(d_i^+ + d_i^-\right)} \tag{7}$$

2.4.3. Criteria and indicators

This study integrates three economic, environmental, and functional perspectives through eight criteria and 19 quantitatively measurable indicators. This hierarchical structure organizes information, systematically evaluating decision-making processes. However, it is essential to note that adding more branches does not necessarily guarantee greater accuracy in the results. Therefore, it is advisable to develop understandable and perceptible dimensions. Table 5 details the criteria and indicators used and the corresponding description.

Economic criteria, C1, C2, and C3: Costs were measured in dollars obtained from the LCC, where future costs associated with ten-year and end-of-life maintenance consider a 2% social discount rate.

Environmental Criteria, C4, C5, and C6: Environmental impacts of

Table 4
Random index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Table 5
Criteria and indicators in decision-making.

Criteria	Indicators		Description
C1 Cost (Design and Test)	I1	Design and semi-destructive testing	Semi-destructive tests, pacometers, sclerometry, ultrasounds and perforated cores. Includes the cost of design and post-installation testing, including compressive strength for RC, penetrating dyes for weld inspection at ST, and pull-out testing for CFRP.
C2 Cost (Construction)	I2	Construction cost	Materials, equipment, machinery, labor, and minor tools. The costs of partial demolition of the slab and subsequent concreting are included for RC.
C3 Cost (Maintenance, EoL)	I3	Preventive maintenance	Protection for carbonation in RC, anti-corrosion paint for ST, and fireproof mortar in the case of ST and CFRP.
	I4	Maintenance first 10 years	Maintenance costs, considering a social discount rate of 2%.
	I5	Demolition, classification of waste	Demolition and waste classification, considering a social discount rate of 2%.
	I6	Treatment and transport waste	In the case of CR of concrete crushing. Transportation to factories of CR and ST materials for recycling, transportation of CFRP to landfill, considering a social discount rate of 2%.
C4 Impacts (Manufacturing)	I7	Ecosystem	Impacts of all raw material production and transportation activities to the site. For RC, it included concrete, reinforcing steel, and structural adhesive; ST, structural steel, and structural adhesive; and CFRP, carbon fiber, and epoxy resin.
	I8	Human health	
	I9	Resources	
C5 Impacts (Construction)	I10	Ecosystem	Impacts due to the use of the machinery necessary to install the retrofit alternative, including, in the case of RC, the partial demolition of the slab and subsequent concreting.
	I11	Human health	
	I12	Resources	
C6 Impacts (Maintenance, EoL)	I13	Ecosystem	Impacts of raw material production and transportation activities to the site: protection for carbonation in RC, anti-corrosion paint for ST, and fireproof mortar in the case of ST and CFRP. Included are the impacts of activities related to machinery used for pre-recycling RC treatment, transportation to RC and ST recycling facilities, and final landfill disposal for CFRP.
	I14	Human health	
	I15	Resources	
C7 Impacts (Construction)	I16	Architectural impact	AHP based on DMs' professional judgment
	I17	Duration of works	Adapted from (Pour, 2015)
C8 Impacts (Technicians)	I18	Need for specialized labor	AHP based on DMs' professional judgment
	I19	Importance of foundation intervention	

the LCA endpoint approach for the Ecosystems, Human Health, and Resources categories measured in points. Future emissions consider a discount rate of zero.

Functional criteria, C7 and C8: Functional impacts of the retrofit alternatives, measured through qualitative classifications or information collected from the literature. For architectural impacts, the need for specialized labor, and the importance of interventions in the foundation, the qualitative judgments of the DMs are converted into quantitative terms using AHP, which Saaty proposed; this involved pairwise comparisons between the three alternatives by the DMs. Consistency verification was performed. In the case of the duration of the work, Pour, 2015 work values were adopted and normalized.

3. Analysis and discussion of results

3.1. Environmental analysis

The results of the midpoint approach offer a comprehensive environmental perspective on the specific impacts induced by the retrofit alternatives considered throughout their useful life. These impact categories directly affect the environment, but their high number makes interpretation difficult. Each impact category has different units, making simultaneous graphical analysis difficult. Fig. 2 a), b) and c) shows the 18 impact categories of each case. The resulting CR values represent 100%, and the relationship of the rest of the alternatives for each impact is shown. RC is the solution with the most significant environmental impact, mainly due to its concrete and steel components.

For ST, the impact categories ALO, FD, IRP, MD, ODP, and WD exceeded 50%; for the 10-story building, POFP TAP was added. Agricultural Land Occupation (ALO) reached 84% in the case of the 10-story building. For CFRP, 16 categories represent values less than 30%, compared to RC, exceeding this ALO and GWP threshold. In the comparison between ST and CFRP, only the GWP category shows a higher percentage for CFRP. The FEPT, FEP, MEPT, MD and WD categories have values for CFRP below 15% of the ST impacts. Numerous studies emphasize results in terms of equivalent CO_2 emissions (in kilograms) for the impact of climate change; Fig. 2 d) shows the Global Warming Potential (GWP) results of the retrofit alternatives. In particular, ST presents the lowest emissions, slightly surpassed by the CFRP case. In contrast, the RC's emissions are remarkably high. On average, ST CO_2 emissions represent only 41% of those emitted by the RC strategy, while CFRP emissions represent 52%. Appendix A included the results of the impacts determined with two recognized methods in the field of LCA studies, where for climate change, similar values are obtained with TRACI 2.1 and slightly higher with EF 3.1, with increases ranging from 0.13% to 1.18%

The endpoint approach combines impacts into three damage categories, producing more easily interpretable results. However, adding uncertainties from mid-point results increases the uncertainty of the final results. However, these results offer a broader perspective on the environmental damage caused by each retrofit alternative. Fig. 3 a), b) and c) illustrates each category's results in their respective units. In all categories, RC consistently shows the highest values. Damage to ecosystems presents similar values for ST and CFRP, reducing around 60% compared to RC. Something similar happens with human health, where ST and CFRP present a damage reduction of approximately 50%.

The environmental advantages of CFRP become evident in resources, where it reduces damage by 80% compared to the concrete and steel materials of the RC. On the other hand, ST presents a decrease of 44%. Fig. 3 d) shows the final normalized scores for the H/H and H/A assessments. CFRP stands out as the alternative with the lowest total impacts. When comparing the results, the decrease in values obtained with

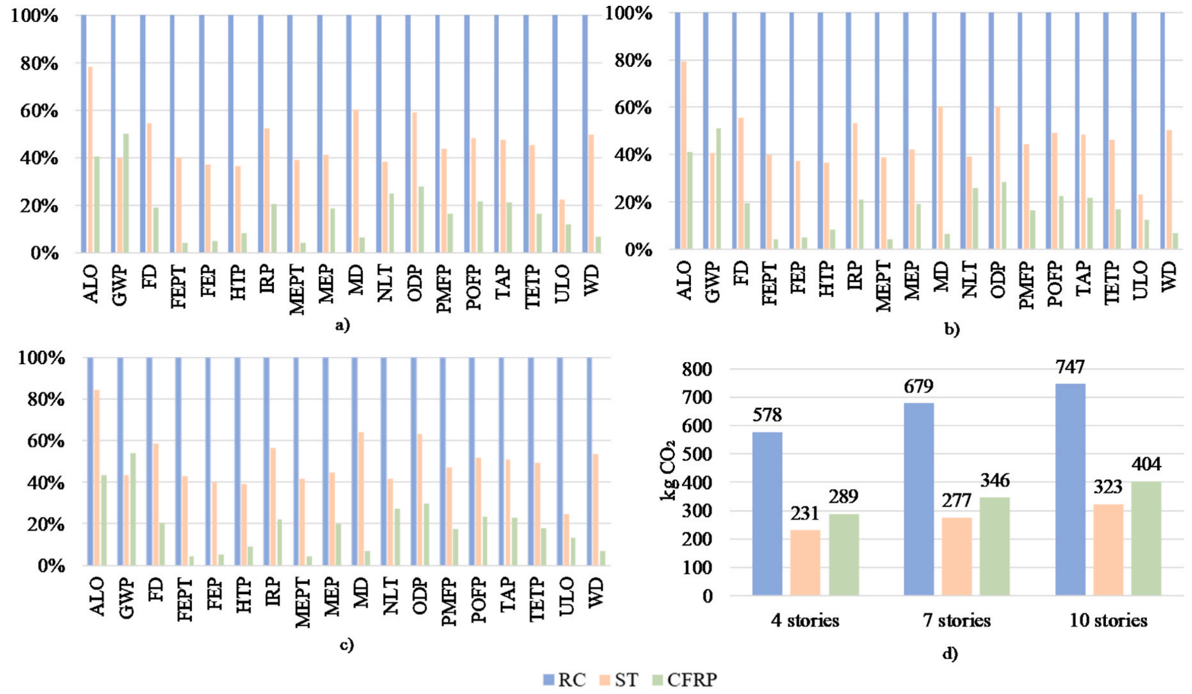


Fig. 2. Environmental impacts with midpoint. a) 4 stories. b) 7 stories. c) 10 stories. d) CO_2 emissions.

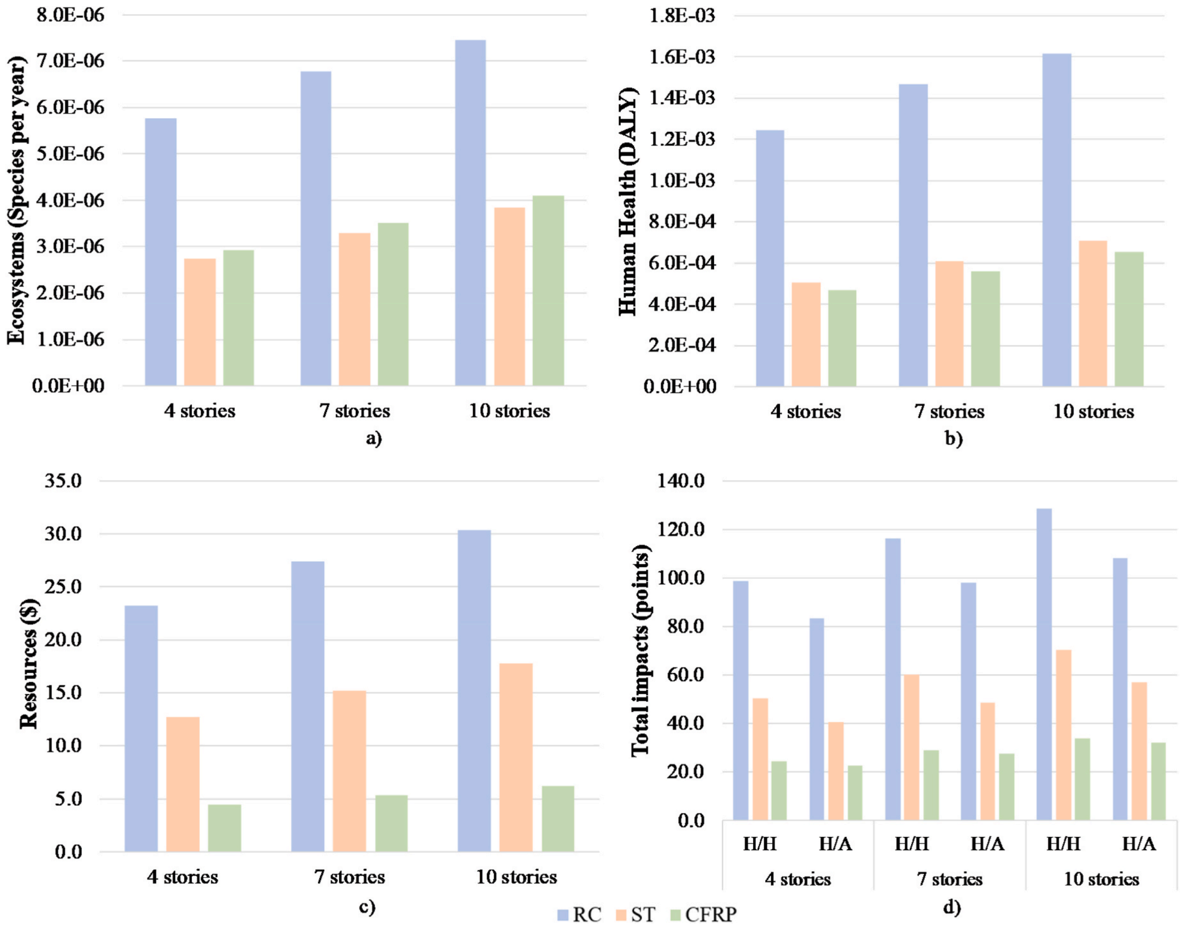


Fig. 3. Environmental impacts with endpoint. a) Ecosystems. b) Human Health. c) Resources. d) Total impacts.

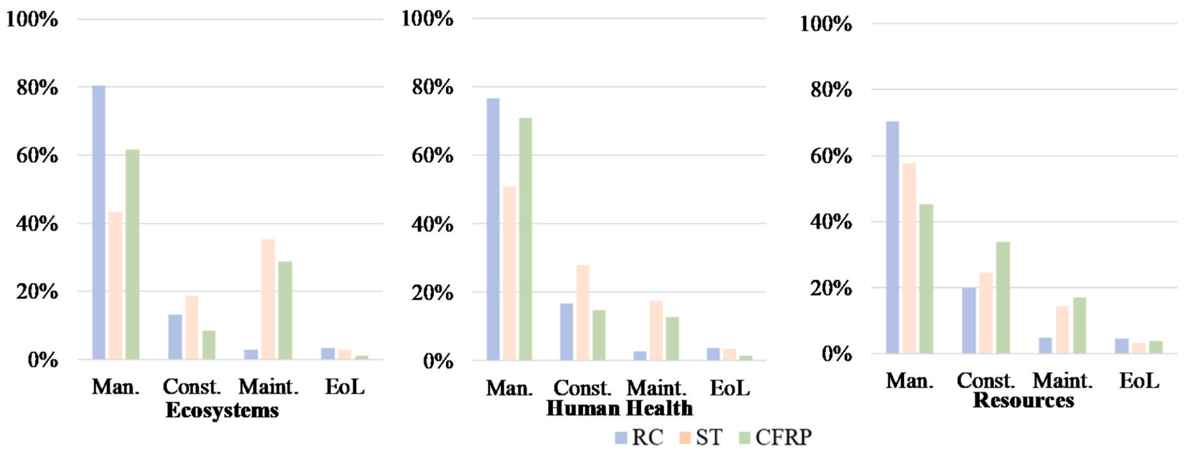


Fig. 4. Endpoint environmental impacts by stages.

H/A is, on average, 16% for RC and 19% for ST. In the case of CFRP, the decrease is 6%, showing that the H/H category favors carbon fiber-reinforced polymer technology.

Using the endpoint approach, Fig. 4 shows the average contribution percentages of the different life cycle stages. In all categories, the manufacturing process is the most important. For ST, the manufacturing stage represents, on average, 43%, followed by the use stage with 35%. This distribution occurs because the equipment and machinery used in construction are relatively minor in the category of damage to ecosystems. However, the manufacturing materials required during the use stage for preventive maintenance, such as epoxy resin-based anticorrosive primer and fireproof mortar (a cement compound), contribute substantially. Similarly, in the case of CFRP, the manufacturing stage constitutes, on average, 62% of the damage to ecosystems, followed by the maintenance stage with 29%. It is worth mentioning that the 4- and 7-story buildings exhibit similar percentages in all categories when RC is used as a reference, with slightly higher values for the 10-story building. The contribution of the EoL phase is minimal, reaching the highest percentages in the resource category, with up to 5% on average for the RC case.

3.2. *Economic analysis*

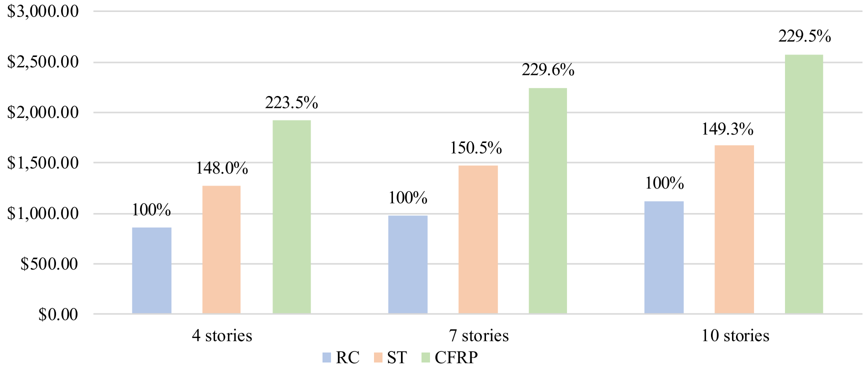
Fig. 5 illustrates LCC as costs accumulated over the entire useful life. The percentages considered RC a reference base due to its lower total cost. In the study and testing stage, ST and CFRP were more expensive by 17% and 43% on average. Moving into the construction stage, ST experiences a 37% cost increase, while CFRP is 158%. This high increase in CFRP is mainly attributed to high raw material costs.

During the use stage, the ST experiences the most significant cost increase because two types of preventive maintenance are considered: anti-corrosion painting and passive fire protection. Consequently, costs increase on average 3.3 times CR costs. In the case of CFRP, which incorporates passive fire protection, costs increase 2.9 times RC's. Only in the end-of-life stage do RC costs exceed the others due to the pre-recycling process the concrete must go through, which generates higher costs in this stage. Considering all stages throughout its useful life, ST costs up to 1.5 times more than RC. On the other hand, if CFRP is used, costs increase up to 2.3 times RC's.

Fig. 6 shows the average percentages corresponding to each stage, highlighting the construction phase with the highest cost of the three alternatives. The design and testing stage is fundamental in the rehabilitation of buildings, reaching a percentage of 18.4% in CR. In the use stage, ST contains a high value (25.5%); this percentage was aligned with the specific preventive maintenance considered. The contribution of the EoL phase is almost zero for ST and CFRP, denoting that the costs for RC reach 5.1% because the crushing process is included before transport to the recycling facilities.

3.3. *Multi-criteria decision making*

This study employs a holistic approach that integrates LCC and LCA results and includes functionality. Table 6 details the eight evaluation criteria examined in each perspective, economic, environmental, and



Design and Test	183.28	213.03	261.08	177.19	206.93	254.98	177.19	206.93	254.98
Construction	535.81	739.62	1,381.56	635.11	875.88	1,657.87	759.91	1,015.35	1,934.18
Maintenance	97.13	309.35	270.78	115.35	378.84	324.93	128.20	440.88	379.09
End on life	42.51	9.06	5.65	50.16	9.86	7.26	57.46	12.61	8.88

Fig. 5. LCC cost values.

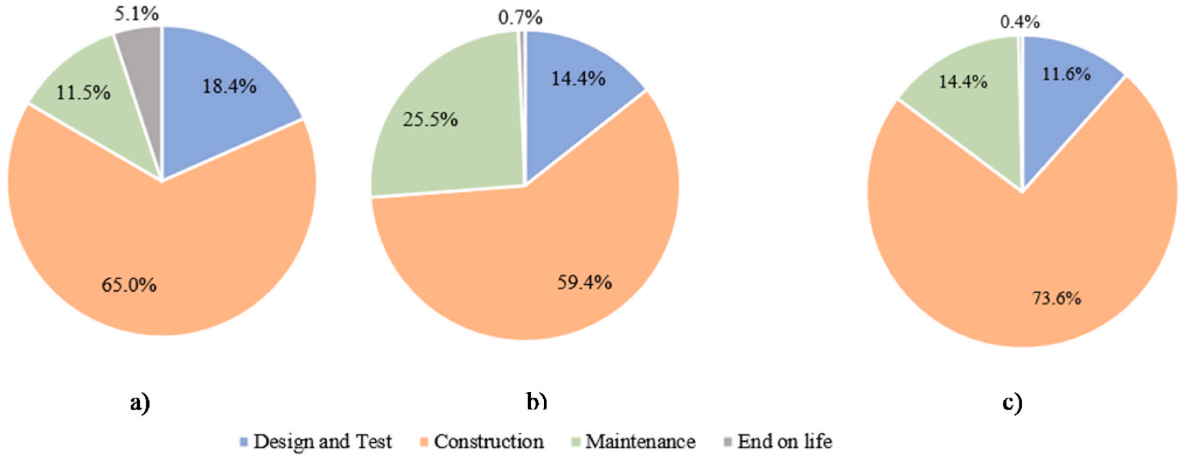


Fig. 6. Percentage of costs by stages. a) RC. b) ST. c) CFRP.

functional, and evaluated through 19 indicators. Expert contributions were optimized, ensuring focused attention on these eight criteria, and avoiding dilution of judgments. Weights were assigned using the procedure detailed in Section 2.4. This value falls below the acceptable CR limit. The exact weighting was considered for the indicators at their respective levels to avoid biased results following previous research findings. Sánchez-Garrido et al. (2022b) states that sensitivity studies demonstrated that weight variations at the indicator level have a minimal impact on preferences for each alternative since their influence is lost as one ascends to the criterion level. Among the criteria, C2, C7, C4 and C3 are the most important, two belonging to the economic perspective and the others to the functional and environmental perspective.

Table 7 shows the weights assigned for the indicators associated with the criteria representing the functionality perspective. These weights were determined following the procedure described in Section 2.4. The DMs considered CFRP less invasive than ST and significantly less invasive than RC regarding architectural impact and potential foundation interventions. On the contrary, the demand for specialized labor is greater for ST. The duration of the work was evaluated using a scale adapted from the values presented in Pour (2015).

The decision matrix with the criteria values for each alternative, along with their distances to both the positive and negative ideal solutions Table 8 presents. The H/H category was considered for environmental impacts. The final ranking of the alternatives is determined based on the highest C_i^* score. ST emerges as the top performer, achieving the highest score with an average value of 0.665. Following closely, CFRP secure a score of 0.543, while RC trails with a value of 0.466. If the H/A category is considered, on average, the CR score increases by 1%, for ST by 2%, while CFRP decreases by 1%.

3.4. Discussion of the results

This study analyzes the local seismic retrofit of reinforced concrete columns by effectively evaluating three traditional retrofit alternatives. From a holistic standpoint, the retrofit alternative that has demonstrated the most favorable performance is ST, followed by CFRP and RC. This ranking is attributed to the equilibrium observed in the economic, environmental, and functional criteria, as illustrated in Fig. 7. This representation depicts the average normalized values for each criterion across all alternatives. ST achieves a well-distributed surface area across all criteria without relying on extreme values.

This study adopts a cradle-to-gate approach in life cycle assessments, emphasizing the significance of considering all stages involved. The design and testing stage, pivotal in building retrofitting, necessitates semi-destructive tests for characterizing concrete's mechanical properties, determining reinforcement, and conducting specific tests ensuring the proper installation of chosen retrofit alternatives. Preventive maintenance addressing material deficiencies, concrete carbonation, steel corrosion, and the fire vulnerability of steel and carbon fibers holds considerable importance in economic and environmental analyses, particularly for ST and CFRP. In addition, although minimal values are obtained when assessing the end-of-life stage, they highlight factors that must be considered, especially in the case of RC. In the case of CFRP, recycling efforts are evolving, reflecting current trends in research; however, landfill disposal was used in this study.

It is necessary to reach a consensus on which discount rate is the most appropriate when assessing future economic and environmental impacts from a holistic sustainability perspective. High discount rates that are generally preferred from a private perspective neglect future costs, not being consistent with the definition of sustainability that seeks to ensure the satisfaction of present needs without compromising the ability of future generations to satisfy their own (Navarro et al., 2020). It has been recognized that the concept of temporal discounting from the economic field allows for addressing temporal issues in LCA, given its value-based nature (Yuan et al., 2015). The choice of a discount rate for environmental impacts is subjective and very decisive. To be meaningful, it must be close to 0 since, with a higher discount rate, even the potential impacts of emissions in the relatively short term (less than 100 years) would virtually disappear (Bakas et al., 2015). Even small rates around 1% marginalize impacts in just a few decades (Lueddeckens et al., 2020). The low social discount rate in economic impacts of 2% (Allacker, 2012) used in this study gives relevance to future expenditures that will burden future generations oriented towards sustainability. In terms of environmental impacts, considering a rate of zero allows us to have conservative values, considering the 50-year time horizon of this study.

Concrete jacketing exhibits significant environmental impacts from producing concrete and steel, both essential raw materials. The impact of using machinery during the construction and crushing concrete in the EoL stage exceeds the other alternatives. Furthermore, CR entails more significant architectural impacts. It also causes more prolonged interruptions in the normal functioning of the structure and may require interventions in the foundation. In the MCDM carried out, RC is the last in the ranking.

Incorporating CFRP as a retrofit yields notably lower environmental impact values when compared to the other two alternatives. According to Sbahieh et al. (2022), fiber-reinforced polymers are more sustainable and eco-friendlier than traditional materials. When comparing steel and CFRP, producing 1 kg of steel has a lower environmental impact than producing 1 kg of carbon fiber from virgin material. Despite this, CFRP demonstrates better environmental impact results due to reduced required material, attributed to its improved mechanical properties

Table 6
Criteria and indicators considered in MCDM.

Perspective	Criteria		Indicators	
Economic	Cost (Design and Test)	C1 (5.18%)	Design and semi-destructive testing ($/column)	I1 (100.00%)
	Cost (Construction)	C2 (27.44%)	Construction cost ($/column)	I2 (100.00%)
	Cost (Maintenance, EoL)	C3 (11.44%)	Preventive maintenance ($/column)	I3 (25.00%)
			Maintenance first 10 years ($/column)	I4 (25.00%)
			Demolition, classification of waste ($/column)	I5 (25.00%)
			Treatment and transport waste ($/column)	I6 (25.00%)
Environmental	Impacts (Manufacturing)	C4 (16.80%)	Ecosystem (Points)	I7 (33.33%)
			Human health (Points)	I8 (33.33%)
			Resources (Points)	I9 (33.34%)
	Impacts (Construction)	C5 (5.94%)	Ecosystem (Points)	I10 (33.33%)
			Human health (Points)	I11 (33.33%)
			Resources (Points)	I12 (33.34%)
	Impacts (Maintenance, EoL)	C6 (5.15%)	Ecosystem (Points)	I13 (33.33%)
			Human health (Points)	I14 (33.33%)
			Resources (Points)	I15 (33.34%)
Functionality	Impacts (Construction)	C7 (19.33%)	Architectural impact (scale)	I16 (50.00%)
			Duration of works/disruption to occupants (scale)	I17 (50.00%)
	Impacts (Technicians)	C8 (8.72%)	Need for specialized labor (scale)	I18 (50.00%)
			Importance of foundation intervention (scale)	I19 (50.00%)

Table 7
Weighting of functionality indicators.

Indicators	RC	ST	CFRP
Architectural impact	0.6738	0.2246	0.1016
Duration of works/disruption to occupants	0.4167	0.3333	0.2500
Need for specialized labor	0.1080	0.6004	0.2916
Importance of foundation intervention	0.6350	0.2204	0.1446

compared to steel (Palacios-Munoz et al., 2018). The environmental impact is reduced by up to 72% on average with respect to RC, according to the final normalized H/A scores. Retrofitting with CFRP implies minimal architectural impact and short installation times and requires no interventions in the foundations. However, the considerable costs of raw materials, fibers and resin remain essential when choosing the optimal alternative.

However, steel jacketing demonstrates intermediate values in five criteria. It faces drawbacks compared to the other two alternatives in the economic criterion C3 due to including two preventive maintenances—anticorrosion protection and passive fire protection. Consequently, it also fares less favorably in C6 due to environmental impacts from producing raw materials for preventive maintenance. Additionally, it is perceived to necessitate a higher level of specialized labor in C8. Nevertheless, these criteria are not significantly divergent from the values represented by the other alternatives.

Table 8
Decision matrix and ranking of alternatives.

Criteria	4 stories			7 stories			10 stories		
	RC	ST	CFRP	RC	ST	CFRP	RC	ST	CFRP
C1	183.28	213.03	261.08	177.19	206.93	254.98	177.19	206.93	254.98
C2	535.81	739.62	1381.56	635.11	875.88	1657.87	759.91	1015.35	1934.18
C3	34.91	79.60	69.11	41.38	97.18	83.05	46.42	113.37	96.99
C4	23.68	9.35	4.69	28.17	11.22	5.63	30.85	13.09	6.57
C5	6.28	4.19	1.93	7.22	5.03	2.32	8.17	5.87	2.71
C6	2.90	3.21	1.47	3.38	3.83	1.76	3.84	4.49	2.06
C7	0.55	0.28	0.18	0.55	0.28	0.18	0.55	0.28	0.18
C8	0.37	0.41	0.22	0.37	0.41	0.22	0.37	0.41	0.22
d_i^+	0.172	0.082	0.145	0.171	0.082	0.147	0.169	0.083	0.145
d_i^-	0.148	0.164	0.174	0.150	0.164	0.173	0.148	0.162	0.171
C_i^*	0.462	0.667	0.545	0.467	0.666	0.542	0.468	0.662	0.541
Rank	III	I	II	III	I	II	III	I	II

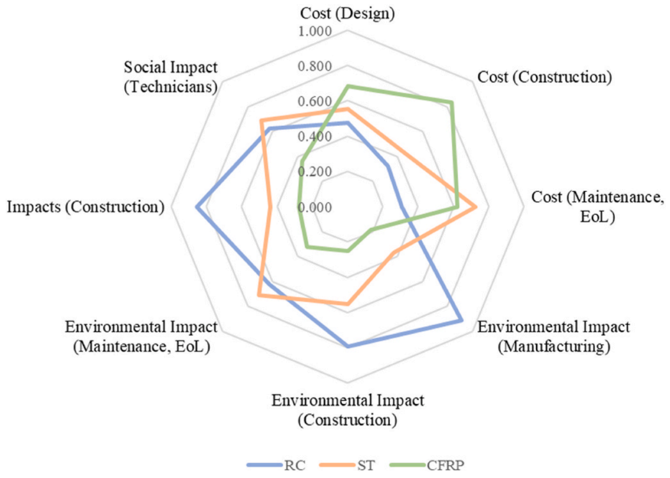


Fig. 7. Comparison of criteria between alternatives.

The DMs considered in this study allow us to ensure different viewpoints and various approaches. The selection of the number of experts in this study has been used in other relevant research, such as in the evaluation of the seismic vulnerability of buildings (Alam and Haque, 2022; Chu et al., 2021; Jamal-ud-din et al., 2023) and the selection of reinforcement strategies (Caterino et al., 2021). The aggregation of individual judgments satisfies the conditions of unanimity and homogeneity. Despite the above, determining the criteria weights is the most important source of uncertainty in the application of MCDMs and can significantly affect decision-making results. A sensitivity analysis of the proposed MCDM model was carried out by varying the weights of the three most significant criteria: construction costs, environmental impacts during the production stage, architectural impacts, and duration of the works (C2, C4, and C7). These weights were reduced and increased by 15% to maintain consistency in the AHP method. An additional scenario was also examined, in which all eight criteria are equally important. Fig. 8 illustrates the final TOPSIS scores of the seven scenarios, clearly demonstrating that ST remains relatively stable despite the weight changes. In the first six scenarios, it emerges as the best alternative.

In the scenario where the weight of the economic criterion is increased, RC improves its score, surpassing CFRP with a slight increase of 2%. Carbon fibers improve the score when the weight of the construction cost is reduced and when the environmental and functional criteria increase. ST achieved the highest score across the six scenarios where the weights of the most relevant criterion were adjusted. Only in the seventh scenario, where all criteria were given equal weight, does the order of the alternatives change. In this case, the CFRP emerged with the highest score.

4. Conclusions

Considering a holistic perspective, this paper presents a comprehensive methodology for assessing three alternatives for column retrofitting in reinforced concrete buildings. The study focuses on traditional column retrofitting alternatives in a high seismic-risk region with confinement deficiencies. The evaluated retrofit options include concrete jacketing, steel jacketing, and the incorporation of carbon fibers. The research employs a cradle-to-grave life cycle assessment methodology, considering economic and environmental factors. The economic assessment (LCC) encompasses the costs associated with design, necessary testing, construction, usage (including preventive maintenance), and end-of-life considerations. Meanwhile, the environmental assessment (LCA) analyzes the production, construction, usage, and end-of-life stages, adopting both midpoint and endpoint approaches to ensure a comprehensive understanding of the environmental impact.

The study assumes a helpful life of 50 years starting from the incorporation of retrofitting. An integrated model has been developed using Multi-Criteria Decision-Making methods, incorporating three economic, three environmental, and two functional criteria. These criteria are assessed through 19 specific indicators. The AHP was employed to determine the weightings of the criteria, and TOPSIS was used for the final ranking of the alternatives.

Within the framework of the hypotheses put forward in this study, the following conclusions can serve as guidance for decision-makers in the selection of reinforcement strategies to improve the confinement of reinforced concrete columns in buildings located in high seismic risk locations.

- Despite having the highest economic costs and environmental impacts associated with the required preventive maintenance, Steel jacketing maintains a balance between the five criteria analyzed, making it emerge as the optimal choice.
- Carbon fiber retrofit is also a viable alternative, mainly due to its lower environmental footprint and higher functionality. It is a more sustainable and environmentally friendly option than conventional

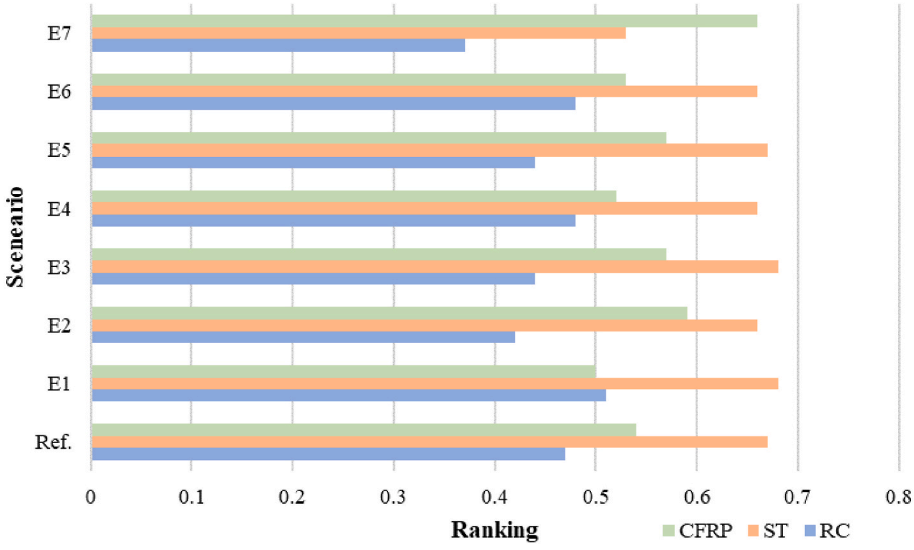


Fig. 8. Mcdm sensitivity analysis.

materials. However, its ranking score is limited by the significant costs associated with raw materials.

- Concrete jacketing appears to be the least favorable option from a holistic perspective. Despite lower expenses in design, testing, construction, and usage, it incurs significant total environmental impacts, primarily stemming from raw material production. Moreover, it poses more significant architectural implications and involves prolonged disruptions during repair work.

Future research could explore two key areas. Firstly, it incorporates the social dimension of sustainability through life cycle analysis. Second, although this study includes sensitivity analysis, it did not address the management of uncertainties. Engineering decisions are often made in uncertain environments, so it is critical to consider uncertainties. Often, the most subjective aspect of decision-making is assigning weights to criteria.

CRediT authorship contribution statement

Paola Villalba: Writing – original draft, Methodology, Conceptualization. **Antonio J. Sánchez-Garrido:** Writing – review & editing, Conceptualization. **Víctor Yepes:** Writing – review & editing, 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.

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Appendix A

Table A.1
Environmental impacts with TRACI 2.1 method.

Impact category	Reference unit	4 stories	7 stories	10 stories
Concrete Jacketing (RC)				
Acidification	kg SO2 eq	2.53	2.97	3.30
Carcinogenics	CTUh	4.82E-04	5.89E-04	6.28E-04
Ecotoxicity	CTUe	12399.34	15031.83	16158.27
Eutrophication	kg N eq	1.41	1.69	1.85
Fossil fuel depletion	MJ surplus	604.34	708.38	791.78
Global warming	kg CO2 eq	578.16	678.73	747.46
Non carcinogenics	CTUh	9.76E-05	1.16E-04	1.27E-04
Ozone depletion	kg CFC-11 eq	5.81E-05	6.81E-05	7.59E-05
Respiratory effects	kg PM2.5 eq	0.52	0.62	0.68
Smog	kg O3 eq	57.41	66.98	74.67
Steel Jacketing (ST)				
Acidification	kg SO2 eq	1.20	1.44	1.69
Carcinogenics	CTUh	6.29E-05	7.54E-05	8.80E-05
Ecotoxicity	CTUe	2911.75	3490.90	4076.39
Eutrophication	kg N eq	0.66	0.79	0.93
Fossil fuel depletion	MJ surplus	387.01	463.97	541.80
Global warming	kg CO2 eq	230.59	276.50	322.82
Non carcinogenics	CTUh	3.48E-05	4.17E-05	4.87E-05
Ozone depletion	kg CFC-11 eq	3.34E-05	4.01E-05	4.68E-05
Respiratory effects	kg PM2.5 eq	0.23	0.28	0.33
Smog	kg O3 eq	27.72	33.25	38.81
Fiber-Reinforced Polymers (CFRP)				
Acidification	kg SO2 eq	0.55	0.66	0.77
Carcinogenics	CTUh	4.91E-06	5.89E-06	6.87E-06
Ecotoxicity	CTUe	284.07	341.29	398.08
Eutrophication	kg N eq	0.12	0.14	0.16
Fossil fuel depletion	MJ surplus	156.45	187.78	219.06
Global warming	kg CO2 eq	288.66	346.27	404.05
Non carcinogenics	CTUh	9.80E-06	1.18E-05	1.37E-05
Ozone depletion	kg CFC-11 eq	1.72E-05	2.06E-05	2.41E-05
Respiratory effects	kg PM2.5 eq	0.06	0.08	0.09
Smog	kg O3 eq	14.84	17.81	20.77

Table A.2
Environmental impacts with EF 3.1 method.

Impact category	Reference unit	4 stories	7 stories	10 stories
Concrete Jacketing (RC)				
Acidification	mol H+ equivalents	2.88	3.38	3.75
Climate change	kg CO2 Equivalents	583.19	684.75	754.05
Climate change-Biogenic	kg CO2-Equivalents	0.49	0.58	0.64
Climate change-Fossil	kg CO2 Equivalents	582.45	683.88	753.10
Climate change-Land use and land use change	kg CO2-Equivalents	0.25	0.29	0.32
Ecotoxicity, freshwater	CTUe	4039.91	4790.44	5413.39
Ecotoxicity, freshwater_inorganics	CTUe	2474.83	2934.92	3274.80
Ecotoxicity, freshwater_organics	CTUe	1565.08	1855.52	2138.59
EF-particulate Matter	disease incidence	5.34E-05	6.28E-05	6.97E-05
Eutrophication marine	kg N equivalents	0.95	1.11	1.24
Eutrophication, freshwater	kg P equivalents	0.14	0.17	0.19
Eutrophication, terrestrial	mol N equivalents	10.11	11.79	13.14
Human toxicity, cancer	CTUh	1.91E-06	2.33E-06	2.49E-06
Human toxicity, cancer_inorganics	CTUh	1.11E-06	1.35E-06	1.44E-06
Human toxicity, cancer_organics	CTUh	8.01E-07	9.74E-07	1.05E-06
Human toxicity, non-cancer	CTUh	4.51E-06	5.34E-06	5.83E-06
Human toxicity, non-cancer_inorganics	CTUh	4.27E-06	5.05E-06	5.51E-06
Human toxicity, non-cancer_organics	CTUh	2.41E-07	2.83E-07	3.13E-07
Ionising radiation, human health	kBq U235 equivalents	26.11	30.79	34.03
Land use	dimensionless (pt)	3031.78	3524.30	3868.72
Ozone depletion	kg CFC11 equivalents	5.39E-05	6.31E-05	7.05E-05
Photochemical ozone formation - human health	kg NMVOC equivalents	3.19	3.75	4.16
Resource use, fossils	MJ	6147.78	7264.32	8040.32
Resource use, minerals and metals	kg Sb equivalents	2.90E-03	3.39E-03	3.77E-03
Water use	m3-world equivalents	45.56	50.80	56.66
Steel Jacketing (ST)				
Acidification	mol H+ equivalents	1.36	1.63	1.90
Climate change	kg CO2 Equivalents	233.31	279.75	326.62
Climate change-Biogenic	kg CO2-Equivalents	0.89	1.07	1.25
Climate change-Fossil	kg CO2 Equivalents	232.28	278.52	325.19
Climate change-Land use and land use change	kg CO2-Equivalents	0.13	0.16	0.18
Ecotoxicity, freshwater	CTUe	3491.28	4182.03	4887.76
Ecotoxicity, freshwater_inorganics	CTUe	1696.66	2032.85	2375.28
Ecotoxicity, freshwater_organics	CTUe	1794.63	2149.18	2512.48
EF-particulate Matter	disease incidence	2.61E-05	3.13E-05	3.65E-05
Eutrophication marine	kg N equivalents	0.45	0.54	0.63
Eutrophication, freshwater	kg P equivalents	0.05	0.06	0.07
Eutrophication, terrestrial	mol N equivalents	4.80	5.76	6.72
Human toxicity, cancer	CTUh	3.60E-07	4.32E-07	5.04E-07
Human toxicity, cancer_inorganics	CTUh	1.49E-07	1.78E-07	2.08E-07
Human toxicity, cancer_organics	CTUh	2.12E-07	2.54E-07	2.96E-07
Human toxicity, non-cancer	CTUh	1.49E-06	1.79E-06	2.09E-06
Human toxicity, non-cancer_inorganics	CTUh	1.35E-06	1.62E-06	1.89E-06
Human toxicity, non-cancer_organics	CTUh	1.39E-07	1.67E-07	1.95E-07
Ionising radiation, human health	kBq U235 equivalents	13.67	16.39	19.13
Land use	dimensionless (pt)	933.18	1119.20	1306.41
Ozone depletion	kg CFC11 equivalents	3.15E-05	3.78E-05	4.41E-05
Photochemical ozone formation - human health	kg NMVOC equivalents	1.54	1.84	2.15
Resource use, fossils	MJ	3394.14	4068.91	4751.70
Resource use, minerals and metals	kg Sb equivalents	1.25E-03	1.50E-03	1.75E-03
Water use	m3-world equivalents	−1.50	−1.80	−2.10
Fiber-Reinforced Polymers (CFRP)				
Acidification	mol H+ equivalents	0.61	0.73	0.86
Climate change	kg CO2 Equivalents	289.05	346.74	404.60
Climate change-Biogenic	kg CO2-Equivalents	0.68	0.82	0.96
Climate change-Fossil	kg CO2 Equivalents	288.35	345.90	403.61
Climate change-Land use and land use change	kg CO2-Equivalents	0.02	0.02	0.03
Ecotoxicity, freshwater	CTUe	333.46	400.25	466.92
Ecotoxicity, freshwater_inorganics	CTUe	269.50	323.48	377.37
Ecotoxicity, freshwater_organics	CTUe	63.95	76.76	89.55
EF-particulate Matter	disease incidence	1.00E-05	1.20E-05	1.40E-05
Eutrophication marine	kg N equivalents	0.24	0.28	0.33
Eutrophication, freshwater	kg P equivalents	6.75E-03	8.10E-03	9.45E-03
Eutrophication, terrestrial	mol N equivalents	2.57	3.09	3.60
Human toxicity, cancer	CTUh	2.64E-08	3.18E-08	3.71E-08
Human toxicity, cancer_inorganics	CTUh	1.45E-08	1.75E-08	2.04E-08
Human toxicity, cancer_organics	CTUh	1.19E-08	1.43E-08	1.67E-08
Human toxicity, non-cancer	CTUh	6.73E-07	8.08E-07	9.42E-07
Human toxicity, non-cancer_inorganics	CTUh	6.52E-07	7.83E-07	9.14E-07
Human toxicity, non-cancer_organics	CTUh	2.06E-08	2.47E-08	2.88E-08
Ionising radiation, human health	kBq U235 equivalents	5.37	6.45	7.52
Land use	dimensionless (pt)	533.31	640.09	746.73

(*continued on next page*)

Table A.2 (*continued*)

Impact category	Reference unit	4 stories	7 stories	10 stories
Ozone depletion	kg CFC11 equivalents	1.63E-05	1.96E-05	2.28E-05
Photochemical ozone formation - human health	kg NMVOC equivalents	0.69	0.83	0.97
Resource use, fossils	MJ	1136.25	1363.78	1590.98
Resource use, minerals and metals	kg Sb equivalents	1.79E-04	2.15E-04	2.51E-04
Water use	m3-world equivalents	−0.06	−0.07	−0.09

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